Interim Report

Consultancy Services & Owner's Engineer for the Synchronisation of WAPP Interconnected Network

Benin

West African Power Pool

Interim Report

Static and Dynamic Analysis of the WAPP interconnected network

ORIGINAL

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1 INTRODUCTION

This document is part of the Interim Report of the Project "Consultancy Services & Owner's Engineer for the Synchronization of WAPP Interconnected Network" and covers the following Tasks and Sub-Tasks:

- Task 3 – Static and dynamic system simulations
    - Task 3.1 – Steady-State Simulation Analysis
    - Task 3.2 – Small-Signal Stability Studies
    - Task 3.3 – Dynamic Stability Studies
    - Task 3.4 – WAMS Study
    - Task 3.5 – Definition of the necessary reinforcements and cost estimation
- Task 4 – Back-to-Back DC link alternative at Sakété substation

The analyses are based on the WAPP model set-up according to the data provided by WAPP and Utilities during the data collection phase and described in the Data Report [2].

The document is organized as follows.

- Chapter 2 includes a brief overview of the analyses and scenarios.
- Chapter 3 includes the steady-state simulations focused on the contingency analysis, sensitivity analysis and short-circuit calculation.
- Chapter 4 includes the dynamic simulations, covering the small signal stability analysis, the dynamic security assessment and the transient stability analysis.
- Chapter 5 includes the WAMS study, consisting of recommendations for developing of a WAMS system in the WAPP network.
- Chapter 6 includes the evaluation of the installation of a back-to-back DC link at the Sakété substation.
- Chapter 7 includes the proposed reinforcements identified through the simulation analyses and related costs estimations.

2 OVERVIEW OF THE ANALYSES

The analyses were performed as per the methodology agreed with WAPP according to the stages summarized in Figure 2.1 and below described.

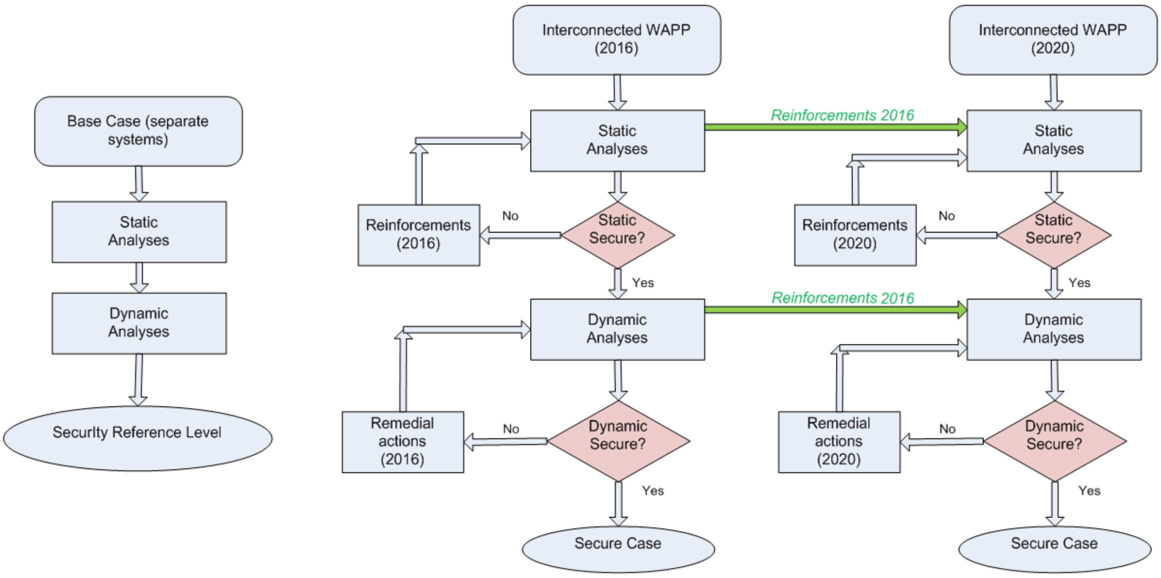


Figure 2.1: Stages of the analysis

1. *Definition of the Security Reference Level*

   The goal of the study is to propose the necessary updates and reinforcements to the WAPP power system in order to achieve the secure operation of the interconnected system for the years 2016 and 2020. In order to compare the improvements of the proposed solutions with respect to the current situation, the analyses are first carried out on the present system model (Base Case) in order to get a reference point.

2. *Execution of the analyses on the 2016 model*

   The initial analyses are related to the static security assessment. Using the outcomes of these analyses, a first reinforcement list and recommendations are provided. The dynamic security analyses and related reinforcements and recommendations are discussed based on the results of the static analysis and considering the preliminary reinforcements list.

3. *Execution of the analyses on the 2020 model*

   Considering the recommendations and reinforcements provided in point 2 already implemented in the 2020 network model, the same analyses are carried out on the 2020 scenarios. The reinforcements and recommendations for the 2020 scenarios are the output of those analyses.

2.1 Scenarios

Following scenarios are considered (details on scenarios are available in the Data Report [2]).

Table 2.1: List of Scenarios

ID	Year	Load	Case	System Interconnection (*)	Dynamic models
S16-CP	2016	Peak	Base Peak	Current network (split in 3 blocks)	Not optimized (**)
S16-CO	2016	Off-Peak	Base Off Peak	Current network (split in 3 blocks)	Not optimized (**)
S16-IP	2016	Peak	Inter Peak	Interconnected network	Not optimized (**)
S16-IO	2016	Off-Peak	Inter Off Peak	Interconnected network	Not optimized (**)
S16-RP	2016	Peak	Inter-Reinf-Peak	Interconnected and Reinforced Network	Optimized (***)
S16-RO	2016	Off-Peak	Inter Reinf Off Peak	Interconnected and Reinforced Network	Optimized (***)
S20-RP	2020	Peak	Base peak	Future planned Interconnected and reinforced network	Optimized (***)
S20-RO	2020	Off-Peak	Base Off Peak	Future planned Interconnected and reinforced network	Optimized (***)
S16-RP-Btb	2016	Peak	Inter-Reinf-BtB Peak	Interconnected and Reinforced Network with BtB at Saketé substation	Optimized (***)
S16-RO-Btb	2016	Off-Peak	Inter Reinf-BtB Off Peak	Interconnected and Reinforced Network with BtB at Saketé substation	Optimized (***)

(*) Operated with power exchanges setup as per bilateral agreements provided by WAPP [13]

(**) Actual dead-band, limited participation in frequency control, PSS/AVR not optimized

(***) Typical dead-band 20 mHz, improved participation in frequency control, PSS/AVR optimized

3 STEADY STATE ANALYSIS

This activity is aimed at performing static analyses for evaluating the security of the WAPP system in different time horizons and, where necessary to suggest the necessary reinforcements. This study covers N and N-1 security analyses, voltage sensitivity analysis and short circuit current assessment.

3.1 Methodology

3.1.1 Contingency analysis

The contingency is applied in order to assess the compliance of the WAPP system with the steady state security standards. The Contingency Analysis considers the following assumptions:

Monitored elements

Network equipment connected to buses with nominal voltage equal or above 132 kV in the whole WAPP system are monitored. The detection of violations of the operational limits is performed in both N and N-1 conditions.

Operational limits

The Operational limits considered for the detection of violations are reported in Table 3.1 [14].

Table 3.1: Operational limits

Conditions	Operational limits	
N	Voltage	±5%
	Loading of lines and transformers	<100%
N-1	Voltage	±10%
	Loading of lines	<110%
	Loading of transformers	<120%

Contingency set

In N-1 conditions, the contingency set involves the following network elements connected to buses with nominal voltages equal or above 90 kV; in particular the individual tripping of lines, breakers, two and three winding transformers and shunts is considered, in addition to the trip of each generating units within the WAPP system.

Primary Frequency Control of Generating Units

In case of generation loss and N-1 contingencies leading to network separations, the contribution of the primary control of the generators is essential to evaluate the possibility of the electrical islands to achieve a new equilibrium point and to determine the post-contingency steady state flows on the system. In steady-state analyses, the steady state primary frequency control contribution is considered and calculated through the generators permanent droop. The permanent droop is set-up into the INL[1] PSSE file and the related values for the machines of the whole system derived from the PSSE DYR file containing the information of the governors [A1] [A2].

Loads voltage dependence

In the WAPP power system PSS®E model, the loads are represented connected to the MV busbars. In the current analysis it's assumed that the short-term electromechanical dynamics have died out, and the load model is represented with active power as constant current and reactive power as constant impedance [4].

Tap changers and switchable shunts

In the short term time horizon, where only short-term electromechanical dynamics have died out, tap changers and switchable shunts are not operated, and then in the post-contingency analysis are considered fixed. Only the SVCs controls are considered enabled in this time horizon.

3.1.2 Voltage sensitivity analysis

The voltage sensitivity analysis is applied in the framework of this study to find the best locations to install the reactive compensation necessary to improve the voltage control especially in N and N-1 conditions.

3.1.2.1 Voltage sensitivity calculation

The voltage sensitivities are calculated as $\frac{\delta V_i}{\delta Q_j}$. The variation of the voltage in the i-th bus (δV_i) is evaluated by injecting 1 Mvar of reactive power in the j-th bus (δQ_j). The set of i-th buses includes all the system buses with nominal voltage equal or above 90 kV.

3.1.2.2 Determination of the best locations for installing reactive compensation

Starting from the results of the contingency analyses (§3.2.1 and §3.4.1) the list of the buses where voltage violations occur (Violated Buses) is available. For such buses the sensitivities against reactive power injection in all system buses is calculated.

The criteria used to select the best location for installing reactive compensation are the following:

1. Buses having the highest sensitivity on the Violated Buses

[1] PSSE Inertia and Governor Response Data Files [5]

2. Buses influencing the largest amount of Violated Buses. The influence is measured by counting the number of occurrences of sensitivities higher than 0.001 p.u. on the Violated Buses.

The buses ranked with these criteria are then filtered on the basis of the following considerations:

3. Buses with high sensitivities only on few Violated Voltage Buses filtered out. This local influence is measured by calculating the mean value of the sensitivities higher than 0.001 p.u. on the Violated Buses.
4. Buses electrically close to locations where reactive compensation resources (generators, shunt compensators, etc.) are already available are filtered out.

3.1.3 Short circuit currents assessment

Short-circuit currents are fundamental quantities to be known for the design of equipment and for the operation of power systems. The short-circuit analysis is required to ensure that existing and new equipment ratings are adequate to withstand the short circuit energy available at each point in the electrical system. In particular, the analysis is aimed at the evaluation of the adequacy of the *rated short-circuit breaking current* [13] against the 1-PH and 3-PH short circuits occurring in the substations belonging to the WAPP Interconnection.

The calculation of the short-circuit levels are performed considering the peak and off-peak conditions related to the 2016 and 2020 scenarios.

3.1.3.1 Calculation Method

The calculations of the short circuits currents are executed according with the IEC 60909 standard [16] considering a voltage factor equal to 1.1.

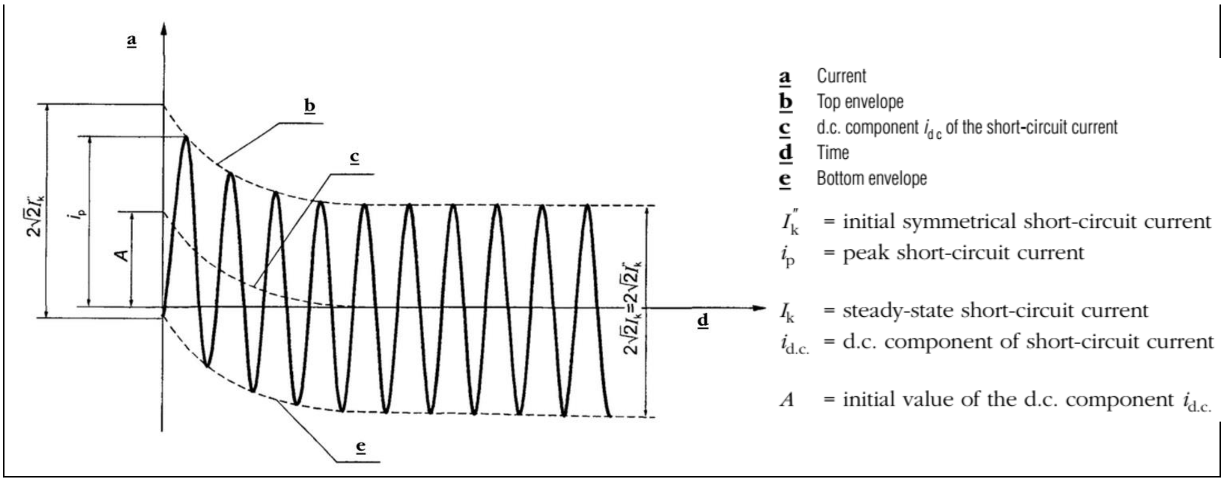
3.1.3.2 Assessment of the rated short circuit breaking current adequacy

According to IEC standard 62271-100 [6], the rated short-circuit breaking current is defined as follows[6][7]:

The *rated short-circuit breaking current* is the highest short-circuit current which the circuit breaker shall be capable of breaking under the conditions of use and behavior prescribed in this standard. The rated short-circuit breaking current is characterized by two values:

- **The R.M.S. value of its A.C. component**
- **The d.c. time constant of the rated short-circuit breaking current which results in a percentage of d.c. component at contact separation**

If the percentage of d.c. component at contact separation does not exceed 20 %, the rated short-circuit breaking current is characterized only by the R.M.S. value of its A.C. component.



In case of d.c. components higher than 20% they shall be clearly stated in the requirements when specifying the circuit breakers: this requires that suitable breaker tests are performed. According to the IEC standard, the selection of the circuit breaker requirement is made on the basis of the "rated short-circuit breaking current" intended as the R.M.S. value of its A.C. component and specifying the % d.c. component at the instant of contact separation.

Considering the above described prescriptions, included in the IEC standard, in order to assess the "rated short-circuit breaking current" adequacy, it has to be compared with the symmetrical component of the short circuit current[2].

For each bus on which the short circuit current are calculated, the symmetrical short-circuit breaking currents Ib (SYM) are reported and considered for the evaluation of the rated short-circuit breaking current adequacy.

3.1.3.3 Breaking Capacities

Since no information about the breaking capacities is available, typical conservative values based on typical values for the different voltage levels, are assumed. The considered values are summarized in Table 3.2.

Table 3.2: Breaking Capacity – Typical Values by Voltage Level

Breaking Capacity [kA]	Voltage Levels [kV]
20	90, 110, 132, 150
31.5	161, 225, 330

[2] It has to be pointed out that according with the standard IEEE C37-04 Standard, even in the cases where the asymmetrical current at contact separation (as per IEEE C37-04 Standard) exceeds the R.M.S. value of the a.c. component of the "Rated short-circuit breaking current", a suitable d.c. component (or the correspondent X/R ratio) is supposed to have been required in the breaker specification.

3.2 Results – 2016 Scenarios

The following Table 3.3 and Table 3.4 summarize the main characteristics of the reference (base) and interconnected cases of the WAPP system described in chapter §2.1.

A load-flow analysis for the 2016 cases in N condition has been performed as a verification test for the static model. In N condition no line overload occurs (monitored voltage level greater or equal to 90 kV). Some transformers overload occurs, mainly concentrated in transformers supplying the load on MV levels, as reported in [2].

Table 3.3: 2016 peak load scenario characteristics

	P_{GEN} (MW)	P_{LOAD} (MW)	LOSSES (MW)	EXCHANGE[3] (MW)	Reserve Base Case		Reserve Rein-forced Case	
					MW	%	MW	%
TCN	4606	4145	114	346	280	5.12	276.3	5.05
CEB	117	430	14	-327	28.8	10.62	35.2	12.98
NIGELEC	127	212	15	-100	0	0	15.6	9.15
SOGEM	231	1	12	219	20.2	7.76	16.5	6.34
GRIDCO	2137	1987	71	79	204	7.77	281	10.64
CIE	1450	1325	42	83	31.5	1.96	112.6	7.02
SONABEL	205	250	6	-50	6.4	3.43	16.7	8.98
EDM-SA	118	255	3	-140	0	0	21	11.69
SENELEC	477	552	4	-80	0	0	43	8.48
SOMELEC	0	30	0	-30	0	0	0	0
TOTALS	**9468**	**9187**	**281**	**0**	**571**		**818**	

[3] Here and in the following similar tables, a positive value of exchanged power means power exported from the country, while a negative value means power imported in the country

Table 3.4: 2016 off-peak load scenario characteristics

	P_{GEN} (MW)	P_{LOAD} (MW)	LOSSES (MW)	EXCHANGE[4] (MW)	Reserve Base Case		Reserve Reinforced Case	
					MW	%	MW	%
TCN	4604	4145	114	344	282	5.16	276	5.05
CEB	72	384	13	-325	21.8	18.49	30	25.41
NIGELEC	41	127	14	-100	0	0	11.3	18.17
SOGEM	181	0	12	168	40.1	16.70	38.4	16
GRIDCO	1922	1789	52	81	183.8	7.98	211	9.17
CIE	758	663	15	80	67.9	5.51	321	26.06
SONABEL	37	85	2	-50	0	0	6.9	15.60
EDM-SA	25	112	1	-88	0	0	6.5	21.8
SENELEC	141	221	1	-80	0	0	15.6	8.79
SOMELEC	0	30	0	-30	0	0	0	0
TOTALS	**7781**	**7557**	**224**	**0**	**596**		**917**	

3.2.1 Results of Contingency Analysis – 2016 Scenarios

The Contingency Analysis has been performed on all the 2016 scenarios (base and interconnected, peak and off-peak) according to the methodology explained in §3.1.1. The main results are summarized in Table 3.5 and Table 3.6, while the detail of the complete analysis are available in [A3]

Table 3.5 is related to the contingencies mainly involved in local violations not significantly impacting the interconnections.

On the contrary Table 3.6 includes the contingencies with a direct impact on the interconnections, which could be critical for the security and stability of the WAPP interconnected system.

In order to present the relevant outcomes of the analyses performed, the results have been filtered out as follows:

- Contingencies related to the single trip of series capacitors or breakers were excluded from the results, to avoid cases with lines operated without load.
- Overloads are reported as percentage of the emergency ratings (see Table 3.1), while voltage violations are reported as percentage of the rated voltage.

Moreover, the following naming convention has been adopted to group the scenarios:

- “Inter” = interconnected scenarios (peak and off-peak)
- “Base” = base/reference scenarios (peak and off-peak)
- “Peak” = peak scenarios (base and interconnected)
- “Off-Peak” = off-peak scenarios (base and interconnected)
- “All” = all scenarios

[4] Here and in the following similar tables, a positive value means power exported from the country, a negative value means power imported in the country

Table 3.5: Contingencies and violations not significantly impacting the interconnections – 2016 scenarios

Contingency	Vnom [kV]	Violations	Scenarios	Area
Kodialani 1 & 2	225/150	Overloads (max 120%) on each transformer caused by the trip of the second one	Peak	EDM-SA
Sikasso – Koutiala	225	Undervoltage at Koutiala 225 kV (89%)	Inter-Peak	EDM-SA
Lafia – Kodialani	150	Undervoltage at Lafia 150 kV (min 85%)	Peak	EDM-SA
Touba – Kaolack	225	Overload (101%) on Kayes – Bakel 225 kV	Inter-Peak	SENELEC
Gombe – Jos	330	Non-convergent power-flow (dynamic analyses high-lighted significant local voltage collapses)	All	TCN
Nhaven – Onitsha.	330	Overloads (132 kV lines): Nhaven – Oji Riv (128%) Agu Awka – Awka (144%) Agu Awka – Oji Riv (135%) Awka – Onitsha BBII (158%) Local undervoltages (min 41%)	All	TCN
Egbin – Ikorodu 1 & 2	132	Trip of a line of the dou-ble circuit overloads the second line (max. 138%)	All	TCN
Ikeja West – Ali-misho 1 & 2	132	Trip of a line of the dou-ble circuit overloads the second line (max. 125%)	All	TCN
Akangba BBII – Amuwo Odofin	132	Overload on Akangba BBII – Apapa RD 132 kV (max 110%)	All	TCN
Aloji – Aba 1 & 2	132	Trip of a line of the dou-ble circuit overloads the second line (max. 101%)	All	TCN
Onitsha – Alaoji	330	Akosombo – Asiekpe 161 kV (107%)	Inter-Peak	TCN
Gombe – Yola	330	Significant local un-dervoltages (min 40%)	All	TCN
Ganmo 3WT	330/132/33	Local undervoltages (min 89%)	All	TCN
Ibadan North – Iwo	132	Overvoltage (max 110.2%) at	All	TCN

		Iseyin 132 kV		
Sokoto – B.Kebbi II	132	Local undervoltages (min 77%)	All	TCN
Sokoto – Tmafara	132	Local undervoltages (min 89%)	All	TCN
B.Kebbi	330/132/33	Local undervoltages (min 82%)	All	TCN
Kaduna – Zaria	132	Local undervoltages (min 63%)	All	TCN
Zaria – Funtua	132	Local undervoltages (min 72%)	All	TCN
Tmafara – Gusau	132	Undervoltage (min 88.8%) at Gusau 132 kV	All	TCN
Tmafara – Gusau	132	Undervoltage (min 88.8%) at Gusau 132 kV	All	TCN
Sakete 1 & 2	330/161	Overloads (max 105%) on each transformer caused by the trip of the second one	All	CEB
Onigbolo – Sakete	161	Local undervoltages (min 88%)	Base	CEB
Parakou shunt	161	Local overvoltages (max 116%)	All	CEB
Kara shunt	161	Local overvoltages (max 113%)	Base-Off-Peak, Inter	CEB
Tarkwa – Prestea	161	Overload on Tarkwa – New Tarkwa 161 kV (128%)	All	GRIDCO
		Overload on New Tarkwa – Prestea 161 kV (106%)	Peak	
Aboadze – Aboadze PSH	161	Overload on Cape Coast – Aboadze T3 161 kV (101.5%)	Peak	GRIDCO
Volta - Aboadze	330	Overload on Cape Coast – Aboadze T3 161 kV (100.3%)	Peak	GRIDCO
Tamale – Buipe	161	Local undervoltages (min 78%).	All	GRIDCO
Buipe - Kintampo	161	Local undervoltages (min 78%).	All	GRIDCO
Ferké – Korhogo	90	Non-convergent power-flow (dynamic analyses highlight significant local voltage collapses)	Peak	CIE

Buyo – Man	225	Non-convergent power-flow (dynamic analyses high-lighted local voltage col-lapses on 90 kV network)	Peak	CIE
		Local undervoltages (73%).	Off-Peak	
Soubre – Buyo	225	Local undervoltages (min 84%)	Peak	CIE
Man – Laboa	225	Local undervoltages (min 84%)	Peak	CIE
Goroubanda Gen – Goroubanda	132	Non-convergent power-flow (dynamic analyses high-lighted significant local voltage collapses in NI-GELEC_FLEUVE area)	Peak	NIGELEC
		Local undervoltages (min 79%)	Off-Peak	
Gazoua – Maradi 2	132	Non-convergent power-flow (dynamic analyses high-lighted significant local voltage collapses/black-out in the disconnected NI-GELEC_NCE area)	Peak	NIGELEC
		Local overvoltages (max 161%)	Off-Peak	
Niamey 2 CS – Guesselbodi	132	Local overvoltages (max 111%)	Off-Peak	NIGELEC
Gazoua – Maradi 2	132	Local overvoltages (max 162%)	Off-Peak	NIGELEC
Maradi 2– Maradi	132	Overvoltage (max 130%) at Maradi 132 kV	Peak	NIGELEC
Maradi 2– Malbaza 2	132	Overvoltage (max 115%) at Malbaza 2 132 kV	Base-Peak	NIGELEC
Niamey 2 Gen	132	Local undervoltages (min 87%)	Off-Peak	NIGELEC
Goudel Gen	132	Local undervoltages (min 89%)	Off-Peak	NIGELEC
Goroubanda Gen	132	Local undervoltages (min 79%)	Off-Peak	NIGELEC

General comments and recommendations on local violations:

Contingencies with local voltage violations, having no direct impact on the interconnection and thus being out of scope the current project, should be further investigated; in some cases local voltage collapses were observed and suitable countermeasures need to be implemented. In other cases less critical violations could be addressed assuring an adequate reactive power support to improve voltage profiles (e.g. implementing shunt compensation or voltage control in power plants).

Following contingencies:

- Gombe – Jos 330 kV (TCN, all scenarios)
- Buyo – Man 225 kV (CIE, peak scenarios)
- Ferké – Korhogo 90 kV (CIE, peak scenarios)
- Goroubanda Gen – Goroubanda 132 kV (NIGELEC, peak scenarios)
- Gazoua – Maradi 2 132 kV (NIGELEC, peak scenarios)

results in non-convergent power flow and the dynamic simulations highlighted significant but local voltage collapses. As recommendations local measures, like network reinforcements, protections or compensations, should be implemented by the TSO to assure the system security in case of trip of the line (N-1 criterion).

Local overloads could be managed with generation redispatching and/or network reconfigurations. It is important to equip the SCADA/EMS system with reliable and efficient alarms, so that the control room operators can supervise the power system effectively.

At Kodialani (EDM-SA) substation an additional 225/150 kV transformer could be a potential reinforcement to avoid overloads in case of trip of one of the two currently installed transformers. The same considerations may be applied at Saketé (CEB) 330/161 kV substation.

Table 3.6: Critical contingencies with direct impact on the interconnections – 2016 scenarios

Contingency	Vnom [kV]	Violations	Scenarios	Area
Kodialani – Kita - Manantali	225	Non-convergent power-flow	Inter-Peak	SOGEM
		Local undervoltages in EDM 150 kV network (min 89%) and at Kodialani 225 kV (87%)	Inter-Off-Peak	
Manantali – Kayes	225	Non-convergent power-flow	Inter-Off-Peak	SOGEM
		Overvoltages in SOGEM 90 kV and 225 kV network (max 111%)	Base-Off-Peak	
		Overloads on Kita – Kodialani 225 kV (109%), Kita – Manantali 225 kV (108%) and Kalabancoro – Kodialani 150 kV (120%) Undervoltage (89%) at Segou 150 kV	Inter-Peak	

Kayes – Bakel	225	Non-convergent power-flow	Inter	SOGEM
		Overvoltages (max. 119%) in SOGEM 90 kV and 225 kV network (max 111%) and part of SENELEC 225 kV network	Base Off-Peak	
Bakel – Matam	225	Non-convergent power-flow	Inter	SOGEM
Matam – Dagana	225	Non-convergent power -flow	Inter	SOGEM
Dagana – Sakal	225	Overloads on Kita – Kodialani 225 kV (104%), Kita – Manantali 225 kV (103%) and Kalabancoro – Kodialani 150 kV (112%)	Inter-Peak	SOGEM
B.Kebbi – Kainji	330	Non-convergent power-flow	All	TCN
Kaduna – Kano	330	Non-convergent power-flow	All	TCN
Kaduna 3WT	330/132/33	Non-convergent power-flow	All	TCN
Katsina – Gazoua	132	Several over and undervoltages in the 132 kV network between Nigeria and Niger (max 138%)	All	TCN/NIGELEC
Gazoua LR – Gazoua	132	Overvoltages (max 138%) in Niger and Nigeria	All	NIGELEC
Ikeja – Sakete	330	Non-convergent power-flow	Base-Off-Peak, Inter	TCN/CEB
Ferké 2WT	225/90	Non-convergent power-flow	All	CIE
Ferké – Bouake 2	225	Non-convergent power-flow	All	CIE
Kossou – Bouake 2	225	Non-convergent power-flow	All	CIE
Taabo – Kossou	225	Non-convergent power-flow	Peak	CIE

Comments and Recommendation on critical contingencies

Some of the most critical contingencies lead to non-convergent power-flows, which could be an indicator of potential instabilities and have to be investigated through dynamic analyses. Details of the dynamic contingency analysis are reported in §4.2.1 and the results and proposed measures are summarized in Table 3.7.

Table 3.7: Results of the dynamic contingency analysis for the critical contingencies

Contingency	Vnom [kV]	Results of Dynamic Analysis	Scenarios	Proposed Measures
Ikeja – Saketé	330	Unstable: separation of part of the CEB network affected by a widespread and significant voltage collapse.	Base	A possible measure to face undervoltages in CEB network could be the installation of controllable reactive compensation (estimated more than 100 MVAR needed and as possible candidate the substation Davie 330 kV). Nevertheless considering the planned 330 kV costal backbone (which should be committed in the short-term) the Ikeja – Saketé contingency becomes neither unstable nor affected by critical undervoltages, also in case of trip of either the Asogli – Davie or the Davie – Saketé 330 kV lines.
		Stable but with undervoltages: in the interconnected scenarios the whole CEB network remains connected to the west block of WAPP network (through the 161 kV interconnection with GRIDCO). Nevertheless widespread and severe undervoltages in the CEB network are detected.	Inter	
Kayes – Bakel	225	Unstable (Inter scenarios), Stable but insecure (base scenarios): separation of SENELEC and part of SOGEM network that remain stable with UFLS intervention, while inside the rest of SOGEM and EDM network over-frequencies and for Interconnected scenarios out of steps of some units occur.	Base, Inter	A proposed measure to face the loss of synchronism in the interconnected case is to install an out-of-step relay which can separate EDM-SA and CIE control areas. Sikasso 225 kV substation is a candidate location. In this case, the relay will be able to trip the 225 kV line Sikasso –

				Ferké in case of detection of “out-of-step” conditions. The proposed reinforcements lead to a situation similar to the base case as shown in §4.2.1.2.3. The over-frequency which occurs in the base case has to be faced with over-speed protections on units (not included in the model) with a proper selective tuning in order to avoid simultaneous generation disconnections.
Ferké	225/90	Stable with undervoltages: the 90 kV CIE Network close to Ferké substation (Ferké, Korhogo, Boundiali, Odienne, Laboa, Seguela) is affected by severe undervoltages (voltages up to 50%).	Base, Inter	In the medium/long-term (2020) a network reinforcement is planned with the 225 kV lines Ferké – Boundiali – Laboa and the installation of an additional 225/90 kV transformer at Ferké. These reinforcements will allow a more stable situation in case of trip of the transformer at Ferké. For the short-term (before the planned network reinforcement) it is recommended to implement an UVLS scheme for the 90 kV network in the Ferké area.
Ferké – Bouake 2	225	Unstable: EDM and SONABEL networks remain connected to CIE network only through the Ferké 225/90 kV transformer. Out of steps of some units were observed in the Ferké area.	Base, Inter	In the medium/long-term (2020) a network reinforcement is planned with the 225 kV lines Ferké – Boundiali – Laboa and the installation of an additional 225/90 kV transform-

				er at Ferké. These reinforcements will allow a more stable situation in case of trip of the line Ferké – Bouake 2. For the short-term (before the planned network reinforcement) it is recommended to install an intertrip relay (with the possible deactivation if the power flows on the line is below a predefined threshold) with the transformer at Ferké, causing a network separation (EDM and SONABEL remain connected only with the 225 kV busbar at Ferké). The trip of the transformer at Ferké could activate the UVLS for the 90 kV network in the Ferké area (CIE), as reported in the previous point.
Kossou – Bouake 2	225	Unstable: Severe voltage collapses on the 90 kV network.	All	In the medium/long-term (2020) a network reinforcement is planned with the 225 kV lines Kossou – Bouake 3 – Bouake 2. These reinforcements will allow a more stable situation in case of trip of the line Kossou – Bouake 2. For the short-term (before the planned network reinforcement) it is recommended to install a Special Protection scheme able to disconnect part of the generation in

				Taabo and Kossou power plants depending on the pre-contingency value of the power flow on the tripped line.
Kossou – Taabo	225	Unstable: Severe voltage collapses on the 90 kV network.	Peak	In the medium/long-term (2020) a network reinforcement is planned with the 225 kV lines Taabo – Yamoussoukro 2 - Kossou. These reinforcements will allow a more stable situation in case of trip of the line Kossou – Taabo. For the short-term (before the planned network reinforcement) it is recommended to install a Special Protection scheme able to disconnect generation in Taabo and Kossou power plants depending on the pre-contingency value of the power flow on the tripped line.
Kainji – B.Kebbi	330	Unstable: NIGELEC-FLEUVE network remain connected to TCN network only through the B.Kebbi 330/132/33 kV transformers (Sokoto – B.Kebbi 132 kV lines are out of service). Out of steps of some units were observed in the B.Kebbi area.	Base, Inter	It is recommended to install an intertrip relay (with the possible deactivation if the power flows on the line is below a pre-defined threshold or different configuration if Sokoto – B.Kebbi lines will be put in operation) with the two 3 winding transformers at B.Kebbi causing a separation with the NIGELEC-FLEUVE network (which remain connected only to the 132 kV busbar at

				B.Kebbi 1). The trip of the 3 winding transformers at B.Kebbi causes undervoltages (up to 70%) in the TCN 132 kV Network close to B.Kebbi (B/Kebbi II – Sokoto – Tmfara – Gusau – Funtua – Zaria – Kaduna1). It is recommended to implement an UVLS scheme or to consider possible alternative local measures
Kaduna – Kano	330	Unstable: NIGELEC-NCE network remain connected to TCN network only through the Kano 330/132/33 kV transformers (through the busbar at Kumb T2A 132 kV). Out of steps of some units were observed in the Kano area.	Base, Inter	It is recommended to install an intertrip relay (with the possible deactivation if the power flows on the line is below a pre-defined threshold) with the two 3 winding transformers at Kano connecting Kumb T2A 132 kV, causing a separation with the NIGELEC-NCE network (which remain connected only to the 132 kV TCN substations of Kumb, Kankia, Katsina).

The 225 kV SOGEM/RIMA backbone (from Kodialani to Tobene) is not always compliant with the N-1 security criteria. The static security analysis shows that for some contingencies (mainly in the peak interconnected scenario) the power-flow cannot converge, as previously discussed. Contingencies are critical also because the trip of an element belonging to the RIMA backbone create a network separation in Senegal/Mali. For the off-peak scenarios (base and inter case) the trip of some lines of the RIMA backbone causes voltage violations in the RIMA network itself and in part of the neighboring EDM/SENELEC network.

Voltage profile can be improved through the installation of controllable reactive compensation, in addition to the already available fixed shunt reactors (present in most of the RIMA substations).

Overloads can be managed through one (or more) of the following measures:

- Installation of Special Protection Schemes in the generating units at Manantali power plant able to reduce the generation in case of a critical trip along the backbone and under critical loading conditions.

- Installation/Tuning of dedicated time-inverse protection along the backbone associated to efficient alarms system in the SCADA/EMS in control rooms, in order to accurately inform operators and allow them to promptly perform generation redispatching and/or network reconfigurations.
- Line “reconductoring” to increase the rating of the 225 kV SOGEM/RIMA network (150 MVA current value for the 225 kV lines)

Voltage profile across Nigeria and Niger can be improved through the installation of additional controllable reactive compensation to limit the under and over voltages due to the trip of interconnection lines TCN/NIGELEC.

3.2.2 Sensitivity Analysis - 2016 Scenarios

The results of the sensitivity analysis are summarized from Table 3.8 to Table 3.10. The tables report the candidate buses for install reactive compensation, for each utility in which violations have been detected during the contingency analysis. The selected buses from the list of candidates are highlighted in green colour. The selection of the buses has been done in accordance with the criteria discussed in §3.1.2 and also taking into account both feed-backs from operators and results of analysis on 2020 scenarios (§3.4.2).

Table 3.8: Candidate Buses for the SOGEM area

Bus Number	Bus Name		Max $\delta V_i/\delta Q_j$ on Violated Buses [pu/Mvar]	Number of occurrences on Violated Buses	Mean $\delta V_i/\delta Q_j$ on Violated Buses [pu/Mvar]
148029	BAKEL225	225.00	0.001281	13	0.00127
148030	MATAM-225	225.00	0.001621	21	0.00121
148037	DAGANA225	225.00	0.001580	22	0.00128
148042	SAKAL-225	225.00	0.001264	17	0.00119

Table 3.9: Candidate Buses for the NIGELEC-FLEUVE area

Bus Number	Bus Name		Max $\delta V_i/\delta Q_j$ on Violated Buses [pu/Mvar]	Number of occurrences on Violated Buses	Mean $\delta V_i/\delta Q_j$ on Violated Buses [pu/Mvar]
16061	BKEBBI 1	132.00	0.002097	6	0.00144
16079	B/KEBBI II	132.00	0.002079	7	0.0014415
19014	BKEBBI 3	330.00	0.001324	5	0.001208
66002	DOSSO	132.00	0.004208	11	0.002218455
66004	SAGA	132.00	0.003664	8	0.00322425
66006	GOUROUBANDA	132.00	0.003788	8	0.00325825
66009	NIAMEY-2	132.00	0.003578	8	0.00318975
66015	GUESSELBODI	132.00	0.003977	8	0.0031625

Table 3.10: Candidate Buses for the NIGELEC-NCE area

Bus Number	Bus Name		Max $\delta V_i/\delta Q_j$ on Violated Buses [pu/Mvar]	Number of occurrences on Violated Buses	Mean $\delta V_i/\delta Q_j$ on Violated Buses [pu/Mvar]
66018	GAZAOUA	132.00	0.003966	24	0.002129583
66019	ZINDER	132.00	0.004499	21	0.002045238
66020	TRANSITION	132.00	0.004492	20	0.0020856

66021	SORAZ	132.00	0.004291	11	0.002608636
66022	MARADI 2	132.00	0.00515	22	0.002306409
66023	MARADI	132.00	0.005232	22	0.0022925
66024	MALBAZA 2	132.00	0.009319	22	0.002478636

3.2.3 Short Circuit Currents Assessment – 2016 Scenarios

3.2.3.1 Results

The results of the 3PH and 1PH short-circuit currents calculation are summarized in Table 3.11 and Table 3.12.

Adequacy of the breaking capacity on the WAPP Interconnection buses

In all interconnection buses the breaking capacity is adequate to interrupt both the maximum 3PH and 1PH short circuit currents. The details of the symmetrical short circuits currents are reported in Table 3.11.

Breaking capacities not adequate on voltage levels equal or above 90 kV

Table 3.12 reports the buses with nominal voltage above 90 kV where the breaking capacity is not adequate to interrupt the short circuits currents. The short circuits currents exceeding the breaking capacities are highlighted in red. The same table shows that even in the non-violating cases the short circuit currents values are close to the breaking capacities.

Table 3.11: 2016 Peak and Off Peak Scenarios – Short circuit currents on the WAPP Interconnection buses

BUS NUM	BUS NAME		BUS AREA	BUS OWNER	BUS KV	PEAK 3PH [kA]	PEAK 1PH [kA]	OFF PEAK 3PH [kA]	OFF PEAK 1PH [kA]	BREAKING CAPACITY [kA]
16061	BKEBBI 1	132.00	TCN	NIGERIA	132	3.11	4.01	2.95	4.01	20
16099	KATSINA 1	132.00	TCN	NIGERIA	132	1.67	2.24	1.54	2.24	20
19004	IKEJA W 3	330.00	TCN	NIGERIA	330	17.77	18.20	17.53	18.20	31.5
27016	LOME AFLAO	161.00	CEB	TOGO	161	8.97	7.52	8.45	7.52	31.5
29001	SAKETE 3	330.00	CEB	BENIN	330	8.90	6.90	8.54	6.90	31.5
37055	AFTAP	161.00	GRIDCO	GHANA	161	8.21	6.50	7.79	6.50	31.5
38001	PRES2-225	225.00	GRIDCO	GHANA	225	5.03	1.53	4.89	1.53	31.5
48006	FERKE	225.00	CIE	COTE IVOIRE	225	1.44	0.91	1.47	0.91	31.5
48013	RIVIERA-225	225.00	CIE	COTE IVOIRE	225	12.34	11.47	9.70	11.47	31.5
58001	KODENI	225.00	SONABEL	BURKINA FASO	225	1.09	0.75	0.98	0.75	31.5
66002	DOSSO	132.00	NIGELEC	NIGER	132	1.79	1.12	1.42	1.12	20
66017	GAZAOUA LR	132.00	NIGELEC	NIGER	132	1.28	1.26	1.12	1.26	20
138001	SIKASSO	225.00	EDM-SA	MALI	225	0.99	0.59	1.02	0.59	31.5
146001	BAKEL90	90.000	SOGEM	SENEGAL	90	0.97	0.91	0.94	0.91	20
146003	SELIBABY90	90.000	SOGEM	MAURITANIA	90	0.84	0.70	0.82	0.70	20
146005	KAE-MAT-90	90.000	SOGEM	MAURITANIA	90	0.84	0.66	0.82	0.66	20
146006	KAEDI-90	90.000	SOGEM	MAURITANIA	90	0.84	0.66	0.82	0.66	20
148028	KAY-BAK-225	225.00	SOGEM	SENEGAL	225	2.72	2.70	2.33	2.70	31.5
148029	BAKEL225	225.00	SOGEM	SENEGAL	225	2.17	1.57	1.84	1.57	31.5
148037	DAGANA225	225.00	SOGEM	SENEGAL	225	2.25	1.58	1.63	1.58	31.5
148038	DAG-ROS-225	225.00	SOGEM	SENEGAL	225	2.23	1.57	1.63	1.57	31.5

Table 3.12: **2016 Peak and Off Peak Scenarios – Buses above 90 kV with short circuit currents violating the breaking capacity**

BUS NUM	BUS NAME		BUS AREA	BUS OWNER	BUS KV	PEAK 3PH [kA]	PEAK 1PH [kA]	OFF PEAK 3PH [kA]	OFF PEAK 1PH [kA]	BREAKING CAPACITY [kA]
16004	IKEJA W 1BB1132.00		TCN	NIGERIA	132	20.47	18.44	20.35	18.44	20
46001	ABOBO	90.000	CIE	COTE IVOIRE	90	23.20	14.93	19.65		20
46002	VRIDI	90.000	CIE	COTE IVOIRE	90	22.99	26.80	19.43	26.80	20

3.2.3.2 Recommendations

In order to solve the violations detected in the substations not belonging to the WAPP Interconnection, the following solutions could be adopted:

- Install breakers with a higher breaking capacity.
- Study different topological configurations of the elements connected to the different bus sections, performing dedicated analyses aimed at verifying that the new configuration satisfy the security criteria adopted by the utilities.
- Install Current Limiting Reactors (CLR) aimed at reducing the short circuit currents contributions from adjacent bus sections. This solution allows a general reduction of the short circuits current while maintaining electrically connected the bus sections.

As a general recommendation, 1PH short circuit currents related to the high voltage sections of the power plants can be reduced by adopting some common practices. The step-up transformers in the power plants are generally delta connected in the medium voltage side and wye connected on the high voltage side. The high voltage side is generally grounded for improving the detection of the fault and for limiting the over-voltages in case of 1PH faults. Nevertheless the grounding of the high voltage side increases the level of the 1PH short circuit currents. In power plants having more than one unit is common practice to ground only some of the step-up transformer provided that the grounding grid is common to all of them.

3.3 Proposed short-term reinforcements from static analysis on 2016 scenarios

Based on the results of the static analysis on 2016 scenarios reported in §3.2.1, 3.2.2 and 3.2.3 the following list of reinforcements are proposed:

- Completion of the costal backbone with the operation of the 330 kV lines Sakété-Davie-Asogli (CEB/GRIDCO).
- Installation of an SVC of +/- 30 MVAR at Matam 225 kV substation (SOGEM).
- Installation of an SVC of +/- 20 MVAR at Dosso 132 kV substation (NIGELEC).
- Installation of an SVC of +/- 20 MVAR at Gazaoua 132 kV substation (NIGELEC).

The 2016 interconnected scenarios were updated considering the abovementioned reinforcements.
In addition considering also the recommendations provided in [3] the following measures are considered:

- Review of the units under primary frequency control in order to obtain an adequate reserve margin (Table 3.3 and Table 3.4) and frequency control performances (e.g. droop, deadband, time response).

The updated scenarios (peak and off-peak) are named as “Interconnected-Reinforced” or “Inter-Reinf”. Annex [A3] includes also the results of the contingency analysis performed on the 2016 reinforced scenarios, which may be compared with the base scenarios, showing the improvement of the network response to critical contingencies. The reinforced scenarios are used for the dynamic analysis described in §4.2 and §4.3.

3.4 Results – 2020 Scenarios

The 2020 static model of WAPP interconnected system has been built starting from the 2016 model, adding the new generating units, substations and lines planned to be operated for the year 2020.

The scenarios were created assuming a generation dispatch in line with countries demand and power exchanges; Table 3.13 and Table 3.14 present the main characteristics of the simulated cases.

Table 3.13: 2020 peak load scenario characteristics

	P_{GEN} (MW)	P_{LOAD} (MW)	LOSSES (MW)	EXCHANGE[5] (MW)	Reserve	
					MW	%
TCN	6809	6204	222	383	229.5	3.14
CEB	386	671	26	-311	31.6	6.93
NIGELEC	306	380	25	-99	42	12.10
SOGEM	258	42	6	210	53	16.87
GRIDCo	3182	3014	112	56	321	9.98
CIE	2101	1941	50	110	115	4.96
SONABEL	414	421	10	-17	22	6.78
EDM-SA	400	608	14	-221	0	0.00
SENELEC	723	864	12	-153	62.8	9.14
SOMELEC	0	24	0	-24	0	0.00
CLSG	212	0	5	207	18	7.43
OMVG	299	0	4	295	21.5	6.71
EDG	340	451	11	-124	12.1	3.06
NPA	0	233	1	-234	0	0.00
LEC	0	0	0	0	0	0.00
EAGB	0	36	0	-36	0	0.00
NAWEC	0	42	0	-42	0	0.00
TOTALS	**15431**	**14931**	**498**	**0**	**928.5**	

[5] Here and in the following similar tables, a positive value of exchanged power means power exported from the country, while a negative value means power imported in the country

Table 3.14: 2020 off-peak load scenario characteristics

	P_{GEN} (MW)	P_{LOAD} (MW)	LOSSES (MW)	EXCHANGE[6] (MW)	Reserve	
					MW	%
TCN	6072	5525	177	370	314	4.79
CEB	251	578	19	-345	21.8	7.32
NIGELEC	175	228	8	-61	35	16.40
SOGEM	181	21	12	148	26	12.56
GRIDCo	2751	2713	80	-42	353	12.35
CIE	1140	971	19	151	37	2.98
SONABEL	167	210	5	-48	14.4	11.73
EDM-SA	163	304	4	-145	2.07	1.74
SENELEC	286	433	4	-151	6.1	1.91
SOMELEC	0	0	0	0	0	0.00
CLSG	210	0	3	207	14	5.78
OMVG	121	0	3	118	23	15.97
EDG	183	226	2	-48	11	5.16
NPA	0	117	0	-117	0	0.00
LEC	0	0	0	0	0	0.00
EAGB	0	18	0	-18	0	0.00
NAWEC	0	21	0	-21	0	0.00
TOTALS	**11700**	**11364**	**334**	**0**	**857.37**	

A load-flow analysis for the 2020 cases in N condition has been performed for checking the static model.

In N condition 2 overloads occur in NIGER (monitored voltage level greater or equal to 90 kV, details available in Table 3.17). Some transformer overload occurs, mainly concentrated in transformers supplying the load on MV levels, as reported in [3].

The following reinforcements have been considered as hypothesis in case of lack of data in order to obtain an acceptable starting voltage profile in the base case of the 2020 scenarios:

- <u>Shunt and series compensation in the North-Core and Niger Networks:</u>

The network of the North-Core and Salkadamna projects were reinforced with the following hypotheses for the compensation of long lines [4][8]:

[6] Here and in the following similar tables, a positive value of exchanged power means power exported from the country, while a negative value means power imported in the country

- line shunt reactive compensation (60-70% distributed at each line end)
- line series capacitive compensation (70% distributed at each line end)
- reactive shunt compensation at the substation to guarantee voltage inside the operational security limits

A detailed electromagnetic analysis shall be performed to investigate all the phenomena related to the compensation (e.g. resonance phenomena, switching, etc.) and to identify the best configuration for the compensations.

Table 3.15: Reactive compensation in the North-Core and Niger Networks (NIGELEC/ CEB/SONABEL)

Line/Substation	Vnom [kV]	Parameters			Shunt Compensation	Series Compensation
		X [ohm]	C [uF]	L [km]		
Goroubanda – Ouaga Est	330	147.3	4.94	445	2 x 50 MVAR	2 x 50 Ω
Goroubanda – Salkadamna	330	132.4	4.43	400	2 x 50 MVAR	2 x 45 Ω
Goroubanda – Zabori	330	61.23	2.055	185	2 x 20 MVAR	-
Goroubanda	330	-	-	-	50 MVAR (preferable controllable)	-
Salkadamna	330	-	-	-	40 MVAR	-
Zabori	330	-	-	-	70 MVAR (preferable controllable)	-
Ouaga Est	330	-	-	-	20 MVAR	-
Malanville	330	-	-	-	20 MVAR	-

- Reactive compensation on HV and MV network:

The following reinforcements are considered as hypothesis to obtain an acceptable voltage profile in the base case of the 2020 scenarios.

Table 3.16: Additional Reactive Compensation in the WAPP Network

Substation	Utility	Vnom [kV]	Shunt Compensation	Notes
Aliade	TCN	330	50 MVAR (reactor)	Added
Zagne	CIE	225	25 MVAR (reactor)	Added
Lossa	NIGELEC	66	30 MVAR (capacitor)	Added

Koulikoro	EDM-SA	30	15 MVAR (capacitor)	Added
Calabar	TCN	33	25 MVAR (reactor)	Replaced 75 MVAR reactor

3.4.1 Results of Contingency Analysis – 2020 Scenarios

The Contingency Analysis was performed on all the 2020 scenarios (peak and off-peak) according to the methodology explained in §3.1.1. The results are available in Annex [A6] and following summarized in Table 3.17 and Table 3.18. The same approach used for the 2016 scenarios (see §3.2.1) has been adopted.

Table 3.17: Contingencies and violations not significantly impacting the interconnections– 2020 scenarios

Contingency	Vnom [kV]	Violations	Scenarios	Area
BASE-CASE (N)		Overloads: Saga – Goroubanda 132 kV (142%) Saga – Niamey 2 132 kV (142%)	Peak	NIGELEC
Free Town	225/160	Undervoltage at Free-Town 160 kV (62%)	All	CLSG
Monrovia - Mano	225	Overvoltages at Mano and Kenema 225 kV (max 112%)	Off-Peak	CLSG
Monrovia - Buchan-an	225	Overvoltage at Buchanan 225 kV (max 110.5%)	Off-Peak	CLSG
Koulikoro Shunt	30	Non-convergent power-flow	Peak	EDM-SA
Sikasso – Koutiala	225	Undervoltages at Segou and Koutiala 225 kV (min 77%)	All	EDM-SA
Sirakoro – Bal-ingue	150	Undervoltage at Balingue and Balingue Gen 150 kV (min 85%)	Peak	EDM-SA
Sirakoro – Fana	150	Overvoltage at Fana and Segou 150 kV (max 127%)	Peak	EDM-SA
Gombe – Jos	330	Non-convergent power-flow (dynamic analyses high-lighted significant local voltage collapses)	All	TCN
Egbin – Ikorodu 1 & 2	132	Trip of a line of the double circuit overloads the second line (max. 139%)	All	TCN

Ikeja West – Ali-misho 1 & 2	132	Trip of a line of the double circuit overloads the second line (max. 137%)	All	TCN
Akangba BBII – Amuwo Odofin	132	Overload on Akangba BBII – Apapa RD 132 kV (max 106%)	All	TCN
Lekki – Aja	132	Overload on the double circuit Egbin – Ikorodu 132 kV (118%)	Off-Peak	TCN
Ayede – Ibadan North	132	Overload on transformer 4T2 330/132 kV at Osogbo 132 kV (max 131%)	All	TCN
Osogbo 4T2	330/132	Overload on the line Ayede– Ibadan North 132 kV (max 102%)	All	TCN
Afam – Phct Main	132	Overload on the line Afam – Rivers IPP 132 kV (max 104%)	Off-Peak	TCN
Afam – Rivers IPP	132	Overload on the line Afam – Phct Main 132 kV (max 104%)	Off-Peak	TCN
Phct Main – Rivers IPP 1 & 2	132	Trip of a line of the double circuit overloads the second line (max. 116%)	All	TCN
Katampe – Gwagwalada	330	Overload on the line Apo – Gwagwalada 132 kV (max 127%)	All	TCN
Gombe – Yola	330	Overloads on the lines Gombe – T-Junction and Yola – T-Junction 132 kV (max 109%) Local undervoltages (min 43%)	All	TCN
B.Kebbi – Kainji	330	Local undervoltages (min 84%)	All	TCN
Afam – Ikot-Ekpene	330	Overload on the line Ala-oji – Ikot Ekpene 132 kV (max 101%)	Off-Peak	TCN
Osogbo 3WT	330/132/33	Local undervoltages 132 kV (min 82%)	All	TCN
Osogbo 2WT	330/132	Local undervoltages 132 kV (min 89%)	Peak	TCN

Sokoto – B.Kebbi	132	Local undervoltages (min 70%)	All	TCN
B.Kebbi	330/132 /33	Local undervoltages (min 75%)	All	TCN
Kaduna – Zaria	132	Local undervoltages (min 81%)	All	TCN
Jos T3A	330/132 /33	Local undervoltages (min 54%)	All	TCN
Yola	330/132 /33	Local undervoltages (min 79%)	All	TCN
Makurdi	330/132 /33	Non-convergent power-flow (dynamic analyses high-lighted significant local voltage collapses)	Peak	TCN
Yandev Shunt	132	Local undervoltages (min 88%)	All	TCN
Kaduna Town Shunt	132	Local undervoltages (min 88%)	All	TCN
Akosombo – Nkawkak	161	Overloads (103%) on Dunk-wa – New Obuasi 161 kV and Nkawkaw – Tafo 161 kV (103%)	Peak	GRIDCO
Volta – Accra East 1 & 2	161	Trip of a line of the double circuit overloads the second line (max. 108%)	All	GRIDCO
Prestea – Obuasi	161	Overloads (109%) on Dunk-wa – New Obuasi 161 kV	Peak	GRIDCO
Dunkwa – Ayanfuri	161	Overloads (max 120%) on Dunkwa – New Obuasi 161 kV	All	GRIDCO
Ayanfur – Asawinso	161	Overloads (max 118%) on Dunkwa – New Obuasi 161 kV	All	GRIDCO
Tafo – Akwatia	161	Overloads (108%) on Dunk-wa – New Obuasi 161 kV	Peak	GRIDCO
Akwatia – New Obuasi	161	Overloads (103%) on Dunk-wa – New Obuasi 161 kV	Peak	GRIDCO
Asawinso – Juabeso	161	Overloads (max 113%) on Dunkwa – New Obuasi 161 kV	All	GRIDCO
Unit Bui-(G1, G2 or G3)	161	Overloads (max 103%) on Dunkwa – New Obuasi 161 kV	Peak	GRIDCO

Sunyani – Bus	161	Local undervoltages (min 84%)	All	GRIDCO
Bolga – Nav-Nv48	161	Local undervoltages (min 89%) and overvoltages (max 111%)	Peak	GRIDCO
Elubo	225/161	Local undervoltages (min 71%)	All	GRIDCO
Kumasi – Kintampo	225	Local undervoltages (min 89%)	All	GRIDCO
Ferké – Kong	225	Local overvoltages (max 111%)	Off-Peak	CIE
Boundokou	225/90	Local overvoltages (max 110.2%)	Off-Peak	CIE
Duekoue – Zagne	225	Local overvoltages (max 122%)	Peak	CIE
Lossa shunt	66	Non-convergent power-flow	Peak	NIGELEC
Saga – Goroubanda	132	Local undervoltages (min 87%)	Peak	NIGELEC
Saga – Niamey 2	132	Local undervoltages (min 87%)	Peak	NIGELEC
Maradi 2 – Maradi	132	Local overvoltage at Maradi 132 kV (137%)	Peak	NIGELEC
Tahoua – Salkadamna	132	Local undervoltage at Tahoua 132 kV (88.8%)	Peak	NIGELEC

General comments and recommendations on local violations:

Contingencies with local voltage violations should be investigated. In some cases local voltage collapse were observed and suitable countermeasures should be implemented. In other cases violations are less critical and could be addressed assuring an adequate reactive power support to improve voltage profiles (e.g. through shunt compensation or voltage control in power plants).

Local overloads could be managed with generation redispatching and/or network reconfigurations. It is important to equip the SCADA/EMS system with reliable and efficient alarms in order to provide timely updates to the control rooms operators.

Overloads occurred in N condition in Niger 132 kV lines have to be faced with local network reinforcements.

The trip of the shunt at Koulikoro 30 kV (EDM-SA) and Lossa 66 kV (NIGELEC) are critical local contingencies, considering the characteristics of the local networks: Koulikoro – Cen Bid long 30 kV line (49.5 km, part in cable) and the 66 kV network Tillabery – Lossa – Karma – Bangoula.

Table 3.18: Critical contingencies with direct impact on the interconnections – 2020 scenarios

Contingency	Vnom [kV]	Violations	Scenarios	Area
Unit: Taiba Wind, Sendou	-	Overloads on Bakel – Matam – Dagana 225 kV(max 125%)	Peak	SEN-LEC/SOGEM
Unit: Malicoun-da	-	Overloads on Bakel – Matam – Dagana – Sakal - Tobene 225 kV(max 140%)	All	SEN-LEC/SOGEM
Kaduna 3WT	330/132/33	Non-convergent power-flow	All	TCN
Kano 3WT	330/132/33	Non-convergent power-flow	All	TCN
Kaduna – Kano	330	Non-convergent power-flow	All	TCN
Malanville – Zabori	330	Local undervoltages (min 85%)	Off-Peak	CEB/NIGELEC
Kodeni	225/90	Non-convergent power-flow	All	SONABEL
Salkadamna – Goroubanda	330	Non-convergent power-flow	Peak	NIGELEC

Comments and Recommendation on critical contingencies

Some of the most critical contingencies lead to non-convergent power-flows, which could be an indicator of potential instabilities and have to be investigated through dynamic analyses. The following contingencies have been further analyzed through time domain simulations (§4.2.2) and the related results are summarized in Table 3.19.

Table 3.19: Results of the dynamic contingency analysis for the critical contingencies (2020 scenarios)

Contingency	Vnom [kV]	Results of Dynamic Analysis	Scenarios	Proposed Measures
Kodeni	225/90	Stable with local undervoltages: Part of the local 90 kV and 33 kV network (including the Bobo power plant) remain connected to the rest of the WAPP network only through the 2 33/225 kV transformers	All	It is recommended to implement local measures like UVLS or special protection schemes.

		at Kodeni substations. The local 90 and 33 kV Network (Kodeni, Bobo, Banfora) is affected by severe undervoltages (voltages up to 35%).		
Salkadamna – Goroubanda	330	Unstable: most of generation of the Salkadamna power plant (180 MW) are exported from NCE area to FLEUVE area through the Salkadamna – Goroubanda 330 kV line (100 MW). After the contingency the local 132 kV network is not able to evacuate this generation and a voltage collapse occur.	Peak	A proposed measure is to install a special protection scheme at Salkadamna power plant, able to reduce the generation in case of trip of the Salkadamna – Goroubanda 330 kV line with the power flow on the line over a pre-defined threshold. This solution should also avoid the activation of overspeed protections on the units.
Kaduna – Kano	330	Unstable: Out of steps of some units were observed in the Kano area.	All	See results of 2016 Scenarios

Voltage profiles in the CEB/NIGELEC 330 kV network can be improved through additional reactive compensation at Malanville substation.

Overloads on the 225 kV SOGEM/RIMA backbone can be managed through one (or more) of the same measures proposed also from the analysis on 2016 scenarios §3.2.1 (increase the rating of the 225 kV lines with low rating, installation of Special Protection Schemes in the generating units, time-inverse protection along the backbone).

In addition, considering the significant number of new interconnections it is advisable to evaluate the installation of equipment (like PSTs or similar FACTS) in some relevant interconnections of the WAPP network to control power flows and manage potential loop-flows. A dedicate study (out of the scope of this project) should be performed to identify the best location and characteristics of the equipment.

3.4.2 Sensitivity Analysis - 2020 Scenarios

The results of the sensitivity analysis are summarized from Table 3.20 to

Table 3.22. The tables report the results on candidate buses for the installation of reactive compensation identified on the 2016 scenarios (in §3.2.2) in order to confirm the validity of the location also in the future scenarios.

Table 3.20: Candidate Buses for the SOGEM area

Bus Number	Bus Name		Max $\delta V_i/\delta Q_j$ on Violated Buses [pu/Mvar]	Number of occurrences on Violated Buses	Mean $\delta V_i/\delta Q_j$ on Violated Buses [pu/Mvar]
148029	BAKEL225	225.00	0.001023	13	0.000915
148030	MATAM-225	225.00	0.001315	14	0.001082
148037	DAGANA225	225.00	0.001216	7	0.000992
148042	SAKAL-225	225.00	0.000768	8	0.000735

Table 3.21: Candidate Buses for the NIGELEC-FLEUVE area

Bus Number	Bus Name		Max $\delta V_i/\delta Q_j$ on Violated Buses [pu/Mvar]	Number of occurrences on Violated Buses	Mean $\delta V_i/\delta Q_j$ on Violated Buses [pu/Mvar]
16061	BKEBBI 1	132.00	0.001301	4	0.00064
16079	B/KEBBI II	132.00	0.001466	4	0.00084
19014	BKEBBI 3	330.00	0.000526	3	0.00048
66002	DOSSO	132.00	0.002233	5	0.00097
66004	SAGA	132.00	0.001466	5	0.00084
66006	GOUROUBANDA	132.00	0.000410	4	0.00041
66009	NIAMEY-2	132.00	0.000606	5	0.00053
66015	GUESSELBODI	132.00	0.001226	5	0.00069

Table 3.22: Candidate Buses for the NIGELEC-NCE area

Bus Number	Bus Name		Max $\delta V_i/\delta Q_j$ on Violated Buses [pu/Mvar]	Number of occurrences on Violated Buses	Mean $\delta V_i/\delta Q_j$ on Violated Buses [pu/Mvar]
66018	GAZAOUA	132.00	0.003382	24	0.001967
66019	ZINDER	132.00	0.003072	10	0.002106
66020	TRANSITION	132.00	0.003088	10	0.002103
66021	SORAZ	132.00	0.003232	10	0.001877
66022	MARADI 2	132.00	0.004056	24	0.001797
66023	MARADI	132.00	0.004237	24	0.001805
66024	MALBAZA 2	132.00	0.002911	8	0.001598

3.4.3 Short Circuit Currents Assessment – 2020 Scenarios

3.4.3.1 Results

The results of the 3PH and 1PH short-circuit currents calculation are summarized inTable 3.23 and Table 3.24.

Adequacy of the breaking capacity on the WAPP Interconnection buses

In all interconnection buses the breaking capacity is adequate to interrupt both the maximum 3PH and 1PH short circuit currents. The details of the symmetrical short circuits currents are reported in Table 3.23.

Breaking capacities not adequate on voltage levels equal or above 90 kV

Table 3.24 reports the buses with nominal voltage above 90 kV where the breaking capacity is not adequate to interrupt the short circuits currents. The short circuits currents exceeding the breaking capacities are highlighted in red. The violations occur mainly in the peak load scenario, but in all cases even in the off-peak scenario the short circuit currents values are approaching the breaking capacities.

Table 3.23: **2020 Peak and Off Peak Scenarios – Short circuit currents on the WAPP Interconnection buses**

BUS NUM	BUS NAME	BUS AREA	BUS OWNER	BUS KV	PEAK 3PH [kA]	PEAK 1PH [kA]	OFF PEAK 3PH [kA]	OFF PEAK 1PH [kA]	BREAKING CAPACITY [kA]
16061	BKEBBI 1 132.00	TCN	NIGERIA	132	4.18	5.53	4.25	5.61	20
16099	KATSINA 1 132.00	TCN	NIGERIA	132	1.70	2.28	1.72	2.31	20
19004	IKEJA W 3 330.00	TCN	NIGERIA	330	19.40	25.29	19.14	24.97	31.5
19014	BKEBBI 3 330.00	TCN	NIGERIA	330	3.75	4.69	3.88	4.82	31.5
27016	LOME AFLAO 161.00	CEB	TOGO	161	9.07	8.19	8.98	8.14	31.5
27025	CINCASSE_161161.00	CEB	TOGO	161	2.18	1.56	2.20	1.56	31.5
29001	SAKETE 3 330.00	CEB	BENIN	330	9.56	7.41	9.40	7.34	31.5
29003	DAVIE (TOGO)330.00	CEB	TOGO	330	7.31	8.76	7.29	8.75	31.5
29004	MALANVILLE 330.00	CEB	BENIN	330	2.43	1.75	2.49	1.77	31.5
37037	ASIEKPE 161.00	GRIDCO	GHANA	161	5.61	4.17	5.57	4.15	31.5
37072	BAWKU 161.00	GRIDCO	GHANA	161	2.24	6.95	8.18	6.91	31.5
38001	PRES2-225 225.00	GRIDCO	GHANA	225	5.72	1.62	2.26	1.63	31.5
38003	NAVRONGO 225225.00	GRIDCO	GHANA	225	3.33	6.30	6.29	6.75	31.5
39003	ASOGLI EXPOR330.00	GRIDCO	GHANA	330	11.01	3.83	3.32	3.81	31.5
39016	DUNKWA 330 330.00	GRIDCO	GHANA	330	8.85	14.19	12.29	15.64	31.5
48006	FERKE 225.00	CIE	COTE IVOIRE	225	3.45	12.26	8.52	11.81	31.5
48011	MAN 225.00	CIE	COTE IVOIRE	225	3.04	2.26	3.60	2.30	31.5
48018	MOYASSUE 225.00	CIE	COTE IVOIRE	225	4.72	1.97	3.04	1.97	31.5
49001	BINGERVILLE 330.00	CIE	COTE IVOIRE	330	5.90	3.56	6.29	4.07	31.5
58001	KODENI 225.00	SONABEL	BURKINA FASO	225	3.27	5.05	5.08	4.62	31.5
58003	ZAGTOULI 225.00	SONABEL	BURKINA FASO	225	5.18	3.53	3.23	3.50	31.5
59001	OUAGAEST 330330.00	SONABEL	BURKINA FASO	330	3.63	7.78	4.57	6.89	31.5
66002	DOSSO 132.00	NIGELEC	NIGER	132	2.06	5.44	3.44	5.16	31.5

66017	GAZAOUA LR	132.00	NIGELEC	NIGER	132	1.62	1.19	2.09	1.19	20
66018	GAZAOUA	132.00	NIGELEC	NIGER	132	1.62	1.67	1.62	1.68	20
69001	ZABORI	330.00	NIGELEC	NIGER	330	4.00	1.67	1.63	1.69	20
69004	GOROUBANDA	330.00	NIGELEC	NIGER	330	4.62	3.83	4.07	3.88	31.5
138001	SIKASSO	225.00	EDM-SA	MALI	225	3.37	4.95	4.49	4.87	31.5
146001	BAKEL90	90.000	SOGEM	SENEGAL	90	1.03	2.84	3.37	2.85	31.5
146003	SELIBABY90	90.000	SOGEM	MAURITANIA	90	0.88	0.97	1.02	0.96	20
146005	KAEDI-90	90.000	SOGEM	MAURITANIA	90	0.88	0.73	0.87	0.73	20
146006	KAE-BOG-90	90.000	SOGEM	MAURITANIA	90	0.88	0.68	0.87	0.68	20
148028	BAKEL225	225.00	SOGEM	SENEGAL	225	3.25	0.68	0.87	0.68	20
148029	MATAM-225	225.00	SOGEM	SENEGAL	225	2.87	2.17	2.94	2.07	31.5
148037	DAG-ROS-225	225.00	SOGEM	SENEGAL	225	2.70	1.77	2.59	1.70	31.5
148038	CX-SAK-225	225.00	SOGEM	SENEGAL	225	2.70	1.77	2.27	1.65	31.5
158001	YEKEPEPA	225.00	CLSG	LIBERIA	225	1.75	1.77	2.27	1.65	31.5
158002	BUCHANAN	225.00	CLSG	LIBERIA	225	1.51	0.95	1.76	0.95	31.5
158003	MONROVIA	225.00	CLSG	LIBERIA	225	1.63	0.68	1.51	0.68	31.5
158004	MANO	225.00	CLSG	LIBERIA	225	1.57	0.64	1.63	0.65	31.5
158005	NZEREKORE	225.00	CLSG	GUINEA	225	1.47	0.61	1.58	0.61	31.5
158006	LINSAN	225.00	CLSG	GUINEA	225	2.74	0.80	1.47	0.80	31.5
158007	KENEMA	225.00	CLSG	SIERRA LEONE	225	1.72	0.93	2.48	0.91	31.5
158008	BIKONGOR	225.00	CLSG	SIERRA LEONE	225	2.11	0.61	1.74	0.61	31.5
158009	BUMBUNA	225.00	CLSG	SIERRA LEONE	225	3.08	0.64	2.14	0.64	31.5
168001	TANAF	225.00	OMVG	SENEGAL	225	1.69	0.71	3.19	0.72	31.5
168003	SAMBANGALOU	225.00	OMVG	SENEGAL	225	2.09	1.51	1.68	1.51	31.5
168005	MALI225	225.00	OMVG	GUINEA	225	2.03	0.89	1.77	0.84	31.5
168006	LABE225	225.00	OMVG	GUINEA	225	2.06	0.85	1.77	0.82	31.5
168007	KALETA225	225.00	OMVG	GUINEA	225	1.82	0.83	1.85	0.81	31.5
168008	BOKE225	225.00	OMVG	GUINEA	225	1.50	0.82	1.73	0.80	31.5
168010	SALTHINO225	225.00	OMVG	GUINEA BISSA	225	1.47	0.81	1.45	0.81	31.5
168011	BAMBANDICA	225.00	OMVG	GUINEA BISSA	225	1.48	0.90	1.44	0.89	31.5
168012	MANSOA225	225.00	OMVG	GUINEA BISSA	225	1.55	0.99	1.46	0.98	31.5

168013	BISSAU225	225.00	OMVG	GUINEA BISSA	225	1.38	1.14	1.53	1.13	31.5
168014	BRIKAMA225	225.00	OMVG	GAMBIA	225	0.99	0.99	1.37	0.98	31.5
168015	SOMA225	225.00	OMVG	GAMBIA	225	1.48	0.67	0.98	0.67	31.5

Table 3.24: 2020 Peak and Off Peak Scenarios – Buses above 90 kV with short circuit currents violating the breaking capacity

BUS NUM	BUS NAME	BUS AREA	BUS OWNER	BUS KV	PEAK 3PH [kA]	PEAK 1PH [kA]	OFF PEAK 3PH [kA]	OFF PEAK 1PH [kA]	BREAKING CAPACITY [kA]
16002	AKANGBA 1 132.00	TCN	NIGERIA	132	19.55	21.88	17.66	20.21	20
16003	EGBIN 1 132.00	TCN	NIGERIA	132	16.16	20.32	17.73	22.07	20
16004	IKEJA W 1BB1132.00	TCN	NIGERIA	132	20.62	24.08	20.46	23.94	20
16009	ALAGBON 1 132.00	TCN	NIGERIA	132	19.83	22.65			20
16011	ALIMOSHO 1 132.00	TCN	NIGERIA	132	17.99	20.16	17.85	20.05	20
16016	IJORA 1 132.00	TCN	NIGERIA	132	19.36	21.49			20
16021	LEKKI 1 132.00	TCN	NIGERIA	132	17.93	20.36			20
16082	BENIN 1 132.00	TCN	NIGERIA	132	17.18	20.67	16.96	20.46	20
37002	VOLTA 161.00	GRIDCO	GHANA	161	27.67	35.45	27.15	34.70	31.5
37047	ABOADZE 161.00	GRIDCO	GHANA	161	24.54	32.27			31.5
37048	ABOADZE-T3 161.00	GRIDCO	GHANA	161	24.46	31.89			31.5
37066	ABOADZE P-SH161.00	GRIDCO	GHANA	161	24.54	32.27			31.5
46001	ABOBO 90.000	CIE	COTE IVOIRE	90	27.80	17.54	20.55	15.42	20
46002	VRIDI 90.000	CIE	COTE IVOIRE	90	21.80	25.60	19.22	23.40	20
46017	PLATEAU 90.000	CIE	COTE IVOIRE	90	20.61	15.29			20
46018	BIANUD 90.000	CIE	COTE IVOIRE	90	22.88	14.65			20
46023	RIVIERA 90.000	CIE	COTE IVOIRE	90	22.11	18.87			20
46024	BIASUD 90.000	CIE	COTE IVOIRE	90	23.00	21.64			20
46025	YOPOUGON 1 90.000	CIE	COTE IVOIRE	90	21.92	18.89			20

3.4.3.2 Recommendations

The results of the analyses are similar to ones related to the 2016 scenarios with the difference that a greater number of buses internal to the control areas. The same recommendations reported in §3.2.3.2 are valid for the 2020 scenarios.

3.5 Proposed medium-term reinforcements from static analysis on 2020 scenarios

Based on the results of the static analysis on 2020 scenarios reported in §3.4.1 and §3.4.2 the following list of reinforcements are proposed as a recommendation for the medium term (2020):

- Shunt and series compensation in the North-Core and Niger Networks as reported in Table 3.15 (evaluate additional reactive compensation at Malanville substation to improve voltage profiles in the CEB/NIGELEC 330 kV network)

- Reactive compensation on HV and MV network as reported in Table 3.16

- Evaluate the installation of equipment (like PSTs or similar FACTS) in some relevant interconnections of the WAPP network to control power flows and manage potential loop-flows.

As for the 2016 scenarios an adequate level of primary frequency reserve and frequency control performances must be guaranteed.

4 DYNAMIC ANALYSIS

In the framework of this study, analyses aimed at assessing the dynamic characteristics - behavior of the system and to propose the necessary reinforcements/remedial actions have been carried out. In particular the following analyses have been executed:

- Small Signal Stability (§4.1)
- Dynamic Security Assessment and Defence Plan (§4.2)
- Transient Stability (§4.3)

4.1 SMALL SIGNAL STABILITY ANALYSIS

4.1.1 GENERALITIES AND SCOPE OF WORK

The scope of this part of the study is to investigate the small signal stability of the WAPP system with the aim to investigate the inter-area modes, the local modes and the generators participating to such oscillations.

These kinds of study have become more and more important in power system planning and operation due to the following facts:

- large-scale system interconnections;
- operation of system closer to transmission limits;
- integration of new generation;
- regulatory requirements for enforcing small signal stability criteria.

Small signal analysis uses a linearized representation of the system, and gives appropriate answers in case of small perturbations around the operating point. Limits, discrete actions, and nonlinearities are not considered in small signal studies. Nevertheless, small signal analysis is useful in determining whether an operating point of the system is stable, and also for determining the natural oscillatory frequencies and the damping in the network. The advantage of small signal analysis lies in the fact that, because the model is linear, the concepts of linear-system analysis and design methods can be exploited. The main uses of a linear model are the calculation of eigenvalues to derive the frequency and damping of oscillations in the system. The calculation of eigenvalues and eigenvectors is the most powerful tool for oscillatory stability studies.

Various parameters influence damping of natural frequencies:

- the asynchronous torque of the generator mainly depends on the dimensions of the generator. The use of cooling of the active windings rather than larger dimensions for some generators causes the reduction of damping factors of the system;
- the interactive relations between the grid and the power plant depend from network strength. The size of the interconnected AC system and longitudinal topology of the networks have a negative effect on network stability and will tend to lead to poorly damped low frequency oscillations involving a very large number of machines;
- voltage regulators with high gains and other non-properly tuned PSS.

The problems related to the electromechanical interaction between the turbine-alternators and the network are of crucial importance to ensure, mainly within an energy market, a full usability of production plants in their entire design field, as well as to guarantee a behavior consistent with security requirements, in view of possible network contingencies.

These issues concern the dynamic behavior and the stability degree of the generators, both in front of small disturbances around the operating points, and in the case of large network contingencies. Regarding the problems of working point stability, commonly referred as the small signal stability problems, an inadequate excitation control (AVR), as a wrong choice of its parameters setting, can lead to instability conditions that appears as growing oscillations of electrical and mechanical turbine-generator variables. Such oscillations can reach amplitudes so high to prevent the operation of the unit in the working point under consideration.

In contrast, a correct excitation control, together with a proper fine-tuning of the regulation parameters, in particular the parameters of the additional power system stabilizer for damping the electromechanical oscillations (PSS), can ensure a stable operation of the generator and adequate dynamic responses across the full allowable working range and for all the normal network conditions. Concerning stability in front of large disturbances, it is of common interest, both from the Power Plant Producer (concerned to ensure the maximum continuity of its supply), and from the Transmission System Operator (concerned to have the maximum support of the plant when the network is in disturbed conditions), to maximize the synchronism capability of the generator. For these purposes, the excitation system performances, as well as the turbine governors characteristics and the speed control performances (limits of acceleration and deceleration, security logics and protection fast-valving) are fundamental.

The analysis will be focused on oscillatory modes and on electromechanical oscillations affecting power systems that are reported in range of 0.1-2 Hz and divided in two types (Figure 4.1):

Figure 4.1: Type of electromechanical oscillation modes.

- Local Oscillations: they concern single (or coherent group of) machines against the rest of the system and are located in the upper part of the range (usually 1-2 Hz).
- Inter-area Oscillations: they are dynamic modes typically between coherent groups of generators and are located in the lower part of the range (usually 0.1-1 Hz).

For both the types of oscillations, damping depends on the operating point of the units (i.e. actual power flows, reactive point on the capability plan), as well as on the external lines conditions (i.e. network meshing, lack of interconnections).

The study analyses the stability of the power plant-network system both in local and in inter-area frequency interval, evaluating damping of oscillation modes and tuning of PSS according to the typical damping objectives (Figure 4.2).

Figure 4.2: Oscillation damping evaluation scale.

In this study the modal analysis is performed considering six different cases representative of the most typical conditions in which the system is operated (or will be operated):

- 2016 peak
- 2016 off peak
- 2016 peak interconnected
- 2016 off peak interconnected
- 2020 peak
- 2020 off peak

4.1.1.1 Evaluation of damping

For each of the eigenvalue calculated in modal analysis the following parameter are reported.
Assuming that one of the conjugate complex pair of eigenvalues is given by:

$$\lambda_i = \sigma_i \pm j\omega_i$$

then the oscillation associate to the eigenvalue can be expressed as:

$$e^{\lambda_i t} = e^{(\sigma_i \pm j\omega_i)t}$$

where the real part

$$e^{\sigma_i t}$$

is associated to the exponential behavior and the imaginary part

$$e^{\pm j\omega_i t}$$

is associated to the pure oscillatory behavior.

As in the general exponential function

$$e^{-\frac{t}{\tau}}$$

the time constant of the exponential is defined as $\boldsymbol{\tau}$; therefore it is also possible to define the time constant ($\boldsymbol{\tau}$) associated to the mode (damping time constant) as

$$\boldsymbol{\tau} = -\frac{1}{\sigma_i}$$

The associate damping of the mode is instead calculated as:

$$d_i = \frac{1}{T_p} \ln\left(\frac{A_n}{A_{n+1}}\right)$$

Where:

- $\frac{1}{T_p}$ is the frequency of the mode defined as $f = \frac{\omega_i}{2\pi}$
- A_n and A_{n+1} are amplitudes of two consecutive swing maxima or minima respectively

Whilst the damping ratio associated to the mode is calculated as follows:

$$\xi = -\frac{\sigma}{\sqrt{(\sigma^2 + \omega^2)}}$$

in the "results" Chapter the following parameters are reported for each mode:

- frequency of the mode f;
- damping ratio ξ ;
- damping time constant $\boldsymbol{\tau}$.

4.1.1.2 Small Signal Analysis – Calculation Tool

The analysis on the WAPP System has been performed using DIgSILENT PowerFactory. This software allows the user to perform the modal analysis by calculating the complete eigenvalues for a linear dynamic system. To solve all eigenvalues of a given state matrix, it is a common practice to use the well-established QR algorithm, which is based on similarity transformation of a state matrix. The advantage of QR algorithm lies in its superior numeric stability and accuracy.

In order to perform the modal analysis to investigate inherent dynamic properties of the studied system, using PowerFactory, the eigenvalues and eigenvector of a linear time invariant (LTI) system have been obtained.

Consequently the approach followed for the identification of the inter-area and local electromechanical oscillations included the following main steps in order to identify the worst (least-damped) modes:

- Estimation of the system oscillation modes of the WAPP system.
- Evaluation of the frequency and damping of the eigenvalues obtained in order to identify not enough damped modes.
- Identification of generator participating in each oscillatory mode by means of right eigenvector analysis (mode shape).

- Evaluation of the participation factor for the mode selected previously, in order to weigh the controllability level of the different power unit to the oscillation modes.

4.1.2 VALIDATION OF POWERFACTORY NETWORK MODEL

Since modal analysis is very sensitive to steady state operating point of the network it is mandatory to reach a good equivalence between load flow results obtained in different software.

In Annex [A8] the single line diagrams related to the grids in PSSE and in PowerFactory are reported; for each scenario is possible to compare the active/reactive power on the lines and voltage (module and phase) of nodes, that are equal in PSSE and DigSilent load-flows.

4.1.3 RESULTS

In this Chapter the results of the modal analysis of the WAPP network are discussed; as reported in §4.1.1.2 the study has been performed using PowerFactory DIgSILENT. In the next paragraphs results will be presented for different scenarios as reported in §4.1.1.

4.1.3.1 Relevant detected modes

For each scenario a graph shows the position of all eigenvalues in the complex plane obtained from the small signal analysis and a table shows the values of the inter-area modes. In particular, the tables include the following parameters:

- The mode number.
- The real part (sigma).
- The imaginary part (omega).
- Damped frequency.
- Damping ratio.

According to our methodology in the next Chapters we focused the attention on inter area modes with a damping ratio lower than 20% and with a frequency between 0.1 and 1 Hz.

In these tables there are also modes with frequency slightly higher than 1 HZ, as these appear to be inter-area modes, whereas local modes in the frequency range of 1-2 Hz are reported in Annex [A9].

In the next paragraphs each scenario will be analyzed focusing on not well damped inter-area modes.

From the analysis of the participation factors of the local modes reported in Annex [A10] it's possible to identify a list of generating units where proper tuning of the power system would be more effective for further improving the damping of local modes. The results of this analysis is reported in paragraph 0.

4.1.3.1.1 2016 Peak scenario

In Figure 4.3 is reported the result of the modal analysis on the WAPP network considering the 2016 scenario with the maximum load. As it can be seen in these figures there aren't modes with damping less than 5 %. On the other hand there are some modes with damping between 5% and 20%.

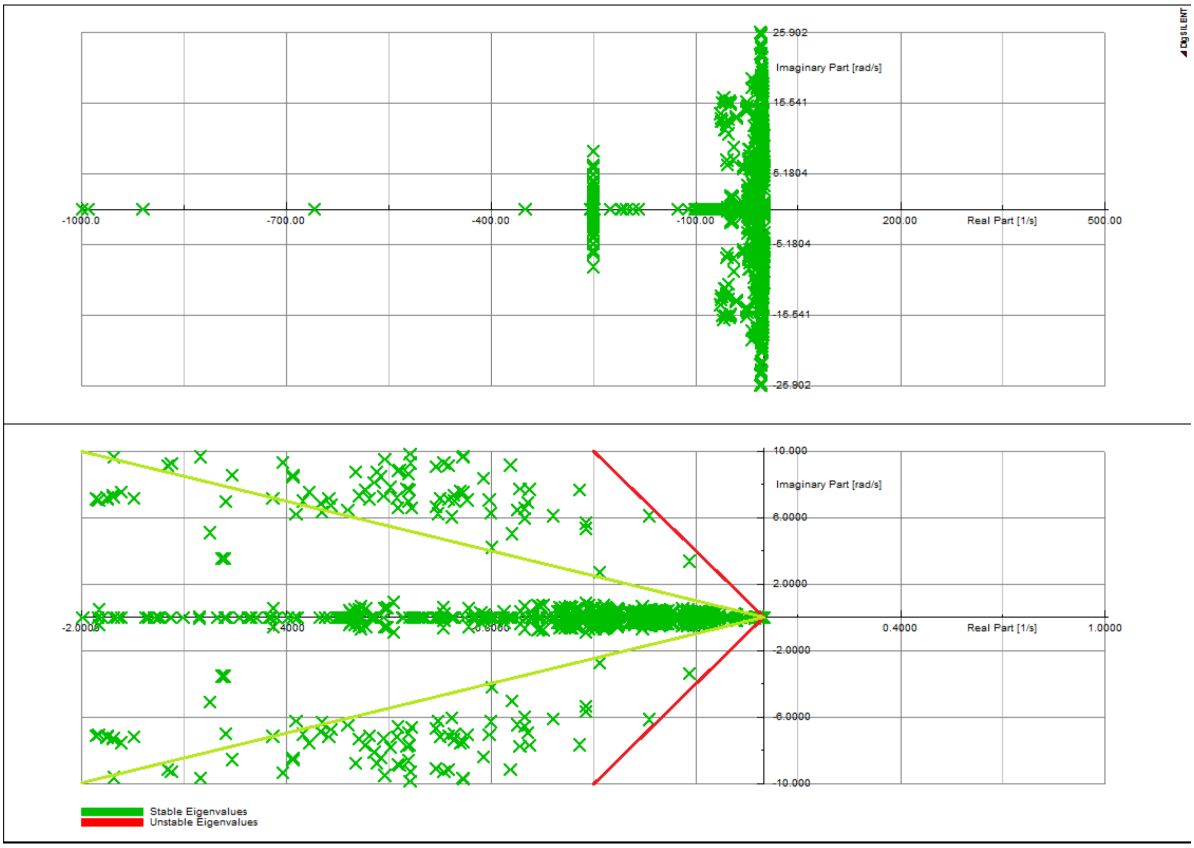


Figure 4.3: Modal analysis result: eigenvalue plot (the red lines in the bottom figure indicate the target damping of 5% and the green lines indicate the target damping of 20%)

In Table 4.1 are reported the relevant inter-area modes in the frequency range of 0.1-1 Hz . As it can be seen this inter-are modes are well damped, having damping more than 5%. The detailed analysis of the mode shape of the eigenvalues reported in this table is reported in Annex [A9].

Table 4.1: Inter-area modes for 2016 peak scenario

Mode Num.	Sigma	Omega	Frequency [Hz]	Damping Ratio [%]
1	-0.483	2.726	0.434	17.453
2	-0.220	3.393	0.540	6.458
3	-0.798	4.211	0.670	18.609
4	-0.740	5.053	0.804	14.483
5	-0.523	5.354	0.852	9.724

6	-0.703	5.976	0.951	11.687
7	-0.914	6.059	0.964	14.922
8	-0.619	6.116	0.973	10.064
9	-0.336	6.136	0.977	5.474
10	-0.956	6.246	0.994	15.132
11	-0.800	6.272	0.998	12.654
12	-0.963	6.673	1.062	14.279

4.1.3.1.2 2016 Peak interconnected scenario

In Figure 4.4 is reported the result of the modal analysis on the WAPP network considering the 2016 interconnected scenario with the maximum Load. As it can be seen in these figures modes with damping less than 5 % are not present, while modes with damping between 5% and 20% exist.

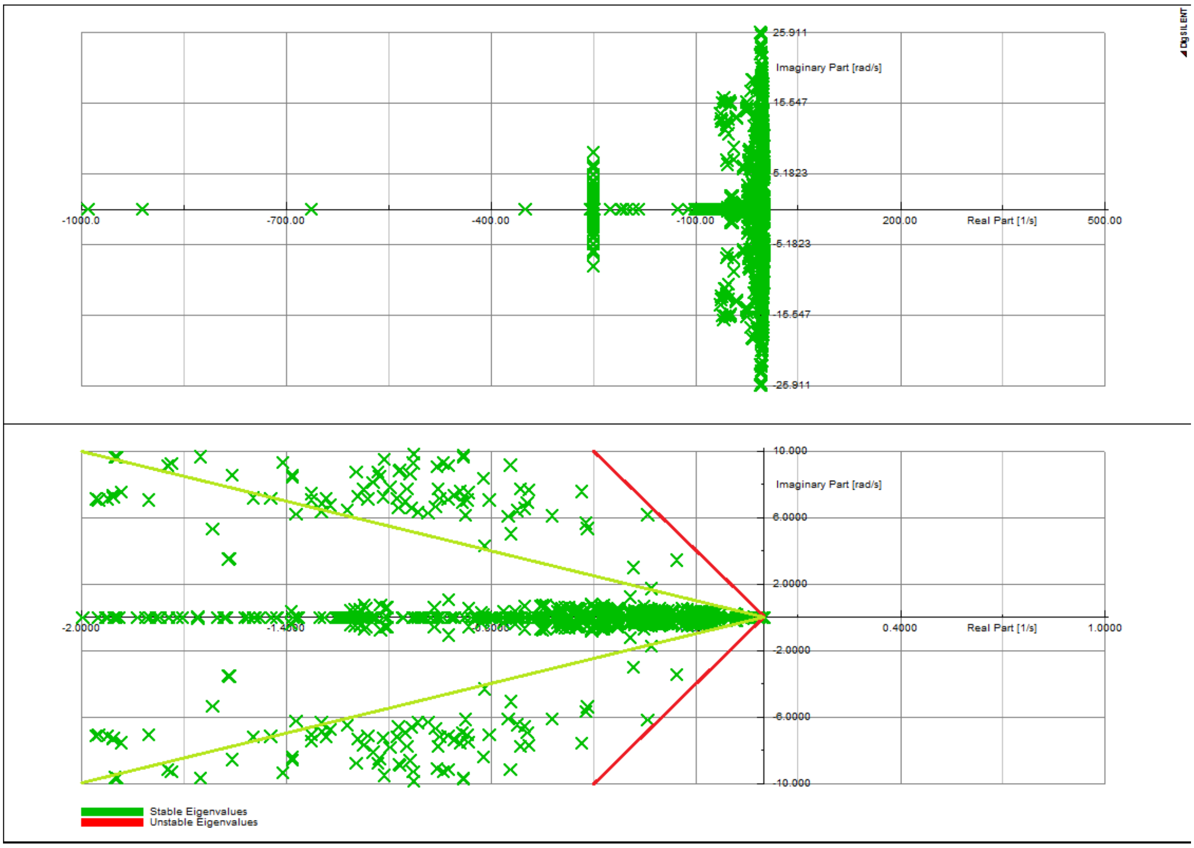


Figure 4.4: Modal analysis result: eigenvalue plot (the red lines in the bottom figure indicate the target damping of 5% and the green lines indicate the target damping of 20%)

Table 4.2 shows the relevant inter-area modes in the frequency range of 0.1-1 Hz . As it can be seen this inter-are modes are well damped. The detailed analysis of the mode shape of the eigenvalues reported in this table is reported in Annex [A9]

Table 4.2: Inter-area modes for 2016 peak interconnected scenario

Mode Num.	Sigma	Omega	Frequency [Hz]	Damping Ratio [%]
1	-0.330	1.725	0.274	18.799
2	-0.384	3.012	0.479	12.650
3	-0.256	3.465	0.551	7.381
4	-0.820	4.290	0.683	18.766
5	-0.743	5.054	0.804	14.546
6	-0.518	5.366	0.854	9.604
7	-0.750	6.108	0.972	12.192
8	-0.621	6.117	0.974	10.093
9	-0.875	6.141	0.977	14.101
10	-0.341	6.164	0.981	5.524
11	-0.985	6.279	0.999	15.502
12	-0.964	6.675	1.062	14.288

4.1.3.1.3 2016 Off-peak scenario

In Figure 4.5 is reported the result of the modal analysis on the WAPP network considering the 2016 scenario with the off-peak load, which shows no modes with damping less than 5 % and modes with damping between 5% and 20%.

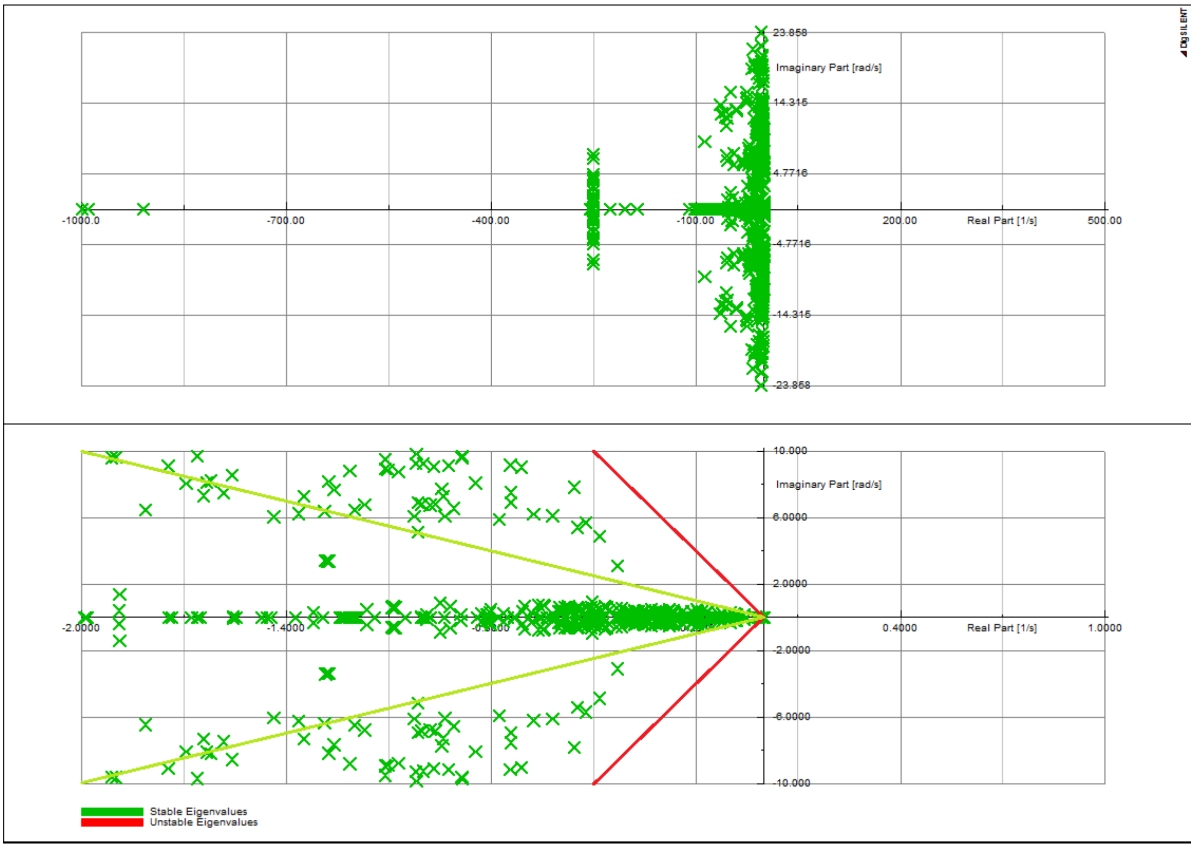


Figure 4.5: Modal analysis result: eigenvalue plot (the red lines in the bottom figure indicate the target damping of 5% and the green lines indicate the target damping of 20%)

Table 4.3 shows the relevant inter-area modes in the frequency range of 0.1-1 Hz, which result to be well damped. The detailed analysis of the mode shape of the eigenvalues reported in this table can be found in Annex [A9]

Table 4.3: Inter-area modes for 2016 off peak scenario

Mode Num.	Sigma	Omega	Frequency [Hz]	Damping Ratio [%]
1	-0.430	3.101	0.494	13.737
2	-0.483	4.881	0.777	9.846
3	-1.015	5.134	0.817	19.389
4	-0.546	5.426	0.864	10.004
5	-0.936	6.071	0.966	15.229
6	-0.619	6.114	0.973	10.080
7	-0.676	6.189	0.985	10.863
8	-0.964	6.831	1.087	13.968

4.1.3.1.4 2016 Off peak interconnected scenario

In Figure 4.6 the result of the modal analysis on the WAPP network considering the 2016 interconnected scenario with the off-peak load is reported. As it can be seen, there aren't modes with damping less than 5 % but modes with damping between 5% and 20%.

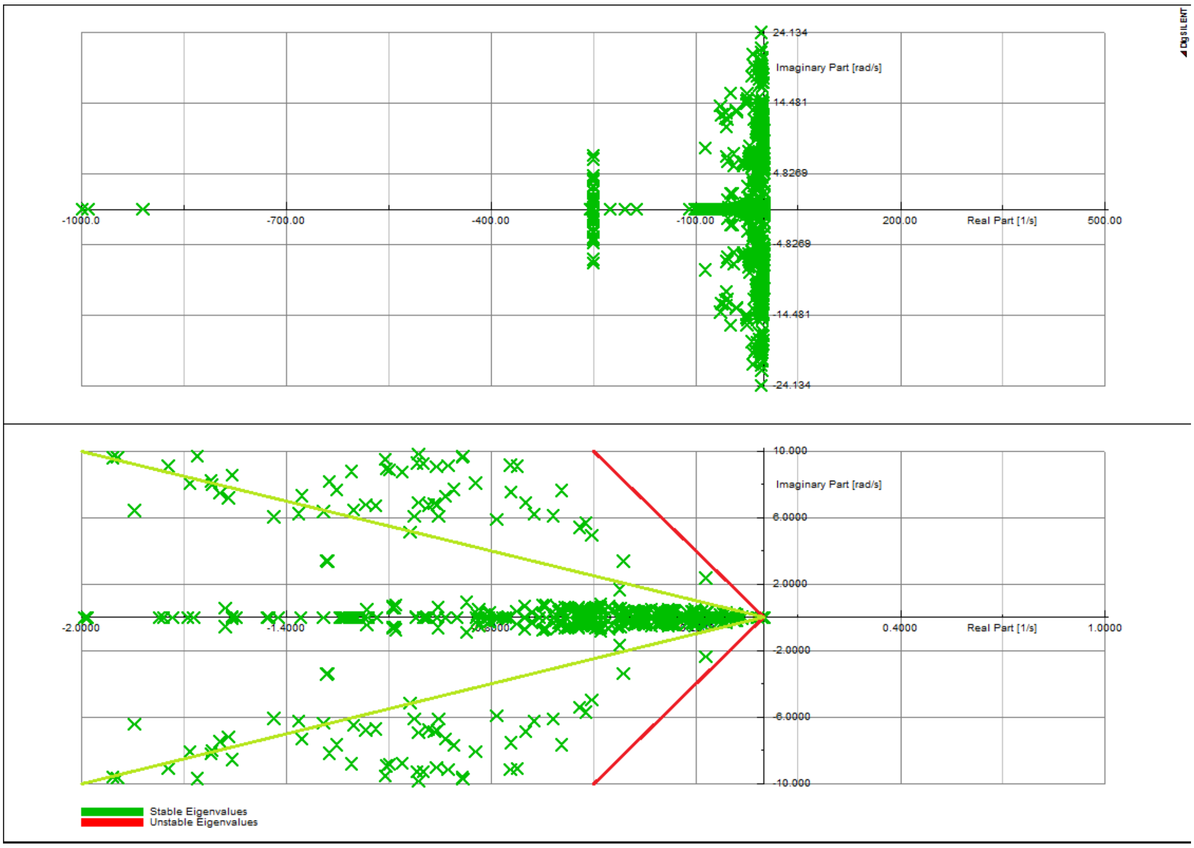


Figure 4.6: Modal analysis result: eigenvalue plot (the red lines in the bottom figure indicate the target damping of 5% and the green lines indicate the target damping of 20%)

Table 4.4 shows the relevant inter-area modes in the frequency range of 0.1-1 Hz . As it can be seen this inter-are mode are well damped because the damping is more than 5%. The detailed analysis of the mode shape of the eigenvalues reported in this table is reported in Annex [A9].

Table 4.4: Inter-area modes for 2016 off peak interconnected scenario

Mode Num.	Sigma	Omega	Frequency [Hz]	Damping Ratio [%]
1	-0.171	2.387	0.380	7.125
2	-0.412	3.386	0.539	12.084
3	-0.506	4.938	0.786	10.185
4	-1.038	5.143	0.819	19.780
5	-0.542	5.429	0.864	9.933

6	-0.954	6.093	0.970	15.474
7	-0.618	6.115	0.973	10.051
8	-0.675	6.225	0.991	10.779
9	-0.959	6.799	1.082	13.963
10	-0.967	6.876	1.094	13.924

4.1.3.1.5 2020 Peak scenario

In Figure 4.7 the result of the modal analysis on the WAPP network considering the 2020 scenario with the peak load is reported. As it can be seen in these figures there aren't modes with damping less than 5 %. Instead there are some modes with damping between 5% and 20%.

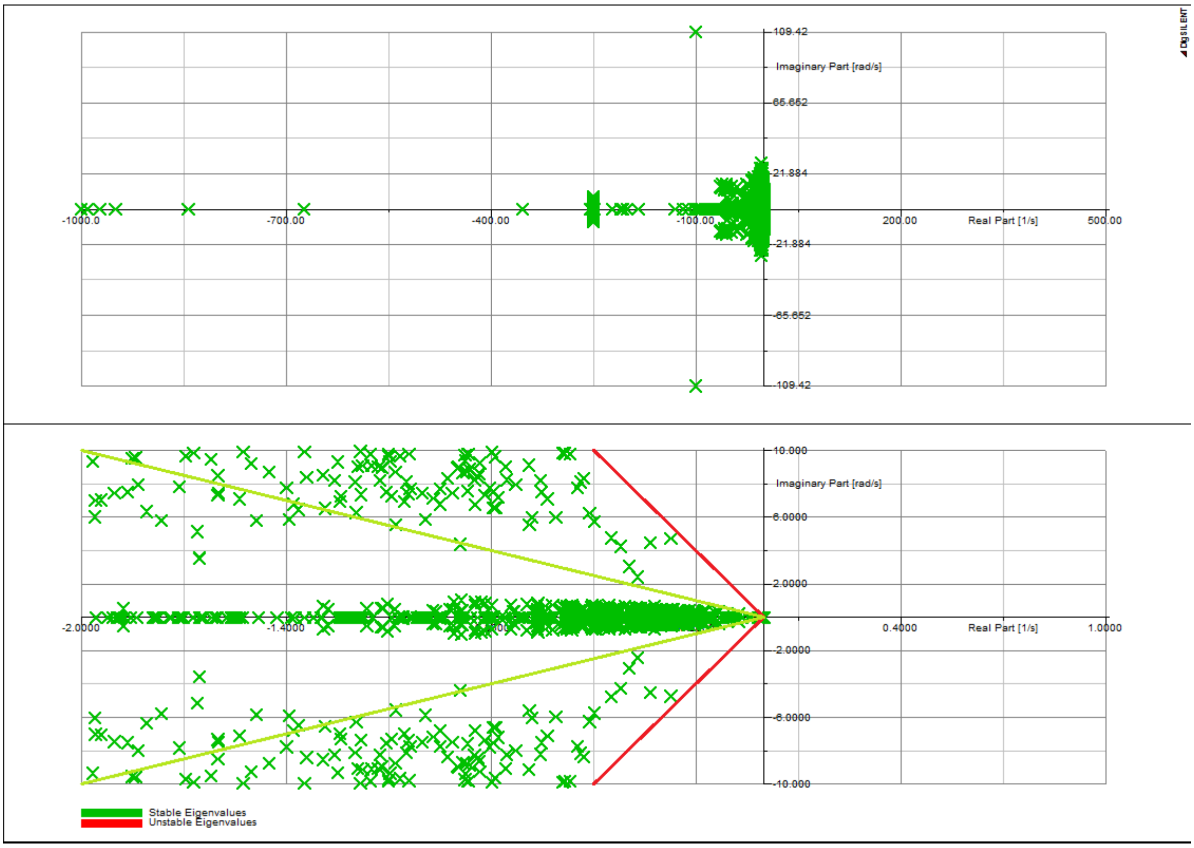


Figure 4.7: Modal analysis result: eigenvalue plot (the red lines in the bottom figure indicate the target damping of 5% and the green lines indicate the target damping of 20%)

Table 4.5 shows the relevant inter-area modes in the frequency range of 0.1-1 Hz . As it can be seen this inter-are mode are well damped because the damping is more than 5%. The detailed analysis of the mode shape of the eigenvalues reported in this table is reported in Annex [A9]

Table 4.5: Inter-area modes for 2020 peak scenario

Mode Num.	Sigma	Omega	Frequency [Hz]	Damping Ratio [%]
1	-0.371	2.409	0.383	15.229
2	-0.397	3.070	0.489	12.813
3	-0.421	4.262	0.678	9.832
4	-0.891	4.378	0.697	19.932
5	-0.335	4.502	0.716	7.413
6	-0.448	4.756	0.757	9.388
7	-1.080	5.542	0.882	19.123
8	-0.688	5.574	0.887	12.244
9	-0.611	5.974	0.951	10.167
10	-0.511	6.238	0.993	8.168
11	-0.793	6.573	1.046	11.981
12	-0.950	6.790	1.081	13.854
13	-0.635	7.100	1.130	8.906
14	-0.780	7.202	1.146	10.761

4.1.3.1.6 2020 Off peak scenario

In Figure 4.8 the result of the modal analysis on the WAPP network considering the 2020 scenario with the off-peak load is reported. As it can be seen in these figures there aren't modes with damping less than 5% but modes with damping between 5% and 20%.

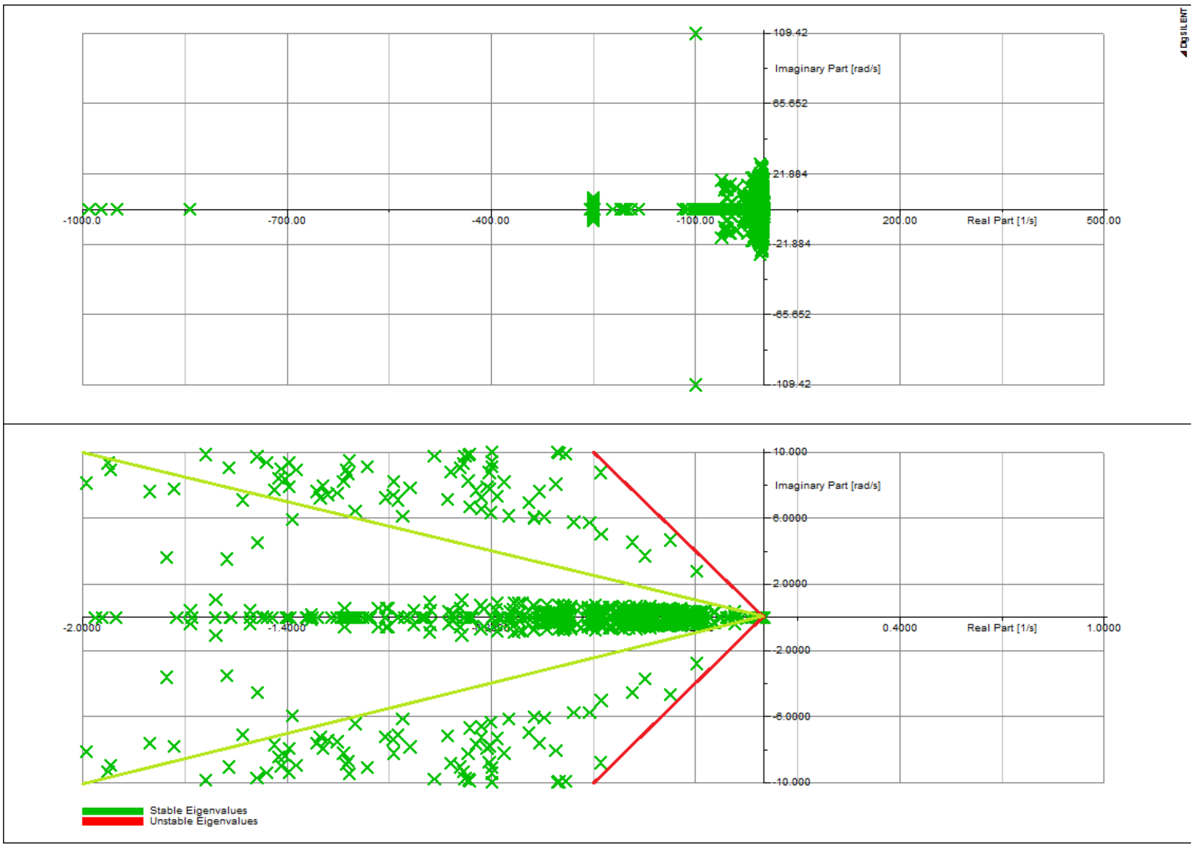


Figure 4.8: Modal analysis result: eigenvalue plot (the red lines in the bottom figure indicate the target damping of 5% and the green lines indicate the target damping of 20%)

Table 4.6 shows the relevant inter-area modes in the frequency range of 0.1-1 Hz (well damped). The detailed analysis of the mode shape of the eigenvalues reported in this table is reported in Annex [A9].

Table 4.6: Inter-area modes for 2020 off-peak scenario

Mode Num.	Sigma	Omega	Frequency [Hz]	Damping Ratio [%]
1	-0.196	2.789	0.444	7.019
2	-0.350	3.713	0.591	9.381
3	-0.386	4.552	0.724	8.441
4	-0.477	5.010	0.797	9.485
5	-0.645	6.082	0.968	10.549
6	-1.061	6.117	0.974	17.084
7	-1.200	6.417	1.021	18.382
8	-0.829	6.577	1.047	12.506
9	-0.863	6.682	1.064	12.811
10	-1.112	7.236	1.152	15.194

11	-0.783	7.319	1.165	10.644

4.1.3.2 Participation factor

As it can be seen from the previous paragraph the inter-area modes are well damped (damping more than 5 %) but there are a lot of local modes that have a damping ratio that is smaller than the optimal typical damping ratio objective (20 %).

Therefore it results necessary to analyze which generator has the controllability on these modes, by calculating the participation factors and obtaining the list of generators to be checked for increasing the damping (power system stabilizer and automatic voltage controller parameters). The list of participation factors for each scenario is reported in Annex [A10].

Table 4.7 shows the list of the candidate machines for installing or fine tuning Power System Stabilizers (PSSs). This table has been obtained by merging the lists of generators for each 2016 scenario as reported in Annex [A10].

Table 4.7: Generating units with the highest participation in local modes for the 2016 scenarios

Bus number	Bus name	Id	PSS model	Bus number	Bus name	Id	PSS model
12020	AES BERG202 11.000	1	-	**32124**	AMERI 13.800	8	-
12021	AES BERG203 11.000	1	-	**32124**	AMERI 13.800	7	-
12029	OLORUNSO GT110.500	1	-	**32124**	AMERI 13.800	1	-
12030	OLORUNSO GT210.500	1	-	**32124**	AMERI 13.800	2	-
12037	OLORNIPPGT1110.500	1	-	**42005**	TAABOGS1 13.800	1	-
12047	OMOTOSO GT1 10.500	2	-	**42006**	TAABOGS2 13.800	1	-
12047	OMOTOSO GT1 10.500	1	-	**42007**	TAABOGS3 13.800	1	-
12050	OMOTOSO GT7 10.500	2	-	**42008**	BUYOGS1 10.500	1	-
12050	OMOTOSO GT7 10.500	1	-	**42009**	BUYOGS2 10.500	1	-
12051	OMOTNIPP GT110.500	1	-	**42010**	BUYOGS3 10.500	1	-
12052	OMOTNIPP GT210.500	1	-	**42011**	AYAM1GS1 5.5000	1	-
12074	GEREGU GT11 10.500	1	-	**42013**	AYAM2GS1 5.5000	1	-
12103	AFAMV GT 19 11.500	1	-	**43004**	KOSSUGS1 17.000	1	STAB1
12104	AFAMV GT 20 11.500	1	-	**43006**	KOSSUGS3 17.000	1	STAB1
12116	IBOM GT3 11.500	1	-	**43015**	CIPREL TAV 15.500	1	-
12117	RIVERS _GT1 10.500	1	-	**52001**	BOBO G1 6.6000	1	-
13010	KAINJ 1G7-8 16.000	1	-	**52002**	BOBO G2 6.6000	1	-
13010	KAINJ 1G7-8 16.000	2	-	**52003**	BOBO G3 6.6000	1	-
13011	KAINJ 1G9-1016.000	1	-	**52005**	BOBO G5 6.6000	1	-
13011	KAINJ 1G9-1016.000	2	-	**52018**	OUAGA G2 6.6000	1	-
13014	JEBBA 2G1 16.000	1	-	**52019**	OUAGA G3 6.6000	1	-
13015	JEBBA 2G2 16.000	1	-	**52020**	OUAGA G4 6.6000	1	-
13016	JEBBA 2G3 16.000	1	-	**52021**	OUAGA G5 6.6000	1	-
13017	JEBBA 2G4 16.000	1	-	**52023**	OUAGA G8 6.6000	1	-
13018	JEBBA 2G5 16.000	1	-	**52024**	OUAGA G9 6.6000	1	-
13020	SHIROR 411G116.000	1	-	**52025**	BAGRE GEN 6.6000	2	-
13021	SHIROR 411G216.000	1	-	**52025**	BAGRE GEN 6.6000	1	-
13022	SHIROR 411G316.000	1	-	**52026**	KOMPIENGAGEN6.6000	1	-
22003	NANGBETOG2 10.300	1	-	**52026**	KOMPIENGAGEN6.6000	2	-

22004	TAG LOME 11.000	1	-
23008	CONTOUR G3-415.000	2	-
23008	CONTOUR G3-415.000	1	-
23009	CONTOUR G5-615.000	1	-
23009	CONTOUR G5-615.000	2	-
23009	CONTOUR G5-615.000	3	-
32001	AKOSOMBO-HG114.400	1	PSS2A
32002	AKOSOMBO-HG214.400	1	PSS2A
32003	AKOSOMBO-HG314.400	1	PSS2A
32004	AKOSOMBO-HG414.400	1	PSS2A
32005	AKOSOMBO-HG514.400	1	PSS2A
32032	KPONG-HG1 13.800	1	-
32034	KPONG-HG3 13.800	1	-
32035	KPONG-HG4 13.800	1	-
32044	TAPCO-TG 13.800	1	PSS2A
32045	TAPCO-TG 13.800	1	PSS2A
32046	TAPCO-TG 13.800	1	PSS2A
32047	TICO-TG 13.800	1	PSS2A
32054	BUI-G1 14.400	1	-
32055	BUI-G2 14.400	1	-
32057	KPONEG1 13.800	1	-
32069	MINES 13.800	2	-
32070	TT1PP-G1 14.400	1	-
32071	CENIT 14.400	1	-
32075	ASOG-G1 11.000	1	-
32076	ASOG-G2 11.000	1	-
32077	ASOG-G3 11.000	1	-
32078	ASOG-G4 11.000	1	-
32079	ASOG-G5 11.000	1	-
32080	ASOG-G6 11.000	1	-
32124	AMERI 13.800	3	-
32124	AMERI 13.800	5	-
32124	AMERI 13.800	10	-
32124	AMERI 13.800	4	-
32124	AMERI 13.800	6	-
52027	KOSSODO G1 11.000	1	-
52028	KOSSODO G4 11.000	1	-
52029	KOSSODO G5 11.000	1	-
52030	KOSSODO G6 11.000	1	-
52031	KOSSODO G7 11.000	1	-
52032	KOSSODO G8 11.000	1	-
53005	KOSSODO G3 15.000	1	-
61014	MALBAZA 0.4000	1	-
61015	MALBAZA 0.4000	1	-
61016	MALBAZA 0.4000	1	-
61017	MALBAZA 0.4000	1	-
62003	GOUDEL 11.000	1	-
62004	GOUDEL 11.000	1	-
62008	GOROUBANDA 11.000	1	-
123004	KOUNONE PW 15.000	3	-
123004	KOUNONE PW 15.000	5	-
123004	KOUNONE PW 15.000	4	-
123004	KOUNONE PW 15.000	7	-
123004	KOUNONE PW 15.000	6	-
123004	KOUNONE PW 15.000	9	-
123004	KOUNONE PW 15.000	8	-
123008	KAOLAC G1 15.000	2	-
123009	KAOLAC G2 15.000	1	-
123009	KAOLAC G2 15.000	2	-
123010	KAOLAC G3 15.000	2	-
123010	KAOLAC G3 15.000	1	-
132007	SOPAM-2-8.7 10.500	4	-
132007	SOPAM-2-8.7 10.500	2	-
132007	SOPAM-2-8.7 10.500	5	-
132007	SOPAM-2-8.7 10.500	3	-
133004	BALINGUE 15.500	1	-
133004	BALINGUE 15.500	4	-
133004	BALINGUE 15.500	2	-
133004	BALINGUE 15.500	3	-
133008	DARSALAM GEN15.000	1	-

Table 4.7 underlines that several generating units don't have PSS (Power System Stabilizer) installed.

As for the 2020 scenarios, Table 4.8 reports the list of the generating units on which the installation or a fine tuning of the Power System Stabilizer (PSS) is recommended. This table includes the list of generators with the highest participation factors for each 2020 scenario (Annex [A10]).

Table 4.8: Generating units with the highest participation in local modes for the 2020 scenarios

Bus Number	Bus Name	Id	PSS model
32071	CENIT 14.400	1	-
32070	TT1PP-G1 14.400	1	-
42008	BUYOGS1 10.500	1	-
42009	BUYOGS2 10.500	1	-
32032	KPONG-HG1 13.800	1	-
152007	BUMBUNA G A 11.000	1	-
152008	BUMBUNA G B 11.000	1	-
133013	KENIE GEN 15.500	2	-

12068	DELTA GT 15 11.500	1	-
12070	DELTA GT17 11.500	1	-
32052	T4 G1 13.800	1	-
32047	TICO-TG 13.800	1	PSS2A
91004	GHUTES G2 3.3000	1	-
91003	GHUTES G1 3.3000	1	-
53014	OUAGE NQ G 15.000	1	-
52010	KOMSILGA G1 11.000	1	-
52003	BOBO G3 6.6000	1	-
52032	KOSSODO G8 11.000	1	-
52027	KOSSODO G1 11.000	1	-
52002	BOBO G2 6.6000	1	-
23008	CONTOUR G3-415.000	1	-
23008	CONTOUR G3-415.000	2	-
123008	KAOLAC G1 15.000	1	-
123008	KAOLAC G1 15.000	2	-
52005	BOBO G5 6.6000	1	-
54029	QUAHIG TG 33.000	1	-
91001	BANEAH G1 3.1000	1	-
123009	KAOLAC G2 15.000	1	-
42014	AYAM2GS2 5.5000	1	-
52001	BOBO G1 6.6000	1	-
32056	BUI-G3 14.400	1	-
143001	GOUINA G1 15.500	1	-
143002	GOUINA G2 15.500	2	-
32124	AMERI 13.8 13.800	10	-
43019	SOUBRE G2 15.500	1	-
43018	SOUBRE G1 15.500	1	-
22003	NANGBETOG2 10.000	1	-
22002	NANGBETOG1 10.000	1	-
23011	VEDOKO T6 15.000	1	-
152003	MT. COFFEE G11.000	1	-
152004	MT. COFFEE G11.000	1	-
54030	BAGRE HG 33.000	1	-
43006	KOSSUGS3 17.000	1	STAB1
22005	ADJARALA_G1 11.000	1	-
22006	ADJARALA_G2 11.000	1	-
12104	AFAMV GT 20 11.500	1	-
12103	AFAMV GT 19 11.500	1	-
92002	GARAFIRI G2 5.7000	1	-
92001	GARAFIRI G1 5.7000	1	-
42005	TAABOGS1 13.800	1	-
133013	KENIE GEN 15.500	1	-
42006	TAABOGS2 13.800	1	-
42013	AYAM2GS1 5.5000	1	-
123019	MALICOUNDA 15.000	1	-
43004	KOSSUGS1 17.000	1	STAB1
12039	OLORNIPPGT2110.500	1	-
12038	OLORNIPPGT1210.500	1	-
43023	SONGON G1 15.500	1	-
43024	SONGON G2 15.500	1	-
32080	ASOG-G6 11.000	1	-
42011	AYAM1GS1 5.5000	1	-
152005	YIBENGEN 11.000	1	-
133008	DARSALAM GEN15.000	1	-

133013	KENIE GEN 15.500	3	-
32034	KPONG-HG3 13.800	1	-
32033	KPONG-HG2 13.800	1	-
12030	OLORUNSO GT210.500	1	-
12029	OLORUNSO GT110.500	1	-
32124	AMERI 13.8 13.800	8	-
32124	AMERI 13.8 13.800	7	-
32124	AMERI 13.8 13.800	6	-
43009	CIPREL TAG 115.500	2	-
43029	GD-BASSAM G215.500	1	-
43030	GD-BASSAM G315.500	1	-
43028	GD-BASSAM G115.500	1	-
92007	GHUTES G4 5.5000	1	-
32126	JACOBSEN PP 14.400	1	-
32126	JACOBSEN PP 14.400	2	-
123012	SENDOU PP 15.000	1	-
92006	GHUTES G3 5.5000	1	-
52025	BAGRE GEN 6.6000	1	-
13010	KAINJ 1G7-8 16.000	1	-
13010	KAINJ 1G7-8 16.000	2	-
13011	KAINJ 1G9-1016.000	1	-
13011	KAINJ 1G9-1016.000	2	-
12037	OLORNIPPGT1110.500	1	-
12053	OMOTNIPP GT310.500	1	-
13021	SHIROR 411G216.000	1	-
12054	OMOTNIPP GT410.500	1	-
12051	OMOTNIPP GT110.500	1	-
12116	IBOM GT3 11.500	1	-
32120	KTPP G1 13.800	1	-
12050	OMOTOSO GT7 10.500	2	-
12050	OMOTOSO GT7 10.500	1	-
62003	GOUDEL 11.000	1	-
123004	KOUNONE PW 15.000	9	-
123004	KOUNONE PW 15.000	4	-
123004	KOUNONE PW 15.000	8	-
123004	KOUNONE PW 15.000	5	-
123004	KOUNONE PW 15.000	7	-
32129	CHRISPOD PP 14.400	3	-
61002	MALBAZA 0.4000	1	-
123004	KOUNONE PW 15.000	2	-
123004	KOUNONE PW 15.000	1	-
123004	KOUNONE PW 15.000	3	-
92014	KALOUM 51G 11.000	1	-
12047	OMOTOSO GT1 10.500	2	-
12047	OMOTOSO GT1 10.500	1	-
25011	GBEGAGEN 63.000	1	-
32069	MINES 13.800	2	-
132006	TAC GEN 11.000	1	-
12020	AES BERG202 11.000	1	-
12021	AES BERG203 11.000	1	-
12078	GER NIPPGT2210.500	1	-
12077	GER NIPPGT2110.500	1	-
92012	KALOUM 33G 6.3000	1	-
92010	KALOUM 31G 6.3000	1	-
92013	KALOUM 34G 6.3000	1	-

13017	JEBBA 2G4 16.000	1	-		**62025**	ZINDER 5.5000	1	-
13015	JEBBA 2G2 16.000	1	-		**53013**	OUAGEST G 15.000	1	-
13016	JEBBA 2G3 16.000	1	-		**12069**	DELTA GT16 11.500	1	-
13018	JEBBA 2G5 16.000	1	-		**53005**	KOSSODO G3 15.000	1	-
13014	JEBBA 2G1 16.000	1	-		**152002**	MT. COFFEE G11.000	1	-
52026	KOMPIENGAGEN6.6000	2	-		**91002**	BANEAH G2 3.1000	1	-
32079	ASOG-G5 11.000	1	-		**32011**	TT2PP2 11.500	1	-
32075	ASOG-G1 11.000	1	-		**92019**	KIPE G1.2.3 11.000	1	-
32076	ASOG-G2 11.000	1	-		**22004**	TAG LOME 11.000	1	-
12032	OLORUNSO GT410.500	1	-		**42016**	SINGROBO G2 11.000	1	-
12031	OLORUNSO GT310.500	1	-		**42015**	SINGROBO G1 11.000	1	-
162001	SAMBAG1 11.000	1	-		**32124**	AMERI 13.8 13.800	9	-
162002	SAMBAG2 11.000	1	-		**32127**	AMANDI PP 14.400	1	-
32078	ASOG-G4 11.000	1	-		**32127**	AMANDI PP 14.400	2	-
13009	KAINJ 1G6 16.000	1	-		**43015**	CIPREL TAV 15.500	1	-
32035	KPONG-HG4 13.800	1	-		**12052**	OMOTNIPP GT210.500	1	-
32005	AKOSOMBO-HG514.400	1	PSS2A		**92011**	KALOUM 32G 6.3000	1	-
32001	AKOSOMBO-HG114.400	1	PSS2A		**32128**	GE PP 14.400	1	-
32004	AKOSOMBO-HG414.400	1	PSS2A		**32132**	T5 PP 14.400	3	-
12117	RIVERS _GT1 10.500	1	-		**61003**	MALBAZA 0.4000	1	-
32054	BUI-G1 14.400	1	-		**43010**	AGGREKO 1 2 15.500	2	-
32055	BUI-G2 14.400	1	-		**43010**	AGGREKO 1 2 15.500	1	-
13020	SHIROR 411G116.000	1	-		**92015**	KALOUM 52G 11.000	1	-
22001	TAG MARIA GL11.000	1	-		**22001**	TAG MARIA GL11.000	2	-

As it can be seen, 2020 scenarios include more machines to be optimized in comparison with the 2016 scenarios because of a larger foreseen installed capacity.

4.1.4 CONCLUSIONS

The study is aimed to perform the small signal analysis on the WAPP network considering different operation scenarios. In particular the following scenarios, representative of the typical operating conditions have been considered:

- 2016 peak and off peak scenario
- 2016 peak and off peak interconnected scenario
- 2020 peak and off peak scenario

The analysis has been focused on the inter-area modes and on the detection of those modes with damping ratio less then damping target of 5%. As it has been explained in the previous pages in each scenario there are inter-area modes but they are well damped.

However, a characterization of the inter-area modes is useful to understand the different behavior of the network in different scenarios. The following table reports the oscillation modes with the lowest frequency and damping, characterized by their mode shape and system configuration.

Table 4.9: **Most important interarea modes in 2016 scenarios**

2016 PEAK				
Mode Num.	Mode description	Sigma	Frequency [Hz]	Damping Ratio
1	Interarea GHANA Interconnection	-0.483	0.434	17.453%
2	Interarea BURKINA FASO	-0.22	0.54	6.458%
3	Interarea MALI interconnection	-0.798	0.67	18.609%
9	Interarea FLEUVE (Niger)	-0.336	0.977	5.474%

2016 PEAK INTERCONNECTED				
Mode Num.	Mode description	Sigma	Frequency [Hz]	Damping Ratio
1	Interarea WAPP interconnection	-0.33	0.274	18.799%
2	Interarea GHANA-COTE D'IVOIRE	-0.384	0.479	12.650%
3	Interarea BURKINA FASO	-0.256	0.551	7.381%
4	Interarea MALI - SENEGAL	-0.82	0.683	18.766%
10	Interarea FLEUVE (Niger)	-0.341	0.981	5.524%

2016 OFF PEAK				
Mode Num.	Mode description	Sigma	Frequency [Hz]	Damping Ratio
1	Interarea GHANA interconnection	-0.43	0.494	13.737%
2	Interarea BURKINA FASO	-0.483	0.777	9.846%

2016 OFF PEAK INTERCONNECTED				
Mode Num.	Mode description	Sigma	Frequency [Hz]	Damping Ratio
1	Interarea WAPP interconnection	-0.171	0.38	7.125%
2	Interarea GHANA-COTE D'IVOIRE	-0.412	0.539	12.084%
3	Interarea BURKINA FASO	-0.506	0.786	10.185%

In the “GHANA interconnection” interarea mode of 2016-Peak scenario, practically all generators of the interconnected system of Ghana-Cote d’Ivoire-Burkina Faso-Togo participate. According to the mode shape the generators of Ghana oscillate against the generators of Cote d’Ivoire and Burkina Faso. Similarly, in the “WAPP interconnection” interarea mode of the 2016-Peak-Interconnected scenario, practically all generators of the WAPP interconnected system participate. Focusing on the biggest control areas, the generators of Nigeria oscillate against the generators of Ghana and Cote d’Ivoire. This is of course a new very important low frequency interarea mode which results from the interconnection of the now three separate systems. Damping for this mode is quite *low* in the off-peak-interconnected case. One reason for this can be that there are less machines in-service with stabilizers in the off-peak case (e.g. unit AKOSOMBO-HG5 at bus 32005).

The “Ghana-Cote d’Ivoire” interarea mode of the interconnected cases is similar to the “Ghana interconnection” mode of the base cases. However, in the interconnected cases the system is significantly different (Mali and Senegal now also participate in this mode) and the frequency increases and damping is significantly ***reduced.***

In peak scenarios the two modes with the lowest damping are:

- The Burkina Faso interarea mode (mode n.2 in base-case and mode n.3 in Inter-case) with all the generators of Burkina Faso oscillating in phase against the rest of the interconnection (Ghana interconnection in base case or WAPP interconnection in the interconnected case);
- The interarea mode of Fleuve Zone of Niger (mode n.9 in base and n.10 in Inter-case) where the generators in Fleuve zone oscillate against the rest.

For both modes, in interconnected case, frequency and damping slightly increase as they are connected to a larger system compared to the base case.

In Burkina Faso there are no stabilizers and in Fleuve zone the generators equipped with stabilizers are not in-service. The stabilizers in the rest of the system increase the damping marginally. The solution to increase the damping of these modes is the introduction of recommended stabilizers in Burkina Faso and Fleuve.

Moreover some short-circuit simulations are carried out in order to demonstrate some results of the small signal analysis. In particular has been applied self-cleared faults (duration: 100 ms) at extremities of tie-lines. The plots show the corresponding MW flow through the examined tie-line. Disturbances are applied at Peak cases.

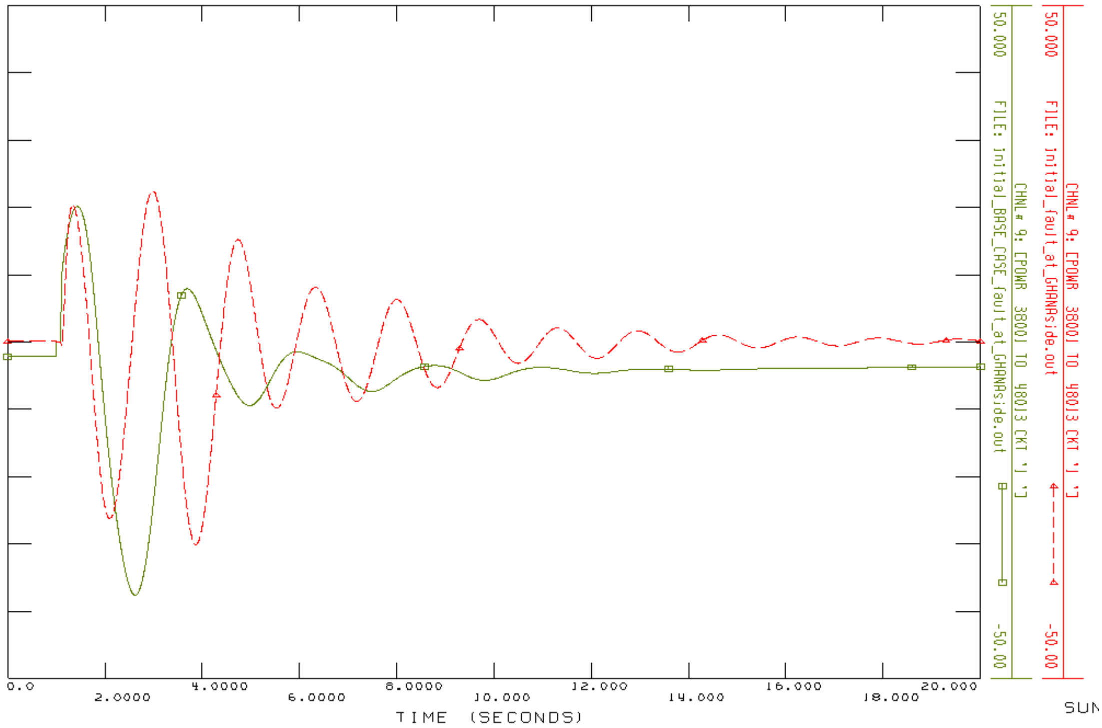


Figure 4.9: Compare fault at GHANA side in base (green) and interconnected case (red)

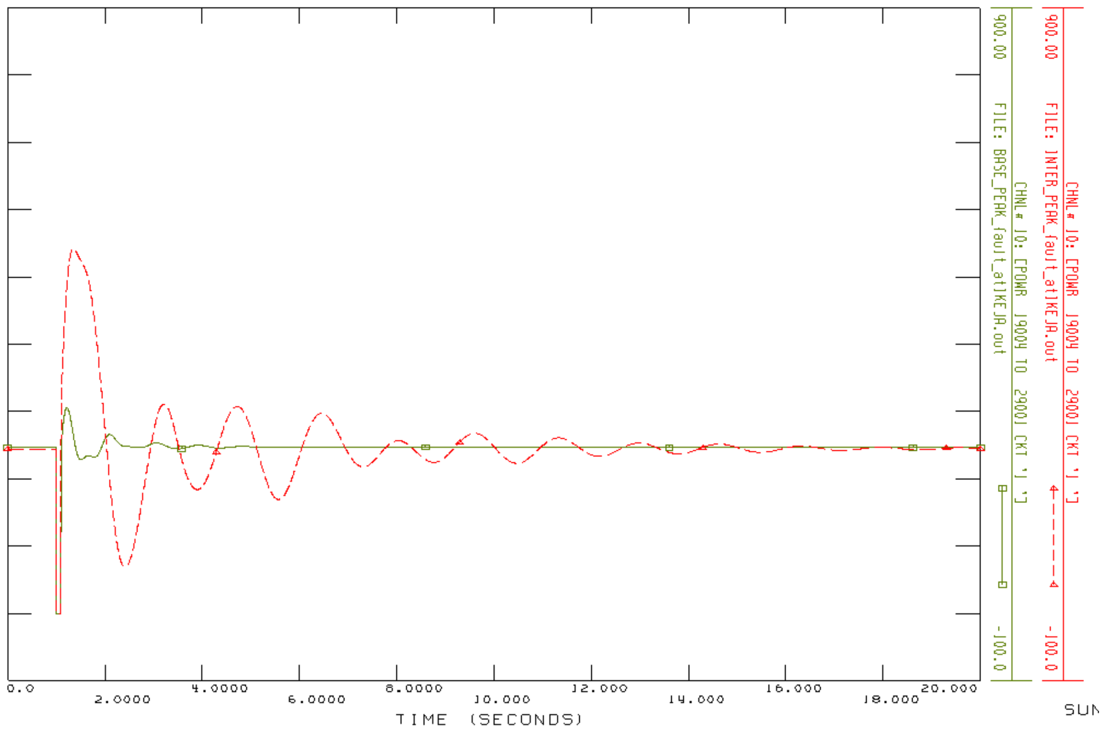


Figure 4.10: Compare fault at IKEJA (Nigeria) in base (green) and interconnected case (red)

The responses reported in Figure 4.9 and Figure 4.10 show that in interconnected scenario low frequency interarea oscillations emerge. Even though the damping is acceptable, it should be stressed that in interconnected operation the application of stabilizers (used in the dynamic model) is more important comparing to the non-interconnected base cases.

The most important interarea modes (low frequency or damping) for 2020 scenarios are listed in Table 4.10.

Table 4.10: Most important interarea modes in 2020 scenarios

2020 PEAK				
Mode Num.	Mode description	Sigma	Frequency [Hz]	Damping Ratio
1	Interarea WAPP 1 (NIGERIA – SE-NEGAL)	-0.371	0.383	15.229%
2	Interarea WAPP 2 (NIGERIA & SENEGAL – GHANA)	-0.397	0.489	12.813%
3	Interarea GUINEA - SENEGAL	-0.421	0.678	9.832%
4	Interarea MALI-SENEGAL	-0.891	0.697	19,932%
5	Intrerarea GUINEA	-0.335	0.716	7.413%
6	Interarea BURKINA FASO	-0.448	0.757	9.388%

2020 OFF PEAK				
Mode Num.	Mode description	Sigma	Frequency [Hz]	Damping Ratio
1	Interarea WAPP 1 (NIGERIA - SENEGAL)	-0.196	0.444	7.019%
2	Interarea WAPP 2 (NIGERIA & SENEGAL – GHANA)	-0.350	0.591	9.381%
3	Interarea GUINEA - SENEGAL	-0.386	0.724	8.441%
4	Interarea GUINEA	-0.477	0.797	9.485%

Also in 2020 peak scenario the frequency of the modes decreases and the damping increases compared to the 2020 off peak scenario.

Several local modes are observed in each scenario (both in 2016 and 2020), having damping ratio less than 20% (damping target).The analysis of the participation factors for the local modes allows to identify the machines in which the PSSs should be installed or tuned. Table 4.7 and Table 4.8 report (for 2016 and 2020 scenarios) the list of candidate machines on which those actions are recommended.

4.2 DYNAMIC SECURITY ASSESSMENT AND DEFENCE PLAN

In this analysis the ability of the system to withstand the occurrence of normative and severe contingencies has been assessed. The results of this study have been used, together with the steady state analyses reported in §3, to identify and propose a list of reinforcements aimed at ensuring a synchronous operation of the WAPP power system.

Normative Contingencies

The analysis of normative contingencies is important for the proper operation of the power systems because it allows to assess the ability of the system to face the typical disturbances addressed by the operational security in the grid codes. Normative contingencies are defined in "Policy 3 – Operational Security" of the WAPP Operation Manual [17]. According the N-1 criterion, single events have to be considered. In the framework of this study the following events have been considered:

- 3PH short circuits, cleared in base time (100 ms), on each tie line interconnecting the WAPP countries
- Loss of the largest unit in each interconnected country

The evaluation criteria have been based on the WAPP Operation Manual security criteria:

- The loss of a single element in the power system must not cause a frequency deviation outside acceptable limits. Emergency frequency limits are not specified in [17]. In the framework of this study it has been verified that the frequency do not activate the first load shedding stage in any country.
- The loss of a single element in the power system must not cause a voltage drop which may lead to voltage instability
- The loss of a single element in the power system must not cause instability in the interconnected system
- The loss of a single element in the power system must not cause cascading outages of other elements as a result of exceeding operational security limits.

Severe Contingencies

The analysis of severe contingencies is important for assessing the proper dynamic response of the system following major faults and outages and for verifying the effectiveness of the defense plan.

The simulated severe contingencies included generation losses, tripping of critical lines from the point of view of the system stability and separation of interconnected areas.

The analysis of both normative and severe contingencies have been focused on the following aspects:

- Evaluation of the adequacy of the regulators to control the system frequency and voltages
- Evaluation of effectiveness of the existing defense plan.

Primary Frequency Response

The performances of the primary frequency controls have been checked both in terms of contribution amount and dynamic response.

Voltage Stability

The occurrence of voltage instabilities have been monitored during the simulations.

Defense Plans

The above described disturbances have been simulated considering the currently implemented Defense Plans affecting the stability and security of the interconnection. The proposed updating of the defense plan have been defined following the harmonization principle which should be adopted in case of interconnected systems.

4.2.1 Analysis Result – 2016 Scenarios

The complete results of the analysis performed on 2016 Scenarios are available in Annex [A11]. In the following are reported the related summaries for the Base and Interconnected-Reinforced scenarios.

4.2.1.1 Analysis Result – 2016 Base Scenarios

In §4.2.1.1.1 and §4.2.1.1.2 are summarized the results of the analyses on the 2016 base scenarios in terms of generation trip and line/transformer trip (after a 100 ms 3-phase fault).

4.2.1.1.1 Loss of generators

As shown in Table 4.11 all the analysed cases are stable. In some cases the contingency activates the UFLS.

Table 4.11: Main results of generation trip for 2016 base scenarios

Contingency	BUS	Area	Scenarios	Pg [MW]	Stability	UFLS	COMMENT
BelAir 4G	122010/1	SENELEC	S16-CP-BELA	26.7	Stable	Stage 1	LSH causes over-frequency
DPC3 G2	122007/1		S16-CO-DPC3	20	Stable	Stage 1	LSH causes over-frequency
Akosombo G1	32001/1	GRIDCO	S16-CP-AKOS	132.8	Stable	--	--
			S16-CO-AKOS	140	Stable	Stage 1	--
Azito GT2	43008/1	CIE	S16-CP-AZIT	121.0	Stable	--	--
			S16-CO-AZIT	61	Stable	--	--
Egbin G1	13001/1	TCN	S16-CP-EGBI	210.1	Stable	--	--
			S16-CO-EGBI	209.7	Stable	--	--
Goroubanda G1	62008/1	NIGELEC	S16-CP-GORO	15.0	Stable	--	--
			S16-CO-GORO	14.0	Stable	--	--
Soraz G1	62026/1	NIGELEC	S16-CP-SORA	11.0	Stable	--	--

			S16-CO-SORA	6.0	Stable	--	--
Tag_lome G1	22004/1	CEB	S16-CP-TAGL	15.0	Stable	--	--
			S16-CO-TAGL	18.0	Stable	--	--
Kossodo G8	52032/1	SONABEL	S16-CP-KOSS	14.3	Stable	--	--
			S16-CO-KOSS	Not in service	--	--	--
Dar salam G1	133008/1	EDM	S16-CP-DARS	25.3	Stable	--	--
			S16-CO-DARS	Not in service	--	--	--
Manantali G1	142001/1	SOGEM	S16-CP-MANA	36.2	Stable	Stage 1	LSH causes over-frequency
			S16-CO-MANA	32.2	Stable	Stage 1	LSH causes over-frequency
EGBIN G1 Akosombo G1 (Reference incident)	13001/1 32001/1	TCN/GRIDCO	S16-CP-EGAK	342.9	Stable	--	--
			S16-CO-EGAK	349.7	Stable	Stage 1	--

4.2.1.1.2 Loss of a line/transformer due to three phase short circuit

As shown in Table 4.12 not all the analysed cases are stable. The unstable contingencies are highlighted in yellow.

Table 4.12: Main results of branch trip for 2016 base scenarios

Contin-gency	BRANCH F-T/ID	Area	Scenar-ios	Ptr F→T [MW]	Stability	UFLS	COMMENT
Ferke – Kodeni	48006-58001/1	CIE/SONABEL	S16-CP-FERK-KODE	50	Stable	3 Stag-es	--
			S16-CO-FERK-KODE	50.5	Unstable	3 Stag-es	black-out (BO) and under-frequency in SONABEL. no reserve, few units in service in SONA-

							BEL
Ferke – Sikasso	48006-138001/1	CIE/EDM	S16-CP-FERK-SIKA	30.3	Stable	--	LVLS triggered in SONABEL
			S16-CO-FERK-SIKA	30.3	Stable	--	LVLS triggered in SONABEL
Riviera – Prestea	48013-38001/1	CIE/GRIDCO	S16-CP-RIVI-PRES	2.5	Stable	--	Damped frequency oscillations in CIE/SONABEL
			S16-CO-RIVI-PRES	-0.2	Stable	--	Damped frequency oscillations in CIE/SONABEL
Lome Aflao – Asiekpe	27016-37037/1	CEB/GRIDCO	S16-CP-LOME-ASIE	-43.5	Stable	--	--
			S16-CO-LOME-ASIE	-43.2	Stable	--	--
Lome Aflao – Aftap	27016-37055/1	CEB/GRIDCO	S16-CP-LOME-AFTA	-37.2	Stable	--	--
			S16-CO-LOME-AFTA	-37.3	Stable	--	--
Davie – Asogli	29003-39003/1	CEB/GRIDCO	S16-CP-DAVI-ASOG	Not in service	--	--	--
			S16-CO-DAVI-ASOG	Not in service	--	--	--
Katsina – Gazaoua	16099-66017/1	TCN/NIGELEC	S16-CP-KATS-GAZA	29.7	Unstable	--	BO UNDERFREQUENCY IN NIGELEC, NO LSH, OUT OF STEP CONDITIONS IN NIGELEC
			S16-CO-KATS-GAZA	30.0	Unstable	--	BO UNDERFREQUENCY IN NIGELEC, NO LSH, LOSS OF SYNCHRONISM IN NIGELEC
Bkebbi –	16061-	TCN/NIGE	S16-CP-BKEB-	70.3	Unstable	--	BO UNDERFREQUENCY

Dosso	66002/1	LEC	DOSS				IN NIGELEC, NO LSH, LOSS OF SYNCHRO-NISM IN NIGELEC
			S16-CO-BKEB-DOSS	70.0	Unstable	--	BO UNDERFREQUENCY IN NIGELEC, NO LSH, LOSS OF SYNCHRO-NISM IN NIGELEC
Sakete – Ikeja	29001-19004/1	CEB/TCN	S16-CP-SAKE-IKEJ	-244.7	Unstable	--	LOSS OF SYNCHRO-NISM IN CEB, NO LSH
			S16-CO-SAKE-IKEJ	-242.5	Unstable	--	LOSS OF SYNCHRO-NISM IN CEB, NO LSH
Bakel-Kayes	148029-148028/1	SOGEM	S16-CP-BAKE-KAYB	-114.4	Unstable	Stage 2	Separation of SENELEC and part of SOGEM network that remain stable with UFLS intervention, while inside the rest of SOGEM and EDM network over-frequency occurs **Proposed measure:** over-frequency has to be faced with overspeed protections on units (not included in the model) with a proper selective tuning in order to avoid simultaneous generation disconnections.
			S16-CO-BAKE-KAYB	-116.9	Stable	Stage 2	As Peak Scenario
Bkebbi-Kainji	19014-19017/1	TCN	S16-CP-BKEB-KAIN	-157.8	Unstable	--	BO UNDERFREQUENCY IN NIGELEC, NO LSH, LOSS OF SYNCHRO-NISM IN NIGELEC

			S16-CO-BKEB-KAIN	-157.6	Unstable	--	BO UNDERFREQUENCY IN NIGELEC, NO LSH, LOSS OF SYNCHRO-NISM IN NIGELEC
Kaduna-Kano	19028-19029/1	TCN	S16-CP-KADU-KANO	213.0	Unstable	--	BO UNDERFREQUENCY IN NIGELEC, NO LSH, LOSS OF SYNCHRO-NISM IN NIGELEC
			S16-CO-KADU-KANO	213.3	Unstable	--	BO UNDERFREQUENCY IN NIGELEC, NO LSH, LOSS OF SYNCHRO-NISM IN NIGELEC
Ferke-Bouake2	48006-48005/1	CIE	S16-CP-FERK-BOUA	-123.9	Unstable	--	BO UN-DERFREQUENCY IN SONABEL/EDM.
			S16-CO-KADU-BOUA	-97.2	Unstable	--	BO UN-DERFREQUENCY IN SONABEL/EDM.
Ferke-TR-225-90	48006-46006/1	CIE	S16-CP-FERK-TR22	42.8	Stable		UVLS TRIGGERED IN SONABEL
			S16-CO-FERK-TR22	16.3	Stable		UVLS TRIGGERED IN SONABEL

4.2.1.2 Analysis Result – 2016 Interconnected reinforced Scenarios

In §4.2.1.2.1 and §4.2.1.2.2 are summarized the results of the analyses on the 2016 interconnected and reinforced scenarios in terms of generation trip and line/transformer trip (after a 100 ms 3-phase fault).

4.2.1.2.1 Loss of generators

As shown in Table 4.13 all the analysed cases are stable. Comparing the results with the 2016 base case it is possible to observe that the UFLS is never activated.

Table 4.13: Main results of generation trip for 2016 interconnected reinforced scenarios

Contingency	BUS	Area	Scenarios	Pg [MW]	Stability	UFLS	COMMENT
BelAir 4G	122010/1	SENELEC	S16-RP-BELA	26.7	Stable	--	--
DPC3 G2	122007/1		S16-RO-DPC3	20.0	Stable	--	--
Akosombo G1	32001/1	GRIDCO	S16-RP-AKOS	136.5	Stable	--	--
			S16-RO-AKOS	142.2	Stable	--	--
Azito GT2	43008/1	CIE	S16-RP-AZIT	125.5	Stable	--	--
			S16-RO-AZIT	73.1	Stable	--	--
Egbin G1	13001/1	TCN	S16-RP-EGBI	209.3	Stable	--	--
			S16-RO-EGBI	209.4	Stable	--	--
Goroubanda G1	62008/1	NIGELEC	S16-RP-GORO	15.7	Stable	--	--
			S16-RO-GORO	14.7	Stable	--	--
Soraz G1	62026/1	NIGELEC	S16-RP-SORA	11.0	Stable	--	--
			S16-RO-SORA	6.0	Stable	--	--
Tag_lome G1	22004/1	CEB	S16-RP-TAGL	15.0	Stable	--	--

			S16-RO-TAGL	18.0	Stable	--	--
Kossodo G8	52032/1	SONABEL	S16-RP-KOSS	15.0	Stable	--	--
			S16-RO-KOSS	Not in Service	--	--	--
Dar Salam G1	133008/1	EDM	S16-RP-DARS	25.3	Stable	--	--
			S16-RO-DARS	Not in Service	--	--	--
Manantali G1	142001/1	SOGEM	S16-RP-MANA	36.7	Stable	--	--
			S16-RO-MANA	32.3	Stable	--	--
EGBIN_G1 Akosombo G1 (Reference incident)	13001/1 32001/1	TCN/GRIDCO	S16-RP-EGAK	345.8	Stable	--	--
			S16-RO-EGAK	351.6	Stable	--	--

4.2.1.2.2 Loss of a line/transformer due to three phase short circuit

As shown in Table 4.14 not all the analysed cases are stable. The unstable contingencies are highlighted in yellow. For these cases the proposed measures are indicated. Some of the most significant and critical contingencies are further detailed in Tables from Table 4.15 to Table 4.20, showing the effects of the proposed reinforcements.

Table 4.14: Main results of branch trip for 2016 interconnected reinforced scenarios

Contingency	BRANCH F-T/ID	Area	Scenarios	Ptr F→T [MW]	Stability	UFLS	COMMENT
Ferke – Kodeni	48006-58001/1	CIE/SONABEL	S16-RP-FERK-KODE	49.9	Stable	1 Stage	--
			S16-RO-FERK-KODE	50.5	Unstable	3 Stage	Frequency instability. Lack of unit in service in SONABEL, low inertia. **Proposed meas-**

							ure: review of generator dis-patching or/and UFLS tuning
Ferke – Sikasso	48006-138001/1	CIE/EDM	S16-RP-FERK-SIKA	26.7	Stable	--	--
			S16-RO-FERK-SIKA	30.4	Stable	--	--
Riviera – Prestea	48013-38001/1	CIE/GRIDCO	S16-RP-RIVI-PRES	0.1	Stable	--	--
			S16-RO-RIVI-PRES	-0.5	Stable	--	--
Lome Aflao – Asiekpe	27016-37037/1	CEB/GRIDCO	S16-RP-LOME-ASIE	-22	Stable	--	--
			S16-RO-LOME-ASIE	-21.4	Stable	--	--
Lome Aflao – Aftap	27016-37055/1	CEB/GRIDCO	S16-RP-LOME-AFTA	-16.7	Stable	--	--
			S16-RO-LOME-AFTA	-16.3	Stable	--	--
Davie – Asogli	29003-39003/1	CEB/GRIDCO	S16-RP-DAVI-ASOG	-45.8	Stable	--	--
			S16-RO-DAVI-ASOG	-47.3	Stable	--	--
Katsina – Gazaoua	16099-66017/1	TCN/NIGELEC	S16-RP-KATS-GAZA	29.7	Unstable	3 Stage	Separation of the NIGELEC_NCE area. Overvoltage instability in NIGELEC follow-ing LSH. **Stable with proposed meas-ure:** trip also enough capaci-tor banks to-

							gether with the LSH.
			S16-RO-KATS-GAZA	30.0	Unstable	3 Stage	Same as Peak Scenario
Bkebbi – Dosso	16061-66002/1	TCN/NIGELEC	S16-RP-BKEB-DOSS	68.0	Stable	3 Stage	Over-frequency caused by LSH in NIGELEC
			S16-RO-BKEB-DOSS	68.8	Stable	3 Stage	Over-frequency caused by LSH in NIGELEC
Sakete – Ikeja	29001-19004/1	CEB/TCN	S16-RP-SAKE-IKEJ	-243	Stable	--	--
			S16-RO-SAKE-IKEJ	-242.2	Stable	--	--
Bakel-Kayes	148029-148028/1	SOGEM	S16-RP-BAKE-KAYB	-114.4	Unstable	3 Stage	Separation of SENELEC and part of SOGEM network that remain stable with UFLS intervention, while inside the rest of SOGEM and EDM-SA network loss of synchronism with rest of WAPP occurs. **Stable (with over-frequency in Senelec) considering the reinforcement:** install an out-of-step relay, which can separate EDM-SA and CIE control areas.
			S16-RO-BAKE-KAYB	-116.9	Unstable	3 Stage	Same as Peak Scenario
Bkebbi-Kainji	19014-19017/1	TCN	S16-RP-BKEB-KAIN	-157.8	Unstable	3 Stage	LOSS OF SYNCHRONISM IN NIGELEC

							Stable with Proposed Meas-ure: tripping 3 windings trans-formers
			S16-RO-BKEB-KAIN	-157.6	Unstable	3 Stage	Same as Peak Scenario
Kaduna-Kano	19028-19029/1	TCN	S16-RP-KADU-KANO	213.0	Unstable	3 Stage	TCN – NI-GELEC_NCE sepa-ration, UNDERVOLTAGES, LOSS OF SYN-CHRONISM, in NIGELEC. **Stable with Proposed meas-ure:** tripping two 3 windings transformers at KANO connecting KUMB T2A 132 kV (at same time line tripping) and an extra protection re-lay (e.g. un-dervoltage) at KATSINA – GAZAOUA inter-connection.
			S16-RO-KADU-KANO	213.3	Unstable	3 Stage	Same as Peak Scenario
Ferke-Bouake2	48006-48005/1	CIE	S16-RP-FERK-BOUA	-123.9	Unstable	3 Stage	LOSS OF SYN-CHRONISM IN EDM/SONABEL **Stable with Proposed meas-ure:** for the short-term it is recommended to install an intertrip relay with the trans-former at Ferké, causing a network sepa-ration.

			S16-RO-KADU-BOUA	-97.2	Unstable	3 Stage	Same as Peak Scenario
Ferke-TR-225-90	48006-46006/1	CIE	S16-RP-FERK-TR22	42.8	Stable	--	--
			S16-RO-FERK-TR22	16.3	Stable	--	--

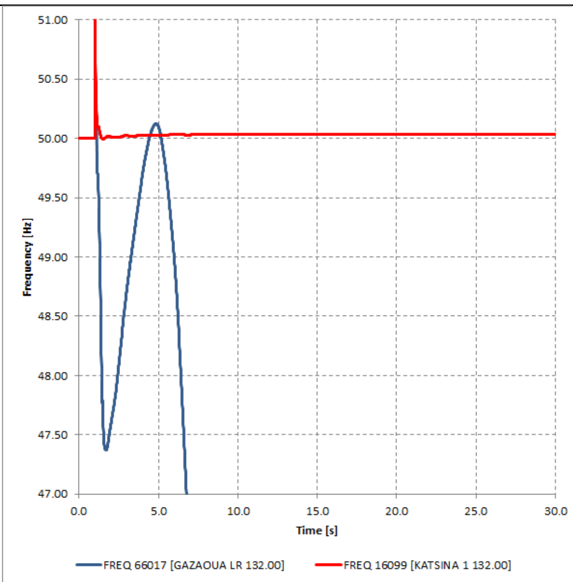
4.2.1.2.3 Results of the most significant contingencies

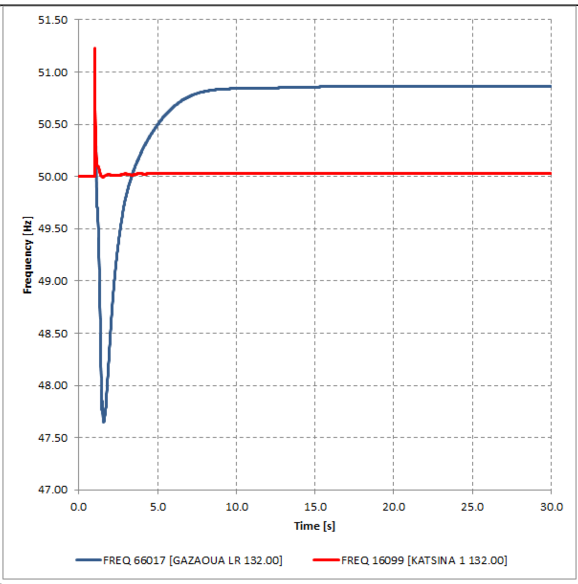
Tables from Table 4.15 to Table 4.20, show the simulation results of the most significant contingencies including the effects of the proposed reinforcements.

Table 4.15: Contingency Katsina – Gazaoua 132 kV line (TCN/NIGELEC)

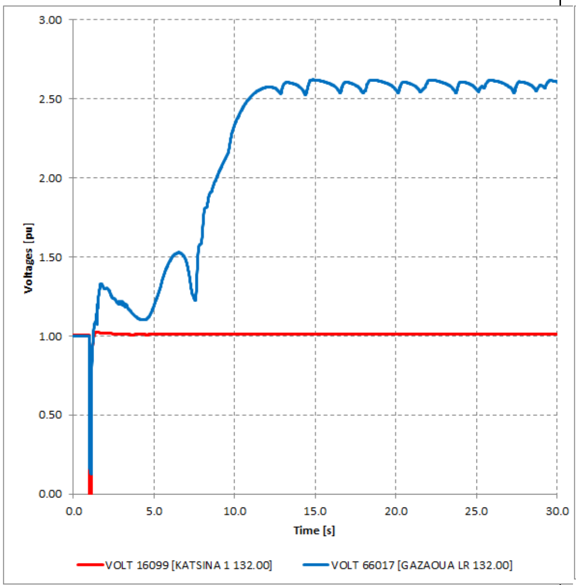
Event	Description	Action Time
Fault	3ph fault 132 kV line KATSINA 1 – GAZAOUA LR (16099–66017 / 1)	
Clearing	Line tripping	0.1 s
Effect	Separation of the NCE area in Niger, UFLS action	
Instability without Remedial measures	Voltage instability after UFLS in NCE	
Proposed Remedial Measures	Tripping capacitors banks in NCE 63024 ZINDER 63026 MARADI 63027 MALBAZA 64009 ILLELA (except for the SVC in GAZAOUA). The amount of capacitors to be tripped should be determined by dedicated analysis.	Indicatively at the same time of 2nd UFLS stage of loads in the same substations (Hypothesis: all loads are equipped with UFLS). Approximately at 1.48s in the performed simulation.

Without Remedial Measures	With Remedial Measures
Frequency:	





Voltage:



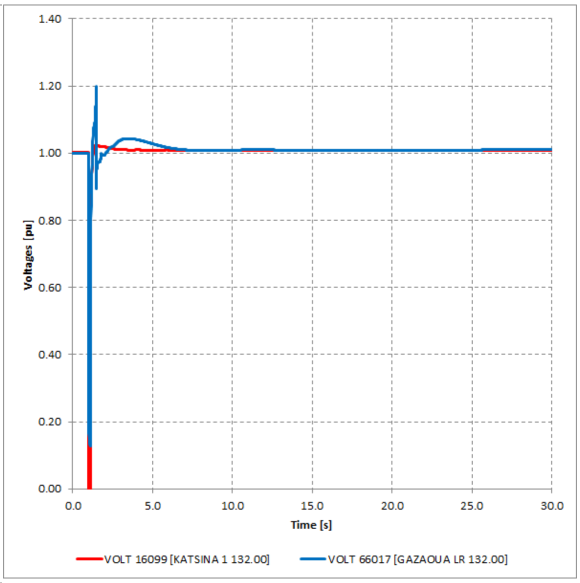
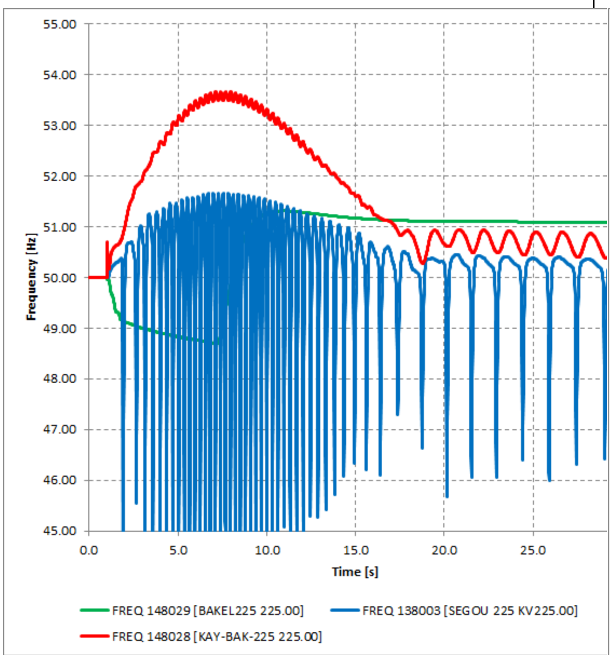
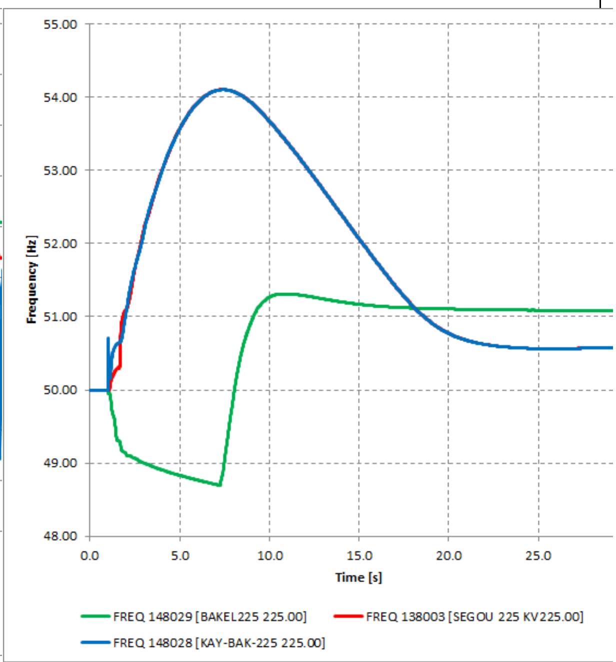
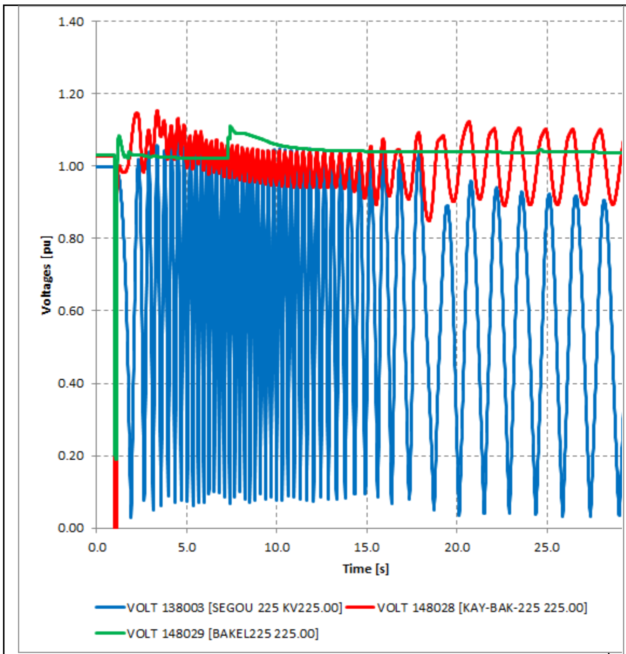


Table 4.16: Contingency Bakel – Kayes 225 kV line (SOGEM)

Event	Description	Action Time
Fault	3ph fault 225 kV line Bakel-Kayes (148029-148028/1)	
Clearing	Line tripping	0.1 s
Effect	Separation of SENELEC and part of SOGEM	

	network	
Instability without Remedial measures	SENELEC remains stable with UFLS intervention, while inside the rest of SOGEM and EDM network loss of synchronism with rest of WAPP occurs	
Proposed Remedial Measures	Install an out-of-step relay which can separate EDM-SA and CIE control areas. Tripping of either: • Segou-Koutiala (138002-138003) or • Sikasso – Ferké (138001-48006)	0.6 s estimated
	As in the base case, overfrequency in SENELEC has to be faced with overspeed protections on units (not included in the actual model) with a proper selective tuning in order to avoid simultaneous generation disconnections.	

Without Remedial Measures	With Remedial Measures
Frequency: 	
Voltage:	


Voltages [pu]
Time [s]
VOLT 138003 [SEGOU 225 KV225.00]
VOLT 148028 [KAY-BAK-225 225.00]
VOLT 148029 [BAKEL225 225.00]

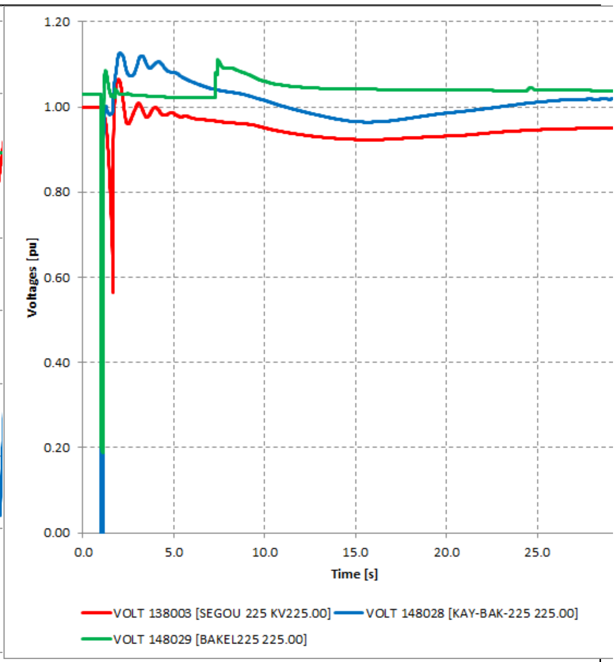
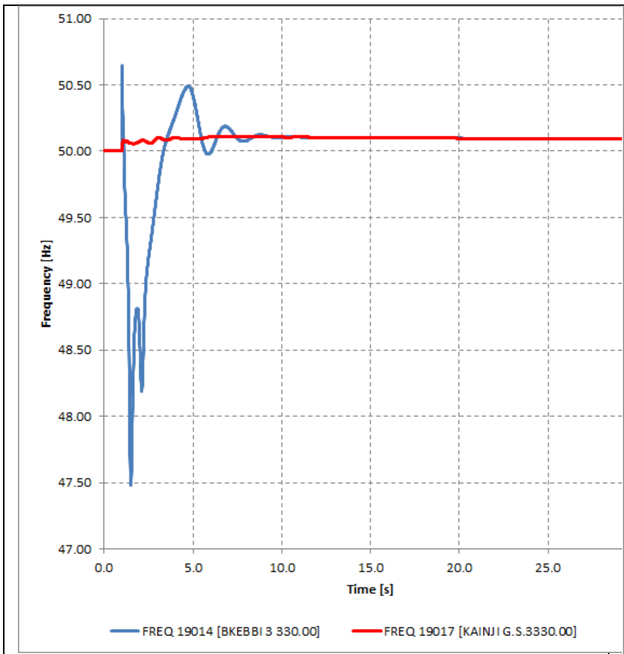
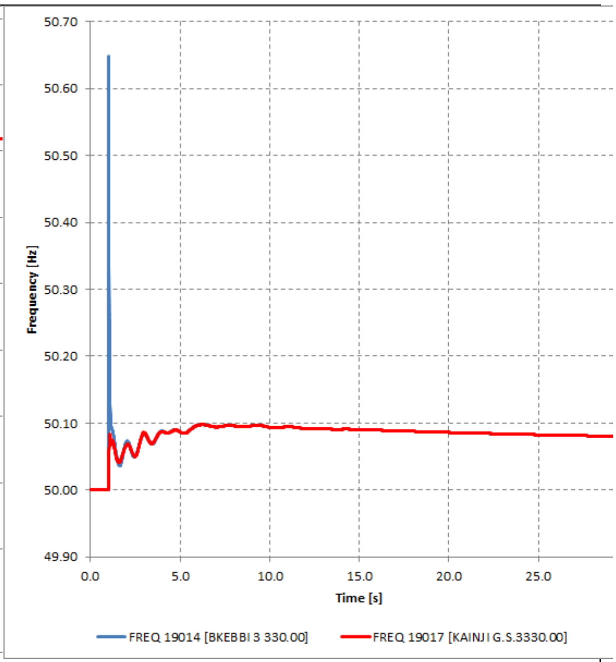

Voltages [pu]
Time [s]
VOLT 138003 [SEGOU 225 KV225.00]
VOLT 148028 [KAY-BAK-225 225.00]
VOLT 148029 [BAKEL225 225.00]

Table 4.17: **Contingency B.Kebbi – Kainji 330 kV line (TCN)**

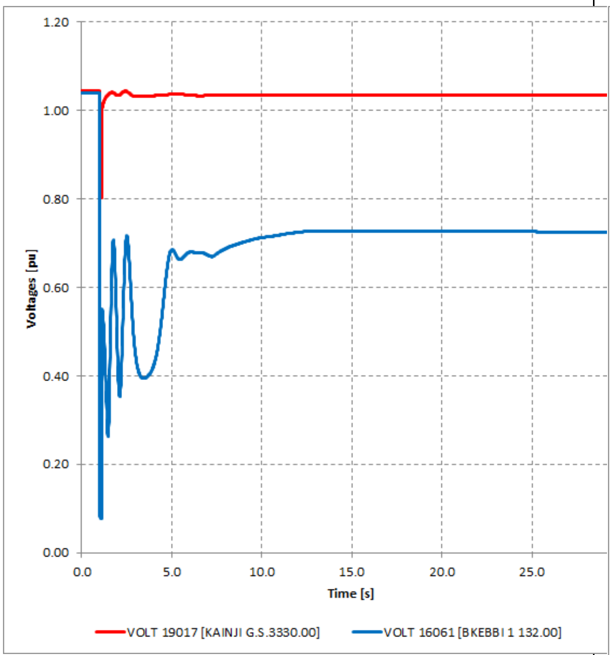
Event	Description	Action Time
Fault	3ph fault 330 kV line Bkebbi-Kainji (19014-19017/1)	
Clearing	Line tripping	0.1 s
Effect	Separation of Nigelec. NIGELEC-FLEUVE network remain connected to TCN network only through the B.Kebbi 330/132/33 kV transformers (Sokoto – B.Kebbi 132 kV lines are out of service).	
Instability without Remedial measures	Undervoltages, Loss of synchronism in Nigelec	
Proposed Remedial Measures	It is recommended to install an intertrip relay (with the pos-sible deactivation if the power flows on the line is below a pre-defined threshold or different configuration if Sokoto – B.Kebbi lines will be put in operation) with the two 3 winding transformers at B.Kebbi: • BKEBBI 3/ BKEBBI 1/ BKB6 (19014, 16061, 12058) • BKEBBI 3/ BKEBBI 1/ BKB5 (19014, 16061, 12059)	Same time line tripping

Without Remedial Measures	With Remedial Measures
Frequency:	


Frequency [Hz]
Time [s]
FREQ 19014 [BKEBBI 3 330.00]
FREQ 19017 [KAINJI G.S.3330.00]


Frequency [Hz]
Time [s]
FREQ 19014 [BKEBBI 3 330.00]
FREQ 19017 [KAINJI G.S.3330.00]

Voltage:


Voltages [pu]
Time [s]
VOLT 19017 [KAINJI G.S.3330.00]
VOLT 16061 [BKEBBI 1 132.00]

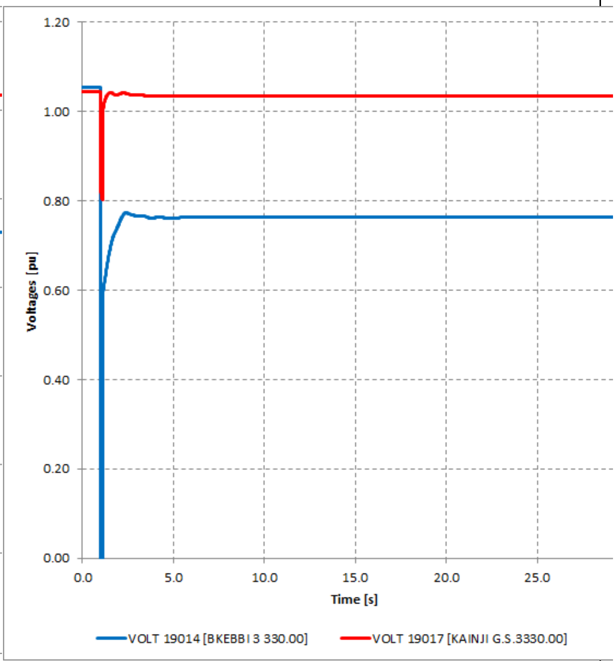

Voltages [pu]
Time [s]
VOLT 19014 [BKEBBI 3 330.00]
VOLT 19017 [KAINJI G.S.3330.00]

Table 4.18: **Contingency Kaduna – Kano 330 kV line (TCN)**

Event	Description	Action Time
Fault	3ph fault 330 kV line KADUNA 3 - KANO 3 (19028 - 19029)	
Clearing	Line tripping	0.1 s
Effect	TCN - NCE separation. NIGELEC-NCE network remain connected to TCN network only through the Kano 330/132/33 kV transformers (through the busbar at Kumb T2A 132 kV). UFLS action. A significant amount of load in KADUNA zone (about 180 MW) separates from Nigeria and remains connected to NCE Area.	
Instability without Remedial measures	Undervoltages and loss of synchronism in NIGELEC	
Proposed Remedial Measures	It is recommended to install an intertrip relay (with the possible deactivation if the power flows on the line is below a pre-defined threshold) with the two 3 winding transformers at Kano connecting Kumb T2A 132 kV: • KANO 3 / KUMB T2A BB / KANO T2A (19029, 16106, 14242 / 2) • KANO 3 / KUMB T2A BB / KANO OLD T (19029, 16106, 14208 / 1)	Same time as line tripping
	It is recommended also to install an undervoltage protection relay at KATSINA - GAZAOUA interconnection	0.3
	It is recommended also to have overvoltage shunt tripping of NCE in order to prevent overvoltage instability: • 63024 ZINDER • 63026 MARADI • 63027 MALBAZA • 64009 ILLELA	With 2nd stage of UFLS (1.5 s indicatively)

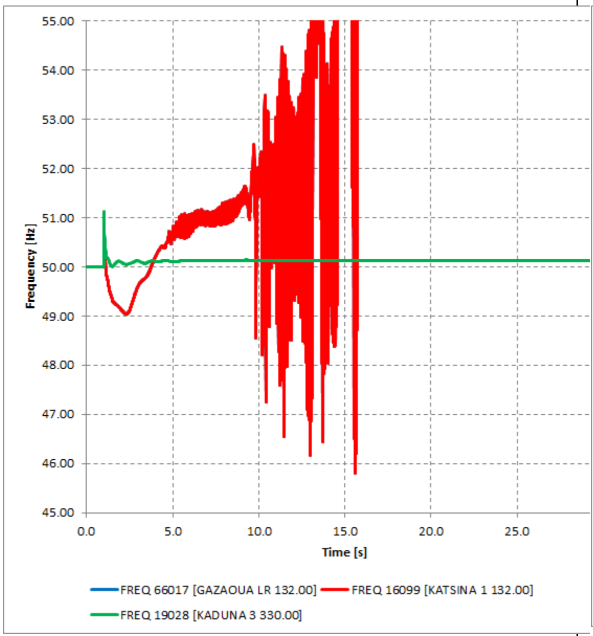
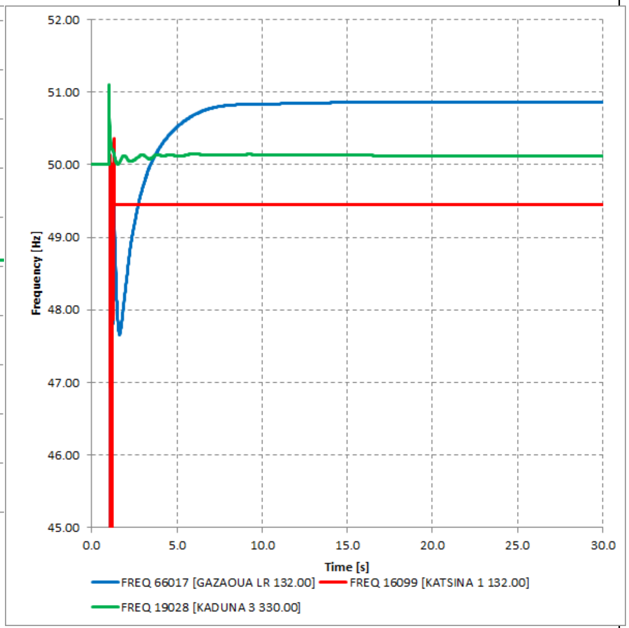
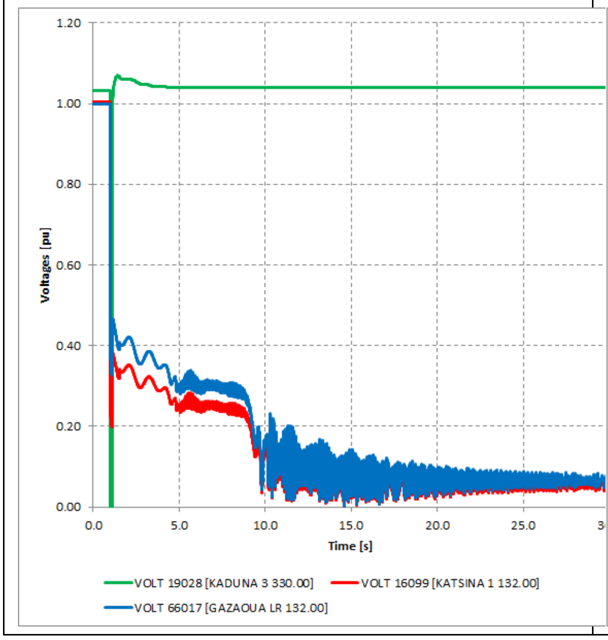
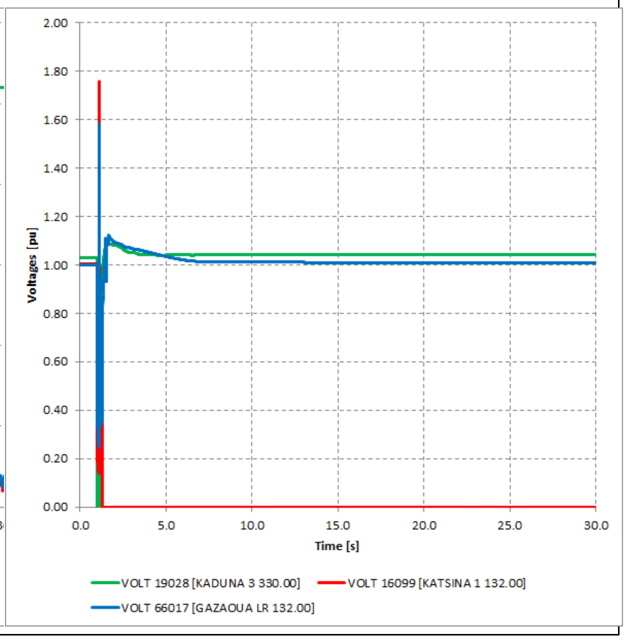
<table>
<tr><th>Without Remedial Measures</th><th>With Remedial Measures</th></tr>
<tr><td>Frequency:

</td><td>
</td></tr>
<tr><td>Voltage:

</td><td>
</td></tr>
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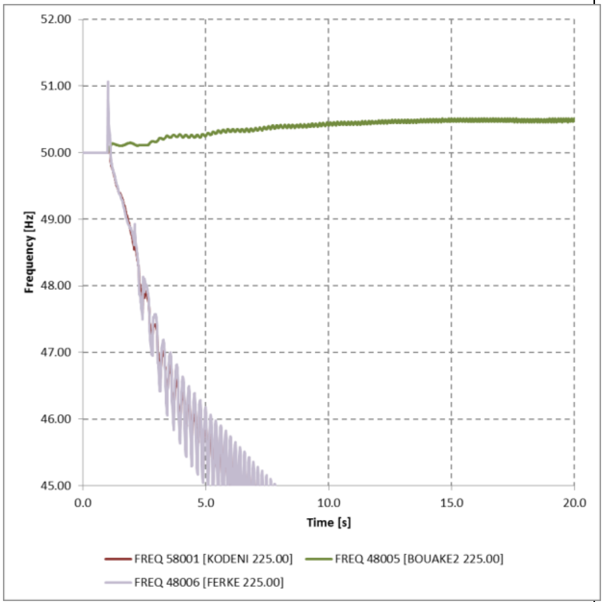
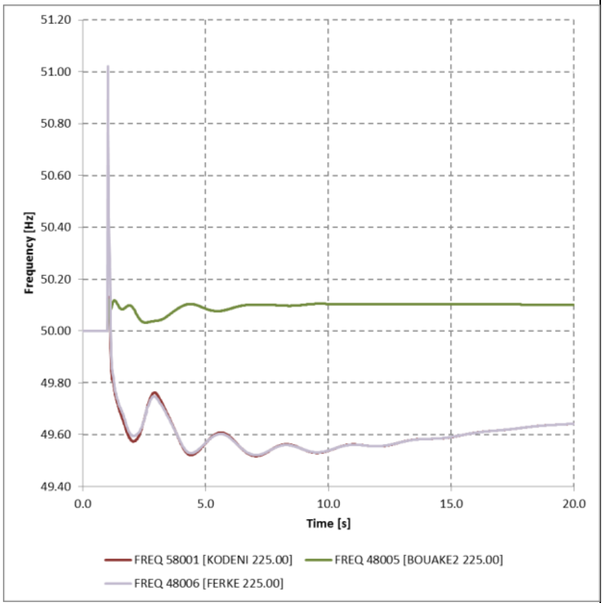
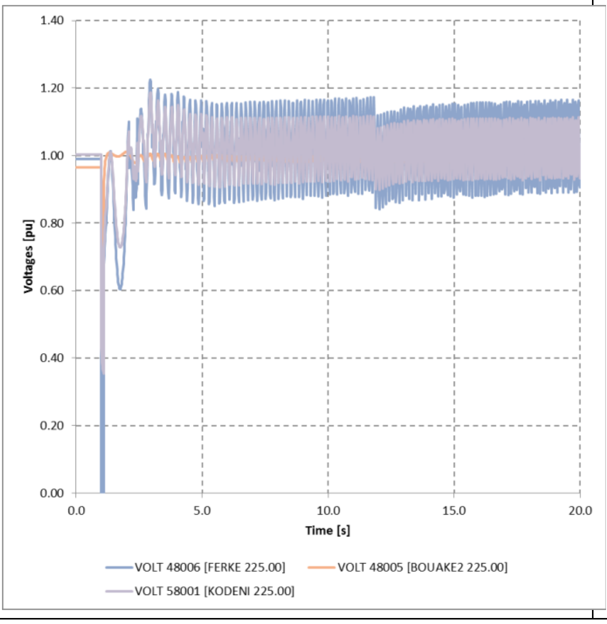
Table 4.19: Contingency Ferké – Bouake 2 225 kV line (CIE)

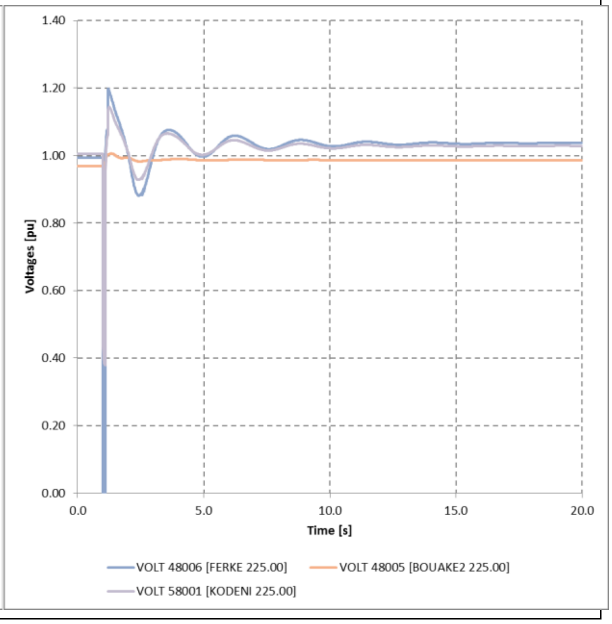
Event	Description	Action Time
Fault	3ph fault 225 kV line FERKÉ – BOUAKE2 (48006-48005/1)	
Clearing	Line tripping	0.1 s
Effect	EDM and SONABEL networks remain connected to CIE network only through the Ferké 225/90 kV transformer.	
Instability without Remedial measures	Out of steps of some units were observed in the Ferké area.	
Proposed Remedial Measures	For the short-term (before the planned network reinforcement) it is recommended to install an intertrip relay (with the possible deactivation if the power flows on the line is below a pre-defined threshold) with the transformer at Ferké (48006-46006/1), causing a network separation.	At the same time line tripping

Without Remedial Measures	With Remedial Measures
Frequency:	
	

Voltage:



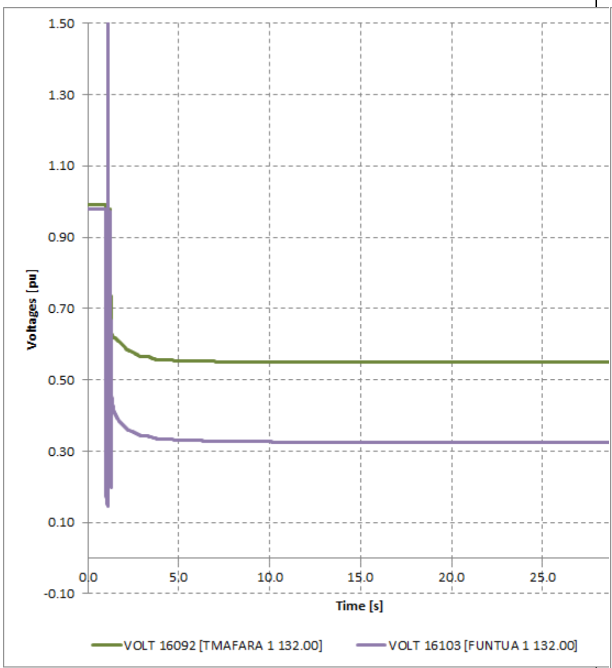
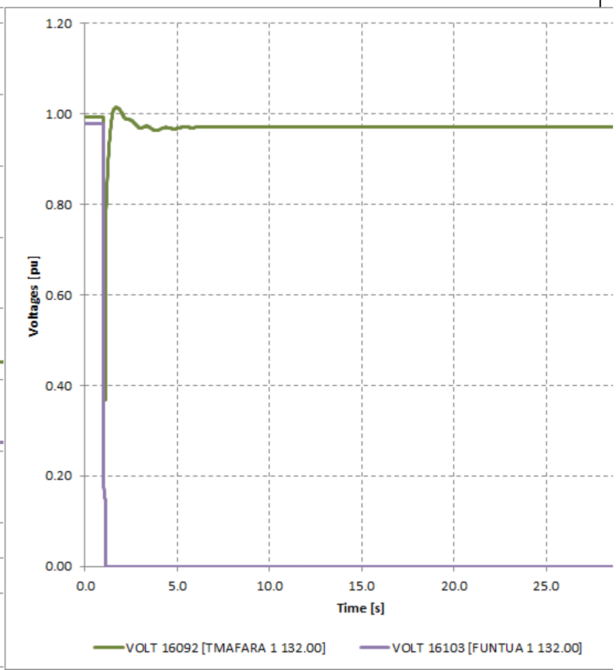
1.40
1.20
1.00
0.80
0.60
0.40
0.20
0.00
Voltages [pu]
0.0
5.0
10.0
15.0
20.0
Time [s]
VOLT 48006 [FERKE 225.00]
VOLT 48005 [BOUAKE2 225.00]
VOLT 58001 [KODENI 225.00]



1.40
1.20
1.00
0.80
0.60
0.40
0.20
0.00
Voltages [pu]
0.0
5.0
10.0
15.0
20.0
Time [s]
VOLT 48006 [FERKE 225.00]
VOLT 48005 [BOUAKE2 225.00]
VOLT 58001 [KODENI 225.00]

Table 4.20: Contingency Kaduna 330 kV (TCN)

Event	Description	Action Time
Fault	3ph fault at 330 kV bus KADUNA (19028)	
Clearing	Tripping of 3WT trf KADUNA 3 – KADUNA 1 – KADUNA T3A (19028/16090/14212)	0.1 s
Effect	The zone (132 kV) B/KEBBI II – SOKOTO – TMFARA – GUSAU – FUNTUA – ZARIA – KADUNA1 becomes unstable	
Instability without Remedial measures	Undervoltages in this 132 zone.	
Proposed Remedial Measures	• Trip also the 132 kV line GUSAU – FUNTUA (16098 – 16103) or • Trip 132 kV line ZARIA – FUNTUA (16102 – 16103) for simulating UVLS protection	0.3 s

Without Remedial Measures	With Remedial Measures
Voltage: 	

4.2.2 Analysis Result – 2020 Scenarios

In §4.2.2.1 and §4.2.2.2 are summarized the results of the analyses on the 2020 scenarios in terms of generation trip and line/transformer trip (after a 100 ms 3-phase fault).

4.2.2.1 Loss of generators

As shown in Table 4.21 all the analysed cases are stable and the UFLS is never activated.

Table 4.21: Main results of generation trip for 2020 scenarios

Contingency	BUS	Area	Scenarios	Pg [MW]	Stability	UFLS	COMMENT
Akosombo G1	32001/1	GRIDCO	S20-RP-AKOS	155	Stable	--	--
			S20-RO-AKOS	165	Stable	--	--
Azito GT2	43008/1	CIE	S20-RP-AZIT	138	Stable	--	--
			S20-RO-AZIT	Not in service	--	--	--
Egbin G1	13001/1	TCN	S20-RP-EGBI	215.3	Stable	--	--
			S20-RO-EGBI	192.4	Stable	--	--
Goroubanda G1	62008/1	NIGELEC	S20-RP-GORO	14.0	Stable	--	--
			S20-RO-GORO	17.0	Stable	--	--
Soraz G1	62026/1	NIGELEC	S20-RP-SORA	11.0	Stable	--	--
			S20-RO-SORA	Not in service	--	--	--
Tag_lome G1	22004/1	CEB	S20-RP-TAGL	20.0	Stable	--	--
			S20-RO-TAGL	23.0	Stable	--	--
Kossodo G8	52032/1	SONABEL	S20-RP-KOSS	15.0	Stable	--	--
			S20-RO-	Not in	--	--	--

			KOSS	service			
Dar Salam G1	133008/1	EDM	S20-RP-DARS	45.0	Stable	--	--
			S20-RO-DARS	Not in service	--	--	--
Manantali G1	142001/1	SOGEM	S20-RP-MANA	33.0	Stable	--	--
			S20-RO-MANA	38	Stable	--	--
ALAOJI_G1	13042/1	TCN	S20-RP-ALAO	240	Stable	--	--
			S20-RO-ALAO	240	Stable	--	--
TAG_MARIA_GLETA_G2	22001/2	CEB	S20-RP-TAGM	140	Stable	--	--
			S20-RO-TAGM	135	Stable	--	--
AYTEPA_G1_2	32134/2	GRIDCO	S20-RP-AYTE	215	Stable	--	--
			S20-RO-AYTE	215	Stable	--	--
AZITO_GT1	43007/1	CIE	S20-RP-AZIT	138	Stable	--	--
			S20-RO-AZIT	142	Stable	--	--
OUAGAOUEST_G1	53013/1	SONABEL	S20-RP-OUAG	100	Stable	--	--
			S20-RO-OUAG	100	Stable	--	--
SALKADAMNA_G1	62031/1	NIGELEC	S20-RP-SALK	46	Stable	--	--
			S20-RO-SALK	35	Stable	--	--
GARAFIRI_G1	92001/1	EDG	S20-RP-GARA	24.5	Stable	--	--
			S20-RO-GARA	24.0	Stable	--	--
SENDOU_G1	123012/1	SENELEC	S20-RP-SEND	96.0	Stable	--	--
			S20-RO-	Not in	--	--	--

			SEND	service			
GOUINA_G1	143001/1	SOGEM	S20-RP-GOUI	38.0	Stable	--	--
			S20-RO-GOUI	39.0	Stable	--	--
BUMBUNA_G1	152007/1	CLSG	S20-RP-BUMB	61.0	Stable	--	--
			S20-RO-BUMB	60.0	Stable	--	--
SAMBA_G1	162001/1	OMVG	S20-RP-SAMB	30.0	Stable	--	--
			S20-RO-SAMB	30.0	Stable	--	--
GE_PP	32128/1	GRIDCO	S20-RP-GEPP	Not in service	--	--	--
			S20-RO-GEPP	230	Stable	--	--
MALICOUNDA_G1	123019/1	SENELEC	S20-RP-MALI	85	Stable	--	--
			S20-RO-MALI	85	Stable	--	--
TAC_GEN_G1	132006/1	EDM	S20-RP-TACG	19.0	Stable	--	--
			S20-RO-TACG	18.0	Stable	--	--
ALAOJI_PP	13042/1 13043/1	TCN	S20-RP-ALPP	480	Stable	--	--
			S20-RO-ALPP	350	Stable	--	--
AYTEPA PP	32134/1/2	GRIDCO	S20-RP-AYTE	345	Stable	--	--
			S20-RO-AYTE	360	Stable	--	--

4.2.2.2 Loss of a line/transformer due to three phase short circuit

As shown in Table 4.22 not all the analysed cases are stable. The unstable contingencies are highlighted in yellow. For these cases the proposed measures are indicated. Some of the most significant and critical contingencies are further detailed in Tables from Table 4.23 to Table 4.24, showing the effects of the proposed reinforcements.

Table 4.22: Main results of branch trip for 2020 scenarios

Contin-gency	BRANCH F-T/ID	Area	Scenarios	Ptr F→T [MW]	Stability	UFLS	COMMENT
Ferke – Kodeni	48006-58001/1	CIE/SONABEL	S20-RP-FERK-KODE	8.5	Stable	--	--
			S20-RO-FERK-KODE	42.8	Stable	--	--
Ferke – Sikasso	48006-138001/1	CIE/EDM	S20-RP-FERK-SIKA	41.6	Stable	--	--
			S20-RO-FERK-SIKA	42	Stable	--	--
Moyas-sue-Elubo [former Riviera – Prestea]	48018-38002/1	CIE/GRIDCO	S20-RP-MOYA-ELUB	49.3	Stable	--	--
			S20-RO-MOYA-ELUB	82.4	Stable	--	--
Lome Aflao – Asiekpe	27016-37037/1	CEB/GRIDCO	S20-RP-LOME-ASIE	-42.8	Stable	--	--
			S20-RO-LOME-ASIE	-32.4	Stable	--	--
Lome Aflao – Aftap	27016-37055/1	CEB/GRIDCO	S20-RP-LOME-AFTA	2.4	Stable	--	--
			S20-RO-LOME-AFTA	8.2	Stable	--	--
Davie – Asogli	29003-39003/1	CEB/GRIDCO	S20-RP-DAVI-ASOG	-70.6	Stable	--	--
			S20-RO-DAVI-ASOG	-65.4	Stable	--	--
Katsina –	16099-66017/1	TCN/NIGELEC	S20-RP-KATS-GAZA	-0.2	Stable	--	--

Gazaoua			S20-RO-KATS-GAZA	-1.3	Stable	--	--
Bkebbi – Dosso	16061-66002/1	TCN/NIGELEC	S20-RP-BKEB-DOSS	22.1	Stable	--	--
			S20-RO-BKEB-DOSS	7.7	Stable	--	--
Sakete – Ikeja	29001-19004/1	CEB/TCN	S20-RP-SAKE-IKEJ	-206.5	Stable Oscillations	--	--
			S20-RO-SAKE-IKEJ	-249.5	Stable oscillations	--	--
Bakel-Kayes	148028-148050/1	SOGEM	S20-RP-BAKE-KAYB	-108.6	Stable, oscillations	3 Stages	--
			S20-RO-BAKE-KAYB	-122.5	Stable, oscillations	3 Stages	--
Ouaga-Gorouban da	59001-59002/1	SONA-BEL	S20-RP-OUAG-GORO	-64.2	Stable	--	--
			S20-RO-OUAG-GORO	-45.5	Stable	--	--
Soma-Birke-lane	168015-168004/1	OMVG	S20-RP-SOMA-BIRK	-23.6	Stable	--	--
			S20-RO-SOMA-BIRK	-1.4	Stable	--	--
Soma-Tanaf	168015-168001/1	OMVG	S20-RP-SOMA-TANA	-18.8	Stable	--	--
			S20-RO-SOMA-TANA	-19.7	Stable	--	--
Tanaf-Mansoa	168001-168012/1	OMVG	S20-RP-TANA-MANS	-23.6	Stable	--	--
			S20-RO-TANA-MANS	-36.1	Stable	--	--
Sam-bagalou-Mali	168003-168005/1	OMVG	S20-RP-SAMB-MALI	-0.6	Stable	--	--
			S20-RO-SAMB-MALI	-37.7	Stable	--	--
Saltinho-Boke	168010-168008/1	OMVG	S20-RP-SALT-BOKE	-60.1	Stable	--	--
			S20-RO-SALT-BOKE	-54.5	Stable	--	--
Linsan-Kamakwie	158006-158011/	CLSG	S20-RP-LINS-KAMA	5.2	Stable, oscillations	--	--

	1		S20-RO-LINS-KAMA	-61.3	Stable, oscillations	--	--
Tambacounda-Kayes	168002-148021/1	OMVG/SOGEM	S20-RP-TAMB-KAYE	-11.4	Stable, oscillations	--	--
			S20-RO-TAMB-KAYE	47.0	Unstable, oscillations	--	--
Tambacounda-Kolda	168002-168016/1	OMVG	S20-RP-TAMB-KOLD	18.5	Stable	--	--
			S20-RO-TAMB-KOLD	-4.7	Stable	--	--
Kenema-Mano	158007-158004/1	CLSG	S20-RP-KENE-MANO	-49.8	Stable	--	--
			S20-RO-KENE-MANO	0.3	Stable, oscillations	--	--
Man-Yekepepa	48011-158001/2	CIE/CLSG	S20-RP-MAN-YEKE	33.6	Stable	--	--
			S20-RO-MAN-YEKE	-19.5	Stable	--	--
Nzerekore-Yekepepa	158005-158001/1	CLSG	S20-RP-NZER-YEKE	-12.4	Stable	--	--
			S20-RO-NZER-YEKE	-10.0	Stable	--	--
Linsan-Labe	158006-168006/1	CLSG	S20-RP-LINS-LABE	20.8	Stable	--	--
			S20-RO-LINS-LABE	48.2	Stable	--	--
Linsan-Kaleta	158006-168007/1	CLSG	S20-RP-LINS-KALE	-27.6	Stable	--	--
			S20-RO-LINS-KALE	9.0	Stable	--	--
Bingerville-Dunkwa	49001-39016/1	CIE/Gridco	S20-RP-BING-DUNK	-22.8	Stable	--	--
			S20-RO-BING-DUNK	3.7	Stable	--	--
Sikasso-Koutiala-3ph	138001-138002/1	EDM	S20-RP-SIKA-KOUT	14.9	Stable	--	--
			S20-RO-SIKA-KOUT	20.5	Stable	--	--
Sikasso-Kodeni	138001-58001/1	EDM/SONABEL	S20-RP-SIKA-KODE	-46.4	Stable	--	--

			S20-RO-SIKA-KODE	-3.5	Stable	--	--
Kaduna-Kano	19028-19029/1	TCN	S20-RP-KADU-KANO	465.4	Unstable	3 stages	Instability and proposed measures as in 2016 intercon-nected scenar-io
			S20-RO-KADU-KANO	362.6	Unstable	3 stages	Instability and proposed measures as in 2016 intercon-nected scenar-io
Bawku-Cincasse	37072-27025/1	GRID-CO/CEB	S20-RP-BAWK-CINC	-19.0	Stable	--	--
			S20-RO-BAWK-CINC	-8.1	Stable	--	
Bkebbi-Zabori	19014-69001/1	TCN/NIGELEC	S20-RP-BKEB-ZABO	153.7	Stable	--	--
			S20-RO-BKEB-ZABO	113.6	Stable	--	--
Malan-ville-Zabori	29004-69001/1	CEB/NIGELEC	S20-RP-MALA-ZABO	-11.3	Stable	--	--
			S20-RO-MALA-ZABO	-12.2	Stable	--	--
Kodeni-Navrongo	58001-38003/1	SONA-BEL/GRIDCO	S20-RP-KODE-NAVR	-32.0	Stable	--	--
			S20-RO-KODE-NAVR	4.3	Stable	--	--
Zagtou-li-Navrongo	58003-38003/1	SONA-BEL/GRIDCO	S20-RP-ZAGT-NAVR	42.8	Stable	--	
			S20-RO-ZAGT-NAVR	33.0	Stable	--	--
Kodeni-2WT 225/150	58001-56016/1	SONA-BEL	S20-RP-KODE-2WT	49.2	Unstable	3 stages	Overfrequency SONABEL. **Stable with proposed measures:** It is recommended to implement local measures like UVLS or special pro-tection

							schemes.
			S20-RO-KODE-2WT	24.0	Stable	--	
Goroubanda-Salka-damna	69004-69007/1	NI-GELEC	S20-RP-GORO-SALK	-95.3	Unstable	3 stages	Loss of Synchronism. **Stable with proposed measures:** install a special protection schemes at Salkadamna power plant, able to reduce the generation in case of trip of the Salkadamna – Goroubanda 330 kV line with the power flow on the line over a pre-defined threshold
			S20-RO-GORO-SALK	18.5	Stable		

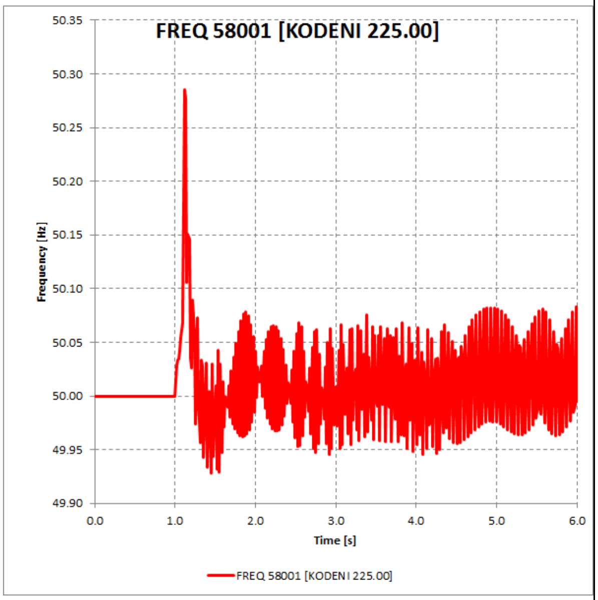
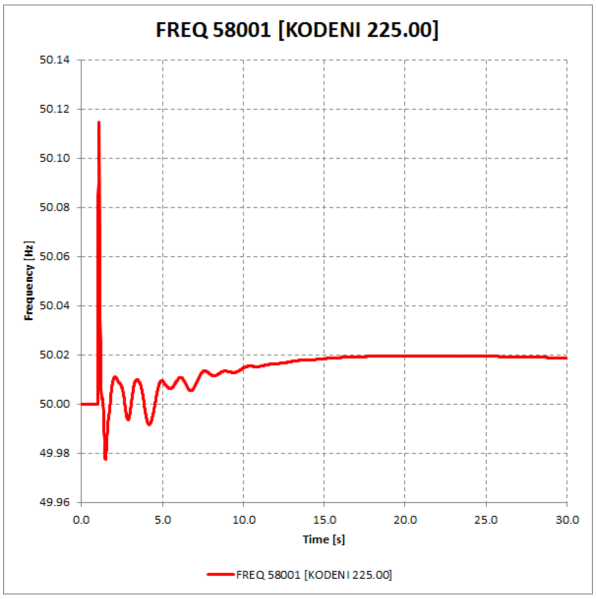
4.2.2.2.1 Results of the most significant contingencies

Tables from Table 4.23 to Table 4.24, show the simulation results of the most significant contingencies including the effects of the proposed reinforcements.

Table 4.23: Contingency Kodeni 225 kV (SONABEL)

Event	Description	Action Time
Fault	3ph fault at 225 kV transformer KODENI (58001-56016)	
Clearing	Tripping of transformer	0.1 s
Effect	Part of the local 90 kV and 33 kV network (including the Bobo power plant) remain connected to the rest of the WAPP network only through the two 33/225 kV transformers at Kodeni substa-	

	tions.	
Instability without Remedial measures	The local 90 and 33 kV Network (Kodeni, Bobo, Banfora) is affected by severe undervoltages (voltages up to 35%).	
Proposed Remedial Measures	It is recommended to implement local measures like UVLS or special protection schemes.	

Without Remedial Measures	**With Remedial Measures**
Frequency: 	
Voltage:	

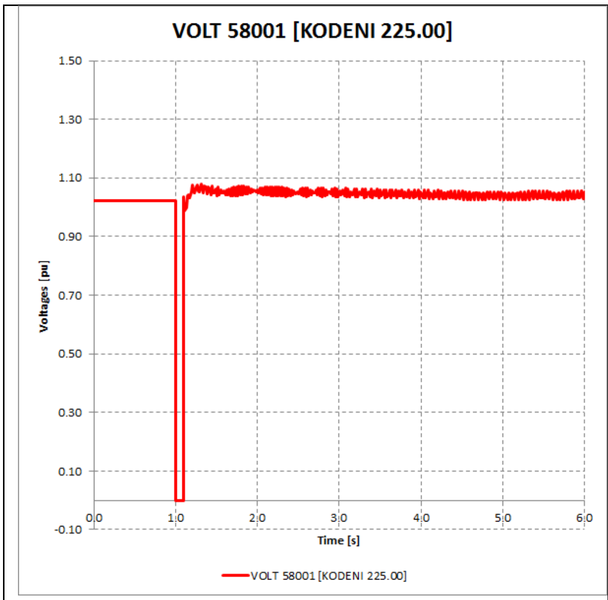
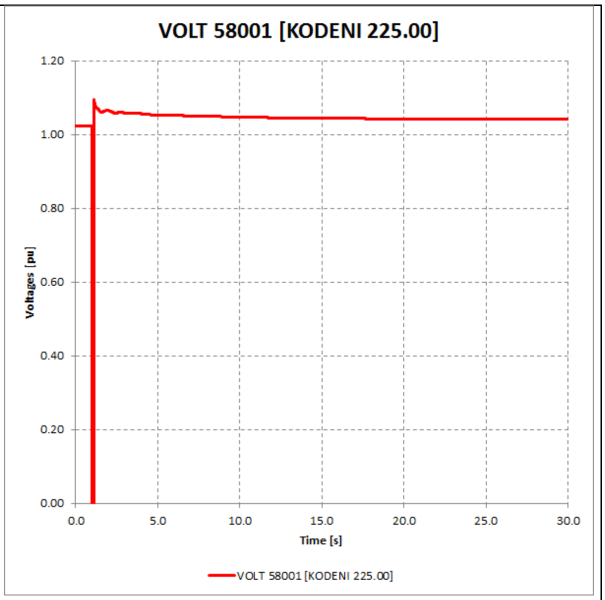
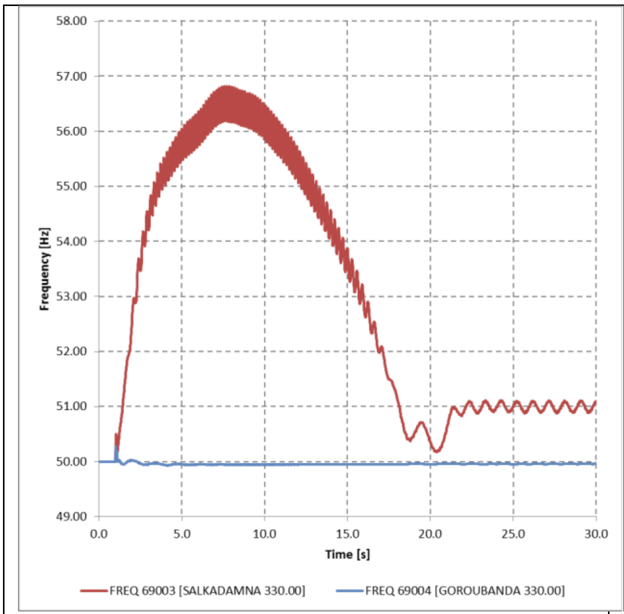
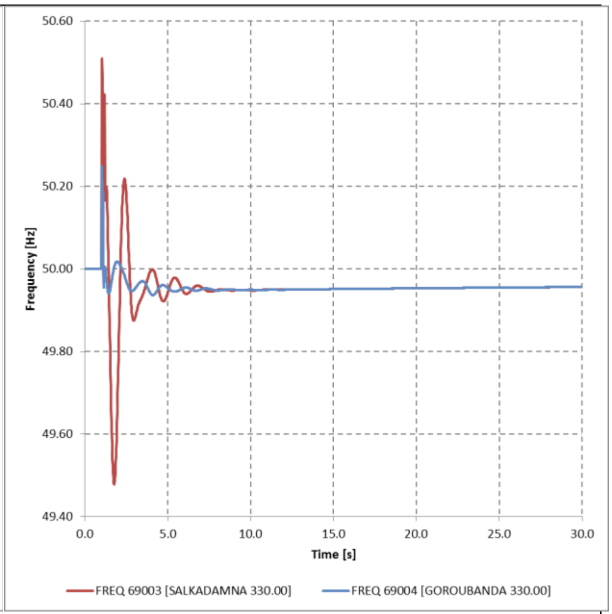
	

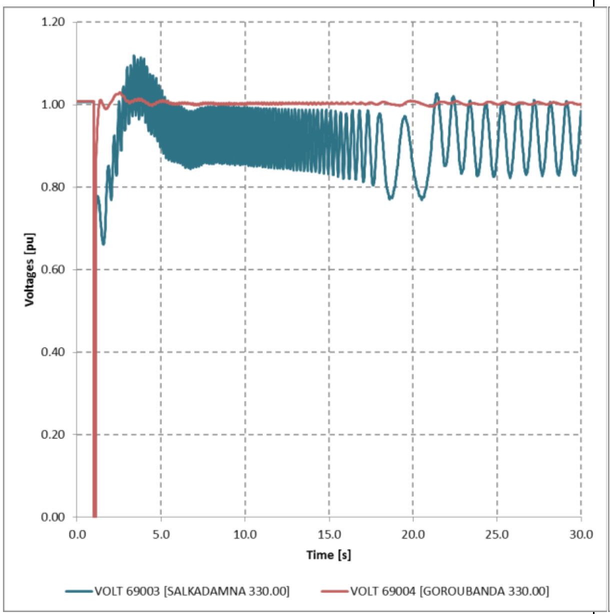
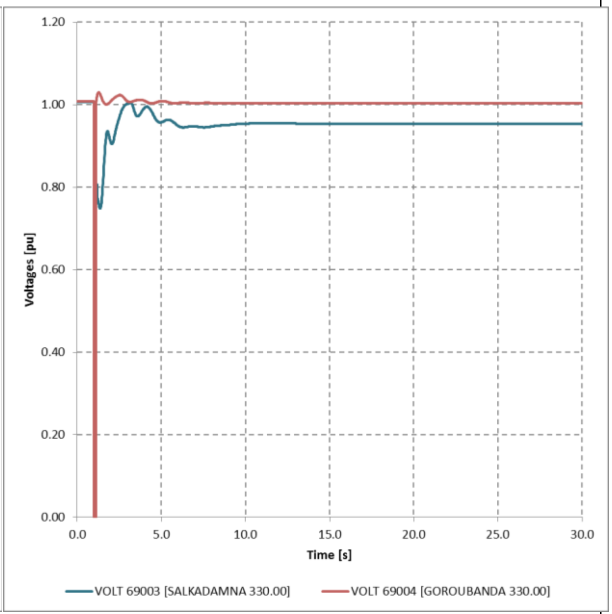
Table 4.24: Contingency Goroubanda – Salkadamna 330 kV line (NIGELEC)

Event	Description	Action Time
Fault	3ph fault at 330 kV Goroubanda-Salkadamna (69004-69007/1)	
Clearing	Line tripping	0.1 s
Effect	Most of generation of the Salkadamna power plant (180 MW) are exported from NCE area to FLEUVE area through the Salkadamna – Goroubanda 330 kV line (100 MW).	
Instability without Remedial measures	After the contingency the local 132 kV network is not able to evacuate this generation and a voltage collapse occur.	
Proposed Remedial Measures	A proposed measure is to install a special protection schemes at Salkadamna power plant, able to reduce the generation in case of trip of the Salkadaman – Goroubanda 330 kV line with the power flow on the line over a predefined threshold. This solution should also avoid the activation of overspeed protections on the units.	At the same time of line tripping.

Without Remedial Measures	With Remedial Measures
Frequency:	


58.00
57.00
56.00
55.00
54.00
53.00
52.00
51.00
50.00
49.00
Frequency [Hz]
0.0
5.0
10.0
15.0
20.0
25.0
30.0
Time [s]
FREQ 69003 [SALKADAMNA 330.00]
FREQ 69004 [GOROUBANDA 330.00]

50.60
50.40
50.20
50.00
49.80
49.60
49.40
Frequency [Hz]
0.0
5.0
10.0
15.0
20.0
25.0
30.0
Time [s]
FREQ 69003 [SALKADAMNA 330.00]
FREQ 69004 [GOROUBANDA 330.00]

Voltages:


1.20
1.00
0.80
0.60
0.40
0.20
0.00
Voltages [pu]
0.0
5.0
10.0
15.0
20.0
25.0
30.0
Time [s]
VOLT 69003 [SALKADAMNA 330.00]
VOLT 69004 [GOROUBANDA 330.00]

1.20
1.00
0.80
0.60
0.40
0.20
0.00
Voltages [pu]
0.0
5.0
10.0
15.0
20.0
25.0
30.0
Time [s]
VOLT 69003 [SALKADAMNA 330.00]
VOLT 69004 [GOROUBANDA 330.00]

4.3 TRANSIENT STABILITY

The transient stability analysis performed in this study is aimed at calculating the following quantities:

- Critical Clearing Time (CCT)
- Maximum Transfer Limit (MTL)

4.3.1 Methodology

The methodology adopted for the two studies are described in the following.

4.3.1.1 Critical Clearing Time calculation

The calculation of the Critical Clearing Time (CCT) for each interconnection have been performed in accordance with the following methodology.

System Model

In order to focus on the system transient (rotor-angle) stability, the following hypothesis have been adopted.

- UFLS schemes or any other protection means (e.g. out of step relays) have not been simulated in order to focus the natural system behavior
- The dynamic behavior of motor models has not been considered since their stall would hinder the simulation of the angular instability.

Selection of the critical disturbance

For each interconnection the most critical N-1 case has been selected using the PV analysis to detect the contingency resulting in the lowest value of transferrable power on the considered interconnection. This allowed to find the most critical disturbance for the angular stability on the corridor. The results of this analysis were the disturbance in terms of fault location (From, To or a near-by Bus of the examined interconnection) as well as the clearing fault (trip) action.

Focusing on transient stability, the critical disturbances examined do not result in system separation or large areas splitting related to the interconnection under analysis.

Critical Clearing Time detection criterion

The Critical Clearing Time is defined by the first generator losing synchronism with respect to system average angle (angle deviation beyond 180 degrees). The CCTs are calculated in a range of 10 milliseconds if CCT is less than a second or in a range of 100 milliseconds alternatively.

4.3.1.2 Maximum Transfer Limits (MTL) calculation

The calculation of the Maximum Transfer Limits (MTL) for each power exchange interface (e.g. TCN-CEB) have been calculated adopting two different methodologies for 2016 and 2020 scenarios.

- 2016 scenarios: Limits calculated on the basis of time domain simulations
- 2020 scenarios: Limits calculated using a linearized model of the system

The choice to adopt a linearized version of the system is related to the higher uncertainties of the 2020 network model compared with the 2016 network model.

4.3.1.2.1 Methodology for the 2016 network model

Interface loading

The maximum transfer limit for each interface has been applied by increasing the power exchange between the countries until the occurrence a disturbance resulted in any instability in the interconnected system. The power exchange on each interface has been increased by shifting the generation from the sending areas (source) and the receiving areas (sinks) at the two ends of the considered section.

Disturbance

The disturbances have been selected by searching the most severe ones adopting the same approach used in the CCT analysis.

MTL

MTL is calculated by increasing the flow on the interface applying the generation shift until the occurrence of the selected critical disturbance resulted in any instability on the system or until the generation limit in the sources areas have been reached. The initial value of the power exchange to start testing the consequences of the disturbance has been calculated shifting the generation until a thermal or voltage limit was met in N conditions.

4.3.1.2.2 Methodology for the 2020 network model

The analyses on the 2020 model have been performed adopting a linearized representation of the system by means of the transmission interchange limit analysis (TLTG) activity of PSS®E [5].

The TLTG estimates the import or export limits of a specified subsystem using a linearized network model [PSS®E POM], by configuring two cases in which the total power injection will be increased (export limits) or decreased (import limits).

The principle and the nomenclature associated with the TLTG analysis is shown in Figure 4.11 and Figure 4.12; the incremental transfer limit is the value of ΔP when one of the following conditions is met:

- Flow on a monitored circuit reaches the limit.
- Flow on a monitored circuit would be at the limit for acceptable post-contingency loading if a contingency were to occur.

As a first step, the power transfer distribution factors are determined; the maximum export and import values are calculated considering as constraint that no monitored elements exceed a specified percentage of a selected rating.

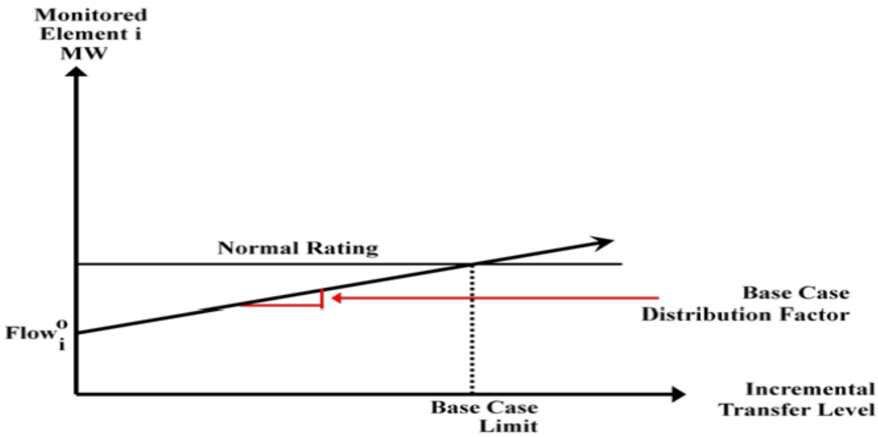


Figure 4.11: Illustration for the ith monitored element, base case only

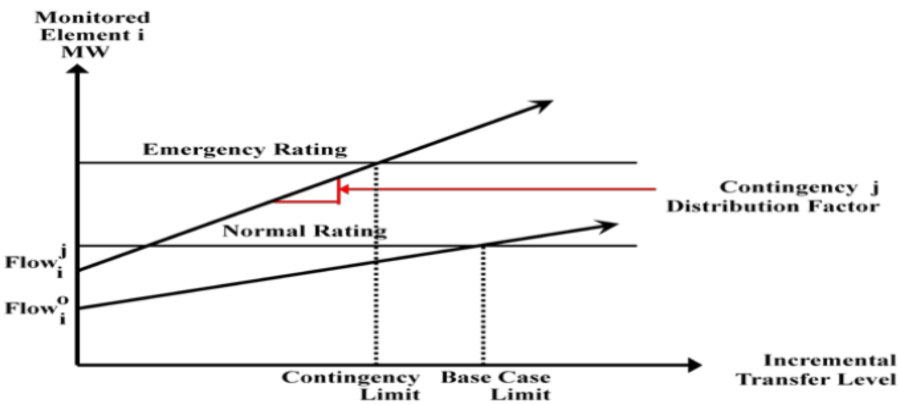


Figure 4.12: Illustration for the ith monitored element, base case & contingency j only

The following assumptions have been made:

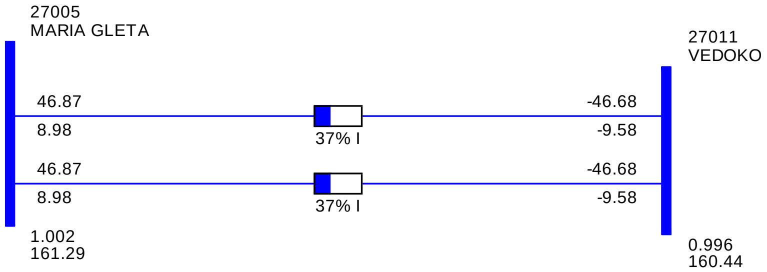
- "DC" load flow solution method has been adopted
- Equal, linear and limitless generator participation has been taken into account

The analysis of the 2020-Peak scenario has been performed with all neighbor Control Areas as "Study" and "Opposing" Systems (e.g. TCN - CEB), excluding those without generation, i.e. modeled only as equivalent loads.

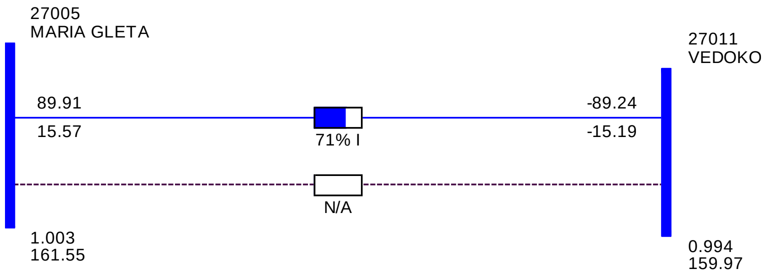
All branches at voltage levels 132kV and above have been monitored. The transfer limit is defined by the incremental transfer limit that results to a new thermal limit violation due a N-1 contingency (compared to the initial power transfer).

An example for the transfer limit calculated from CEB to TCN is presented in Figure 4.13, where the initial power flow transfer between the 161 kV buses of MARIA GLETA and VEDOKO is shown (% of loading is on base of RATE A, RATE B equals 110% of RATE A).

Initial Flows:



Flows after applying the limiting contingency:



Flows after applying the 160 MW incremental transfer limit (increase accordingly generation in CEB and decrease in TCN):

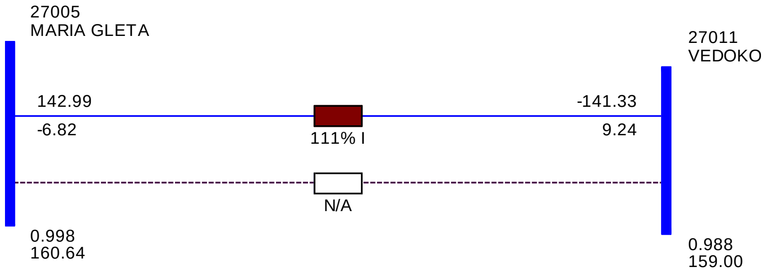


Figure 4.13: Example of transfer limit calculation (case "CEB to TCN")

4.3.2 Analysis Result – 2016 Scenarios

§4.3.2.1 illustrates the calculation of the CCT (Critical Clearing Time), while §4.3.2.2 discusses the MTL (Maximum Transfer Limit) calculation for the 2016 scenarios (detailed results available in Annexes [A13] and [A14]).

4.3.2.1 Critical Clearing Time – 2016 Scenarios

Table 4.25 reports a summary of results, including for each interconnection the fault location, the tripping action and the calculated CCT is described. Additionally in Annex [A13], the plots of all examined cases are available, with the rotor angle of the most critical unit. For those cases that first swing instability or large angle deviation is not obvious an extra clearing time response is plotted.

For GRIDCO – CEB interconnection the UHV line DAVIE (TOGO) – ASOGLI EXPOR is tripped, since it does not lead to examined systems separation, and thus two CCTs are calculated for fault applied to the interconnection bus.

For both SIKASSO-FERKE and FERKE-KODENI tie-lines the disturbance “Fault at FERKE cleared with tripping of transformer FERKE 225/90” (Case #9 below and Figure 4.14) is analyzed, as it has been found to be a critical contingency in static analysis. However, as the reported non-convergence in static analysis for this contingency is related to local low voltage issues, it is not the only disturbance examined for these interconnections. In particular the following two disturbances are taken into account:

- SIKASSO – FERKE interconnection: fault applied to FERKE and the FERKE – KODENI 225 kV line is tripped (Burkina Faso splits).
- FERKE – KODENI interconnection: fault applied to FERKE and the SIKASSO – FERKE 225 kV line is tripped (Mali – Senegal – Mauritania Island splits).

In both cases the split systems are ignored after clearing the fault since the UFLS schemes are not present in the dynamic model of the system.

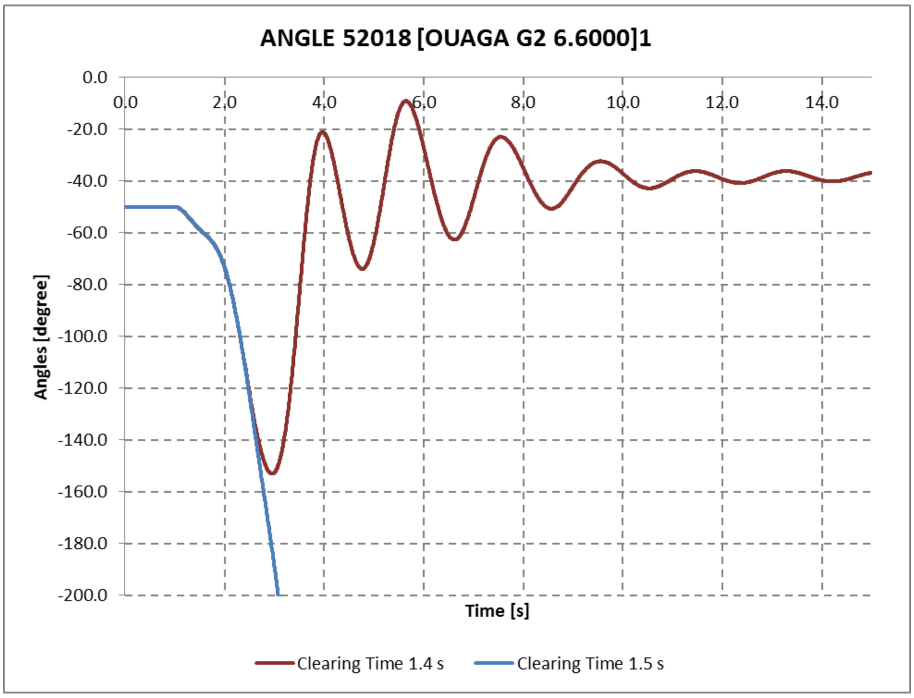


Figure 4.14: Angles of the critical unit for case #9 (fault at FERKE cleared with tripping of transformer FERKE 225/90, 2016 peak inter-reinf scenario)

Table 4.25: Results of CCT calculation for 2016 scenarios

Case	Fault at Bus	Fault Clearing	Scenario	CCT [sec]	Critical Unit
#1: TCN – NIGELEC_NCE	Bus KUMB T2A BB (16106) (connected to KATSINA 1 (16099))	Trip 3WT (19029 – 16106 – 14208)	S16-RP	0.55	ZINDER GEN (62022)
			S16-OP	0.50	
#2: NIGELEC_NCE – TCN	Bus GAZAOUA (66018)	Trip 2WT GAZAOUA 132/20 (66018 – 63023)	S16-RP	0.32	MARADI G1 (62028)
			S16-OP	0.35	ZINDER GEN (62022)
#3: TCN – NIGELEC_FLEUVE	Bus BKEBBI 1 (16061)	Trip 3WT (19014 – 16061 – 12058)	S16-RP	0.22	NIAMEY-2 GEN (62002)
			S16-OP	0.22	GOUDEL GEN (62003)
#4:NIGELEC_FL	DOSSO (66002)	Trip 2WT	S16-RP	0.25	GOUDEL GEN

EUVE – TCN		DOSSO 132/20 (66002 – 63001)	S16-OP	0.61	(62003)
#5:CEB – TCN	Bus SAKETE 3 (29001)	Trip 2WT SAKETE 330/161 (29001 – 27009)	S16-RP	0.84	CIPREL TAV GEN (43015)
			S16-OP	0.68	OUAGA G2 GEN (52018)
#6:TCN – CEB	IKEJA W 3 (19004)	Trip Line EGBIN 3 – IKEJA W 3 (19003 – 19004)	S16-RP	0.29	NIAMEY-2 G1 GEN (62002)
			S16-OP	0.29	MANANTALI G3 GEN (142001)
#7: GRIDCO – CEB (330 kV)	Bus ASOGLI EXPOR (39003)	Trip Line DAVIE (TO-GO) – ASO-GLI EXPOR (29003 – 39003)	S16-RP	0.59	OUAGA G2 GEN (52018)
			S16-OP	0.53	
#8: GRIDCO – CEB (161 kV)	Bus AFTAP (37055)	Trip Line LOME AFLAO – AFTAP (27016 – 37055)	S16-RP	0.57	CONTOUR G5 GEN (23009)
			S16-OP	0.47	TAG LOME G5 GEN (22004)
#9: CEB – GRIDCO (330 kV)	Bus DAVIE (TOGO) (29003)	Trip Line DAVIE (TO-GO) – ASO-GLI EXPOR (29003 – 39003)	S16-RP	12.6	TAG LOME GEN (22004)
			S16-OP	3.9	
#10: CEB – GRIDCO (161 kV)	Bus LOME AFLAO (27016)	Trip Line LOME AFLAO – AFTAP (27016 – 37055)	S16-RP	0.43	TAG LOME G5 GEN (22004)
			S16-OP	0.37	
#11: GRIDCO – CIE	Bus PRES2 225 (38001)	Trip 3WT (38001 – 37022 – 32020)	S16-RP	3.8	OUAGA G2 GEN (52018)
			S16-OP	3.0	BELAIR 1G GEN (52021)
#12: GRIDCO – CIE	Bus RIVIERA-225 (48013)	Trip Line VRIDI – RIVERA_225 (48013 – 48002)	S16-RP	0.27	CIPREL TAV GEN 1 (43015)
			S16-OP	0.3	VIDRI1 TAG GEN (42001)
#13:CIE –	Bus FERKE	Trip Line	S16-RP	1.4	OUAGA G2 GEN

SONABEL	(48006)	FERKE – SIKASSO (48006 – 138001)	S16-OP	0.75	(52018)
#14: SONABEL – CIE	Bus KODENI (58001)	Trip 2WT KODENI 225/33 (58001 – 54001)	S16-RP	0.49	BOBO G6 GEN (52006)
			S16-OP	0.49	
#15: CIE – EDM	Bus FERKE (48006)	Trip Line FERKE – KODENI (48006 – 58001)	S16-RP	3.8	SOPAM - 2 GEN (52018)
			S16-OP	2.1	C6 EXTENSION GEN (123003)
#16: EDM – CIE	Bus SEGOU 225 (138003)	Trip 2WT SEGOU 225/150 (138003 – 136012)	S16-RP	6.8	SOPAM 2 GEN (132007)
			S16-OP	2.2	C6 EXTENSION GEN (12303)
#17: CIE – SONABEL – EDM	Bus FERKE (48006)	Trip 2WT FERKE 225/90 (48006 – 46006)	S16-RP	1.5	OUAGA G2 GEN (52018)
			S16-OP	0.8	
#18: SOGEM – SENELEC	Bus KAY-FEL-225 (148022)	Trip Line KAY-FEL-225 – FEL-KAY-225 (148022 – 148023)	S16-RP	0.27	DARSALAM GEN (133008)
			S16-OP	0.19	KAOLAC G1 GEN (123008)
#19: SENELEC – SOGEM	Bus BAKEL 225 (148029)	2WT BAKEL 225/ 90 (148029 – 146001)	S16-RP	0.36	FELOU G3 GEN (142006)
			S16-OP	0.25	KAOLAC G1 GEN (123008)
#20: SOGEM – EDM	Bus RX-KOD225 (148002)	Trip 2WT KODIALANI-	S16-RP	0.48	MANANTALI G3 GEN (142001)

		150 – RX-KOD225-225 (136007 – 148002)	S16-OP	0.53	KAOLAC G1 GEN (123008)
#21:EDM – SOGEM	Bus KODIALANI-150 (136007)	Trip 2WT KODIALANI-150 – RX-KOD225-225 (136007 – 148002)	S16-RP	0.95	SOPAM 2 GEN (132007)
			S16-OP	0.45	

4.3.2.2 Maximum Transfer Limits – 2016 Scenarios

Summary of the results is given in the following Table 4.26 (peak scenario) and Table 4.27 (off-peak scenario) and the plots of the dynamic simulations testing the transient stability of each MTL are available in Annex [A14].

Table 4.26: Summary of results of Maximum Transfer Limits – Peak Scenario 2016

From	To	Max Shift (MW) from PV	Interface MW flow		MW flow through examined tie-line			Limitation for MW shift in PV analysis	Transient Stability check
			Initial	Final	Tie-line	Initial	Final		
SOGEM	SENELEC	25	80.0	105.1	148028-148029	117.2	147.1	Cannot reach transfer increment = 26.0 in subsystem "SOGEM" due to active power limits	OK
SENELEC	SOGEM	107	-80.0	26.4	148028-148029	117.2	5.6	Cannot reach transfer increment = 108.0 in subsystem "SENELEC" due to active power limits	OK
SOGEM	EDM	25	112.0	135.2	148001-148002	104.9	129.2	Cannot reach transfer increment = 26.0 in subsystem "SOGEM" due to active power limits	OK

EDM	SOGEM	105	-112.0	-9.8	148001-148002	104.9	0.9	Cannot reach transfer increment = 106.0 in subsystem "EDM" due to active power limits	OK
CIE	EDM	18	26.7	45.2	48006-138001	26.7	45.2	Bus 48005 [BOUAKE2 225.00] voltage below normal low limit; |V| = 0.94885 Limit = 0.95	OK
EDM	CIE	39	-26.7	7.4	48006-138001	26.7	-7.4	Bus 136012 [RX-SEGOU 150.00] voltage below normal low limit; |V| = 0.94973 Limit = 0.95	OK
CIE	SONABEL	17	50.0	67.8	48006-58001	50.0	67.8	Bus 48005 [BOUAKE2 225.00] voltage below normal low limit; |V| = 0.94891 Limit = 0.95	OK
SONABEL	CIE	52	-50.0	2.1	48006-58001	50.0	-2.1	Cannot reach transfer increment = 53.0 in subsystem "SONABEL" due to active power limits	OK

CIE	GRIDCO	143	-0.1	138.8	38001-48013	0.1	-138.8	Bus 38001 [PRES2-225 225.00] voltage below normal low limit; |V| = 0.94997 Limit = 0.95	OK
GRIDCO	CIE	73	0.1	75.6	38001-48013	0.1	75.6	Bus 38001 [PRES2-225 225.00] voltage below normal low limit; |V| = 0.94994 Limit = 0.95	OK
GRIDCO	CEB	55	85.1	139.1	37055-27016	22.2	32.9	Cannot reach transfer increment = 56.0 in subsystem "CEB" due to active power limits	OK
CEB	GRIDCO	160	-85.1	74.2	37055-27016	22.2	-6.2	Cannot reach transfer increment = 161.0 in subsystem "CEB" due to active power limits	OK
CEB	TCN	160	-244.4	-79.2	19004-29001	244.4	79.2	Cannot reach transfer increment = 161.0 in subsystem "CEB" due to active power limits	OK

TCN	CEB	55	244.4	302.7	19004-29001	244.4	302.7	Cannot reach transfer increment = 56.0 in subsystem "CEB" due to active power limits	OK
TCN	FLEUVE	21	68.0	103.7	16061-66002	68.0	103.7	Bus 66002 [DOSSO 132.00] voltage below normal low limit; |V| = 0.94827 Limit = 0.95 Bus 66007 [NIAMEY-2 CS 132.00] voltage below normal low limit; |V| = 0.94981 Limit = 0.95 Bus 66009 [NIAMEY-2 132.00] voltage below normal low limit; |V| = 0.94981 Limit = 0.95	Limited to 15MW
FLEUVE	TCN	41	-68.0	-17.1	16061-66002	68.0	17.1	Cannot reach transfer increment = 42.0 in subsystem "FLEUVE" due to active power limits	OK

TCN	NCE	23	29.7	55.8	16099-66017	29.7	55.8	Bus 16122 [JALINGO 1 132.00] voltage below normal low limit; |V| = 0.94996 Limit = 0.95	OK
NCE	TCN	4	-29.7	-25.4	16099-66017	29.7	25.4	Cannot reach transfer increment = 5.0 in subsystem "NCE" due to active power limits	OK

An example of PV results for "SOGEM to SENELEC" is shown in Figure 4.15; the horizontal axis shows the incremental transfer (shift) going up to 25 MW, limited by the active power limits of the SOGEM generators. The vertical axis shows the corresponding interface MW flow starting from 80MW and reaching 105MW.

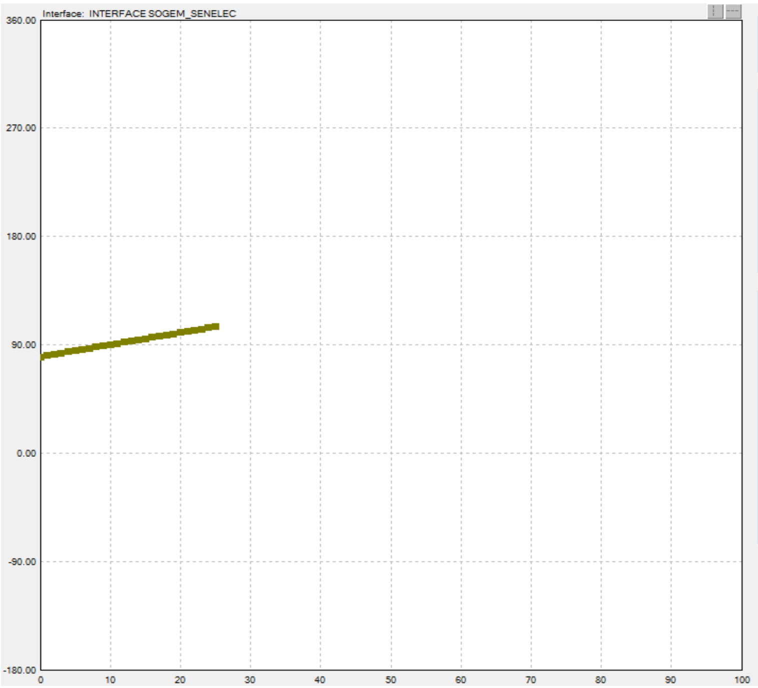


Figure 4.15: Example of PV results for "SOGEM to SENELEC"

An example of bus voltage limitation can be found in the case “CIE to EDM”, as shown in Figure 4.16. The limitation is at 39 MW due to voltage at bus RX-SEGOU (136012) dropped at 95%.

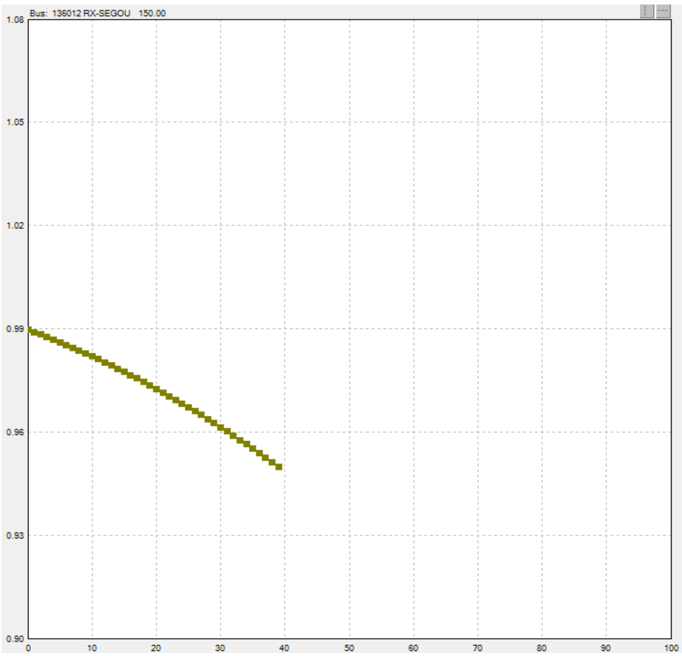


Figure 4.16: Example of limitation because of bus voltage (case “CIE to EDM”)

The only case where the power transfer is limited because of transient stability is the “TCN to NIGELEC_FLEUVE”. In the following Figure 4.17, the rotor angle (with respect to system average angle) of Goudel generator of Fleuve zone of Niger is shown after a fault at Bus BKEBBI 1 (16061), cleared by tripping of 3 winding transformer (19014 – 16061 – 12058). Results for the marginally stable case of 15 MW power shift (green continuous line) and marginally unstable case of 16MW power shift (red dashed line) are shown.

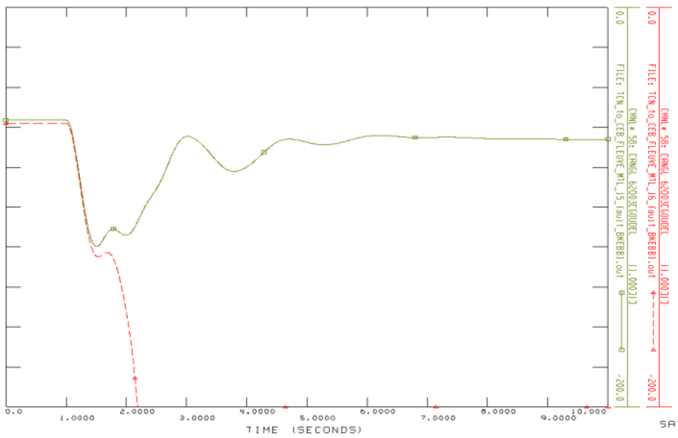


Figure 4.17: Example of limitation because of transient stability (case “TCN to NIGELEC-FLEUVE”)

Table 4.27: **Summary of results of Maximum Transfer Limits – Off-Peak Scenario 2016**

From	To	Max Shift (MW) from PV	Interface MW flow		MW flow through examined tie-line			Limitation for MW shift in PV analysis	Transient Stability check
			Initial	Final	Tie-line	Initial	Final		
SOGEM	SENELEC	23	80.0	103.1	148028-148029	118.9	147.2	Loading above threshold circuit "1" from 148029 [BAKEL225 225.00] to 148028 [KAYBAK-225 225.00]; loading = 100.16%	OK
SENELEC	SOGEM	51	-80.0	-29.0	148028-148029	118.9	61.2	Cannot reach transfer increment = 52.0 in subsystem "SENELEC" due to active power limits	OK
SOGEM	EDM	17	59.7	76.1	148001-148002	56.9	73.7	Cannot reach transfer increment = 18.0 in subsystem "EDM" due to active power	OK

								limits	
EDM	SOGEM	17	-59.7	-43.2	148001-148002	56.9	40.1	Cannot reach transfer incre-ment = 18.0 in subsys-tem "EDM" due to active power limits	OK
CIE	EDM	17	30.2	47.6	48006-138001	30.5	48.3	Cannot reach transfer incre-ment = 18.0 in subsys-tem "EDM" due to active power limits	OK
EDM	CIE	17	-30.2	-13.9	48006-138001	30.5	13.9	Cannot reach transfer incre-ment = 18.0 in subsys-tem "EDM" due to active power limits	OK
CIE	SONABEL	25	50.5	77.4	48006-58001	50.5	77.4	Cannot reach transfer incre-ment = 26.0 in subsys-tem	OK

								"SONA-BEL" due to active power limits	
SONABEL	CIE	26	-50.5	-23.5	48006-58001	50.5	23.5	Cannot reach transfer increment = 27.0 in subsystem "SONA-BEL" due to active power limits	OK
CIE	GRIDCO	175	-0.5	166.5	38001-48013	0.5	-166.5	Bus 38001 [PRES2-225 225.00] voltage below normal low limit; |V| = 0.94992 Limit = 0.95	OK
GRIDCO	CIE	113	0,5	118,0	38001-48013	0,5	118,0	Bus 38001 [PRES2-225 225.00] voltage below normal low limit; |V| = 0.95 Limit = 0.95	OK
GRIDCO	CEB	35	84.9	118.9	37055-27016	16.3	23.3	Cannot reach transfer increment =	OK

								36.0 in subsys-tem "CEB" due to active power limits	
CEB	GRIDCO	54	-84.9	-31.9	37055-27016	16.3	6.0	Cannot reach transfer incre-ment = 55.0 in subsys-tem "CEB" due to active power limits	OK
CEB	TCN	54	-244.0	-187.8	19004-29001	244.0	187.8	Cannot reach transfer incre-ment = 55.0 in subsys-tem "CEB" due to active power limits	OK
TCN	CEB	35	244.0	280.9	19004-29001	244.0	280.9	Cannot reach transfer incre-ment = 36.0 in subsys-tem "CEB" due to active power limits	OK
TCN	FLEUVE	8	68.9	80.6	16061-66002	68.9	80.6	Starting solution with transfer incre-	OK

								ment = 9.0 *** Success-ful so-lution not achieved : Blown up ***	
FLEUVE	TCN	14	-68.9	-49.8	16061-66002	68.9	49.8	Cannot reach transfer incre-ment = 15.0 in subsys-tem "FLEUVE" due to active power limits	OK
TCN	NCE	9	30.0	40.3	16099-66017	30.0	40.3	Cannot reach transfer incre-ment = 10.0 in subsys-tem "NCE" due to active power limits	OK
NCE	TCN	8	-30.0	-21.4	16099-66017	30.0	21.4	Cannot reach transfer incre-ment = 9.0 in subsys-tem "NCE" due to active power limits	Limited to 5 MW

In the off-peak scenario, “NCE to TCN” is the single case for which the power transfer is limited by transient stability. In the following Figure 4.18, the rotor angle (with respect to system average angle) of Zinder generator (bus 62022) of NCE zone of Niger is shown after a 100 ms fault at Bus KUMB T2A BB (16106), cleared by tripping a 3W transformer (19029 – 16106 –14208). Results for the marginally stable case of 5MW power shift (green continuous line) and marginally unstable case of 6MW power shift (red dashed line) are shown.

Also, the corresponding response of MW flow through the line 16099 (KATSINA 1) -66017 (GAZAOUA LR) is shown in Figure 4.19, again for the marginally stable (green continuous) and the marginally unstable case (red dashed).

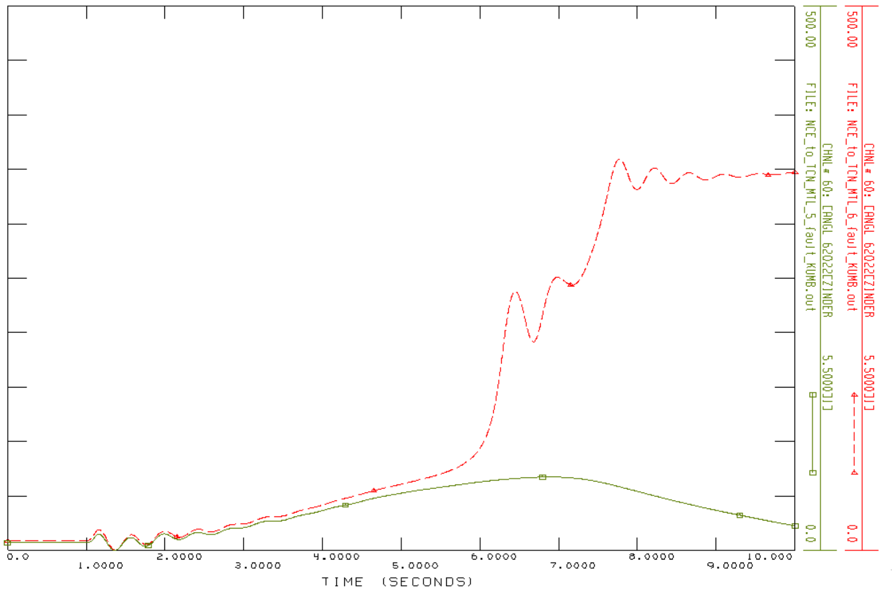


Figure 4.18: **Example of limitation because of transient stability (case "NIGELEC_NCE to TCN")**

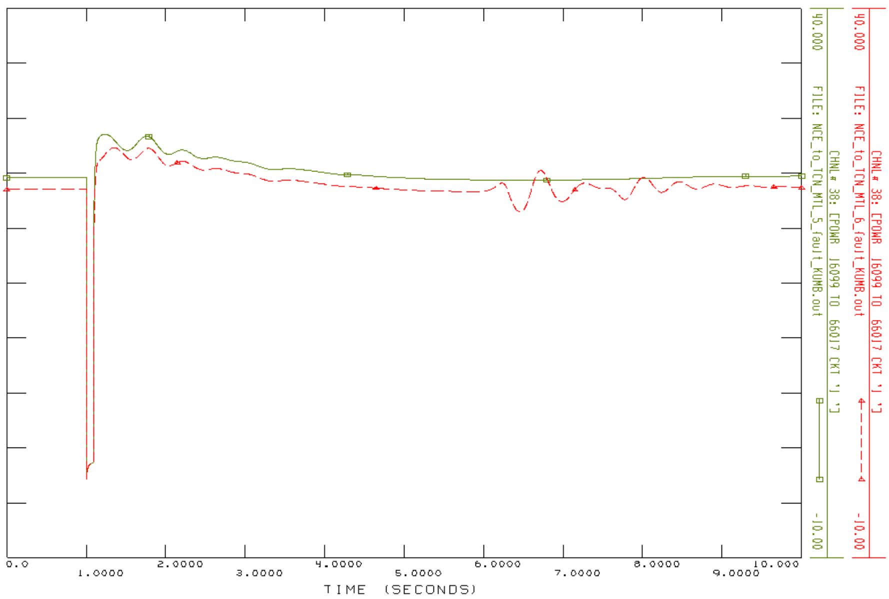


Figure 4.19: **Example of limitation because of transient stability (case "NIGELEC_NCE to TCN")**

4.3.3 Analysis Result – 2020 Scenarios

§4.3.3.1 illustrates the estimation of the MTL for the 2020 scenarios based on the TLTG approach.

4.3.3.1 Maximum Transfer Limits – 2020 Scenarios

A summary of the TLTG results for the 2020-Peak scenario is shown in the following Table 4.28. As expected the higher transfer limits are within the stronger Control Areas. Also, as the system is significantly meshed, limiting contingencies may be found in other Control Areas (e.g. contingency in TCN resulting to overloading of a branch in GRIDCO is limiting the power exchange between CIE and SONABEL).

Table 4.28: Summary of results of Maximum Transfer Limits (2020)

From Area	To Area	Incr. Transfer Limit (MW)	Limiting element		Limiting Contingency	
			Description	Area(s)	Description	Area(s)
TCN	NIGELEC	12.8	66026 SALKADAMNA 132.00 69003 SALKADAMNA 330.00 2	NIGELEC	OPEN 19028 [KADUNA 3 330.00] TO 19029 [KANO 3 330.00] CKT 1	TCN
NIGELEC	TCN	43.2	66018 GAZAOUA 132.00 16099 KATSINA 1 132.00 1	NIGELEC	OPEN 69003 [SALKADAMNA 330.00] TO 69009 [SALKAD-CS1-G330.00] CKT 1	NIGELEC
TCN	CEB	230.2	16152 PHCT MAIN1 132.00 16157 RIVERS_IPP 132.00 1	TCN	OPEN 16147 [AFAM 1 132.00] TO 16157 [RIVERS_IPP 132.00] CKT 2	TCN
CEB	TCN	160.3	27005 MARIA GLETA 161.00 27011 VEDOKO 161.00 1	CEB	OPEN 27005 [MARIA GLETA 161.00] TO 27011 [VEDOKO 161.00] CKT 2	CEB
CEB	GRIDCO	277.7	27005 MARIA GLETA 161.00 27011 VEDOKO 161.00 1	CEB	OPEN 27005 [MARIA GLETA 161.00] TO 27011 [VEDOKO 161.00] CKT 2	CEB
GRIDCO	CEB	241.4	37023 DUNKWA 161.00 37036 NEW OBUASI 161.00 1	GRIDCO	OPEN 37001 [AKOSOMBO 161.00] TO 37029 [TAFO 161.00] CKT 2	GRIDCO
NIGELEC	SONABEL	43.2	66018 GAZAOUA 132.00 16099 KATSINA 1	NIGELEC	OPEN 69003 [SALKADAMNA 330.00] TO 69009 [SALKAD-CS1-G330.00] CKT 1	NIGELEC

SONA-BEL	NIGELEC	12.8	66026 SALKADAMNA 132.00 69003 SALKADAMNA 330.00 2	NIGELEC	OPEN 19028 [KADUNA 3 330.00] TO 19029 [KANO 3 330.00] CKT 1	TCN
GRIDCO	SONABEL	29.1	37023 DUNKWA 161.00 37036 NEW OBUASI 161.00 1	GRIDCO	OPEN 19014 [BKEBBI 3 330.00] TO 19017 [KAINJI G.S.3330.00] CKT 1	TCN
SONA-BEL	GRIDCO	230.7	37059 NAV-NV48 161.00 38003 NAVRONGO 225 225.00 1	GRIDCO	OPEN 37059 [NAV-NV48 161.00] TO 38003 [NAVRONGO 225225.00] CKT 2	GRIDCO
GRIDCO	CIE	216.4	48013 RIVIERA-225 225.00 48032 BINGERVILLE 225.00 1	CIE	OPEN 48033 [ANANI 225.00] TO 48035 [GD-BASSAM 225.00] CKT 1	CIE
CIE	GRIDCO	30.6	37023 DUNKWA 161.00 37036 NEW OBUASI 161.00 1	GRIDCO	OPEN 19014 [BKEBBI 3 330.00] TO 19017 [KAINJI G.S.3330.00] CKT 1	TCN
SONA-BEL	EDM	162.8	136001 KALABANCORO 150.00 136007 KODIALANI 150.00 1	EDM	OPEN 136006 [LAFIA 150.00] TO 136007 [KODIALANI 150.00] CKT 1	EDM
EDM	SONABEL	37.9	37023 DUNKWA 161.00 37036 NEW OBUASI 161.00 1	GRIDCO	OPEN 19014 [BKEBBI 3 330.00] TO 19017 [KAINJI G.S.3330.00] CKT 1	TCN
CIE	EDM	24.6	37023 DUNKWA 161.00 37036 NEW OBUASI 161.00 1	GRIDCO	OPEN 19014 [BKEBBI 3 330.00] TO 19017 [KAINJI G.S.3330.00] CKT 1	TCN
EDM	CIE	207.7	136001 KALABANCORO 150.00 136002 SIRAKORO 150.00 1	EDM	OPEN 138002 [KOUTIALA 225.00] TO 138003 [SEGOU 225 KV225.00] CKT 1	EDM
CIE	SONABEL	14.9	37023 DUNKWA 161.00 37036 NEW OBUASI 161.00 1	GRIDCO	OPEN 19014 [BKEBBI 3 330.00] TO 19017 [KAINJI G.S.3330.00] CKT 1	TCN
SONA-BEL	CIE	306	37059 NAV-NV48 161.00 38003 NAVRONGO 225225.00 1	GRIDCO	OPEN 37059 [NAV-NV48 161.00] TO 38003 [NAVRONGO 225225.00] CKT 2	GRIDCO
CIE	CLSG	37.9	37023 DUNKWA 161.00 37036 NEW OBUASI 161.00 1	GRIDCO	OPEN 19014 [BKEBBI 3 330.00] TO 19017 [KAINJI G.S.3330.00] CKT 1	TCN

CLSG	CIE	131.8	148001 KITA-225 225.00 148003 MAN-KOD225 225.00 1	SOGEM	OPEN 148028 [BAKEL225 225.00] TO 148030 [RX1-MAT-BAK 225.00] CKT 1	SOGEM
CLSG	EDG	187.5	148018 RX-KAY-225 225.00 148019 RX1-MAN-225 225.00 1	SOGEM	OPEN 158010 [YIBEN 225.00] TO 158011 [KAMAKWIE 225.00] CKT 1	CLSG
EDG	CLSG	87.3	96001 LINSAN110 110.00 158006 LINSAN 225.00 1	EDG, CLSG	BASE CASE	
EDG	OMVG	87.3	96001 LINSAN110 110.00 158006 LINSAN 225.00 1	EDG, CLSG	BASE CASE	
OMVG	EDG	382.4	168002 TAMBACOUNDA 225.00 168003 SAMBANGALOU 225.00 1	OMVG	OPEN 168005 [MALI225 225.00] TO 168006 [LABE225 225.00] CKT 1	OMVG
OMVG	SENEL EC	39.8	148028 BAKEL225 225.00 148030 RX1-MAT-BAK 225.00 1	SOGEM	BASE CASE	
SENELE C	OMVG	139.1	148001 KITA-225 225.00 148003 MAN-KOD225 225.00 1	SOGEM	OPEN 148028 [BAKEL225 225.00] TO 168002 [TAMBACOUNDA 225.00] CKT 1	SOGEM, OMVG
SOGEM	SENEL EC	27.1	148001 KITA-225 225.00 148003 MAN-KOD225 225.00 1	SOGEM	OPEN 148021 [KAYES-225 225.00] TO 148050 [KAY-BAK-225 225.00] CKT @1	SOGEM
SENELE C	SOGEM	141.9	148042 SAK-TOB-225 225.00 148043 TOB-SAK-225 225.00 1	SOGEM	BASE CASE	
SOGEM	EDM	27.1	148001 KITA-225 225.00 148003 MAN-KOD225 225.00 1	SOGEM	OPEN 148021 [KAYES-225 225.00] TO 148050 [KAY-BAK-225 225.00] CKT @1	SOGEM
EDM	SOGEM	121.8	148018 RX-KAY-225 225.00 148019 RX1-MAN-225 225.00 1	SOGEM	OPEN 138012 [LOULO 225.00] TO 148004 [MANANTALI 225.00] CKT 1	EDM, SOGEM

4.4 Proposed short-term reinforcements according to dynamic analysis on 2016 scenarios

Based on the results of the dynamic analyses on 2016 scenarios reported in §4.2.1 and §4.3.2 the following list of reinforcements are proposed as a priority for the short-term horizon in addition to the measures reported in §3.3:

- Installation of an out-of-step relay that separates EDM-SA and CIE control areas. Out-of-step relays are commonly introduced at one end of transmission lines. For example, Sikasso (EDM-SA) 225 kV substation is a candidate location. In this case, the relay will be able to trip the 225 kV line Sikasso – Ferké in case of detection of "out-of-step" conditions. In addition also the installation of an out-of-step relay at Segou (EDM-SA) 225 kV substation is recommended; the relay shall trip the 225 kV line Segou – Koutiala in case of detection of "out-of-step" conditions.
- Special protection schemes at the Ferké (CIE) substation, consisting of the installation of an intertrip relay which trips the 225/90 kV transformer in case of trip of Ferké – Bouake 2 225 kV line.
- Special protection schemes at the B.Kebbi (TCN) substation, consisting in the installation of an intertrip relay which trips the two 330/132/33 kV transformers (connecting B.Kebbi 1 132 kV busbars) in case of trip of Kainji – B.Kebbi 330 kV line.

It can be also stated that compared to the base case (non-synchronous operation), the interconnected case needs at minimum the following reinforcements in order to ensure that non severe contingencies will lead to unstable and unsecure operation of the interconnected case:

- Operation of the 330kV lines Sakete-Davie-Asogli.
- Appropriately tuned out-of-step relays able to separate EDM-SA and CIE Control Areas.

In addition, taking into account the results of the small signal analysis the following measure is recommended as well:

- The small signal analysis highlighted a significant amount of local modes with a damping ratio smaller than the optimal typical damping ratio objective (20 %). A list of units was identified based on their participation factors to the most critical modes (Table 4.7). For these units it is recommended either to install a Power System Stabilizer (PSS) or to perform a fine tuning of its parameters.

4.5 UFLS Harmonization

The Under Frequency Load Shedding (UFLS) plan is one of the typical remedial actions implemented in the power systems and is considered part of the Defense Plan. The UFLS is designed to quickly and automatically balance the system in case of large generation deficits occurring after the loss of generation or network separations. The contingencies or the sequence of events typically leading to such unbalances are classified as extreme contingencies/events. In case of occurrence of these kinds of contingencies, the spinning reserve is not sufficient for controlling the frequency decay and then disconnection of loads have to be operated.
In case of interconnected areas the principle of mutual support is generally implemented for guaranteeing the stability of the whole system. The mutual support is realized both in terms of generation through the sharing of the primary reserve and in terms of load shedding by sharing the amount of load disconnected.

In order to realize the sharing of the UFLS the coordination in the choice of the following quantities needs to be considered among the interconnected areas:

- Number of stages
- Threshold of the stages
  - Frequency based
  - Derivative based
  - Frequency and derivative based
- Amount of load shed at each stage

This coordination is necessary for all the stages that can be activated when the system Interconnected.
Simulations have been performed to determine harmonized settings for three stages of UFLS which may be adopted in the WAPP system. The proposed settings are listed in Table 4.29

Table 4.29: Proposed harmonized UFLS stages

UTILITY	f1 [Hz]	df1 [Hz/s]	t1 [s]	LS1 [pu]	f2 [Hz]	df2 [Hz/sec]	t2 [s]	LS2 [pu]	f3 [Hz]	df3 [Hz/sec]	t3 [s]	LS3 [pu]
NIGERIA	49.5	0.3	0.15	0.1	49	0.2	0.15	0.15	48.7	0.05	0.15	0.3
BENIN	49.5	0.3	0.15	0.1	49	0.2	0.15	0.15	48.7	0.05	0.15	0.3
NIGER	49.5	0.3	0.15	0.1	49	0.2	0.15	0.15	48.7	0.05	0.15	0.4
TOGO	49.5	0.3	0.15	0.1	49	0.2	0.15	0.15	48.7	0.05	0.15	0.3
GHANA	49.5	0.3	0.15	0.1	49	0.2	0.15	0.15	48.7	0.05	0.15	0.3
COTE IVOIRE	49.5	0.3	0.15	0.1	49	0.2	0.15	0.15	48.7	0.05	0.15	0.3
BURKINA FASO	49.5	0.3	0.15	0.1	49	0.2	0.15	0.15	48.7	0.05	0.15	0.15
MALI	49.5	0.3	0.15	0.1	49	0.2	0.15	0.15	48.7	0.05	0.15	0.3
SENEGAL	49.5	0.3	0.15	0.1	49	0.2	0.15	0.15	48.7	0.05	0.15	0.2
MAURITANIA	49.5	0.3	0.15	0.1	49	0.2	0.15	0.15	48.7	0.05	0.15	0.3

The settings reported in Table 4.29 have to be considered as preliminary settings based on a limited amount of significant simulations. In order to design an exhaustive setting a dedicated study should be performed.

4.6 General consideration on system protections

During the operation of power systems, in case of occurrence of major disturbances, unstable phenomena involving large variations of the electrical quantities and wide portions of the network are named system phenomena. In case of poorly meshed interconnected systems, as the WAPP system, the angular transient instability and the voltage collapse are the most risky phenomena which may occur in the system. In such systems the phenomena can be clearly observed on the interconnections and then the possibility to identify it through the measurement of local electrical quantities allows to use local protections for splitting the system in case of instabilities. For this reason such protections are named system protections. Typical kinds of system protections are:

Out-of-step protections (OST)

Protections able to identify the out of step condition by monitoring the apparent impedance measured in the installation point.

Power Swing Blocking (PSB)

Protection able to detect the swings by monitoring the apparent impedance measured in the installation point. This protection blocks the operation of the distance protection in case of swings and issue the tripping command only in the case in which the swing is unstable (out of step).

Undervoltage protections

Protection monitoring the trend of the voltage and issue the tripping command when the voltage exceed pre-defined threshold for more than a pre-defined temporization time. This protection is used to split the system when a voltage collapse is approaching. Sometimes it’s also used to split the system in case of out of step, since during the unstable swing the voltage drop to very low values especially in proximity of the electrical center.

Based on the information supplied from WAPP, the provided list of protections installed on the interconnection lines is shown in Table 4.30.

Table 4.30: Provided protections installed on WAPP interconnections

1	Katsina - Gazaoua	Katsina - Gazaoua 132 kV (TCN)	Distance, Overcurrent & Over/Undervoltage protection	X
		Gazaoua 132 kV (NIGELEC)		
2	B.Kebbi - Dosso	B.Kebbi- Niamey 132 kV (TCN)	Distance, Overcurrent, Overvoltage, Earth fault, Broken-Conductor,Switch on to fault, PSB protection	X
		Dosso 132 kV (NIGELEC)		
3	Ikeja - Sakété	Ikeja - Sakete 330 kV (TCN)	Distance & switch on to Fault protection	X
		Sakété 330 kV (CEB)		

Focusing on the system protections, undervoltage and PSB protections are installed in two substations. The results of the simulations have shown that under some conditions and following severe events for the system, loss of synchronism phenomena may occur on the system. For this reason the presence of such protections is advisable for the system security.

4.7 General considerations on UVLS

Power systems with heavy loading on transmission facilities and limited reactive power control can be vulnerable to voltage instability. In severe situations, load shedding when voltage collapse is imminent may preserve system stability. For low probability events and extreme contingencies, UVLS may be the most economical solution in preventing voltage collapse [30][31][32][33][34].

Although in many systems UVLS could be very effective in preventing voltage collapse, it may not benefit all systems. For example, systems with fast voltage decay characteristics (less than a second) may find direct load tripping to be a better alternative. However, systems that are at a risk of fast voltage decay may also be at a risk of slower voltage decay under different conditions. Studies should be performed to determine which systems are the potential candidates for a suitable UVLS scheme.

Long-term (slow) voltage collapse

Voltage collapse may occur, in case of contingencies, when transferring power between electrically distant areas. System studies are needed to determine which systems are the potential candidates for a suitable UVLS scheme. It is most useful in a slow-decaying voltage system with the under-voltage relay time delay settings typically between 3 to 10 seconds.

When overloads occur on long transmission lines in conjunction with a significant local voltage dip, then the effect of UVLS action would also be to reduce such overloads.

Transient Instability

Generally, the UVLS settings are in the range of 85 to 95 percent of the operating voltages, with time delays ranging from tens of cycles to minutes. As a practical example, considering cases where "Fast Collapses" may occur and then "Quick Load Shedding Actions" should be activated, it could be stated that UVLS should operate within 200 – 300 ms while AVRs operates within 4-5 s. The relay time delay should be set in order to avoid false tripping but occur fast enough to mitigate a transient stability event.

4.8 Back-to-Back HVDC alternative at Sakété

The back-to-back HVDC link alternative at Sakété substation is a solution to be considered in case the observed criticalities [2][3] (in particular generation deficit and lack of primary reserve) in the Nigerian power system cannot be successfully solved.

If the critical issues in the Nigerian power system will not be properly addressed with suitable reinforcements, the HVDC link is the best technical way to ensure stable and reliable interconnected system operation. On the other hand an effective resolution of the deficiencies in the Nigerian power system, with the implementation of the recommended measures [3] to fill the gap with the WAPP operational manual may lead to a stable and reliable interconnected system also without the HVDC link.

The impact of the HVDC link at Sakété into the WAPP interconnected network has been assessed through simulation analysis and related cost evaluations (§6 and §7.1).

The results of the performed analysis show that both the current available technology – namely VSC and LCC – are feasible from a technical point of view. The advantages and disadvantages of the available technologies, as well as the cost estimated for both options have been deeply assessed in §7.1, including the required solutions of a power transfer capacity of 300 MW extendible to 600 MW.

It is important also to underline that in the future scenarios (2020) the Nigerian power system should be interconnected not only through the Ikeja – Sakete 330 kV line, since new interconnections are planned (e.g. North Core project). The installation of the back-to-back at Sakété is compatible with future new AC (or DC) links, but it is important to take into account that in the nearly future similar issues related to the new interconnections could be addressed.

4.9 Proposed medium-term reinforcements according to dynamic analysis on 2020 scenarios

Based on the results of the dynamic analyses on 2020 scenarios reported in §4.2.2 and 4.3.3 the following list of reinforcements are proposed for the medium-term in addition to the measures reported in §3.5:

- Special protection schemes at the Salkadamna (NIGELEC) substation, consisting in the trip of generation at Salkadamna power plant in case of trip of Goroubanda – Salkadamna 330 kV line.

Furthermore, according to the results of the Small Signal Analysis, the following measures are recommended:

- The Small Signal Analysis highlighted a significant amount of local modes with a damping ratio smaller than the optimal typical damping ratio objective (20 %).
  A list of units was identified based on their participation factors to the most critical modes (Table 4.8). For these units it is recommended either to install or to perform a fine tuning of the Power System Stabilizer (PSS).

5 WAMS STUDY FOR WAPP NETWORK

A large interconnected network like WAPP system is prone to voltage and angle instabilities, when variances in load and generation sources may cause wide-area disruptions with possible cascade effects.

Synchrophasor technology provides observability of the status of the power system to operators in real time, facilitating the calculation of the maximum loading condition for each system bus connected to the transmission network. Furthermore, pre-planned corrective actions can be considered to minimize the risk of wide-area disruptions and to increase the power transfer capability of the system. The availability of a high-speed, high-bandwidth network architecture makes synchrophasors ideal for this application.

5.1 Scope of WAMS technology

WAMS is typically deployed on large geographical networks for monitoring complex and fast phenomena that cannot be captured by traditional SCADA systems. WAMS data can be used both for real time processing and for offline post-event analysis. The deployment of this technology in the WAPP network can have the following main objectives:

- Upgrade of information systems.
- Islanding detection.
- Loss of synchronism.
- Real time observation of system performance.
- Real time determination of transmission capacity.
- Early detection of system disturbances.
- Implementation of DLR (Dynamic Line Rating) algorithm to estimate the real time thermal limit of transmission lines.

For this purposes is recommended that WAPP develops a customized solution for wide-area measurement that uses the synchrophasor functionalities to monitor the whole network. Furthermore, there are some expected benefits:

- Increased system loading while maintaining adequate stability margins;
- Improvement of operator response time to system contingencies, such as overload conditions, transmission outages, or generator shutdown;
- The achievement of advance system knowledge with correlated event reporting and real-time system visualization;
- The promotion of system-wide data exchange with a standardized synchrophasor data format; and
- The validation of planning studies to improve system load balance and station optimization.

Over the mid-term time scale horizon these predicted benefits could be achieved by successfully exploiting the WAMS technology, which has to cover as much of the transmission network as possible. A pilot project may be a good starting point to study the best way to develop WAMS on a larger scale and in particular to test some functions and applications before deciding to implement them across the system.

Thus, it is important to define a development strategy that could be divided into three main steps:

- PMU devices selection and positioning.
- Communication system improvement.
- WAMS applications implementation.

5.2 Introduction to PMU devices selection and their positioning strategy

PMU positioning strategy is fundamental to achieving effective observability of the dynamic behavior of the network. The installation of PMUs in the most important nodes of the WAPP system will greatly improve the ability to monitor the transmission lines in terms of voltage and angle instabilities.

To this end, the international experience could serve as a useful benchmark for developing an appropriate PMU positioning strategy. In fact, even if complete system observability may be impossible to achieve, it should be possible to focus successfully on monitoring its most critical portions, i.e. areas subject to specific events (e.g. line trip with possible cascading) or phenomena (e.g. voltage collapse, oscillations) which may jeopardize system stability.

Before detailing the PMU positioning strategy, it is worthwhile to make a few comments on the choice of the models of the device to be installed and the related issues. In order to obtain reliable results from applications that will use PMU data it will be necessary to ensure high module and phase performance, which depends on time synchronization accuracy. So, the first step is to decide the required measurement accuracy and, consequently the appropriate PMU models to be installed. The international experience provides a good reference point, but the latest commercial products offer far more satisfactory yields, especially in terms of synchronization accuracy.

In this phase, not only operation and planning, but also asset management functions must be involved. This collaboration could make a significant contribution for choosing the right devices to be installed and, above all, it must consider if the substitution of other equipment is necessary. For example, voltage and current transducers have to be very precise so CTs and VTs must have a high accuracy class (possibly 0.2%). So, if CTs and VTs are quite old and/or not very precise, it would be better to verify this first and substitute them, if necessary, before connecting a PMU. Otherwise the data gathered will have a high sampling rate and good synchronization but remain extremely inaccurate in terms of the module and thus prove not useful for monitoring and control applications.

Following the decision about the most appropriate device models the next task is to select the best location for the PMUs. One of the best ways to do this is by using heuristic-analytical criteria, in order to maximize the operating value of the measurements.

The experience on transmission network operation is especially helpful in pointing out some heuristic criteria (e.g. proximity to large generating units, known bottlenecks, borders, etc.) that could help determine the most suitable location to install PMU, especially in the low voltage level network.

On the other hand the development of an analytical approach should be also taken into account as this aims to find the places in which PMU installation could improve observability for event identification, oscillation detection, angle, voltage and frequency stability monitoring.

To this end the output of small signal stability study is a very useful starting point to analytically identify the more suitable nodes for PMU installations.

Therefore, combining heuristic and analytical approach, the recommended candidates' nodes for PMU installation are suggested according to these criteria:

- From/to nodes of relevant lines, especially if they connect different areas/countries.
- High value of observability of significant inter-area modes.
- Proximity to important power plants, especially if they are characterized by a high participation factor in some oscillatory modes.

5.3 WAPP PMU positioning solutions

As said before, even if complete system observability may be impossible to achieve, it should be possible to focus successfully on monitoring its most critical portions with an adequate choice of a relatively small number of PMUs.

This positioning analysis proposes three incremental solutions, characterized by a growing number of installed devices:

- **Solution 1**: Monitoring interconnections.
- **Solution 2**: Monitoring interconnections and nodes characterized by a high value of observability of significant inter-area modes.
- **Solution 3**: Monitoring interconnections, nodes characterized by a high value of observability of significant inter-area modes and nodes located near to important power plants.

Looking to 2020 scenario it could be noted that the network structure significantly changes, particularly regarding the number of interconnections among different countries.

Therefore, in order to be compliant with 2020 scenario, for each PMU positioning solution a proper upgrade is proposed.

5.3.1 Solution 1 – 2016

Looking to 2016 WAPP network and considering one PMU for each ends of the interconnections the nodes that should be equipped with PMUs are reported in the following table.

Table 5.1: Nodes to be equipped with PMUs to monitor interconnections in 2016 WAPP network

Node Name	Area Name	Interconnection
16061 – B.KEBBI 132 kV	TCN	TCN – NIGELEC_FLEUVE
16099 – KATSINA 132 kV	TCN	TCN – NIGELEC_NCE

19004 – IKEJA 330 kV	TCN	TCN – CEB
66002 – DOSSO 132 kV	NIGELEC	TCN – NIGELEC_FLEUVE
66017 – GAZOUA 132 kV	NIGELEC	TCN – NIGELEC_NCE
29001 – SAKETE 330 kV	CEB	TCN – CEB
29003 – DAVIE 330 kV	CEB	GRIDCO – CEB
27016 – LOME AFLAO 161 kV	CEB	GRIDCO – CEB
39003 – ASOGLI 330 kV	GRIDCO	GRIDCO – CEB
37055 – AFTAP 161 kV	GRIDCO	GRIDCO – CEB
37037– ASIEKPE 161 kV	GRIDCO	GRIDCO – CEB
38001– PRESTEA 225 kV	GRIDCO	GRIDCO – CIE
48013– RIVIERA 225 kV	CIE	GRIDCO – CIE
48006– FERKE 225 kV	CIE	CIE – EDM and CIE - SONABEL
138001– SIKASSO 225 kV	EDM-SA	CIE – EDM-SA
58001– KODENI 225 kV	SONABEL	CIE – SONABEL
148002 – KODIALANI 225 kV	SOGEM	SOGEM – EDM-SA
148021 – KAYES 225 kV	SOGEM	SOGEM – EDM-SA
148029 – BAKEL 225 kV	SOGEM	SOGEM – SENELEC
148037 – DAGANA 225 kV	SOGEM	SOGEM – SENELEC
148050 – NOUAKCHOTT 225 kV	SOGEM	SOGEM – SOMELEC
148045 – TOBENE 225 kV	SOGEM	SOGEM – SENELEC

5.3.2 Solution 2 – 2016

The second solution proposes to equip with PMUs also the nodes characterized by a high value of observability of significant inter-area modes obtained in 2016 off peak interconnected scenario (§4.1.3.1.4). The off peak condition is the most critical for inter-area modes because a low load is usually strictly connected with low damping of oscillation. The ranking of the node observability has been obtained setting two successive thresholds:

1. Looking to all the power plants an inter-area mode is considered well “observable” by the reference node of a particular generator if its Speed Observability Amplitude is above 0.5;
2. Subsequently, the reference node of a particular generator has been considered as a node to be equipped with PMU if the sum of the Speed Observability Amplitude of all the significant inter-area modes is above 1.

In this way the list of the nodes to be equipped with PMUs includes the ones which have a good level of observability (first threshold) on at least 2 significant inter-area modes (second threshold). Therefore, the nodes to be equipped with PMUs are reported in the following table.

Table 5.2: Nodes to be equipped with PMUs to monitor nodes characterized by a high value of observability

Node Name	Area Name	Total Observability
52018 - OUAGA G2 6.6000	SONABEL	2.75
52030 - KOSSODO G6 11.000	SONABEL	2.51
53005 - KOSSODO G3 15.000	SONABEL	2.25
12068 - DELTA GT 15 11.500	TCN	2.00
42008 - BUYOGS1 10.500	CIE	2.00
42009 - BUYOGS2 10.500	CIE	2.00
52023 - OUAGA G8 6.6000	SONABEL	1.96
52011 - KOMSILGA G2 11.000	SONABEL	1.91
52010 - KOMSILGA G1 11.000	SONABEL	1.87
52027 - KOSSODO G1 11.000	SONABEL	1.87
62003 - GOUDEL 11.000	NIGELEC	1.81
32124 - AMERI 13.800	GRIDCO	1.54
22004 - TAG LOME 11.000	CEB	1.47
62001 - NIAMEY-2 10.500	NIGELEC	1.18
61002 - AGGREKO-1A 0.4000	NIGELEC	1.15
61006 - AGGREKO-1B 0.4000	NIGELEC	1.15
61009 - AGGREKO-1B 0.4000	NIGELEC	1.15
61001 - AGGREKO-2 0.4000	NIGELEC	1.11
62008 - GOROUBANDA 11.000	NIGELEC	1.11
13014 - JEBBA 2G1 16.000	TCN	1.08
13015 - JEBBA 2G2 16.000	TCN	1.08
13016 - JEBBA 2G3 16.000	TCN	1.08
13017 - JEBBA 2G4 16.000	TCN	1.08
13018 - JEBBA 2G5 16.000	TCN	1.08
122009 - AGGREKO IPP 12.500	SENELEC	1.00

23009 - CONTOUR G5-615.000	CEB	1.00
32057 - KPONEG1 13.800	GRIDCO	1.00
32070 - TT1PP-G1 14.400	GRIDCO	1.00

5.3.3 Solution 3 – 2016

The third solution proposes to equip with PMUs also the nodes located near to important power plants. In particular, it has been decided to look to the nodes that have one or more generators directly connected and in which the sum of all electrical machines sizes is more than 150MVA. The nodes to be equipped with PMUs according to this rule are reported in the following table. The nodes already monitored in one of the previous solutions are highlighted in green.

Table 5.3: Nodes located near to important generators – More than 150MVA connected to the node

Node Name	Area Name	Total MVA
13043 - ALAOJI_STB2 17.000	TCN	382
13042 - ALAOJI_STB1 17.000	TCN	382
32124 - AMERI 13.800	GRIDCO	300
13005 - EGBIN ST 5 16.000	TCN	245.8
13003 - EGBIN ST 3 16.000	TCN	245.8
13001 - EGBIN ST 1 16.000	TCN	245.8
13006 - EGBIN ST 6 16.000	TCN	245.8
13002 - EGBIN ST 2 16.000	TCN	245.8
13004 - EGBIN ST 4 16.000	TCN	245.8
12078 - GER NIPPGT2210.500	TCN	226.6
12077 - GER NIPPGT2110.500	TCN	226.6
12079 - GER NIPPGT2310.500	TCN	226.6
12117 - RIVERS _GT1 10.500	TCN	225
12108 - AFAM VI ST1011.500	TCN	220
12086 - OKPAI GT12 11.500	TCN	210
43007 - AZITO GT11 15.800	CIE	210
43008 - AZITO GT12 15.800	CIE	210
12087 - OKPAI ST18 11.500	TCN	210
12085 - OKPAI GT11 11.500	TCN	210

32060 - EF38-HG2 13.800	GRIDCO	200
32072 - MRP NEW 13.800	GRIDCO	200
32005 - AKOSOMBO-HG514.400	GRIDCO	179.5
32004 - AKOSOMBO-HG414.400	GRIDCO	179.5
32006 - AKOSOMBO-HG614.400	GRIDCO	179.5
32001 - AKOSOMBO-HG114.400	GRIDCO	179.5
32003 - AKOSOMBO-HG314.400	GRIDCO	179.5
32002 - AKOSOMBO-HG214.400	GRIDCO	179.5
13021 - SHIROR 411G216.000	TCN	177
13020 - SHIROR 411G116.000	TCN	177
13022 - SHIROR 411G316.000	TCN	177
13023 - SHIROR 411G416.000	TCN	177
12105 - AFAM VI GT1111.500	TCN	176
12107 - AFAM VI GT1311.500	TCN	176
12106 - AFAM VI GT1211.500	TCN	176
43013 - AZITO TAV 15.800	CIE	175
12075 - GEREGU GT12 10.500	TCN	174
12074 - GEREGU GT11 10.500	TCN	174
12076 - GEREGU GT13 10.500	TCN	174
13010 - KAINJ 1G7-8 16.000	TCN	170
13011 - KAINJ 1G9-1016.000	TCN	170
12101 - AFAM4GT15-1611.500	TCN	166.6
12100 - AFAM4GT13-1411.500	TCN	166.6
12102 - AFAM4GT17-1811.500	TCN	166.6
12104 - AFAMV GT 20 11.500	TCN	162.7
12103 - AFAMV GT 19 11.500	TCN	162.7
13045 - TRANS_AMADI 15.000	TCN	156.25
12052 - OMOTNIPP GT210.500	TCN	156.25
12054 - OMOTNIPP GT410.500	TCN	156.25
13054 - TRANS_AMADI 15.000	TCN	156.25
12053 - OMOTNIPP GT310.500	TCN	156.25

13055 - TRANS_AMADI 15.000	TCN	156.25
13056 - TRANS_AMADI 15.000	TCN	156.25
12051 - OMOTNIPP GT110.500	TCN	156.25
32123 - KARPWR G2 13.800	GRIDCO	150
32121 - KTTP G2 13.800	GRIDCO	150
12038 - OLORNIPPGT1210.500	TCN	150
12039 - OLORNIPPGT2110.500	TCN	150
32120 - KTPP G1 13.800	GRIDCO	150
12040 - OLORNIPPGT2210.500	TCN	150
32122 - KARPWR G1 13.800	GRIDCO	150
12041 - OLOR NIPPST110.500	TCN	150
12042 - OLOR NIPPST210.500	TCN	150
12037 - OLORNIPPGT1110.500	TCN	150

This solution allows to directly monitor the most important electric machines, but looking to power plants it is worth to consider the high voltage end of the transformers. This approach allows to reduce the number of PMUs and to monitor power plants the size of which is more than 150MVA. The nodes to be equipped with PMUs according to this rule are reported in the following table.

Table 5.4: Nodes located near to important power plants – More than 150MVA connected to the node

Node Name	Area Name	Total MVA
19043 - AFAM IV 3 330.00	TCN	1573.2
19003 - EGBIN 3 330.00	TCN	1474.8
19044 - ALAOJI 3 330.00	TCN	1329
19005 - OLORUNSOGO3 330.00	TCN	1318.4
19024 - SAPELE 3 330.00	TCN	1234.85
19025 - GEREGU 330.00	TCN	1201.8
37047 - ABOADZE 161.00	GRIDCO	1153.8
37001 - AKOSOMBO 161.00	GRIDCO	1077
19011 - OMOTOSHO3 330.00	TCN	1043.4
19023 - DELTA IV 3 330.00	TCN	1005.9
19017 - KAINJI G.S.3330.00	TCN	820

19016 - JEBBA G.S.3 330.00	TCN	714
19019 - SHIRORO 3 330.00	TCN	708
19048 - CALABAR_PS_3330.00	TCN	706.25
48002 - VRIDI 225.00	CIE	647.4
19039 - OKPAI 3 330.00	TCN	630
16166 - TRAMADI 132.00	TCN	625
48010 - AZIT0 225.00	CIE	595
19027 - EYEAN_3 330.00	TCN	568.9
37048 - ABOADZE-T3 161.00	GRIDCO	506
16160 - OMOKU 1 132.00	TCN	466.5
37060 - BUI 161.00	GRIDCO	443.4
37011 - NEW TEMA 161.00	GRIDCO	412.61
46002 - VRIDI 90.000	CIE	383.8
16003 - EGBIN 1 132.00	TCN	376.12
126004 - CDB 90.000	SENELEC	342.3
37012 - MINES RESERV161.00	GRIDCO	315
37072 - KARPOWER TM 161.00	GRIDCO	300
37071 - KTPP 161.00	GRIDCO	300
37061 - KPONE 161.00	GRIDCO	264.7
66026 - SALKADAMNA 132.00	NIGELEC	252
16150 - EKET 1 132.00	TCN	236
48003 - TAABO 225.00	CIE	234
16157 - RIVERS_IPP 132.00	TCN	225
37014 - ASOGLI 161.00	GRIDCO	217.74
48009 - BUYO 225.00	CIE	183
37034 - KPONG GS 161.00	GRIDCO	177.76
126001 - BEL AIR 90.000	SENELEC	169.8
27017 - LOMEPORT 161.00	CEB	169

5.3.4 Solution 1 – 2020

Looking to 2020 WAPP network and considering one PMU for each ends of the interconnections the nodes that should be equipped with PMUs are reported in the following table. The nodes already monitored in one of 2016 solutions are highlighted in yellow.

Table 5.5: Nodes to be equipped with PMUs to monitor interconnections in 2020 WAPP network

Node Name	Area Name	Interconnection
19014 – B.KEBBI 330 kV	TCN	TCN – NIGELEC
16061 – B.KEBBI 132 kV	TCN	TCN – NIGELEC
16099 – KATSINA 132 kV	TCN	TCN – NIGELEC_NCE
19004 – IKEJA 330 kV	TCN	TCN – CEB
69001 – ZABORI 330 kV	NIGELEC	TCN – NIGELEC and CEB – NIGELEC
66002 – DOSSO 132 kV	NIGELEC	TCN – NIGELEC
66017 – GAZOUA 132 kV	NIGELEC	TCN – NIGELEC
69004 – GOROUBANDA 330 kV	NIGELEC	NIGELEC – SONABEL
29001 – SAKETE 330 kV	CEB	TCN – CEB
29003 – DAVIE 330 kV	CEB	GRIDCO – CEB
27016 – LOME AFLAO 161 kV	CEB	GRIDCO – CEB
27025 – CINCASSE 161 kV	CEB	GRIDCO – CEB
29004 – MALANVILLE 330 kV	CEB	NIGELEC – CEB
39003 – ASOGLI 330 kV	GRIDCO	GRIDCO – CEB
37055 – AFTAP 161 kV	GRIDCO	GRIDCO – CEB
37037– ASIEKPE 161 kV	GRIDCO	GRIDCO – CEB
37072– BAWKU 161 kV	GRIDCO	GRIDCO – CEB
38003– NAVRONGO 225 kV	GRIDCO	GRIDCO – SONABEL
39016– DUNKWA 330 kV	GRIDCO	GRIDCO – CIE
38001– PRESTEA 225 kV	GRIDCO	GRIDCO – CIE
48013– MOYASSUE 225 kV	CIE	GRIDCO – CIE
48011– MAN 225 kV	CIE	CLSG – CIE
48006– FERKE 225 kV	CIE	CIE – EDM and CIE - SONABEL
138001– SIKASSO 225 kV	EDM-SA	CIE – EDM-SA and EDM – SONABEL
59001– OUAGA EST 330 kV	SONABEL	NIGELEC – SONABEL

58001– KODENI 225 kV	SONABEL	CIE – SONABEL and EDM – SONABEL
58003– ZAGTOULI 225 kV	SONABEL	GRIDCO – SONABEL
148002 – KODIALANI 225 kV	SOGEM	SOGEM – EDM-SA
148021 – KAYES 225 kV	SOGEM	SOGEM – EDM-SA
148029 – BAKEL 225 kV	SOGEM	SOGEM – SENELEC
148037 – DAGANA 225 kV	SOGEM	SOGEM – SENELEC
148050 – NOUAKCHOTT 225 kV	SOGEM	SOGEM – SOMELEC
148045 – TOBENE 225 kV	SOGEM	SOGEM – SENELEC
158001 – YEKEPEPA 225 kV	CLSG	CLSG – CIE and CLSG – LEC
158004 – MANO 225 kV	CLSG	CLSG – LEC
158007 – KENEMA 225 kV	CLSG	CLSG – NPA
158011 – KAMAKWIE 225 kV	CLSG	CLSG – NPA
158005 – NZEREKORE 225 kV	CLSG	CLSG – EDG
158006 – LINSAN 225 kV	CLSG	CLSG – EDG – OMVG
168008 – BOKE 225 kV	OMVG	EDG – OMVG
168012 – MANSOA 225 kV	OMVG	EDG – OMVG
168005 – MALI 225 kV	OMVG	EDG – OMVG
168010 – SALTHINO 225 kV	OMVG	EAGB – OMVG
168001 – TANAF 225 kV	OMVG	SENELEC – OMVG
168003 – SAMBANGALOU 225 kV	OMVG	SENELEC – OMVG
168004 – BIRKELANE 225 kV	OMVG	SENELEC – OMVG
168015 – SOMA 225 kV	OMVG	NAWEC – OMVG

5.3.5 Solution 2 – 2020

The second solution proposes to equip with PMUs also the nodes characterized by a high value of observability of significant inter-area modes obtained in 2020 off peak scenario (§4.1.3.1.6). The ranking of the node observability has been obtained setting two successive thresholds:

1. Looking to all the power plants an inter-area mode is considered well “observable” by the reference node of a particular generator if its Speed Observability Amplitude is above 0.5;

2. Subsequently, the reference node of a particular generator has been considered as a node to be equipped with PMU if the sum of the Speed Observability Amplitude of all the significant inter-area modes is above 1.

In this way the list of the nodes to be equipped with PMUs includes the ones which have a good level of observability (first threshold) on at least 2 significant inter-area modes (second threshold). Therefore, the nodes already monitored in one of 2016 solutions are highlighted in yellow.

Table 5.6: Nodes to be equipped with PMUs to monitor nodes characterized by a high value of observability

Node Name	Area Name	Total Observability
91004 - GHUTES G2 3.3000	EDG	5.55
91003 - GHUTES G1 3.3000	EDG	5.00
123008 - KAOLAC G1 15.000	SENELEC	2.75
122009 - AGGREKO IPP 12.500	SENELEC	2.68
123019 - MALICOUNDA 15.000	SENELEC	2.51
122011 - CDBCONGLOG1 6.6000	SENELEC	2.49
122012 - CDBCONGLOG2 6.6000	SENELEC	2.49
123001 - BELAIR 1G 15.000	SENELEC	2.34
123006 - KAHON 1G 15.000	SENELEC	2.29
123004 - KOUNONE PW 15.000	SENELEC	2.29
42008 - BUYOGS1 10.500	CIE	2.28
92019 - KIPE G1.2.3 11.000	EDG	2.25
91001 - BANEAH G1 3.1000	EDG	2.23
91002 - BANEAH G2 3.1000	EDG	2.23
122003 - CDB 2G 6.6000	SENELEC	2.20
122002 - CDB 1G 6.6000	SENELEC	2.19
92006 - GHUTES G3 5.5000	EDG	2.03
123011 - IPP TOBENE 15.000	SENELEC	1.61
152005 - YIBENGEN 11.000	CLSG	1.42
92011 - KALOUM 32G 6.3000	EDG	1.37
152008 - BUMBUNA G B 11.000	CLSG	1.37
92008 - KINKON G1,2 6.3000	EDG	1.34
92009 - KINKON G3,4 6.3000	EDG	1.34

142005 - MANANTALIG5 11.000	SOGEM	1.33
142001 - MANANTALIG3 11.000	SOGEM	1.33
142004 - MANANTALIG4 11.000	SOGEM	1.33
152007 - BUMBUNA G A 11.000	CLSG	1.32
92001 - GARAFIRI G1 5.7000	EDG	1.31
92015 - KALOUM 52G 11.000	EDG	1.29
152002 - MT. COFFEE G11.000	CLSG	1.27
152003 - MT. COFFEE G11.000	CLSG	1.27
92017 - KALOUM 1 G 11.000	EDG	1.27
92018 - KALOUM 2 G 11.000	EDG	1.27
142003 - MANANTALIG2 11.000	SOGEM	1.25
13014 - JEBBA 2G1 16.000	TCN	1.00
13015 - JEBBA 2G2 16.000	TCN	1.00
13016 - JEBBA 2G3 16.000	TCN	1.00
13017 - JEBBA 2G4 16.000	TCN	1.00
13018 - JEBBA 2G5 16.000	TCN	1.00
22004 - TAG LOME 11.000	CEB	1.00
32044 - TAPCO-TG 13.800	GRIDCO	1.00
32057 - KPONEG1 13.800	GRIDCO	1.00

5.3.6 Solution 3 – 2020

The third solution proposes to also equip the nodes close to important power plants. In particular, it has been adopted the criterion to check the nodes that have one or more generators directly connected and in which the sum of all electrical machines size is more than 150MVA. The nodes to be equipped with PMUs according to this rule are reported in the following table. The nodes already monitored in one of 2016 solutions are highlighted in yellow, while the nodes already monitored in one of the previous 2020 solutions are highlighted in green.

Table 5.7: Nodes of important generators – More than 150MVA

Node Name	Area Name	Total MVA
32128 - GE PP 14.400	GRIDCO	937.5
32132 - T5 PP 14.400	GRIDCO	937.5

13061 - GEOMETRIC_AB15.000	TCN	856.47
32133 - ROTAN PP 14.400	GRIDCO	825
13062 - NOTORE 15.000	TCN	617.6
13058 - GEN DANGOTE 15.000	TCN	588.2
32131 - GLOBELEC PP 14.400	GRIDCO	562.5
22001 - TAG MARIA GL11.000	CEB	562.5
32129 - CHRISPOD PP 14.400	GRIDCO	437.52
32126 - JACOBSEN PP 14.400	GRIDCO	437.49
32134 - AYTEPA PP 14.400	GRIDCO	416.67
13042 - ALAOJI_STB1 17.000	TCN	382
13043 - ALAOJI_STB2 17.000	TCN	382
32124 - AMERI 13.8 13.800	GRIDCO	312.5
32127 - AMANDI PP 14.400	GRIDCO	300
13060 - GEN_KADUNA 15.000	TCN	252.9
13001 - EGBIN ST 1 16.000	TCN	245.8
13003 - EGBIN ST 3 16.000	TCN	245.8
13002 - EGBIN ST 2 16.000	TCN	245.8
13004 - EGBIN ST 4 16.000	TCN	245.8
13006 - EGBIN ST 6 16.000	TCN	245.8
13005 - EGBIN ST 5 16.000	TCN	245.8
32130 - ASG PP 14.400	GRIDCO	237.5
12078 - GER NIPPGT2210.500	TCN	226.6
12079 - GER NIPPGT2310.500	TCN	226.6
12077 - GER NIPPGT2110.500	TCN	226.6
123013 - IPP COAL PP 15.000	SENELEC	225
12108 - AFAM VI ST1011.500	TCN	220
12087 - OKPAI ST18 11.500	TCN	210
43008 - AZITO GT12 15.800	CIE	210
12085 - OKPAI GT11 11.500	TCN	210
12086 - OKPAI GT12 11.500	TCN	210
43007 - AZITO GT11 15.800	CIE	210

32072 - MRP NEW 13.800	GRIDCO	200
32060 - EF38-HG2 13.800	GRIDCO	200
152006 - BIKONGORGEN 11.000	CLSG	200
32001 - AKOSOMBO-HG114.400	GRIDCO	179.5
32005 - AKOSOMBO-HG514.400	GRIDCO	179.5
32006 - AKOSOMBO-HG614.400	GRIDCO	179.5
32002 - AKOSOMBO-HG214.400	GRIDCO	179.5
32003 - AKOSOMBO-HG314.400	GRIDCO	179.5
32004 - AKOSOMBO-HG414.400	GRIDCO	179.5
13021 - SHIROR 411G216.000	TCN	177
13020 - SHIROR 411G116.000	TCN	177
13023 - SHIROR 411G416.000	TCN	177
13022 - SHIROR 411G316.000	TCN	177
12117 - RIVERS _GT1 10.500	TCN	176
12106 - AFAM VI GT1211.500	TCN	176
12118 - RIVERS_GT2 10.500	TCN	176
12105 - AFAM VI GT1111.500	TCN	176
12107 - AFAM VI GT1311.500	TCN	176
43013 - AZITO TAV 15.800	CIE	175
12076 - GEREGU GT13 10.500	TCN	174
12075 - GEREGU GT12 10.500	TCN	174
12074 - GEREGU GT11 10.500	TCN	174
13011 - KAINJ 1G9-1016.000	TCN	170
13010 - KAINJ 1G7-8 16.000	TCN	170
122015 - TAIBA WPP 11.000	SENELEC	166.67
12100 - AFAM4GT13-1411.500	TCN	166.6
12101 - AFAM4GT15-1611.500	TCN	166.6
12102 - AFAM4GT17-1811.500	TCN	166.6
12104 - AFAMV GT 20 11.500	TCN	162.7
12103 - AFAMV GT 19 11.500	TCN	162.7
12053 - OMOTNIPP GT310.500	TCN	156.25

12051 - OMOTNIPP GT110.500	TCN	156.25
12052 - OMOTNIPP GT210.500	TCN	156.25
12054 - OMOTNIPP GT410.500	TCN	156.25
13045 - GEN_AMADI 15.000	TCN	156.25
123012 - SENDOU PP 15.000	SENELEC	156
43025 - SONGON G3 15.500	CIE	153.75
43023 - SONGON G1 15.500	CIE	153.75
43028 - GD-BASSAM G115.500	CIE	153.75
43030 - GD-BASSAM G315.500	CIE	153.75
43029 - GD-BASSAM G215.500	CIE	153.75
43024 - SONGON G2 15.500	CIE	153.75
12039 - OLORNIPPGT2110.500	TCN	150
32122 - KARPWR G1 13.800	GRIDCO	150
32121 - KTTP G2 13.800	GRIDCO	150
32120 - KTPP G1 13.800	GRIDCO	150
12038 - OLORNIPPGT1210.500	TCN	150
12042 - OLOR NIPPST210.500	TCN	150
12041 - OLOR NIPPST110.500	TCN	150
12037 - OLORNIPPGT1110.500	TCN	150
32123 - KARPWR G2 13.800	GRIDCO	150
32125 - KTTP G3 13.800	GRIDCO	150
12040 - OLORNIPPGT2210.500	TCN	150

As in 2016 third solution, looking to power plants, it is worth considering the high voltage ends of the transformers. This approach allows to reduce the number of PMUs and to monitor power plants the size of which is more than 150MVA. The nodes to be equipped with PMUs according to this rule are reported in the following table. The nodes already monitored in one of 2016 solutions are highlighted in yellow.

Table 5.8: Nodes located near to important power plants – More than 150MVA

Node Name	Area Name	Total MVA
19044 - ALAOJI 3 330.00	TCN	2185.47
19043 - AFAM IV 3 330.00	TCN	1911.2

19003 - EGBIN 3 330.00	TCN	1474.8
19005 - OLORUNSOGO3 330.00	TCN	1318.4
19025 - GEREGU 330.00	TCN	1201.8
37047 - ABOADZE 161.00	GRIDCO	1166.3
37001 - AKOSOMBO 161.00	GRIDCO	1077
19023 - DELTA IV 3 330.00	TCN	1045.9
19011 - OMOTOSHO3 330.00	TCN	1043.4
39005 - GE 330 330.00	GRIDCO	937.5
39011 - T5 330 330.00	GRIDCO	937.5
39012 - ROTAN 330 330.00	GRIDCO	825
19017 - KAINJI G.S.3330.00	TCN	820
19024 - SAPELE 3 330.00	TCN	803.82
19054 - OBAJANA_3 330.00	TCN	729.45
19016 - JEBBA G.S.3 330.00	TCN	714
19019 - SHIRORO 3 330.00	TCN	708
19048 - CALABAR_PS_3330.00	TCN	706.25
27005 - MARIA GLETA 161.00	CEB	674.5
48002 - VRIDI 225.00	CIE	647.4
19039 - OKPAI 3 330.00	TCN	630
19061 - ONNIE_3 330.00	TCN	617.6
48010 - AZITO 225.00	CIE	595
19027 - EYEAN_3 330.00	TCN	568.9
39008 - GLOBELEC 330330.00	GRIDCO	562.5
37048 - ABOADZE-T3 161.00	GRIDCO	506
48035 - GD-BASSAM 225.00	CIE	461.25
48034 - SONGON 225.00	CIE	461.25
37070 - KTPP 161.00	GRIDCO	450
37060 - BUI 161.00	GRIDCO	443.4
39009 - CHRISPOD 330330.00	GRIDCO	437.52
39004 - JACOBSEN 330330.00	GRIDCO	437.49
19047 - EGBEMA_3 330.00	TCN	423.75

39013 - AYTEPA 330 330.00	GRIDCO	416.67
37011 - NEW TEMA 161.00	GRIDCO	412.61
16160 - OMOKU 1 132.00	TCN	396.5
16003 - EGBIN 1 132.00	TCN	385.62
46002 - VRIDI 90.000	CIE	383.8
16157 - RIVERS_IPP 132.00	TCN	352
37012 - MINES RESERV161.00	GRIDCO	315
39006 - AMANDI 330 330.00	GRIDCO	300
37071 - KARPOWER TM 161.00	GRIDCO	300
16161 - GBARAIN UBIE132.00	TCN	282.5
37061 - KPONE 161.00	GRIDCO	264.7
39010 - ASG 330 330.00	GRIDCO	237.5
16150 - EKET 1 132.00	TCN	236
48003 - TAABO 225.00	CIE	234
48007 - SOUBRE 225.00	CIE	225
37014 - ASOGLI 161.00	GRIDCO	217.74
48009 - BUYO 225.00	CIE	183
37034 - KPONG GS 161.00	GRIDCO	177.76
27017 - LOMEPORT 161.00	CEB	169
16166 - TRAMADI 132.00	TCN	156.25

5.4 Future steps for WAMS deployment

5.4.1 Telecommunication system improvement

The telecommunication system is crucial for the development and effectiveness of WAMS. PMUs, in fact, acquire and send data with quite a high sampling rate (e.g. 50 times per second). This data (measurements, time stamp, and the other status information) is formatted according to the IEEE C37.118 standard and continuously transmitted to a central server.

This requires a very high-reliability, high-performance redundant communication (e.g. dedicated numerical circuits) system and all the rules defined by the IEEE standard must be implemented.

Moreover, all of the data acquired by PMUs must be stored on WAMS servers called Phasor Data Concentrator (PDC). A PDC is responsible for processing and streaming time-series data in real-time, making it available for the applications that use them. The number of PDCs to be installed, their locations and design must be accurately planned, taking into account both needs and performance required by the WAMS system, the number of PMUs installed, the measurements required and the structure of the telecommunication system.

Finally, this huge amount of data must be managed in an efficient way and is entirely reliant on the IT system. In particular, it has to guarantee fast access to real-time data and to the measurements acquired in the near past (few hours). It is worth storing older data, even if it is only required on a less critical basis both in terms of access time and sampling rate. If any alarm management application using PMU data is implemented, it would be appropriate to develop a dedicated storing facility for the events identified by the trigger of alarms in order to allow real-time on line access to them.

5.4.2 WAMS applications implementation

WAMS is a key Smart Grid application because its data provides the basic raw input for a large number of advanced functions regulating network operation and control such as undervoltage load shedding of noncritical loads, contingency-based remedial action schemes, automatic generation tripping, switching of shunt capacitors and system islanding detection.

All of them will be extremely useful but there are further applications that can use PMU data to deliver improved monitoring and control of the transmission network, namely oscillation detection and monitoring, phase angle monitoring, voltage stability monitoring, event detection and management, alarming, backup and integration for SCADA system.

One of the key applications of the wide area synchronized system consists of a real time and off-line identification of oscillatory behaviors. The identification of unstable modes and the knowledge of their damping made it possible to determine the degree of stability of the operating condition. The subsequent analysis of the participation factors of such a condition can suggest the appropriate countermeasures that will need to be implemented.

Among the available techniques for stability monitoring, there are nonparametric, parametric and subspace methods, maximum likelihood estimation. All of them aim at identifying weakly damped oscillatory behaviors, mainly inter-area, with a particular focus on the time at which these dynamics took place and their trend. All these techniques are usually fed by highly informative network quantities, like active power flows or system frequency, where the power spectral density of the electromechanical modes is greatest.

These measures have merits and disadvantages that are often complementary and, for this reason, the use of more than one method not only validates the various improvements, but also helps to better define the information obtained.

A proper implementation of these algorithms will facilitate full monitoring of electromechanical phenomena as well as benefitting the daily system operation activities, by providing thorough and up-to-date measurements for evaluations and improving the knowledge of the system dynamics.

Furthermore, post-event analysis of the results obtained by the application of these techniques, both of single events (contingencies, relevant oscillations, etc.) and of long sequences of events, could help to identify the characterization of the dynamic behavior of the WAPP transmission system and increase awareness of transient stability assessment. Towards this purpose it is worth highlighting the importance of statistical analysis of these results. The study of the distribution of frequency and damping has proven useful with the identification of typical oscillatory modes crossing the different parts of the electrical network and, thus aided in the investigation of the effects of possible different damping values.

Finally, monitoring oscillatory modes, especially inter-area, will be very useful for future interconnections with neighboring countries. In a large interconnected network, inter-area oscillations are frequent and it is important to be prepared to identify and adopt countermeasures against this type of system behavior.

6 BACK-TO-BACK ALTERNATIVE ANALYSIS AT SAKETE SUBSTATION

The objective of the activity is to evaluate the costs and effects on the stability of the system of a back to back 600 MW DC link alternative at the substation of Sakété. The adoption of a back to back DC link will be evaluated considering the frequency and voltage variations and the short circuit power levels on the AC busbars of the back to back converter station. The possibility of an alternative configuration was explored, consisting of a 300MW Back-to-Back DC link expandable to a 2 X 300MW capacity, compared to the 600MW single Back-to-Back HVDC link originally proposed.

The analysis is limited to some of the most significant cases observed in the static and dynamic simulations.

6.1 HVDC station technologies

At present time, two HVDC converter station technologies are available in the market:

- LCC (Line Commutated Converter) stations
- VSC (Voltage Source Converter) stations – the most recent one

Main characteristics of the two technologies are following reported.

6.1.1 LCC technology

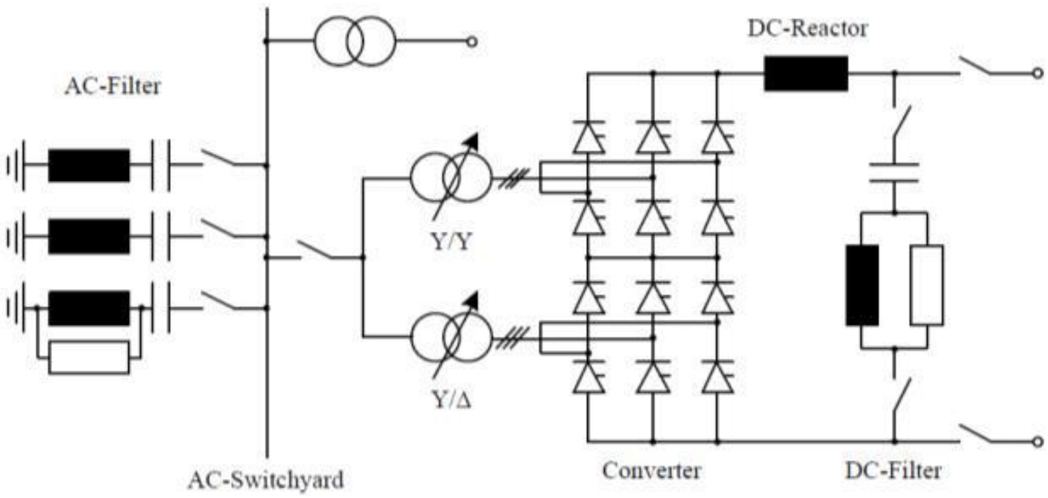


Figure 6.1: Typical LCC-HVDC configuration with a single 12-pulse converter

LCC has a modular design and is based on a block of six-pulse bridges. Usually converter consists of two 6-pulse bridges with a 30° phase shift between them. One bridge connected as a star winding and the second bridge as a delta winding for reduction of AC harmonic currents and DC harmonic voltages. LCC-HVDC converters require a relatively strong synchronous voltage for the process of commutation. Commutation is the change of current flow from one valve to another in a synchronized firing sequence of the thyristor valves during operation. The available short circuit ratio, which is the ratio of three phase AC short circuit capacity to the power rating of the converter, at the connection point should be two or greater for LCC-HVDC. Line commutated converters require reactive power, which has to be provided by additional switched capacitors, filter equipment or other reactive compensation sources. Due to the higher harmonic stress and additional DC voltage component at the secondary winding, special transformers have to be used for an LCC-HVDC converter station. DC smoothing reactors are used to avoid current interruption at minimum load and limit overcurrents during a DC fault [18].

LCC station equipment includes:

- Converter valves (thyristors)
- Converter transformers
- AC filters
- Reactive compensation equipment
- Smoothing reactor
- DC filters
- Controls
- Valve cooling systems

Configurations of LCC HVDC links available include back-to-back ties, bipolar, monopolar and multi terminal systems. Back-to-back HVDC solutions are used for the connection of two asynchronous systems. With back to back converter stations there is no DC transmission line as both converters are located within one converter building. A back-to-back scheme typically consists of two valve groups and a smoothing reactor on the DC side. The HVDC supplier selects the optimum DC voltage and current ratings to give the lowest converter cost. Usually the DC voltage rating will be low and the DC current rating high to make full use of the thyristor current rating [18].

The key characteristic of LCC-HVDC is governed by the attributes of the switching thyristors. The power flow controllability is provided by the control of the firing of the thyristor valves. As a consequence of their basic physical structure thyristor switches can only be switched on but require a zero current in order to switch off. The switching process is responsible for the harmonic distortion and the demand for reactive power dependent on the firing angle. LCC converters can only absorb reactive power. Harmonics and reactive power have to be compensated at the station to prevent negative impacts on the AC transmission system. The AC filters and shunt compensation banks occupy a large area in the switchyard. Black-start capability is not easily available with LCC converters [18].

6.1.2 VSC technology

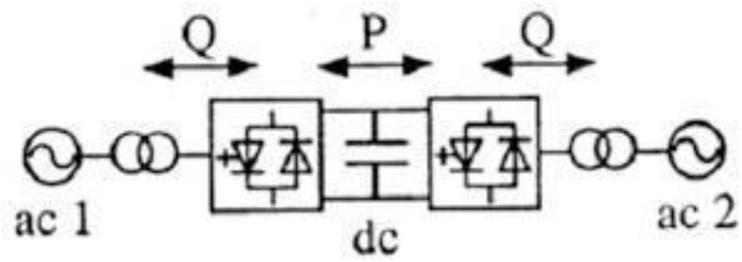


Figure 6.2: Typical VSC-HVDC configuration

Thanks to the introduction of insulated gate bipolar transistor (IGBT) based switching valves in the 1980s a new HVDC technology became feasible. VSCs are also referred to as self-commutated converters. The fundamental difference between the voltage source converter and conventional line commutated technology (LCC) is that VSC uses IGBTs (or equivalent semiconductors), which are able to switch off the current. Hence there is no demand for a synchronous voltage for the commutation process. Moreover VSC has the ability to control the reactive power at both converter stations independent of active power flow and with the only constraint being the maximum apparent power and output voltage, which is limited by the rating of the VSC valves. Thus VSC can be placed anywhere in the AC network without concerns about the available short circuit ratio [18].
VSC-HVDC stations do not require the large amount of reactive compensation and DC filter equipment hence requiring fewer footprints than LCC-HVDC stations.

VSC station equipment includes:

- Converter valves
- Converter transformers
- AC filters
- Converter reactors
- Smoothing capacitor
- Controls
- Cooling system

Different manufacturers of HVDC systems have different technologies. Today, the following technological principles can be differentiated:

- Pulse width modulated (PWM) two level or three level VSC converters which was introduced
- first by ABB in the 1990s. This technology is known under the brand “HVDC Light”
- Multilevel modular converters (MMC-VSC) which has been introduced around 2006 by SIEMENS and is known under the brand “Plus- Technology”
- Hybrid multilevel approach (HML-VSC) which has been announced by Alstom Grid in 2010 to be under development. Technology wise this approach is a combination of the other technologies mentioned above.

- Cascaded two level converters which have been introduced by ABB in 2010 (CTL-VSC). This approach is a further development of the two level resp. three-level PWM-VSC technology which will be marketed under the same brand: “Light-Technology” [18].

The reversal of power is got through the reversal of current polarity and for this reason Extruded cables can be used. Self-commutated converters used for VSC-HVDC are based on IGBT valves that facilitate fast-on and fast-off switching operations. The active and reactive power flow can be continuously controlled independently of each other. PWM VSC-HVDC still generates harmonics caused by the switching process that have to be filtered at the converter station. The level of the harmonics generated by the PWM voltage source converters is only a fraction of that generated by LCC converters and the size and required space for AC filter equipment is reduced significantly. No shunt capacitors or reactors are required. In fact, the VSC-HVDC station may act as static reactive compensation device. VSC-HVDC converters also provide black-start capability and can also supply passive networks. The black-start capability of a VSC depends on the auxiliary power supplies. For a 1000MW scheme, approximately 1MW of auxiliary power is needed for black-start.

The table below summarize the main technological features of VSC and LCC.

Table 6.1: LCC and VSC technology Summary

Subject	LCC	VSC
Maximum voltage level	800 kV DC	≤ 640 kV DC
Maximum power rating	<7500 MW	< 1600 MW
Maximum transmission Distance	Unlimited	Theoretically unlimited (limit of voltage drop/losses)
Footprint [w x l x h]	200 x 120 x 20 m (600 MW): by far larger	120 x 50 x 11 m (550 MW); 48 x 25 x 27 m (500 MW) [w x l x h]
Active power flow control	Continuous, min. 10% load	Fast continuous
Reactive power demand	50% - 60% of converter power rating, compensated by breaker switched AC harmonic filters and reactive power banks	Can provide or consume controlled reactive power as required
AC Voltage control	Slow, transformer tap change	Continuous, full response in < 100 ms
Power Reversal	DC voltage reversal	DC current reversal
Necessary filter equipment	High demand	Low demand (PWM); Not necessary with other topologies
Grid connection requirements	Short Circuit Ratio > 2,5	Can supply power to a passive network
Black start	Not inherently available	Black-start capability and island

		supply (with an auxiliary power system to initially energize the cooling system, e.g. by means of a diesel generator)
Typical Power Losses in one converter station at full load at no load	 ≈0.75% ≈0.1%	 ≈1.1% ≈0.1%

LCC is the most widely adopted technology with many years of service experience but has strong limitations for very quick power flow reversal. VSC technology allows bi-directional flow of power and control of both real and reactive power. VSC converters have already been implemented or in construction for a dozen of projects, for a rated voltage up to +/- 350kV.

There is no theoretical limitation to the voltage level of VSC converter stations and +/- 500kV VSC converter is feasible and available depending to the submarine cable timing constraints.

The factors limiting the current through the VSC converter are current rating of semiconductors and thermal rating of converter components. The voltage limitation mainly comes from the transmission medium (technology of DC circuit). For overhead lines there are almost no limitations for the VSC technology. Here the converter rating limits the voltage level. This is not only due to high voltage equipment ratings but also due to the "computing" power of VSC controller. Each level of modules in all VSC technologies except the PWM-VSC needs a certain amount of computing power in order to generate the switching signals for IGBTs. As of 2012 some commercial projects are listed in Table 6.2.

Table 6.2: Examples of projects in different DC technologies

#	Name	Type	DC Vol-tage	Rated Power	DC-Circuit	Commissioning
1	Caprivi Link	VSC	350 kV	300 MW	OHTL	2009
2	BorWin 1	VSC	± 150 kV	400 MW	Sea Cable	2009
3	Estlink	VSC	± 150 kV	350 MW	Sea Cable	2006
4	Murraylink	VSC	± 150 kV	220 MW	Land Cable	2002
5	Transbay	VSC	± 200 kV	400 MW	Sea Cable	2010
6	Inelfe	VSC	± 320 kV	2 x 1000 MW	Land Cable	2013
7	NorNed	LCC	± 450 kV	700 MW	Sea Cable	2007
8	BritNed	LCC	± 450 kV	1.000 MW	Sea Cable	2011
9	Ballia-Bhiwadi	LCC	± 500 kV	2.500 MW	OHTL	2010
10	Hukunbeir-Liaonin	LCC	± 500 kV	3.000 MW	OHTL	2009
11	Yunnan-Guangdong	LCC	± 800 kV	5.000 MW	OHTL	2010
12	Xiangjiaba-Shanghai	LCC	± 800 kV	6.400 MW	OHTL	2010

6.2 Technical Evaluation

The choice between LCC and VSC is based both on technical and economical evaluation. In order to evaluate the Back-to Back solution the following schemes have been considered:

- 300 MW Monopolar BTB System
- Initial 300 MW Monopolar BTB System with future extension to 600MW Bipolar System
- 600 MW bipolar BTB System

Figure 6.3: Back-to-back HVDC System Scheme

From the technical point of view the main features of both technologies are presented in Table 6.1. The adoption of either VSC or LCC technology is technically preferred depending on the peculiarities of the analyzed power system.

The items reported in the following paragraphs (§6.2.1 and §6.2.2) have to be considered for technical evaluations, while §7.1 provides an economical evaluation of the Back-to-back alternatives.

6.2.1 Effective short circuit ratio

In case of LCC converter shunt capacitors including AC filters connected at the AC terminal of a DC link can significantly increase the effective AC system impedance. As a measure of the strength of the AC system, it is used the index called **Effective Short Circuit Ratio (ESCR)** defined as follows:

$$ESCR = \frac{S_{scr} - Q_c}{P_{DC}}$$

Where:

- S_{scr} is the AC system three phase symmetrical short circuit level in MVA at the converter terminal AC bus.
- P_{DC} is the rated DC terminal power in MW.
- Q_c is the value of three phase fundamental MVAr of shunt capacitors connected to the converter AC busbars (AC filters and plain shunt banks).

For the evaluation of the ESCR the values of three-phase short circuit power at 330 kV Saketé station (where the BtB should be installed) have been estimated. In Table 6.3 the minimum value contingency and the "base case" for peak and off-peak 2016 scenarios are reported. The minimum S_{SCR} for the ESCR calculation should be the one in the contingency and off-peak scenario.

Table 6.3: Short Circuit Power level at Saketé Station

Contingency	Scc [MVA] Off-peak	Scc [MVA] Peak
Base Case	4017.1	4187.2
LINE 19004-19011-1 [IKEJA W 3 330.00 - OMOTOSHO3 330.00]	3722.9	3893.0

The Q_C is estimated at around half of the rated DC terminal Power (e.g: 300 MVAr for 600MW of transfer capacity).

The ESCR calculated values are reported in the table below:

Table 6.4: ESCR Calculated Values

ESCR		
Pdc (MW)	300	600
Sscr (MVA)	3723	3723
Qc (MVAr)	150	300
ESCR	**11.9**	**5.7**

The available short circuit ratio at the connection point should be two or greater for LCC-HVDC. The ESCR Values are far greater than 2.5 in both 300MW and 600MW schemes thus allowing the adoption of the LCC solutions.

6.2.2 Summary of Technical Evaluation

In Table 6.5 are presented the main control functionalities supported by each HVDC technology and in Table 6.6 a summary of the related technical consideration is reported.

Table 6.5: Technology dependent inherent functionality

	HVAC w/o FACTS	HVAC with FACTS	LCC-HVDC	VSC-HVDC
Fast active power flow control	-	Available	Available	Fast control
Fast reactive power flow control	-	Available	-	Fast control
Transient stability improvement	Inherent	Available	Available	Available
Damping Control	-	Available	Active Power Modulation	Active and reactive power control
Black-start / island supply	-		-	Full support
System loss reduction	-	Depending on situation by means of reactive power control	-	Depending on situation by means of reactive power control

Table 6.6: Summary of Technical Evaluation

Feature	Technical Preferred Solution
Grid connection requirements	Both
Active power flow control	VSC
Reactive power demand	VSC
AC Voltage control	Both
Power Reversal	VSC
Black start	VSC
Typical Power Losses in the converter stations	LCC

7 DEFINITION OF THE NECESSARY REINFORCEMENTS AND COST ESTIMATION

A list of measures was proposed to allow a synchronous operation and enhance the stability of the WAPP system. In order to prioritize them for achieving a reliable operation of the WAPP interconnected power system, a cost evaluation of the different solutions has been performed.

7.1 Economical Evaluation of the back-to-back at Sakété substation

On the basis of information gathered from previous studies, technical brochure and converter station manufacturers, an economic evaluation of the investment needed for the two available technical solutions has been performed.

The investment evaluation has been made considering different sources in order to reduce the estimate error but it shall be underlined that each HVDC scheme is unique and caution is needed when utilizing the turnkey cost declared in such surveys. In view of market volatility, the estimates should be treated as having accuracy no better than ±20%. These costs can be used to explore development options but confirmatory figures obviously need to be obtained from manufacturers. Here below the main information sources are reported.

Table 7.1: Costs of Converter Stations obtained by JWG-B2.B4.C1.17 from manufacturers FOB (2007) [19][20]

Bipolar Rating MW	kV	Technology	Suggested Cost (MUSD)	Project Management and Engineering	Commissioning
750	±300	VSC	165	24 Months	6 Months
750	±300	LCC 6 pulse	155	24 Months	6 Months
750	±300	LCC 12 pulse	165	24 Months	6 Months

Table 7.2: Investment Cost of Station USD Million (492 CIGRE' VSC- HVDC for Power Transmission 2012) [18]

Rating	HVAC	LCC-HVDC	VSC-HVDC
500 MW	21	51	65
1000 MW	36	115	141
1500 MW	51	154	196

Table 7.3: BTB system investment cost (CESI Study 2015)

Equipment	Unit Cost	
VSC BTB 1100MW	300000	US$(000s)
VSC BTB 600MW	200000	US$(000s)
VSC BTB 400MW	145000	US$(000s)
VSC BTB 150MW	75000	US$(000s)

Table 7.4: Cost of VSC Converter Station (Electricity Ten Year Statement 2015 – National Grid) [22]

Specifications	Cost (£M)	Avg(£M)	MUSD
VSC 800MW–320kV	84–94	90	140
VSC 1000MW–320kV	110–125	117,5	182
VSC 1200MW–320kV	157–166	162	251
VSC 1800MW–500kV	175–185	180	279

Table 7.5: BTB system investment cost (CESI Study 2016)

Equipment	Unit Cost	
VSC 300MW+-345kV	96.681	US$(000s)
VSC 600MW+-345kV	144.300	US$(000s)
LCC 300MW+-345kV	74.370	US$(000s)
LCC 600MW+-345kV	111.000	US$(000s)

As regards the back-to-back HVDC, the total costs should be slightly reduced compared to a classic DC link because of some characteristics typical of the B2B, such as:

- Reduced filters at DC side (for example, there is only one smoothing inductance instead of two)
- Less amount of devices on the DC side
- Less space is required for the construction of the stations compared to two converter stations of a typical HVDC
- The voltage adopted at DC side is lower in respect to a normal DC link because there is not the need to increase it for reducing losses

This last point implies to adopt an higher current and, for this reason, the B2B DC link are generally built in a modular way, adding modules for increasing the power of the DC link. On the basis of that, it is possible to have a cost saving compared to the classic DC link in the range of 10-20%, even though this cost saving tends to decrease when increasing the rated power of the B2B, due to the logic of the modularity adopted in the construction. Nevertheless, today there are not experiences of B2B with power higher than 2 GW. In conclusion, as an estimation of the B2B capital costs, it is possible to consider a unit price of a B2B converter station in the range of 80%-90% of a "classic" converter station. Due to the fact that there is little exact information on already commissioned projects the specific VSC-HVDC converter costs are taken from specific studies performed by CESI relevant to the implementation of BTB VSC projects.

Table 7.6: Breakdown of VSC BTB components costs (CESI Study 2016)

Components	%
Valve Group	33
Converter Transformer	14
DC Switchyard	2
AC Switchyard and filter	6
Control, protection, communication	8
Civil, mechanics, works	16
Auxiliary Power	5
Project engineering, administration	16
Total	**100**

From the elaboration of the different sources a BTB cost equation has been estimated for VSC option and the results are reported in the graph below.

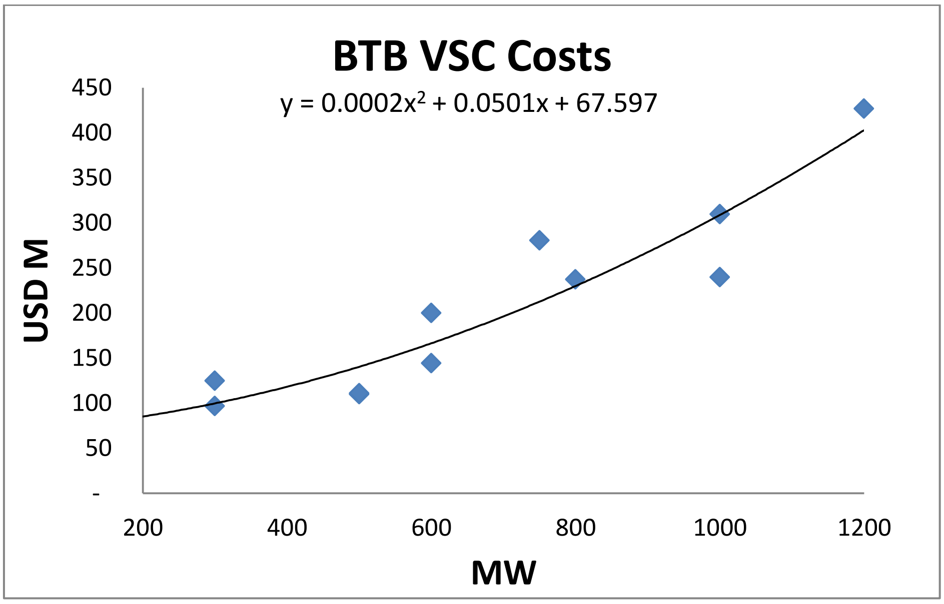


Figure 7.1: BTB VSC costs as a function of Transfer Capacity (MW)

Three different investment options have then been evaluated:

- 300 MW VSC BTB: through the BTB cost Equation
- 600 MW VSC BTB: through the BTB cost Equation
- Initial 300 MW VSC BTB with future extension to 600 MW VSC BTB: starting from the initial cost of a 300 MW VSC BTB solutions the costs have been estimated considering the impact on the different components of this option.

Table 7.7: VSC BTB Cost Equation Investment Estimate

	300 MW VSC BTB	600 MW VSC BTB
Cost MUSD	101	170

In order to evaluate the third option, relevant to the 300 MW VSC BTB upgradable to 600 MW, some specific factors have been considered. The cost of the first step is slightly higher than the 300 MW option considered in a stand-alone way due to the fact that some components are designed to be upgraded to the 600 MW scheme.

Table 7.8: VSC BTB Investment Estimate Summary

Components	%	300 MW VSC BTB Stand Alone	Cost Increase per component	300 MW VSC BTB Upgradable	Upgrade to 600 MW	600 MW VSC BTB Upgraded	600 MW VSC BTB Stand Alone
Valve Group	33	33		28	28	56	56
Converter Transformer	14	14		12	12	24	24
DC Connection Equipment	2	2		1	1	3	3
AC Switchyard and filter	6	6		5	5	11	11
Control, protection, communication	8	8	82%	15	5	16	14
Civil, mechanics, works	16	16	42%	23	17	33	28
Auxiliary Power	5	5	24%	6	3	8	8
Project engineering, administration	16	16	94%	31	5	31	27
Total	**100**	**101**		**121**	**76**	**182**	**170**

Table 7.9: VSC BTB Estimated time to commissioning

		300 MW VSC BTB Stand Alone		300 MW VSC BTB Upgradable	Upgrade to 600 MW		600 MW VSC BTB Stand Alone
Time to commisioning		30 Months		30 Months	10 Months		30 Months

As regards the LCC-HVDC several technical brochure have been considered in order to evaluate the turnkey cost breakdown in the different components:

Table 7.10: Breakdown of LCC BTB components costs (HVDC Transmission 2009)

Components	%
Valve Group	19
Converter Transformer	22,5
DC Switchyard and filter	3
AC Switchyard and filter	11
Control, protection, communication	8,5
Civil, mechanics, works	13
Auxiliary Power	2
Project engineering, administration	21
Total	100

From the elaboration of the different sources a BTB cost equation has been estimated also for the LCC option and the results are reported in the graph below.

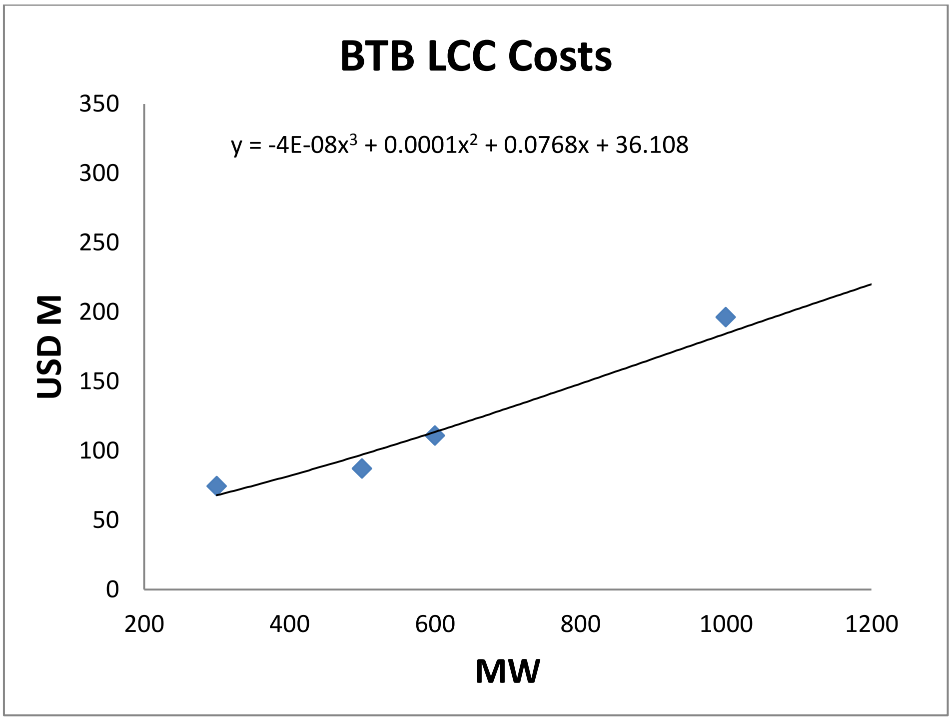


Figure 7.2: BTB LCC costs as a function of Transfer Capacity (MW)

Three different investment options have been evaluated:

- 300 MW LCC BTB: through the BTB cost Equation
- 600 MW LCC BTB: through the BTB cost Equation
- Initial 300 MW LCC BTB with future extension to 600 MW LCC BTB: Starting from the initial cost of a 300 MW LCC BTB solutions the costs have been estimated considering the impact on the different components of this option

Table 7.11: LCC BTB Cost Equation Investment Estimate

Cost MUSD	300 MW LCC BTB	600 MW LCC BTB
Cost MUSD	**67**	**110**

In order to evaluate the third option relevant to the 300 MW LCC BTB upgradable to 600 MW, some specific factors have been considered. The cost of the first step is slightly higher than the 300 MW option considered in a stand-alone way due to the fact that some components are designed to be upgraded to the 600 MW scheme.

Table 7.12: LCC BTB Investment Estimate Summary

Components	%	300 MW LCC BTB Stand Alone	Cost Increase per component	300 MW LCC BTB Upgradable	Upgrade to 600 MW	600 MW LCC BTB Upgraded	600 MW LCC BTB Stand Alone
Valve Group	19	13		10	10	21	21
Converter Transformer	23	15		12	12	25	25
DC Connection Equipment	3	2		2	2	3	3
AC Switchyard and filter	11	7		6	6	12	12
Control, protection, communication	9	6	76%	10	3	11	9
Civil, mechanics, works	13	9	37%	12	9	17	14
Auxiliary Power	2	1	20%	2	1	2	2
Project engineering, administration	21	14	88%	26	4	26	23
Total	**100**	**67**		**80**	**47**	**118**	**110**

Table 7.13: LCC BTB Estimated time to commissioning

		300 MW LCC BTB Stand Alone		300 MW LCC BTB Upgradable	Upgrade to 600 MW		600 MW LCC BTB Stand Alone
Time to commisioning		24 Months		24 Months	10 Months		24 Months

7.1.1 Final investment Evaluation

A summary of the achieved economic estimates is reported in the following Table 7.14.

Table 7.14: LCC vs VSC Investment Comparison

BTB Investment (MUSD)	300 MW	300 MW Up-gradable	600 MW	600 MW Up-graded
VSC Solution	**101**	**121**	**170**	**182**
LCC Solution	**67**	**80**	**110**	**118**

7.2 Economic evaluation of reactive compensations

From the technical studies the following network reinforcement have been selected:

- SVC (controllable reactive shunt compensation).
- Line Shunt and Series (fixed) Compensation.
- Fixed shunt compensation in substation.

An economic cost estimate has been performed considering different sources.

7.2.1 SVC: Static Var Compensator

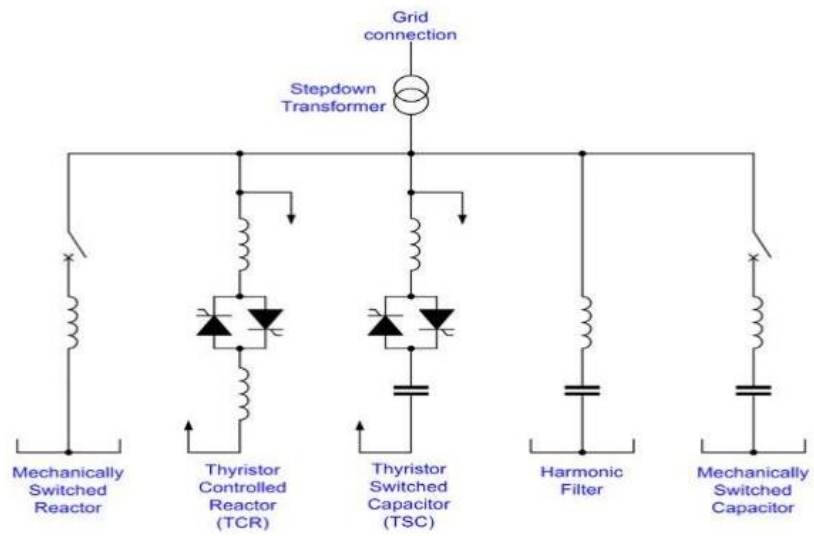


Figure 7.3: Example of SVC Configuration

The SVC is part of the flexible AC transmission system (FACTS) and is designed to preserve voltage stability by rapidly supplying reactive power to support the voltage during the transient period. SVCs also provide power oscillation damping where instabilities could arise between different parts of a power system. The SVC function provides variable inductive and capacitive reactive power using a combination of thyristor controlled reactors (TCR), thyristor switched reactors (TSR) and thyristor switched capacitors (TSC). These are connected to the AC network using a compensator transformer or via the transformer tertiary winding.

An SVC can provide a fast, continuously variable reactive power response using the TCRs, with the coarser reactive control provided by the TSRs and TSCs. The reactive power MVAr output of the SVC may be controlled directly or be configured to automatically control the voltage by changing its MVAr output accordingly. As the SVC uses AC components to provide reactive power, the MVAr production reduces in proportion to the square of the voltage.

Given the specific features of the Static Var Compensator, the economic evaluation has been based on several sources in order to achieve a reliable estimate, considering literature brochures or papers that usually specify a cost out of MVAr reactive power provided by the SVC. A second source of information comes from the budget of specific recent projects that tends to confirm the figures that can be found in literature. The main sources are reported below.

Table 7.15: SVC Costs Trend (JRC ETRI 2014) [21]

		2013	2020	2030	2040	2050
CAPEX ref	€2013/kVAr	39	35	32	28	26
CAPEX low	€2013/kVAr	39	37	35	33	32
CAPEX high	€2013/kVAr	39	33	29	25	21

Table 7.16: Cost comparison of various facts device (IJSRP - 2013)

	FACTS Device	Cost (Rs/kVAr)	Cost [7](USD/kVAr)	
1.	SVC	2160	48	controlled portions
2.	TCSC	2160	48	controlled portions
3.	STATCOM	2700	60	
4.	UPFC Series Portions	2700	60	Through power

[7] All cost converted in USD Currency using the average exchange rate of the publication year of the source reference

5.	UPFC Shunt Portions	2700	60	controlled portions

Table 7.17: Investment cost ranges for FACTS (ERSE, JRC - 2010) [26]

	FACTS Device	Cost (kEUR/MVAr) Min	Cost (kEUR/MVAr)Max	Average Cost (USD/kVAr)
1.	SSSC	50	80	72
2.	SVC	30	50	44
3.	TCSC	35	50	47
4.	STATCOM	50	75	69
5.	UPFC	90	130	122

Table 7.18: SVC Cost (Exponent Report - 2016) [25]

FACTS Device	Cost (kUSD/MVAR) Min	Cost (kUSD/MVAR) Max
SVC	40	60

Table 7.19: SVC Cost Pakistan transmission Project (ADB - 2012) [24]

2012 ADB Pakistan: Power Transmission Enhancement Investment Program	MUSD	Cost (kUSD/MVAr)
SVC 220kV -150+450 MVAR	27.4	46

Table 7.20: SVC Cost New Mexico Project (Cargill Power Markets – 2014) [23]

2014 Static VAR compensator ("SVC") at Guadalupe Station (New Mexico)	MUSD	Cost (kUSD/MVAr)
SVC 345 kV Station +175-75	21.5	86

From the analysis of the different sources the final economic estimate for the SVC is shown in the table below.

Table 7.21: SVC Economic Estimate

FACTS Device	Cost (kUSD/MVAr)
SVC	50

The final cost for the implementation of the SVC solution refers to countries with low labor costs. Additional infrastructure costs in the range of 50% should be considered when installation is foreseen in mountains or densely populated areas. For hilly conditions this increase should be in the range of 20%. In view of market volatility, the estimates should be treated as having accuracy no better than ±20%. These costs can be used to explore development options but confirmatory figures obviously need to be obtained from manufacturers.

From the technical studies performed the implementation of the following SVC has been settled.

- Dosso 132 kV (country: Niger, Utility: NIGELEC): 20 MVAR (+/-).
- Gazaoua 132 kV (country: Niger, Utility: NIGELEC): 20 MVAR (+/-).
- Dagana 225 kV (country: Senegal, Utility: SOGEM): 30 MVAR (+/-).

The economic evaluation considers that the three SVCs will be located in hilly areas with a cost increase in the range of 20% respect to the SVC Economic Estimate reported in Table 7.21[8].

Table 7.22: SVC Investments Estimate

SVC	Estimated Investment (MUSD)
Niger: Dosso SVC 20 MVAR (+/-)	2.4
Niger: Gazaoua SVC 20 MVAR (+/-)	2.4
Senegal: Dagana SVC 30 MVAR (+/-)	3.6

7.2.2 Shunt and Series Compensation

Following is reported a cost estimation for fixed shunt and series reactive compensations.

[8] According to our knowledge of the SVCs future sites. Additional infrastructure costs shall be considered in case of worst conditions such as mountain or densely populated areas.

7.2.2.1 Shunt Reactors

Shunt reactors are used to compensate for the capacitive reactive power in AC transmission networks, regulating the network voltage. Reactors have either an air core or gapped iron core design. Iron core reactors are commonly immersed in a tank of oil with a similar construction to power transformers, but the gapped iron core makes it harder for a higher magnetizing current to flow. Air core reactors (ACR) are larger but simpler than iron core reactors, and need less maintenance. As they do not have non-linear iron cores, they are not subject to core saturation effects. Shunt reactors may be connected to tertiary windings on power transformers or connected to the HV busbar via switchgear for operational switching and protection. Generally, ACRs are cheaper but larger, so where space is limited and high ratings are required, oil immersed units dominate. ACRs are commonly available up to 72kV and 100MVAr. Higher voltages and ratings are possible but generally regarded as special designs. Oil immersed iron core reactors are available up to 800kV and 250MVAr. The following sources have been evaluated in order to consider the cost of Shunt Reactor technology.

Table 7.23: Bus Reactor Investment Cost (National Grid 2014) [28]

2014 National Grid: North West Coast Connections	MUSD	Cost (kUSD/MVar)
400kV -200 MVAr Standard Shunt Reactor	5.5	28

Table 7.24: Shunt Reactors Cost (Electricity Ten Year Statement 2015 – National Grid) [22]

Shunt Reactors	Cost (£M)	Avg(£M)	MUSD	Cost (kUSD/MVar)
60MVAr–33kV	1.0–1.3	1.15	1.78	30
100MVAr–220kV	3.8–4.1	3.9	6.05	60
200MVAr–400kV	4.0–4.3	4.15	6.43	32

Table 7.25: Shunt Reactors Cost WB Turkey Project 2015 [29]

2015 WB Turkey: Renewable Energy Integration	MUSD	Cost (kUSD/MVar)
Four 170kV 24.43 MVAr Shunt Reactors (97,72 MVAr)	1.6	16
Four 420kV, 146.59 MVAr Shunt Reactors (586.36 MVAr)	4.18	7

The available sources are mainly related to developed OECD-countries such as the United Kingdom, while some other information have been gathered from multilateral development bank financed project. Taking into account the voltage level of 330 kV and, a low labour cost country for the implementation of the specific project compared to the UK, a cost in kUSD per MVAr which as an average of the different sources has been considered:

Table 7.26: Shunt Reactor Economic Estimate

Component	Cost (kUSD/MVAr)
Shunt Reactor	20

7.2.2.2 Series Compensation

Series compensation (SC) is widely used in many transmission systems around the world, typically in long transmission lines where increased power flow, increased system stability or power oscillation damping is required. Sometimes, series compensation can be an alternative to building new or additional transmission lines, but before it is installed, network complexities must be analyzed and mitigated. SC operates at system voltage, in series with the existing transmission lines; so to provide an economic solution, the equipment is installed on insulated platforms above ground. In a transmission system, the maximum active power that can be transferred over a power line is inversely proportional to the series reactance of the line. So by compensating the series reactance using a series capacitor, the circuit appears to be electrically shorter than it really is and a higher active power transfer can be achieved. Since the series capacitor is self-regulated – which means that its output is directly (without control) proportional to the line current itself – it will also partly balance the voltage drop caused by the transfer reactance. Consequently, the voltage stability of the transmission system is raised.

The following sources have been evaluated in order to consider the cost of Series compensation technology.

Table 7.27: Line Capacitor Investment Cost (CESI Study 2016)

Equipment	Unit Cost		Cost (kUSD/MVar)
line capacitor 300 Mvar	5000	US$(000s)	17

Table 7.28: Line Capacitor Investment Cost (CESI Study 2014)

Equipment	Unit Cost		Cost (kUSD/MVar)
33 kV Capacitor 4 x 10 MVAR	600	US$(000s)	15

Table 7.29: Series Compensation Cost (Electricity Ten Year Statement 2015 – National Grid) [22]

Series Compensation	Cost (£M)	Avg(£M)	MUSD	Cost (kUSD/MVar)
400MVA - 400 kV	4.0-5.3	4.7	7.29	18

The information sources available are mainly related to developed and OECD- countries such as the United Kingdom. Taking into account a low labour cost country for the implementation of the specific project compared to the UK, a cost in kUSD per MVAr which is lower compared to the evaluated sources has been considered:

Table 7.30: Series Capacitor Economic Estimate

Component	Cost (kUSD/MVAr)
Series Capacitor	**12**

7.2.2.3 Economic Evaluation of 2020 Grid Reinforcements

According to the technical studies performed the implementation of the reinforcement reported in Table 3.15 has been settled for 2020. The correspondent cost estimation is reported in the following Tables.

Table 7.31: Goroubanda – Ouaga Est 330 kV Reinforcement costs[9]

Component	Cost (kUSD/MVAr)	MVAr	Cost (MUSD)
Shunt Reactors	20	50	1.0
Series Capacitor	12	265	3.2
Line Ends	2		
Total			8.4

Table 7.32: Goroubanda – Salkadamna 330 kV Reinforcement costs [9]

Component	Cost (kUSD/MVAr)	MVAr	Cost (MUSD)
Shunt Reactors	20	50	1.0
Series Capacitor	12	239	2.9
Line Ends	2		
Total			7.7

Table 7.33: Goroubanda – Zabori 330 kV Reinforcement costs [9]

Component	Cost (kUSD/MVAr)	MVAr	Cost (MUSD)
Shunt Reactors	20	20	0.4
Line Ends	2		
Total			**0.8**

Table 7.34: Salkadamna Substation Reinforcement costs

Component	Cost (kUSD/MVAr)	MVAr	Cost (MUSD)
Shunt Reactors	20	40	0.8

[9] A single-circuit line has been considered in the economic estimates. The cost shall be doubled in case of double circuit line.

Table 7.35: Goroubanda Substation Reinforcement costs

Component	Cost (kUSD/MVAr)	MVAr	Cost (MUSD)
Shunt Reactors	20	50	1.0

Table 7.36: Zabori Substation Reinforcement costs

Component	Cost (kUSD/MVAr)	MVAr	Cost (MUSD)
Shunt Reactors	20	70	1.4

Table 7.37: Ouaga Est Substation Reinforcement costs

Component	Cost (kUSD/MVAr)	MVAr	Cost (MUSD)
Shunt Reactors	20	20	0.4

Table 7.38: Malanville Substation Reinforcement costs

Component	Cost (kUSD/MVAr)	MVAr	Cost (MUSD)
Shunt Reactors	20	20	0.4

The overall estimated cost for 2020 reinforcements is reported in Table 7.39. In view of market volatility, the estimates should be treated as having accuracy no better than ±20%. These costs can be used to explore development options but confirmatory figures obviously need to be obtained from manufacturers.

Table 7.39: Overall Reinforcement Costs (2020)

Component	Cost (kUSD/MVAr)	MVAr	Cost (MUSD)
Shunt Reactors	20	440	8.8
Series Capacitor	12	1.008	12.1
Total			**20.9**

7.3 Economic considerations on PSS

Among the recommended reinforcements the installation or tuning of Power System Stabilizers in some relevant units was proposed.

In case of units not equipped with PSS the following alternatives with increasing costs can be implemented:

- Software update of the exciter (in case of digital exciter).
- Hardware update (in case of exciter furnished with additional channels).
- Installation of a new exciter (in case of exciter without possible upgrades).

In case of units already equipped with PSS and after the installation of new PSS an optimal tuning of the PSS parameters, aimed at damping the local oscillations, shall be performed through the following activities:

- Calculation of the optimal parameters with dedicated simulation tools.
- On-field tuning and test of the PSS (estimated 1 day on-site with the possibility to have access and to take the control of the excitation system).

According to the abovementioned considerations a cost estimation of the recommended measures on PSS is extremely dependent on the specific characteristics of the excitation system of the generating unit to be upgraded.

7.4 Economic considerations on protections

Among the recommended reinforcements the installation of Protections or Special Protection Schemes in some critical substations was proposed.

The following alternatives, with increasing costs, are possible:

- Software updates (in case of digital protections already installed).
- Hardware updates (in case of protections to be installed in a single substation).
- Hardware updates and telecommunication system (in case of protections to be installed in different substations).

Furthermore, in addition to the pure cost of equipment (relay, control system, communication system, etc.) a significant share of the total costs may be allocated to the installation, which costs are dependent on the specific characteristics of the system (e.g. if a new panel has to be installed, if enough space for the panel is available, if spare CT/VT terminals are available, etc.).

According to the abovementioned considerations a cost estimation of the recommended measures on protections is extremely dependent on the specific characteristics of the system interested by the upgrades.

7.5 Summary of estimated Investments

Following tables (Table 7.40 and Table 7.41) summarized the estimated total investments (excluded the back-to-back at Sakété) identified with the analyses on both the 2016 and 2020 scenarios. The estimation is based on preliminary assumptions and should be refined through a more detailed information collection during the bidding process.

Table 7.40: Estimated Investments

Output from study	Equipment	Type	Estimated Investment (MUSD)
2016 static	Niger: Dosso SVC ±20 MVAR	SVC	2.4
	Niger: Gazaoua SVC ±20 MVAR	SVC	2.4
	Senegal: Matam SVC ±30 MVAR	SVC	3.6
2016 dynamic	Overall interconnection	PSS	0.5
2016 dynamic	Overall interconnection	SPS	0.35
2016 dynamic	Overall interconnection	PMU	1.6
2020 static	Goroubanda – Ouaga Est 330 kV	Shunt reactors, Series capacitor, Line ends	8.4
	Goroubanda – Salkadamna 330 kV	Shunt reactors, Series capacitor, Line ends	7.7
	Goroubanda – Zabori 330	Shunt reactors, Line ends	0.8
	Salkadamna Substation	Shunt reactors	0.8
	Goroubanda Substation	Shunt reactors	1
	Zabori Substation	Shunt reactors	1.4
	Ouaga Est Substation	Shunt reactors	0.4
	Malanville Substation	Shunt reactors	0.4
2020 dynamic	Overall interconnection	SPS	0.2
2020 dynamic	Overall interconnection	PMU	1.3
Total			**33**
Range			**[27-40]**

Table 7.41: **Investments per country**

Country	Utility	Investments 2016 (MUSD)	Investments 2020 (MUSD)
Nigeria	TCN	1.24	0.56
Niger	NIGELEC	4.80	16.0
Togo/Benin	CEB	0.02	0.4
Ghana	GRIDCo	0.41	0.265
Cote d'Ivoire	CIE	0.41	0.175
Burkina Faso	SONABEL	0.035	6.64
Mali	EDM-SA/SOGEM	0.14	0.05
Senegal	SENELEC/SOGEM/OMVG	3.73	0.078
Guinea	EDG/CLSG/OMVG	-	0.048
Liberia	LEC/CLSG	-	0.011
Sierra Leone	NPA/CLSG	-	0.021
Guinea Bissau	EAGB/OMVG	-	0.005
Gambia	NAWEC/OMVG	-	0.005
Total		10.8	**22.36**

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9 ANNEXES

[A1] Annex 1, WAPP Network Model in PSSE format, 2016 Scenarios

[A2] Annex 2, WAPP Network Model in PSSE format, 2020 Scenarios

[A3] Annex 3, Contingency analysis results, 2016 Scenarios

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