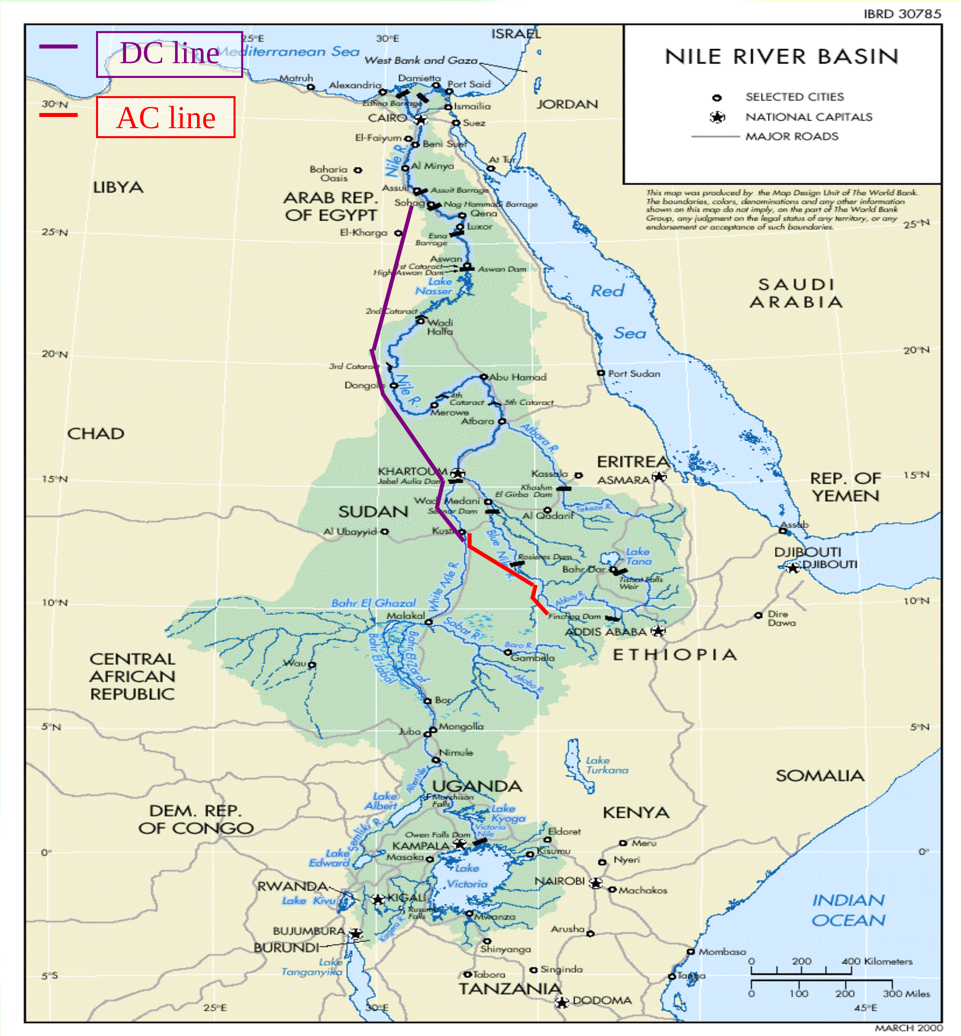
Publication Number
ENPT 002 2009

Nile Basin Initiative
Eastern Nile Subsidiary Action Program
Eastern Nile Technical Regional Office

FINAL REPORT

EASTERN NILE POWER TRADE PROJECT

VOLUME 2: POWER STUDY APPENDIXES



EDF

Scott Wilson

EPS Electrical Power Systems Engineering Company

Nile Basin Initiative

Eastern Nile Subsidiary Action Program

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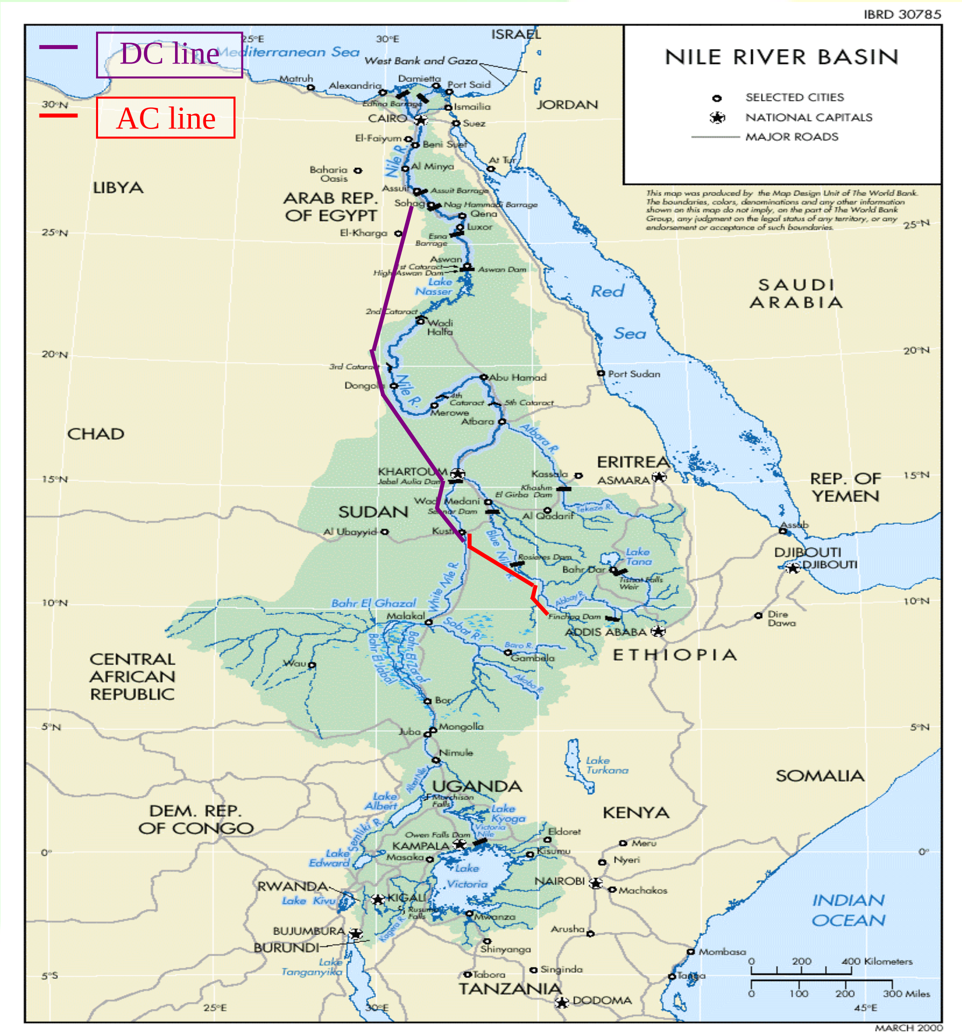
EASTERN NILE POWER TRADE PROGRAM STUDY



EXECUTIVE SUMMARY

EASTERN NILE POWER TRADE PROGRAM STUDY

EXECUTIVE SUMMARY

The Eastern Nile Power Trade Program Study is fully funded by the African Development Bank with the general **objective of promoting regional power trade between Egypt, Ethiopia and Sudan** through creation of an enabling environment, coordinated regional investment planning of power generation and transmission interconnection projects.

The **Eastern Nile Power Trade Program Study** is divided in 2 phases:

- Phase 1: **Cooperative Regional Assessment of Power Trade Opportunities** between Ethiopia, Egypt and Sudan
- Phase 2: **Feasibility Study of the Power Interconnection** between Egypt, Ethiopia and Sudan to export, from Ethiopia, 2 000 MW to Egypt and 1 200 MW to Sudan.

In phase 2, two implementation scenarios have been analyzed :

- Commissioning a 700 MW capacity interconnection Ethiopia-Sudan in 2015 then commissioning the whole Egypt-Ethiopia-Sudan interconnection after Mandaya commissioned in 2020 (with anticipation)
- Commissioning the whole interconnection in 2020 (without anticipation)

The **Phase 1** concluded on the **economic profitability** of the Egypt-Ethiopia-Sudan power interconnection. The project is characterized by good business indicators, as a short payback period and a high benefit to cost ratio under a wide range of hypothesis.

The **Phase 2** concludes on **technical, environmental and financial feasibility**, according the development of a strong institutional framework allowing the building and the operation of this regional interconnection in a progressive way.

<u>Key Contributors</u>

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Technical Specifications :
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- Egypt : EPS, SPEEDOTRANS
- Ethiopia : TROPICS
- Sudan : YAM CdC

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Project Manager

Economic results

Investment costs are estimated about **1 860 MSD_{2006}** , O&M costs are about **18 MSD_{2006} per year** and revamping costs about **230 MSD_{2006}** Social mitigation costs are about **16 MSD_{2006}** .

Net present value (NPV) of the project is positive for both demand scenarios: **1 810 MSD_{2006}** for medium Ethiopian demand and **2 210 MSD_{2006}** for low Ethiopian demand, 10% discount rate, medium fuel price projection. About 160 MUD to 320 MUSD must be added to NPVs from CO_2 savings, if this project is eligible to Clean Development Mechanism.

The **payback period** is reached after **8 full years** of operation for low Ethiopian demand and **7 full years** for medium Ethiopian demand.

The Benefit to Cost Ratio (**BCR**) of the both scenarios are **above 3** for a 10% discount rate, and remains superior to 2 for 8% and 12% discount rates.

Both scenarios have high Economic Internal Rate of Return (EIRR), **respectively 18% and 17%**.

The **sensitivity analysis** executed for a low Ethiopian demand including updated fuel prices projection, shows that the variant with anticipation is even more profitable, with a BCR of 4.9. High fuel prices assumption enhances the interest of the Eastern Nile Regional Power Interconnection project, with a BCR as high as 8.1.

Financial results

With anticipation, assuming a quinquennial tariff mode, a public financing and corporate income tax exoneration, the optimal transmission tariff, ensuring its viability, is **USD_{2006} 7.6 / MWh excluding tax** (equivalent to USD_{2010} 10.6 / MWh)

The variant **without anticipation** is less attractive, requiring a 13% higher average transmission tariff. Under a technical scenario without anticipation, the tariff is **USD_{2006} 8.6 / MWh** excluding tax (equivalent to USD_{2010} 12.0 / MWh).

Transmission tariff is highly sensitive to the proportion of private financing in the financing plan. The average tariff would double under a private financing scheme **USD_{2006} 15.2 /MWh excluding tax** (equivalent to USD_{2010} 21.2 / MWh) compared with the base public financing scheme. The financing strategy will therefore have to focus on raising the large amount of public resources, marketing the project to development aid partners in order to negotiate optimal concessional terms for long-term loans.

Regarding hydrologic risk mitigation, it is recommended to set tariffs for the first 10 years at a level around 5% higher than the equilibrium for the base hydrology scenario, at around USD_{2006} 8.0 / MWh (equivalent to USD_{2010}11.1 / MWh).

Regarding sensitivity on financing plan, the financial and tariff modeling shows that the financing strategy will have to take into account both long-term optimization and the capacity for the stakeholders' states to raise fund from public budget.

Regarding loan negotiation with lenders, the strategy will also have to conciliate long-term optimization and the maximum admissible transmission tariff during the debt service period.

The introduction of a 30% corporate income tax has a limited impact under public financing (+ 2% on average tariffs) but a stronger impact under a private financing (+25%) as profit have to be generated, and therefore taxed, to pay out shareholders. Nevertheless, the decision to exempt the Project Company from corporate income tax or not shall depend of an economic “arbitrage” between the additional cost of electricity transmission and the revenue generated by this taxation.

Institutional Recommendations

A global institutional scheme emphasizing the **necessity of a collaborative approach**, mixing multilateral agreements and multilateral institutions, is proposed so as to finance, build, own and operate the Egypt-Sudan-Ethiopian power interconnection.

A suitable model turns out to be a scheme carried out by transnational entity distinct from national Transmission System Operators.

A **convention binding the three EN Countries** is proposed **to set-up a project structure**, in charge of implementing a **Project Company** and of running the **financing project**. The project structure will refine finance, build and operate schemes, in the objective to minimize risks and therefore, costs.

In addition, a multinational **Interconnection Regulator** shall guarantee a continuous control of the development, scrutinizing the compliance with future transparent and non-discriminatory rules.

According a Convention signed in 2009, the financing closure could happen by 2011, making the challenging anticipation scenario possible.

Social and Environmental impacts

This environmental and social impact assessment of the project-affected areas in the three EN Countries reveals no significant issue because the line route has been designed to avoid populated areas. It has also been optimized to avoid sensitive zones such historical & archeological sites, wildlife reserves, large crop areas, existing overhead line crossing.

A **16 MUSD$_{2006}$** environmental and social mitigation measure plan has been estimated to mainly compensate crop and fruit trees in Ethiopia and Sudan and to enforce community gains in Egypt. This budget represents less than **1%** of the total project budget.

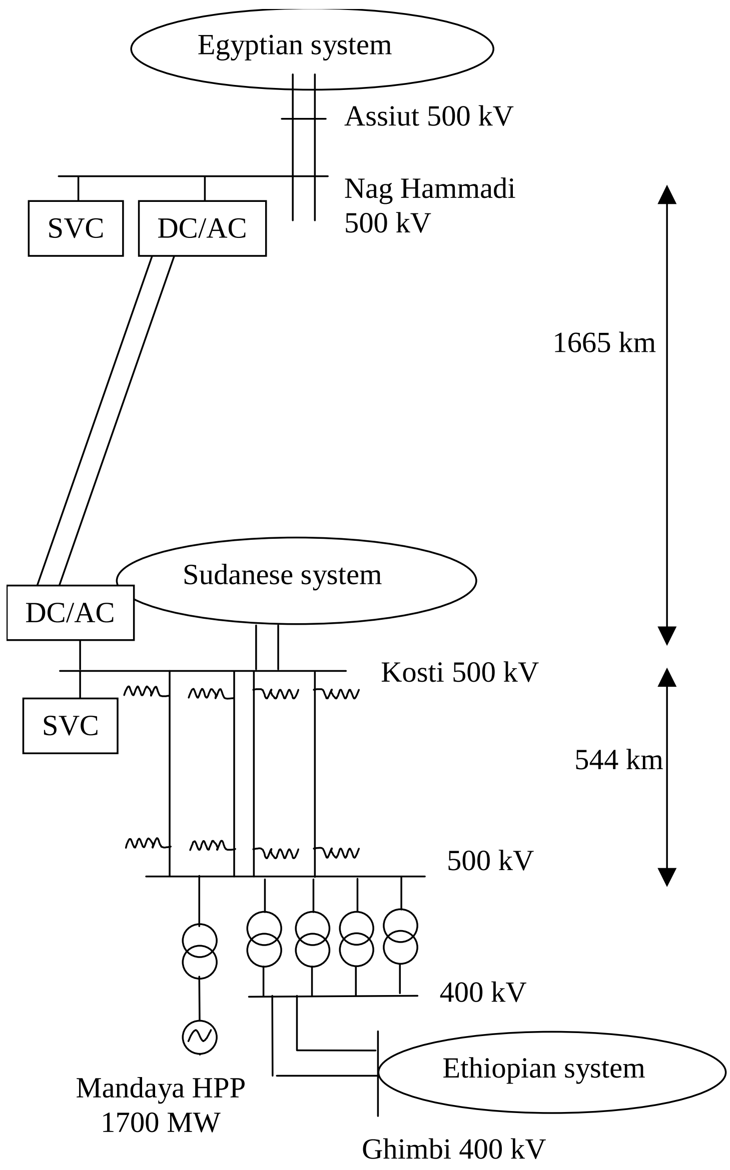
Despite this small ratio, this **Resettlement Action Plan is a key point for the implementation** of the interconnection. The project company shall take a special care and monitor closely that Contractor to fulfill ESIA recommendations and assignments.

Technical Feasibility

EN countries have selected an interconnection scheme consisting in:

- One AC 500 kV link including two 544 km double circuit lines between a 500/400 kV substation at Mandaya in Ethiopia and the AC 500 kV station at Kosti in Sudan
- One DC +/-600 kV link including a 1 665 km bipolar DC line between Kosti and Nag Hammadi in Egypt, a 2 150 MW AC/DC converter station located at each end of the link. One 500 MVAr and one 300 MVAr static var compensators are installed at Kosti and Nag Hammadi.

This interconnection operates in parallel with the Gonder (Ethiopia) and Gedaref (Sudan) 220 kV to be commissioned in the coming year 2009.



Power Studies

To assess the feasibility of this interconnection, different situations were analyzed :

- Peak load situation in 2015
- Peak and intermediate load situation in 2020/2021
- Peak load situation in 2025/2026
- Peak load situation in 2029/2030

The study has demonstrated that **it is possible** to export 3 200 MW from Ethiopia, delivering 1200 MW to Sudan and 2000 MW to Egypt.

The operation of whole interconnected systems **is acceptable**.

DC interconnection optimization study: An economical optimization study for the DC interconnection have lead to select a DC 600 kV scheme.

Operation in parallel of the 220 and 500 kV interconnections: It is advantageous to operate in parallel the 220 and the 500 kV interconnections, for security and economical reasons, with a 250 MVA phase-shift transformer.

DC +/-600 kV, AC 220 kV and 500 kV interconnections: The tripping of one of the poles of the DC interconnection is acceptable. The tripping or a short-circuit on the 220 kV interconnection has a limited impact on the system behavior. In case of short circuit on 500 kV interconnection, for stability reasons the export power to Egypt has been reduced to half. The increase of the short-circuit power and the commissioning of Border lift up this constraint.

Egyptian system : Egyptian system behavior is satisfying with a 300 MVA SVC in Nag Hammadi. The system face safely the tripping of Egypt main steam unit.

Ethiopian system: Ethiopian system behavior is satisfying. In 2020, the Mandaya and Addis Ababa 400 kV backbone is heavily loaded, fulfilling N-1 criteria. The commissioning of Geba 1&2 in 2021 and specifically Border in 2030 will release load constraints. The Ethiopia - Sudan system faces safely the tripping of Ethiopia main unit.

Sudanese system: The behavior of the Sudanese system is satisfying in case of tripping and short-circuit on the neighboring circuits of Kosti. The Ethiopia - Sudan system face safely the tripping of Sudan main unit.

Anticipation of the AC 500 kV interconnection in 2015: The anticipation of Mandaya-Kosti AC interconnection would enable to export the Ethiopian hydro surplus before 2020, and to increase the power export from 200 MW (with the 220 kV AC interconnection) to 700 MW. The energizing of the interconnection is an issue due to harmonic transient over-voltage risks, generated by 400/500 kV Mandaya transformers. This potential issue needs to be studied in a detailed way with the final known characteristics of the network. Several technical and operational alternatives were analyzed, and the black-start with low voltage energizing from a gas turbine plant at Kosti appeared to be the best solution.

Line Routing

AC circuits between Mandaya and Kosti substation face some difficult access and relief characterized by hilly area and flooded zone near Nile.

Kosti substation localization will be decided according with other 500 kV Sudanese project lines to be committed in 2030.

Corridor of ± 600 kV DC Line between Kosti and North Omdurman is located on the West bank of the White Nile River. This line route skirts urban area between Rabak/Kosti-Khartoum, Khartoum agglomeration, future International Khartoum Airport and existing 220 kV lines.

After field investigations, the proposed areas, for ± 600 kV DC Line connection in Sudan and Egypt, are located in free of obstructions places, as highly populated areas, power lines crossing, private agricultural areas and cemeteries.

No major constraint for AC and DC line corridors has been identified after site visits.

Phasing

Arrangement works are divided in ten lots: five for AC and DC overhead lines construction, four for HVDC and SVC substations and one for control center and appropriate supervision.

This **challenging** phasing considers the time for study validation and works construction but does not take into account the bidding processes for construction and consulting services.

AC and DC Technical Specifications

No cutting-edge technologies have been chosen. **Well proven technologies** have been selected for the most part of technical equipments (cables, towers, power stations subsystems, controls systems, transformers, ..). Turn key buys are recommended, one for the both HVDC stations and one for SVC stations.

Operation and Maintenance

A **dedicated control center**, designed to **not depend on the location** and **operated in close cooperation but distinctly** from national transmission operators, handles metering, supervision and controls with local substations and telecommunication links.

Training is a significant part of the development of this project and covers numerous technical and management fields.

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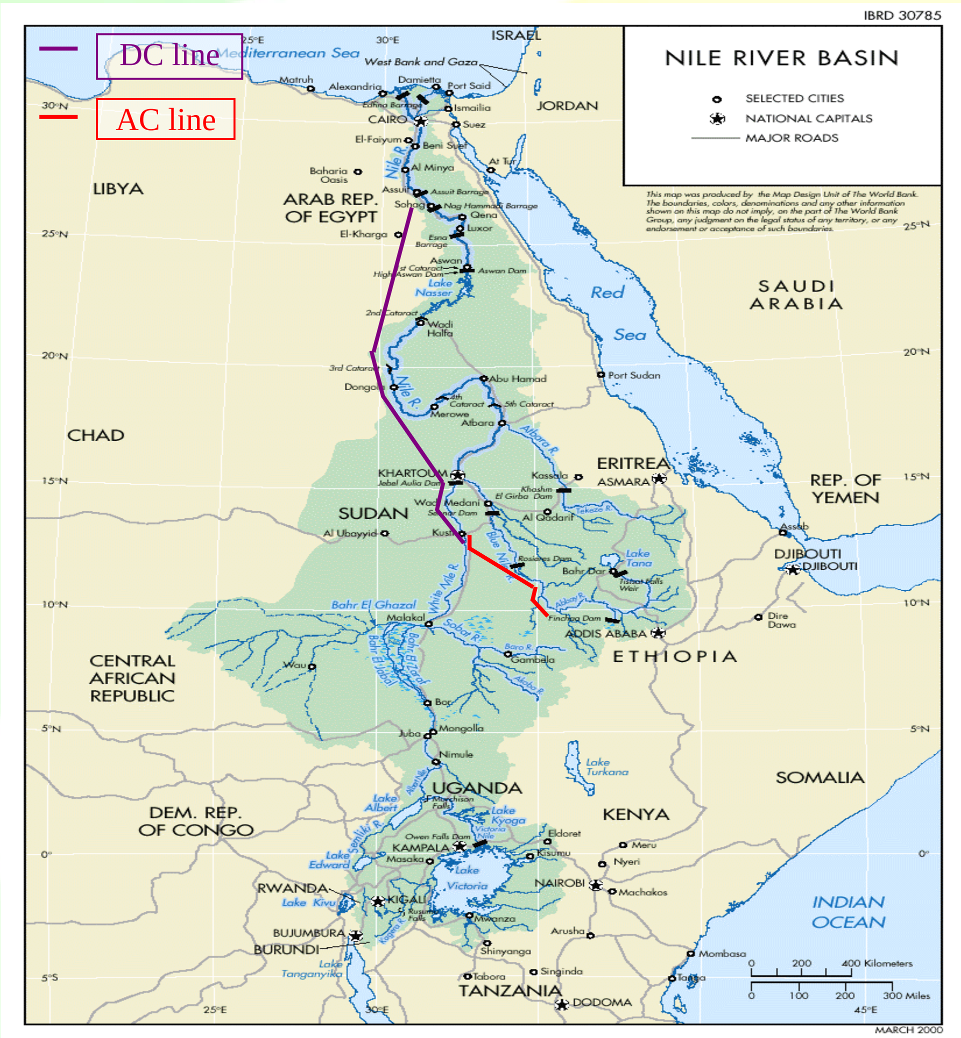

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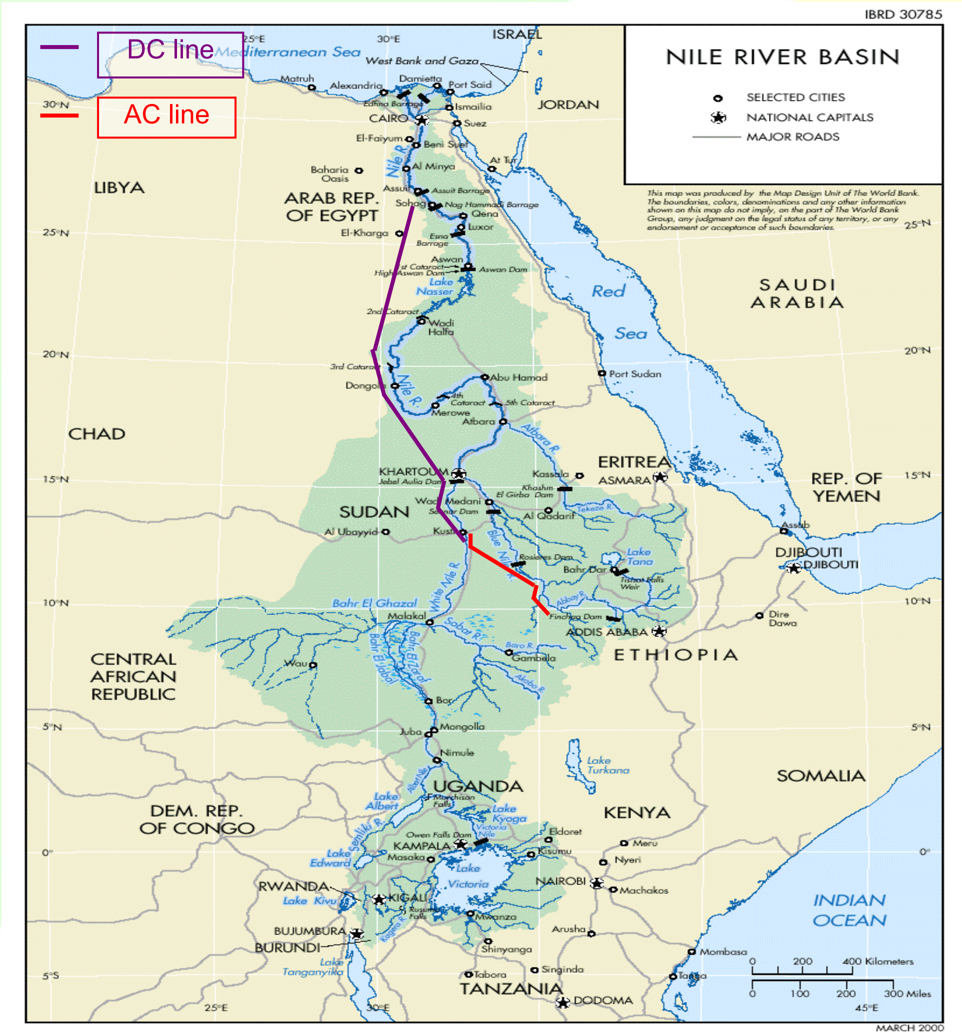
EASTERN NILE POWER TRADE PROGRAM STUDY



M1 - 2015 APPENDIX - STABILITY STUDY

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ABBREVIATIONS AND ACRONYMS

AC	Alternative Current
CCG	Combined Cycle Gas turbine
DC	Direct Current
ENPTPS	Eastern Nile Power Trade Program Study
EDF	Electricité de France
EN	Eastern Nile
ENTRO	Eastern Nile Technical Regional Office
GEP	Generation Expansion Plan
HPP	Hydro Power Plant
HD	High Dam
HV	High Voltage
HVDC	High Voltage Direct Current
NBI	Nile Basin Initiative
NH	Nag Hammadi
OHL	Over Head Line
pu	per unit
SC	Short Circuit
ST	Steam Turbine
SVC	Static Voltage Compensator
SW	Scott Wilson

Note : Rabak / Kosti

The location of the interconnection in Sudan was modified during the Line Routing study.

Initially located at Rabak (east side of the Nile) in Phase I, the line routing study (during Phase II) located the interconnection substation in Sudan on the west side of the Nile river at Kosti.

The name used in the simulation was Rabak.

1 TRANSIENT STABILITY ANALYSIS HYPOTHESIS

The volume of spinning reserve set as followed :

- Sudan : 199 MW
- Ethiopia : 134 MW (hydropower plant only)

Load voltage and frequency dependency coefficients

	dP/dV	dP/df	dQ/dV	dQ/df
Ethiopia	0.94	1.26	3.67	-1.29
Sudan	0.79	1.53	4.14	-0.72

Table 1. Load voltage and frequency dependency coefficients

Calculation of the damping magnitude of the power oscillations

The power oscillations evolve according to the formula :

$$A.e^{-\alpha t}.\cos(\omega t+\varphi) \quad \text{with } \omega=2\pi f_x$$

From the curves it is possible to measure the frequency, f_x of the oscillations. (generally a low value close to 0.3Hz or 0.5Hz)

The apparent damping coefficient D of the oscillation mode is equal to :

$$D=\frac{\alpha}{\sqrt{(\alpha^2+\beta^2)}} \quad \text{with } \beta = 2\pi f$$

and α is like that $e^{-\alpha t}=0.05$ with ***t*** is the damping duration.

The international literature concerning the inter-area oscillations, indicates that an inter-area oscillation mode is acceptably damped if the damping coefficient is close to 5% and it is well damped if the damping coefficient is higher than 5%.

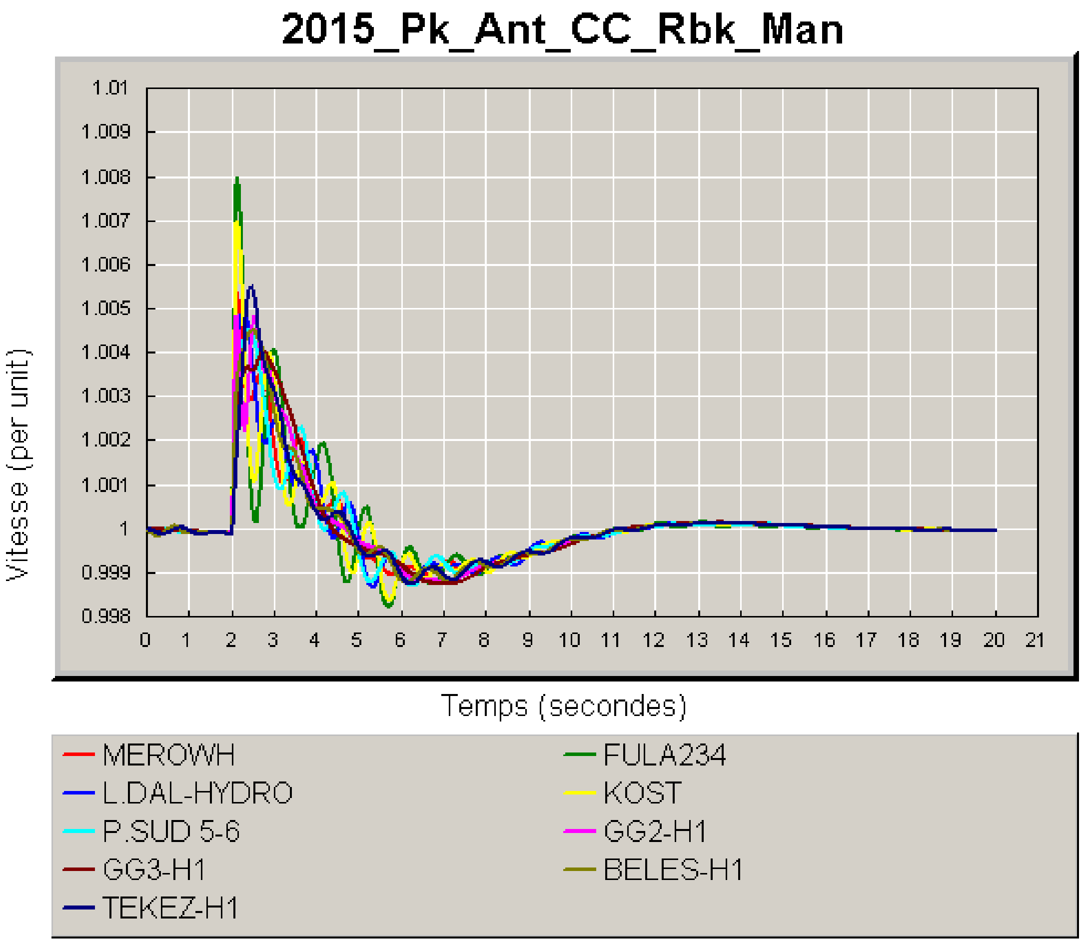
According to the above formula, the apparent damping coefficient for the average frequency was estimated from the curves and the results.

2 2015 PEAK LOAD SITUATION

2.1 SHORT-CIRCUIT AT KOSTI ON ONE OF THE 2 KOSTI - MANDAYA CIRCUITS

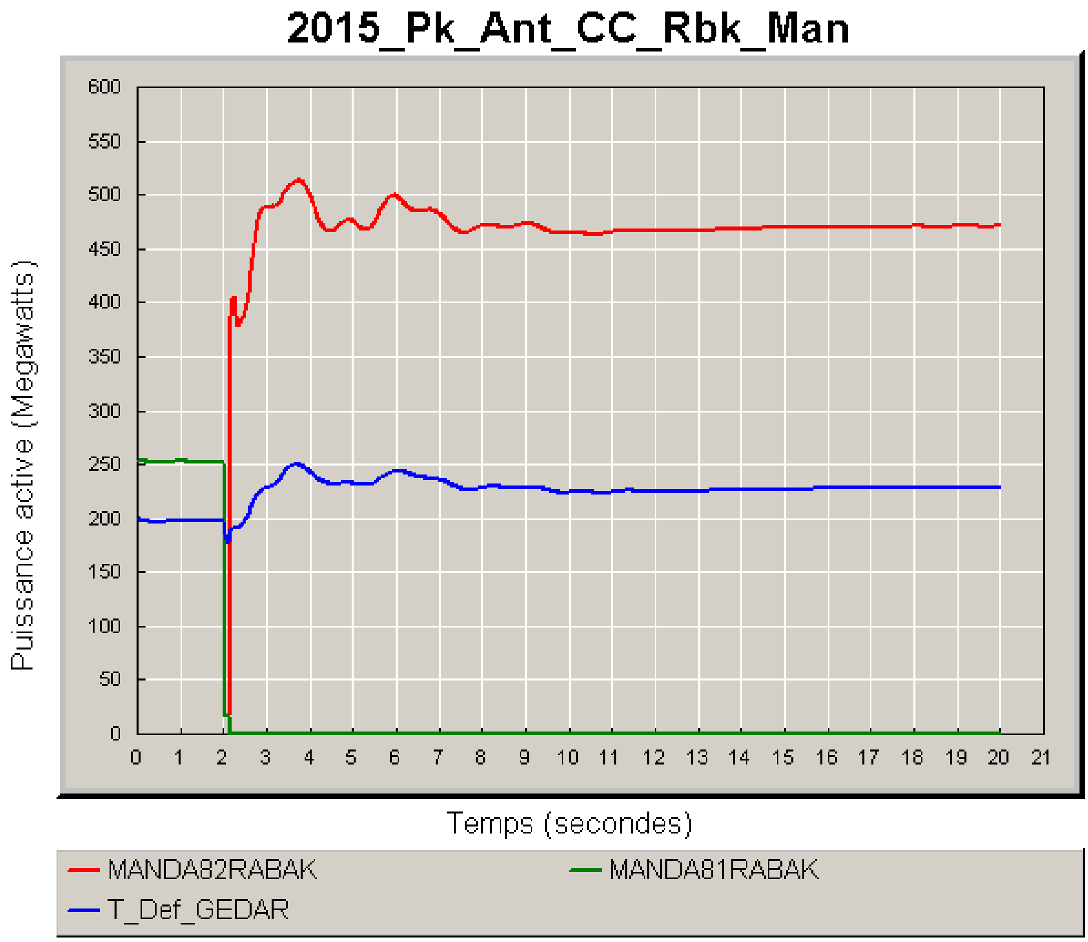
Event : a 3 phase short-circuit at Kosti end, on one of the 2 circuits Mandaya - Kosti, cleared in 120 ms by the opening of the circuit breakers.

2.1.1 GENERATORS FREQUENCY VARIATION

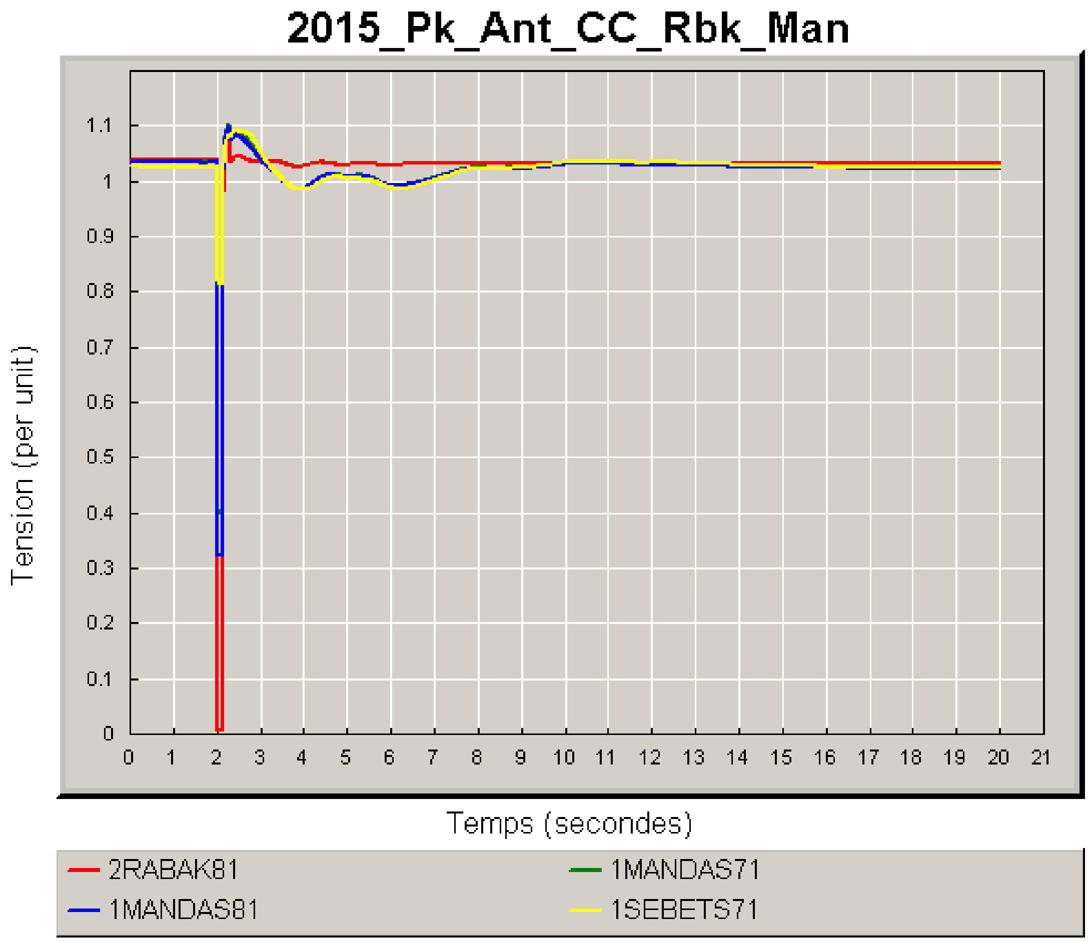


GG2 is Gibel Gibe II
GG3 is Gibe III

2.1.2 POWER FLOW VARIATION ON THE INTERCONNECTION



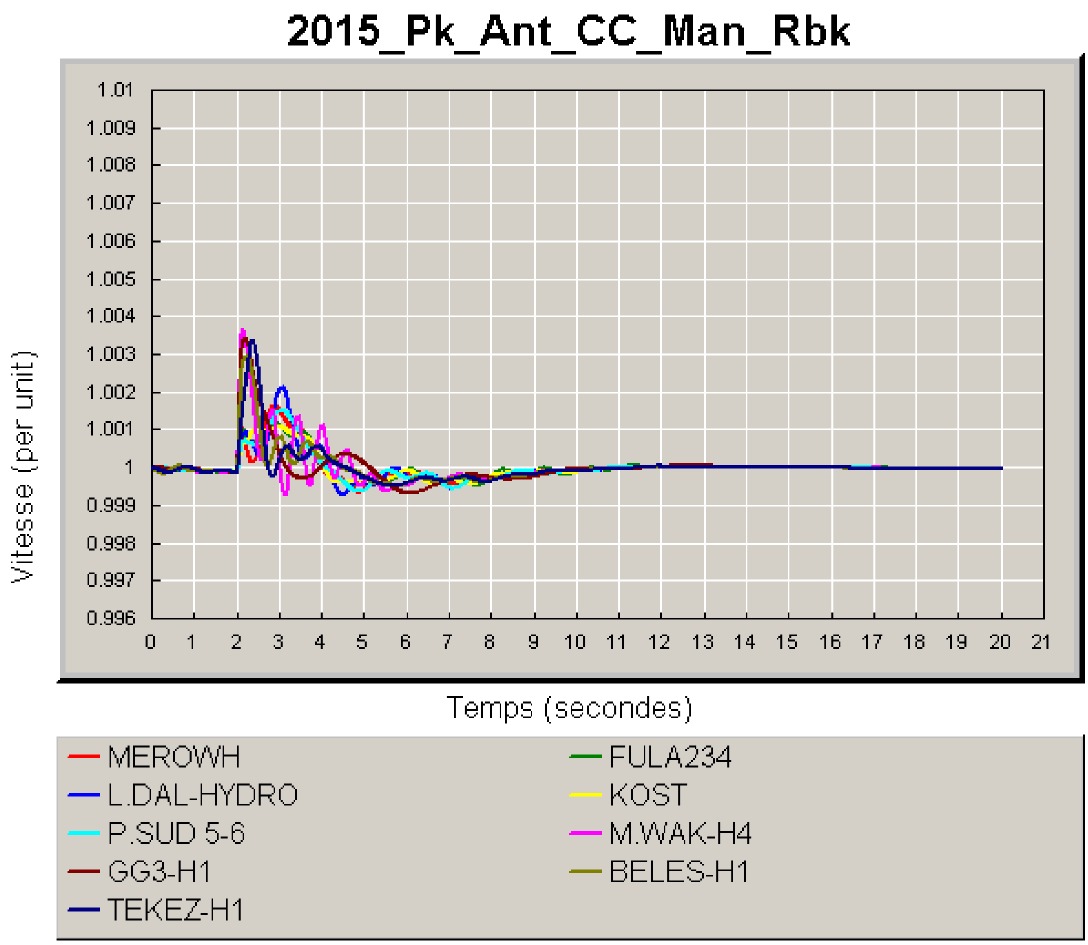
2.1.3 VOLTAGE VARIATION ON THE 400/500 KV INTERCONNECTION



2.2 SHORT-CIRCUIT AT MANDAYA ON ON ONE OF THE 2 MANDAYA - KOSTI CIRCUITS

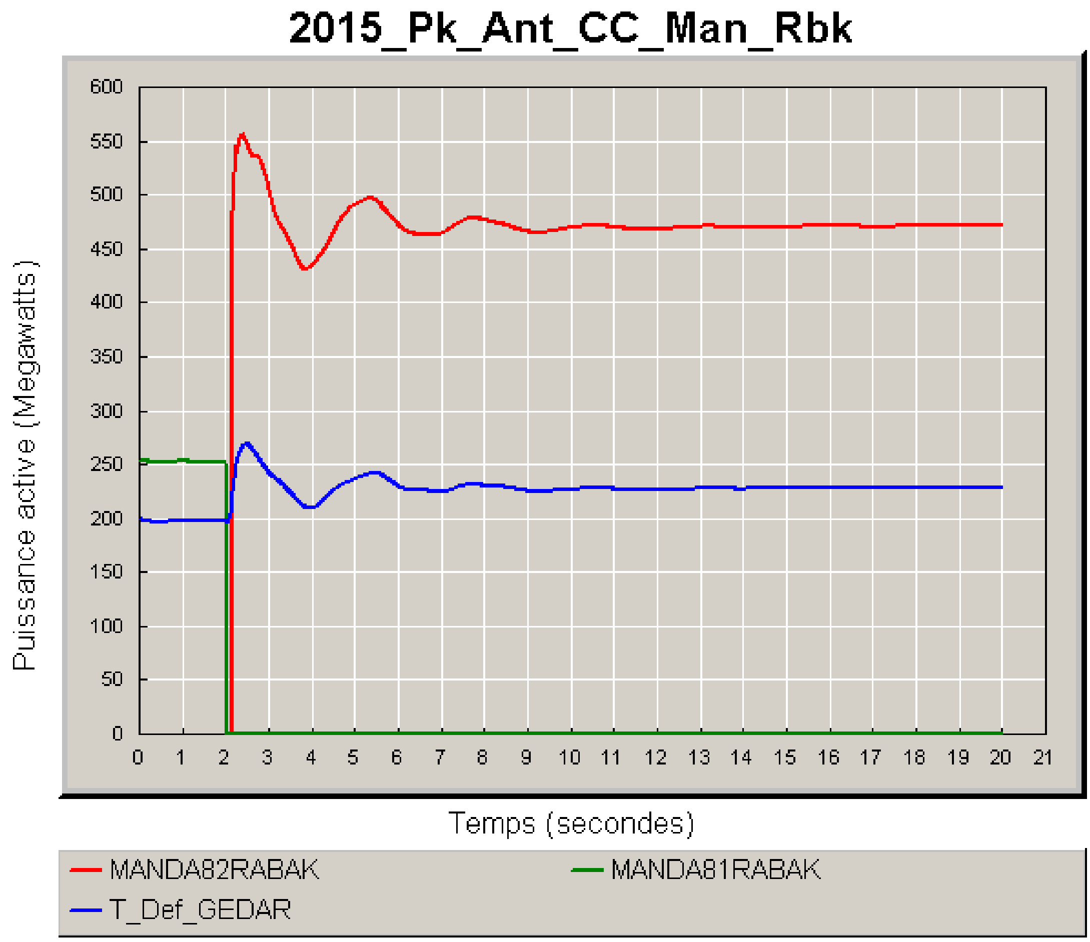
Event : a 3 phase short-circuit at Mandaya end, on one of the 2 circuits Mandaya - Kosti, cleared in 120 ms by the opening of the circuit breakers.

2.2.1 GENERATORS FREQUENCY VARIATION

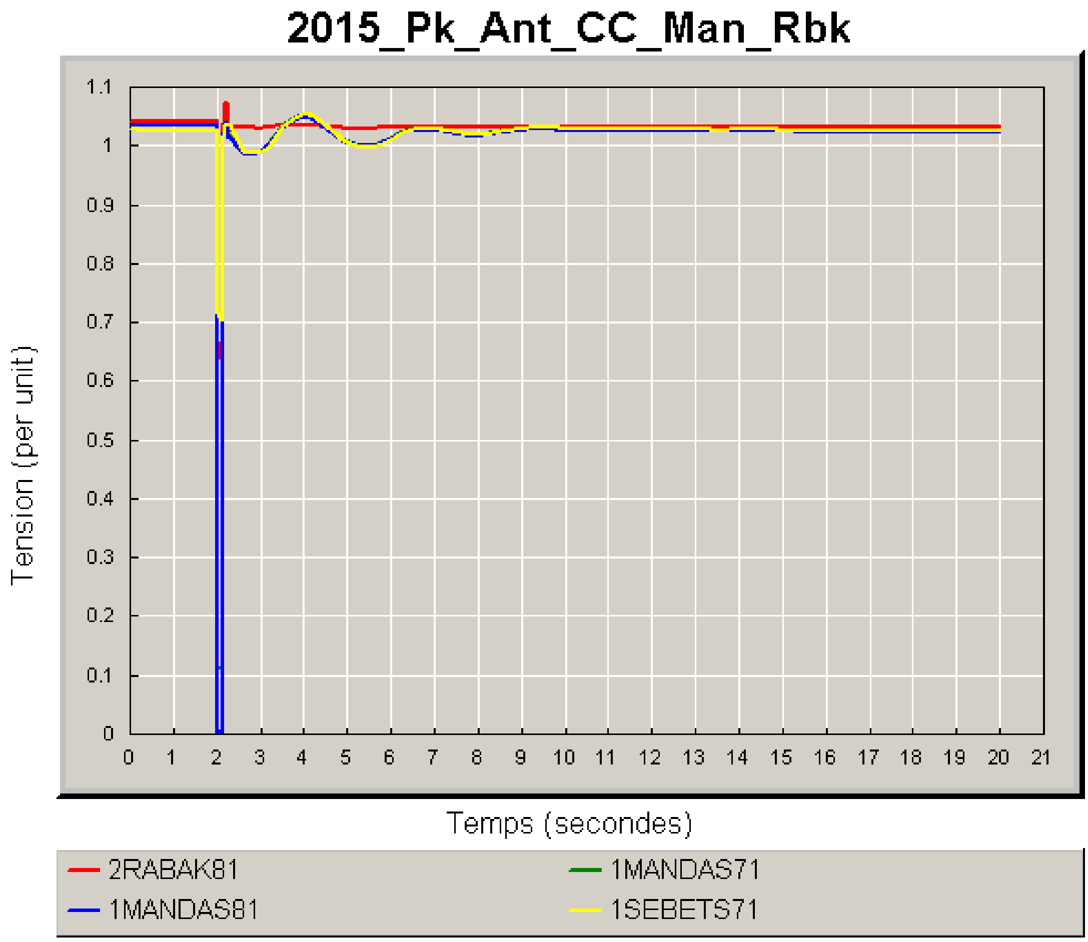


GG3 is Gibe III

2.2.2 POWER FLOW VARIATION ON THE INTERCONNECTION



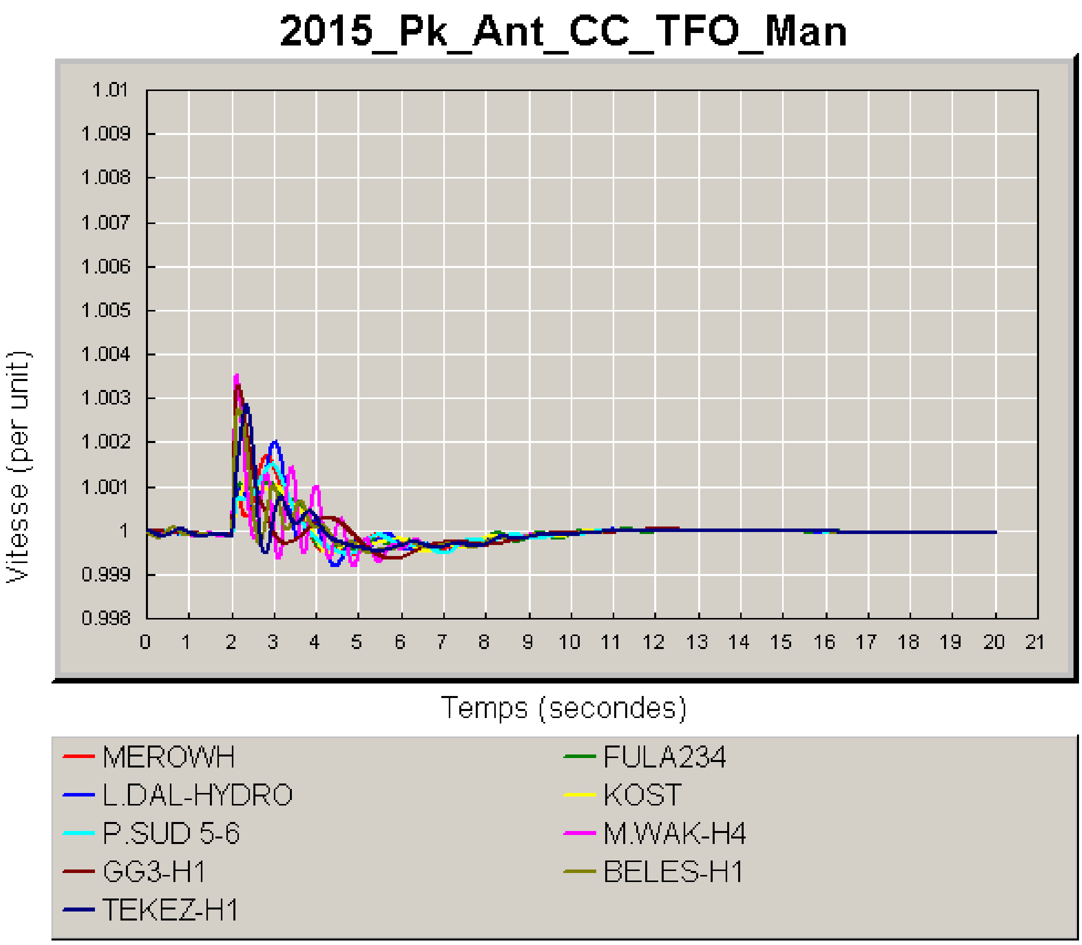
2.2.3 VOLTAGE VARIATION ON THE 400 AND 500 KV



2.3 SHORT-CIRCUIT ON ONE OF THE FOUR 400/500 KV TRANSFORMERS AT MANDAYA

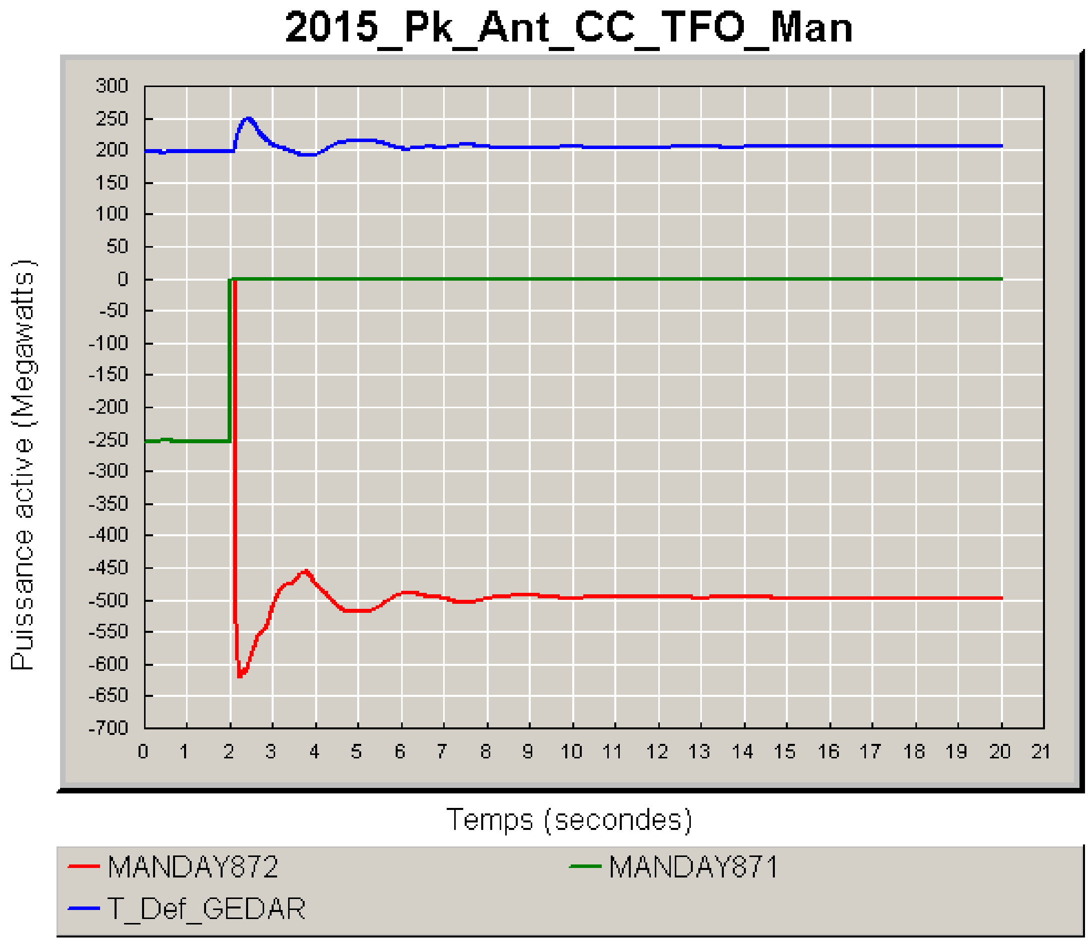
Event : a 3 phase short-circuit at the 500 kV side on one of the four 500/400 kV transformers at Mandaya, cleared in 120 ms by the opening of the circuit breakers.

2.3.1 GENERATORS FREQUENCY VARIATION

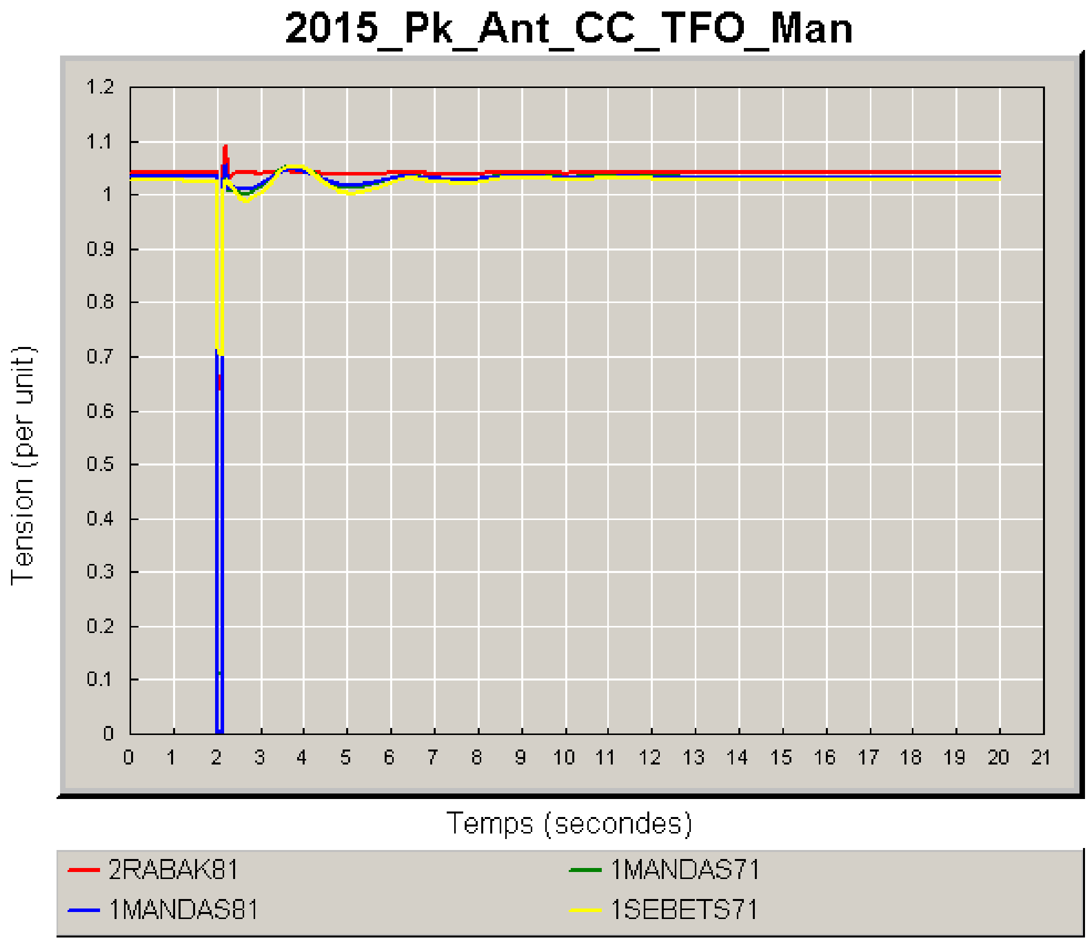


GG3 is Gibe III

2.3.2 POWER FLOW VARIATION ON THE INTERCONNECTION AND ON MANDAYA 500/400 KV TRANSFORMERS



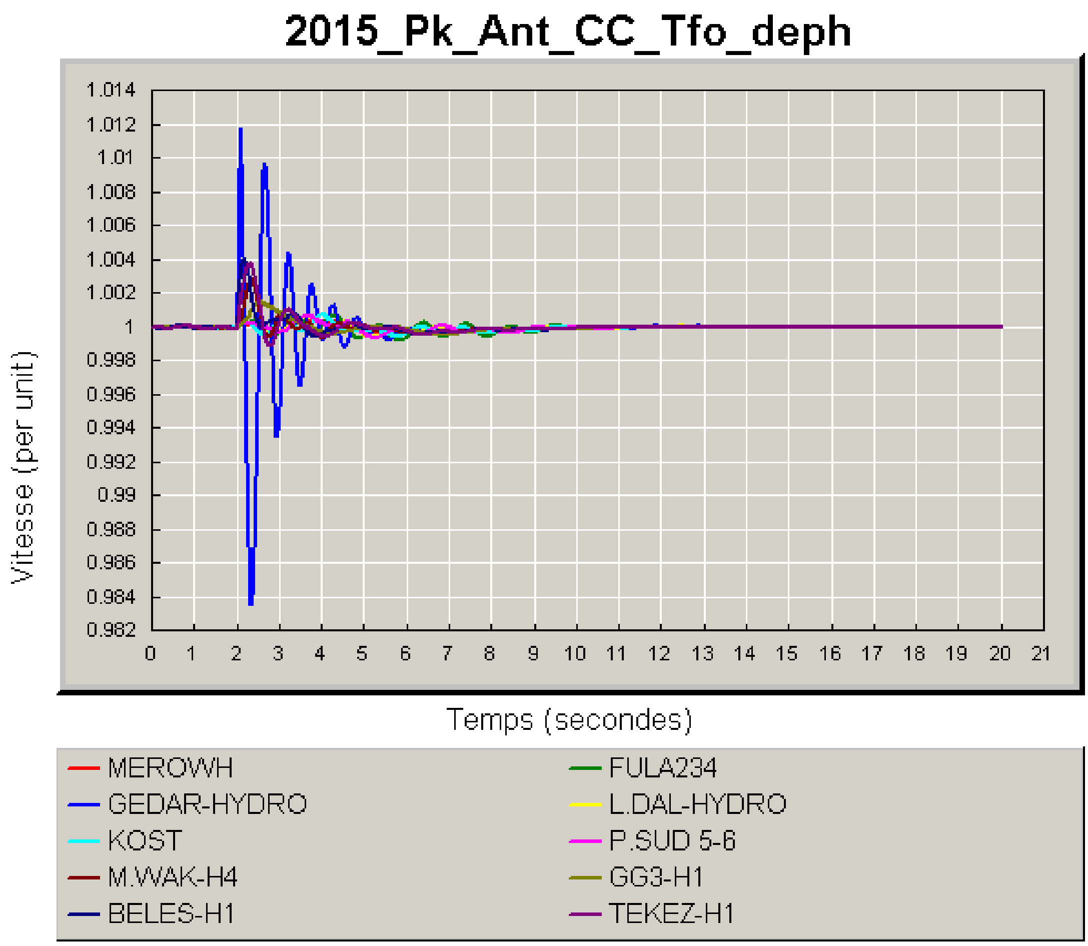
2.3.3 VOLTAGE VARIATION ON THE 500 KV



2.4 SHORT-CIRCUIT AT GEDAREF, ON THE 220 KV PHASE-SHIFT TRANSFORMER

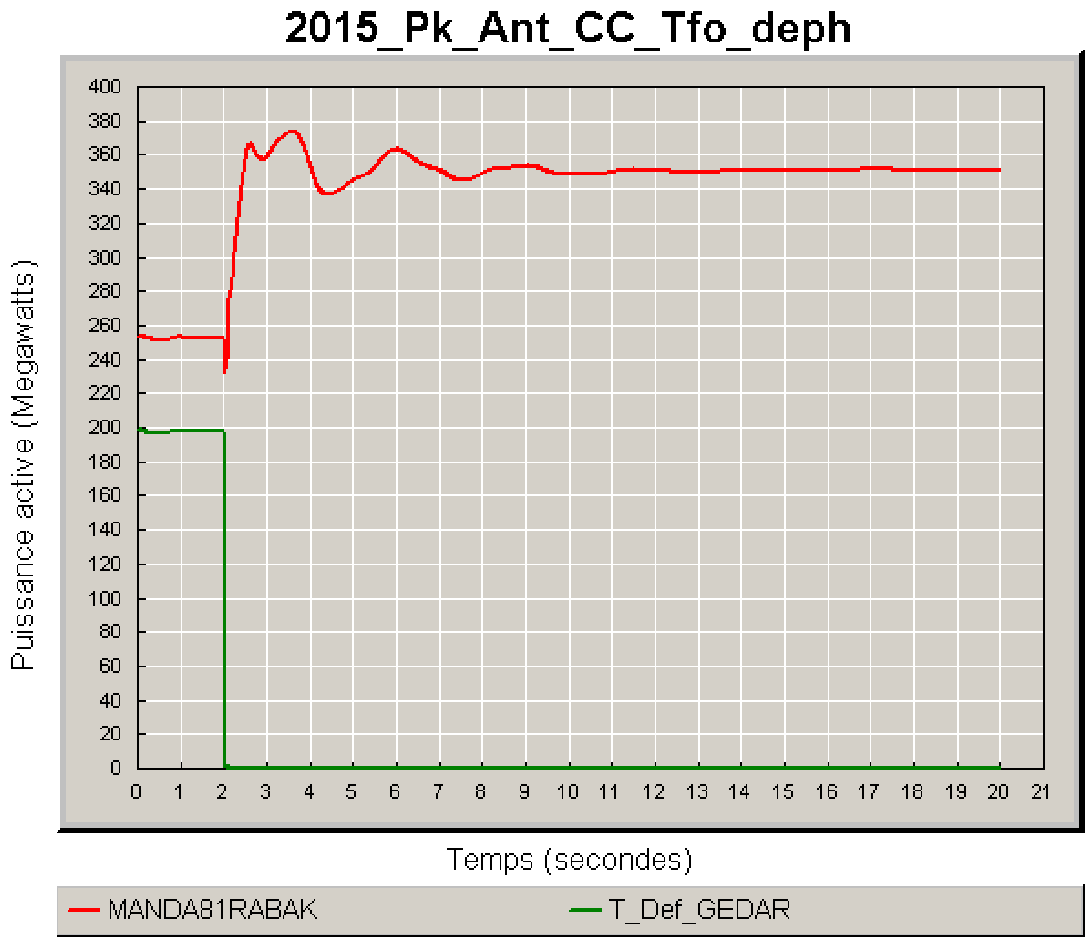
Event : a 3 phase short-circuit at Gedaref 220 kV end, on the 220 kV phase shift transformer, cleared in 120 ms by the opening of the circuit breakers.

2.4.1 GENERATORS FREQUENCY VARIATION

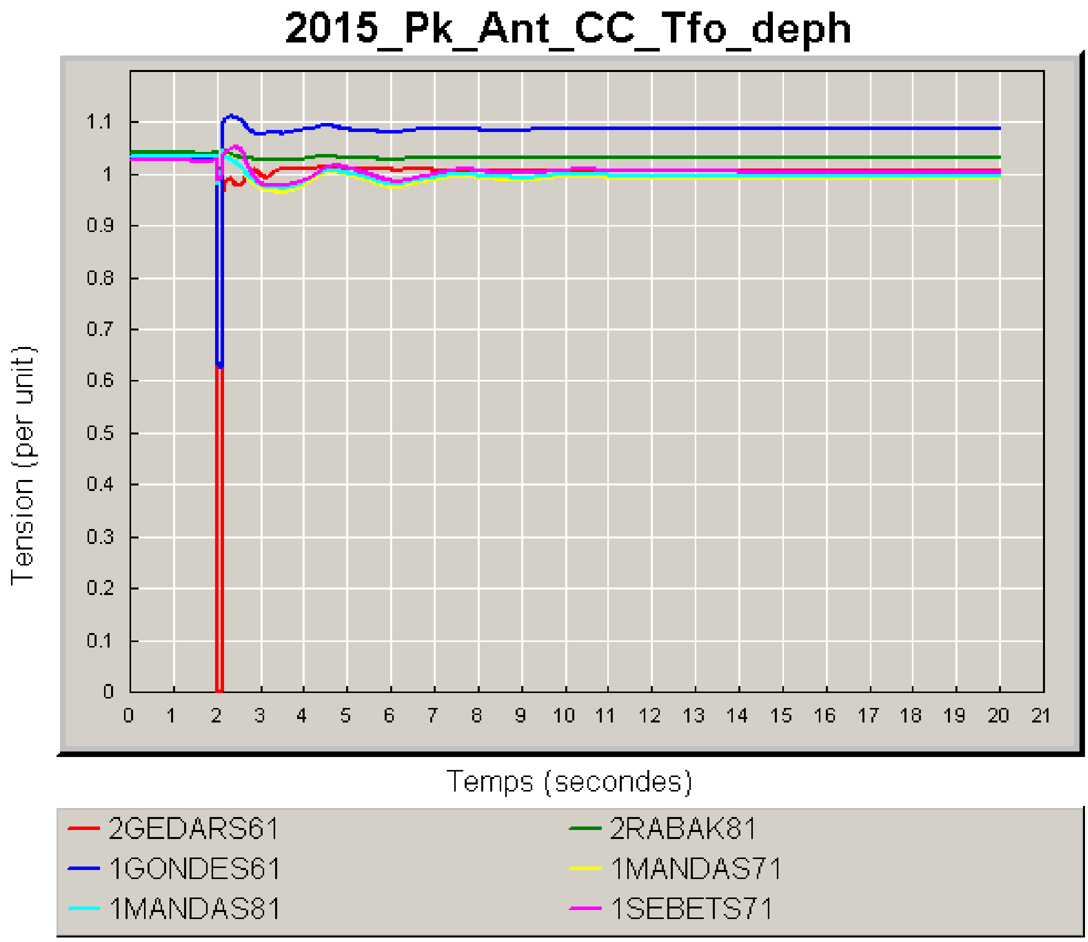


GG3 is Gibe III

2.4.2 POWER FLOW VARIATION ON ENTRO INTERCONNECTION



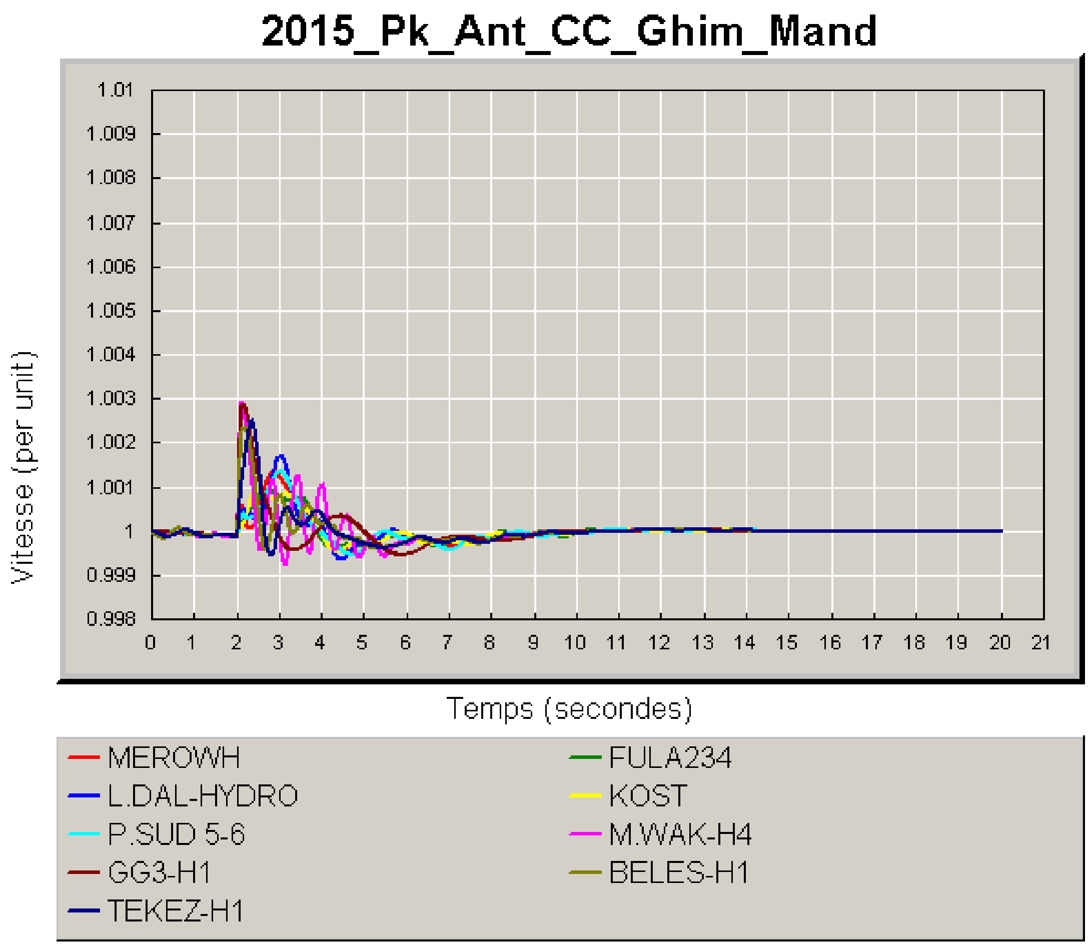
2.4.3 VOLTAGE VARIATION



2.5 SHORT-CIRCUIT AT MANDAYA ON ONE OF THE 2 CIRCUITS MANDAYA - GHIMBI

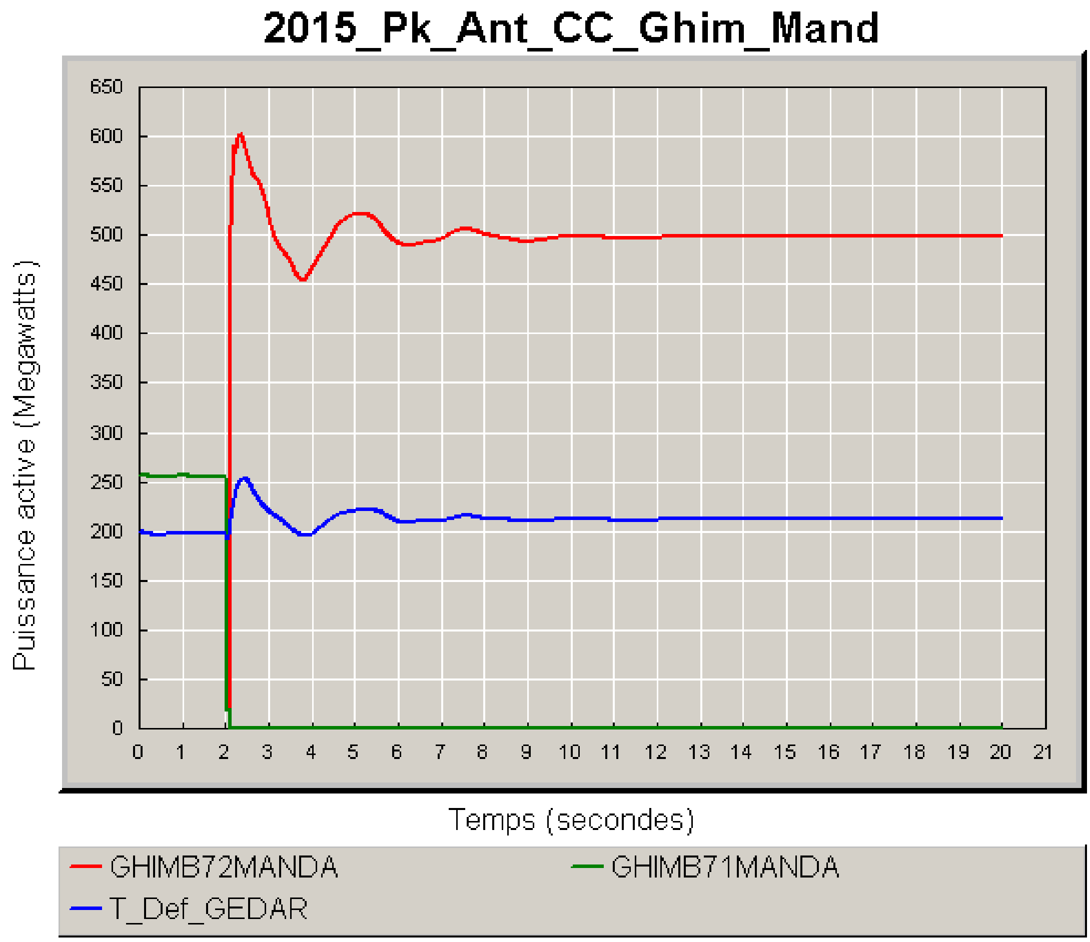
Event : a 3 phase short-circuit at Ghimbi end, on one of the 2 circuits Mandaya - Ghimbi, cleared in 100 ms by the opening of the circuit breakers.

2.5.1 GENERATORS FREQUENCY VARIATION

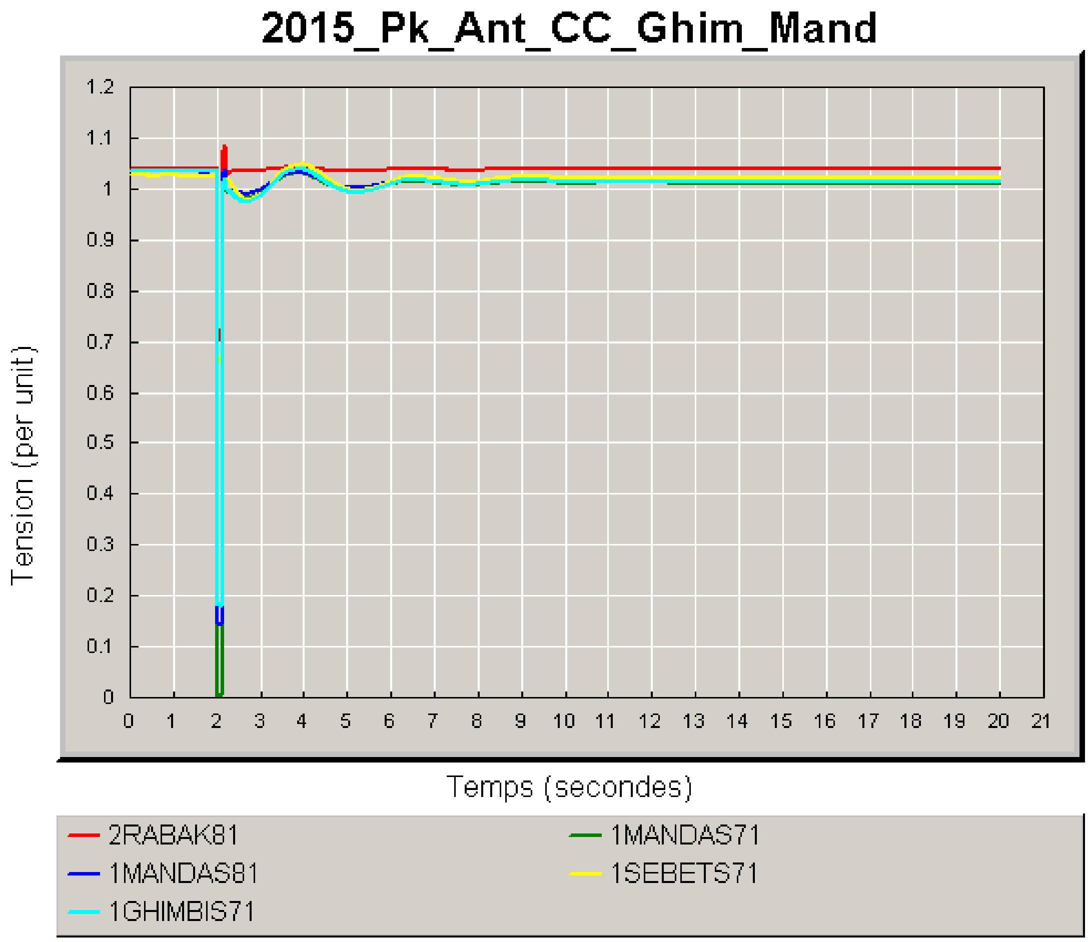


GG3 is Gibe III

2.5.2 POWER FLOW VARIATION ON THE INTERCONNECTION AND ON MANDAYA - GHIMBI



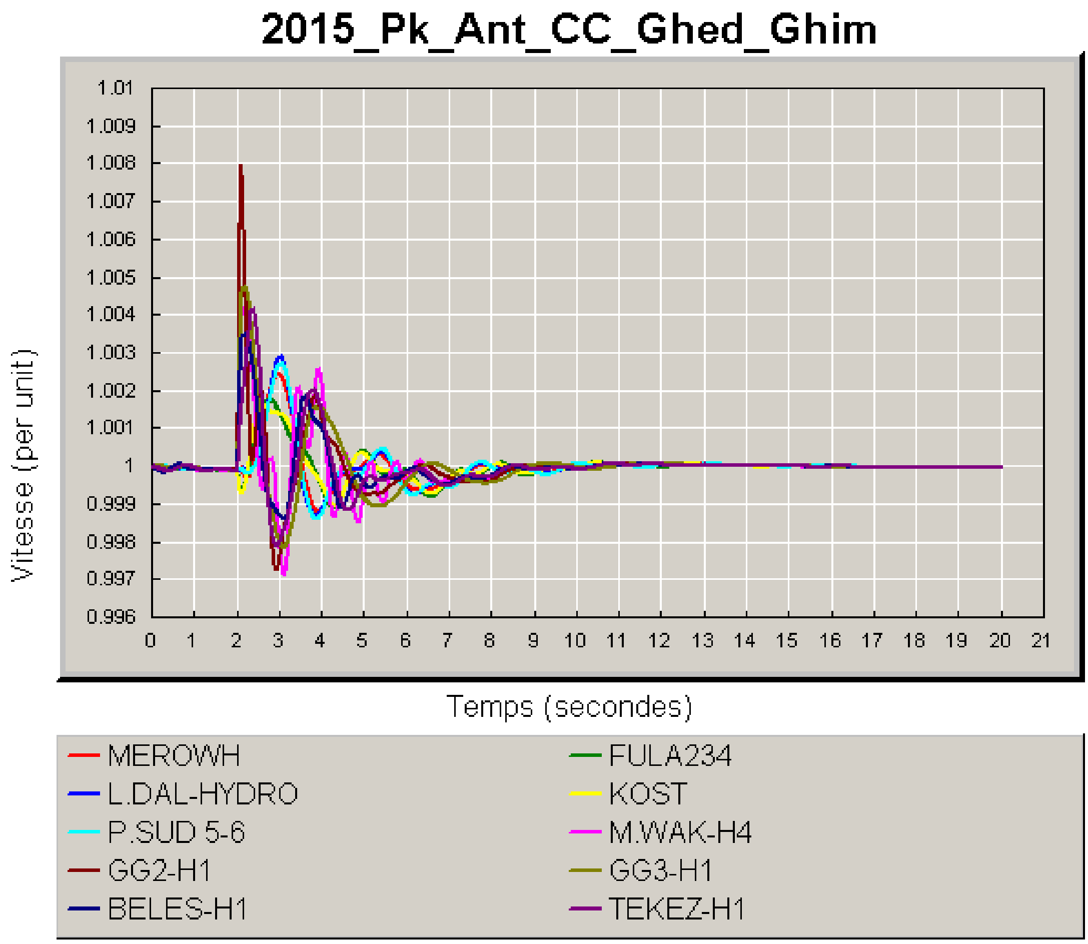
2.5.3 VOLTAGE VARIATION ON THE 400 AND 500 KV



2.6 SHORT-CIRCUIT AT GHEDO ON ONE OF THE 2 CIRCUITS GHIMBI - GHEDO

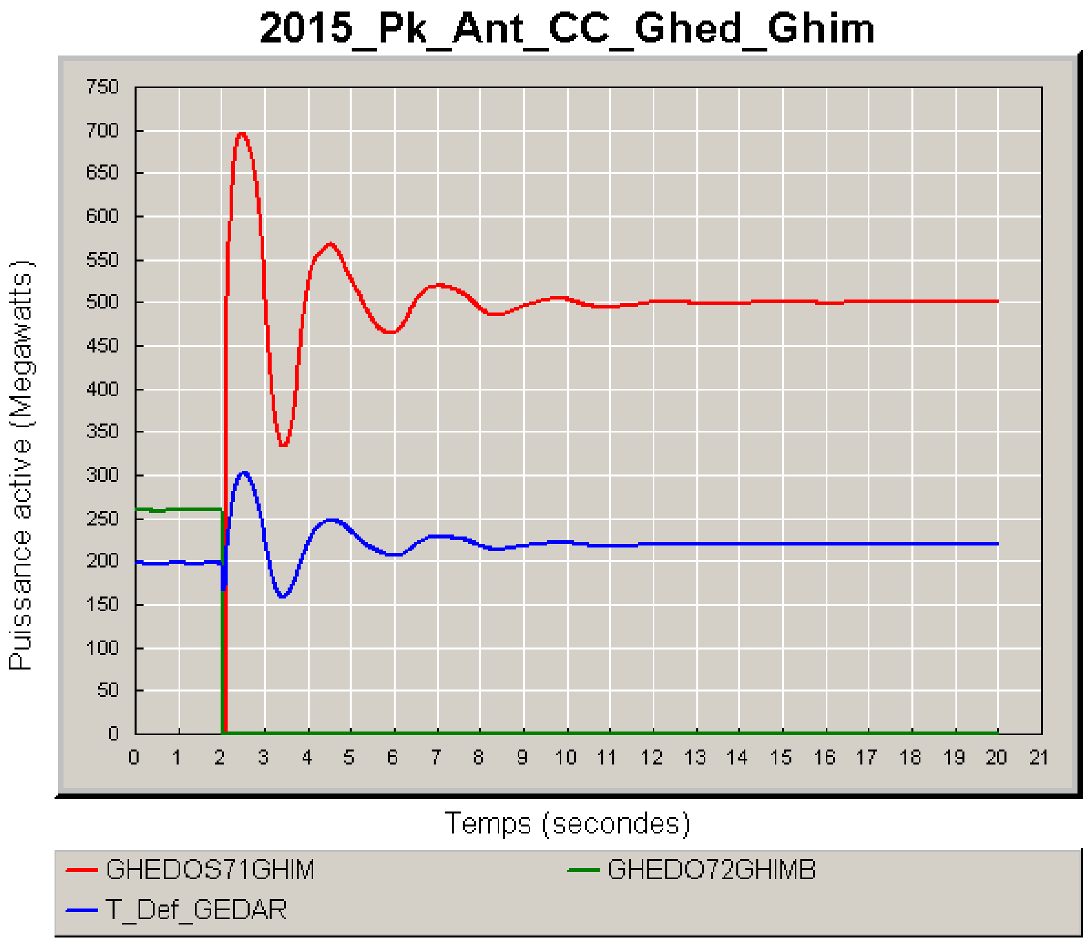
Event : a 3 phase short-circuit at Ghedo end, on one of the 2 circuits Ghimbi - Ghedo, cleared in 100 ms by the opening of the circuit breakers.

2.6.1 GENERATORS FREQUENCY VARIATION

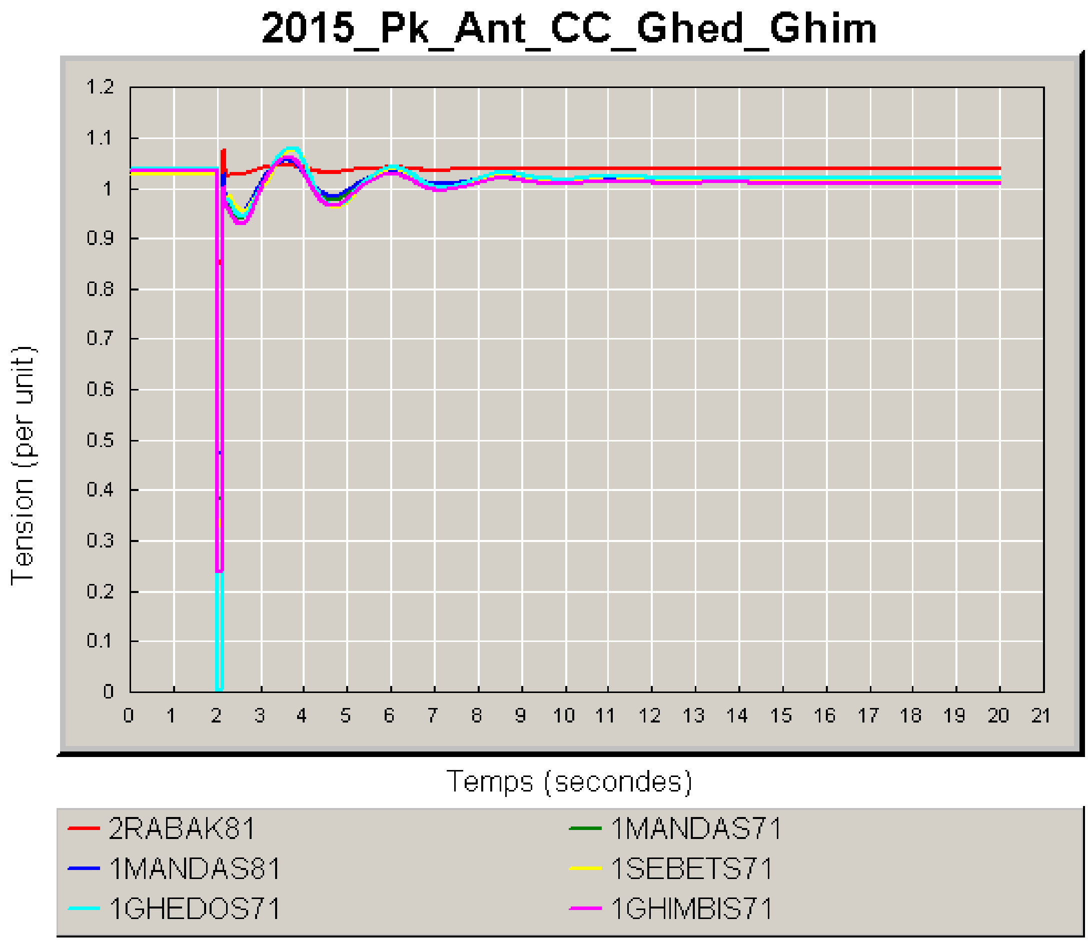


GG2 is Gigel Gibe II
GG3 is Gibe III

2.6.2 POWER FLOW VARIATION ON THE INTERCONNECTION AND ON GHEDO - GHIMBI



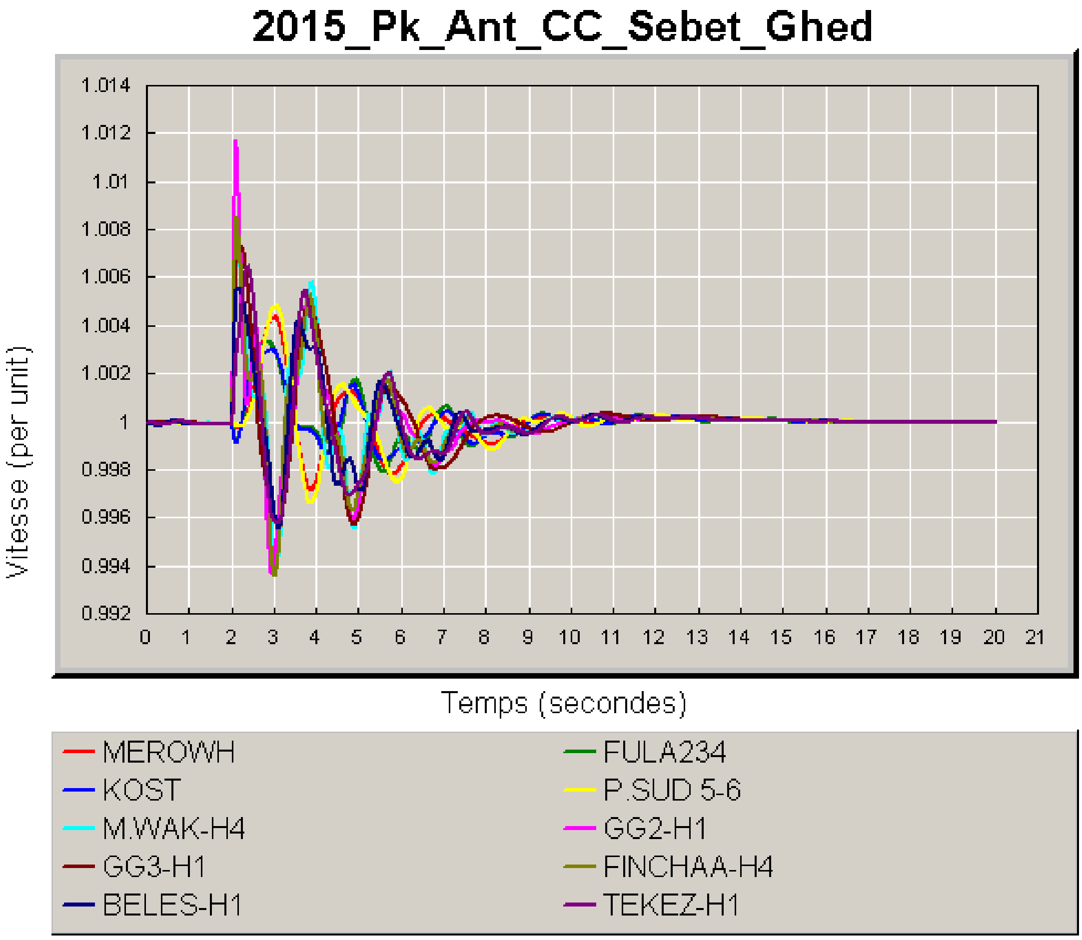
2.6.3 VOLTAGE VARIATION ON THE 400 AND 500 KV



2.7 SHORT-CIRCUIT AT SEBETA ON ONE OF THE 2 CIRCUITS SEBETA - GHEDO

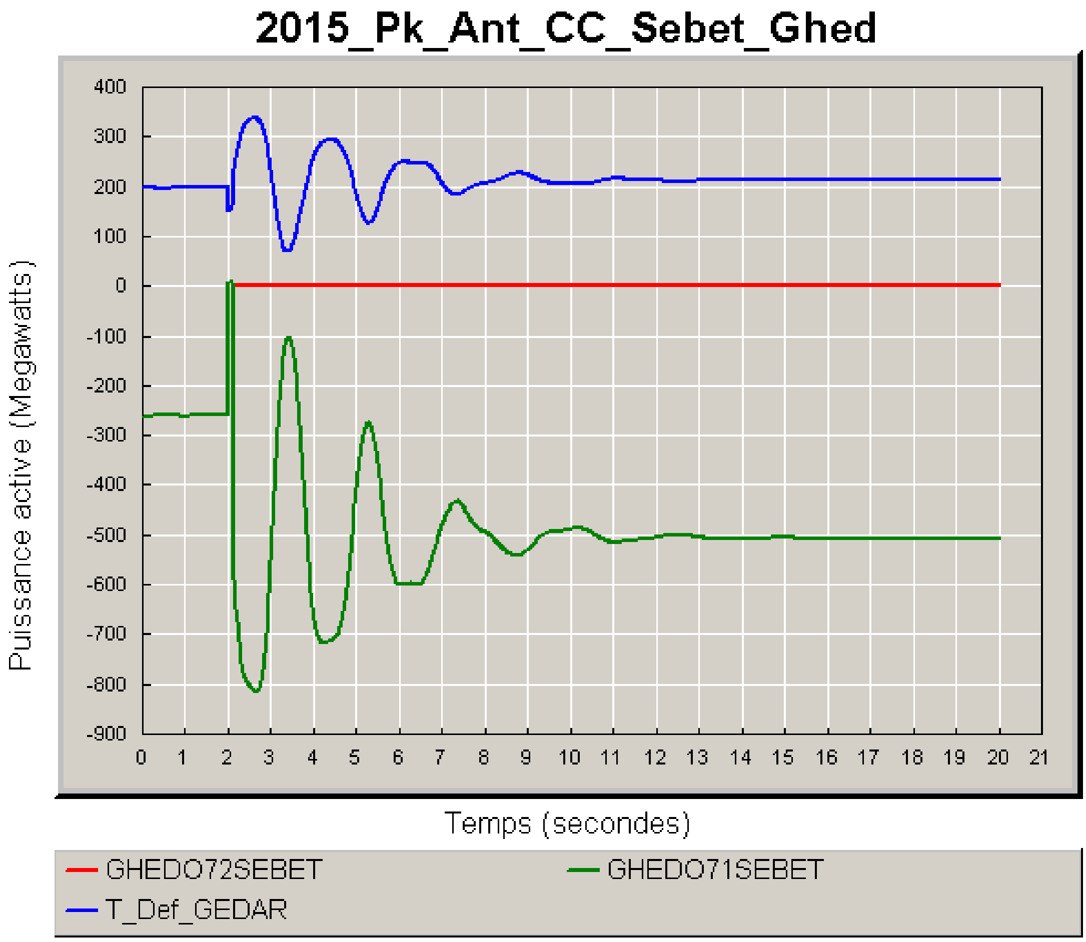
Event : a 3 phase short-circuit at Sebeta end, on one of the 2 circuits Sebeta - Ghedo, cleared in 100 ms by the opening of the circuit breakers.

2.7.1 GENERATORS FREQUENCY VARIATION

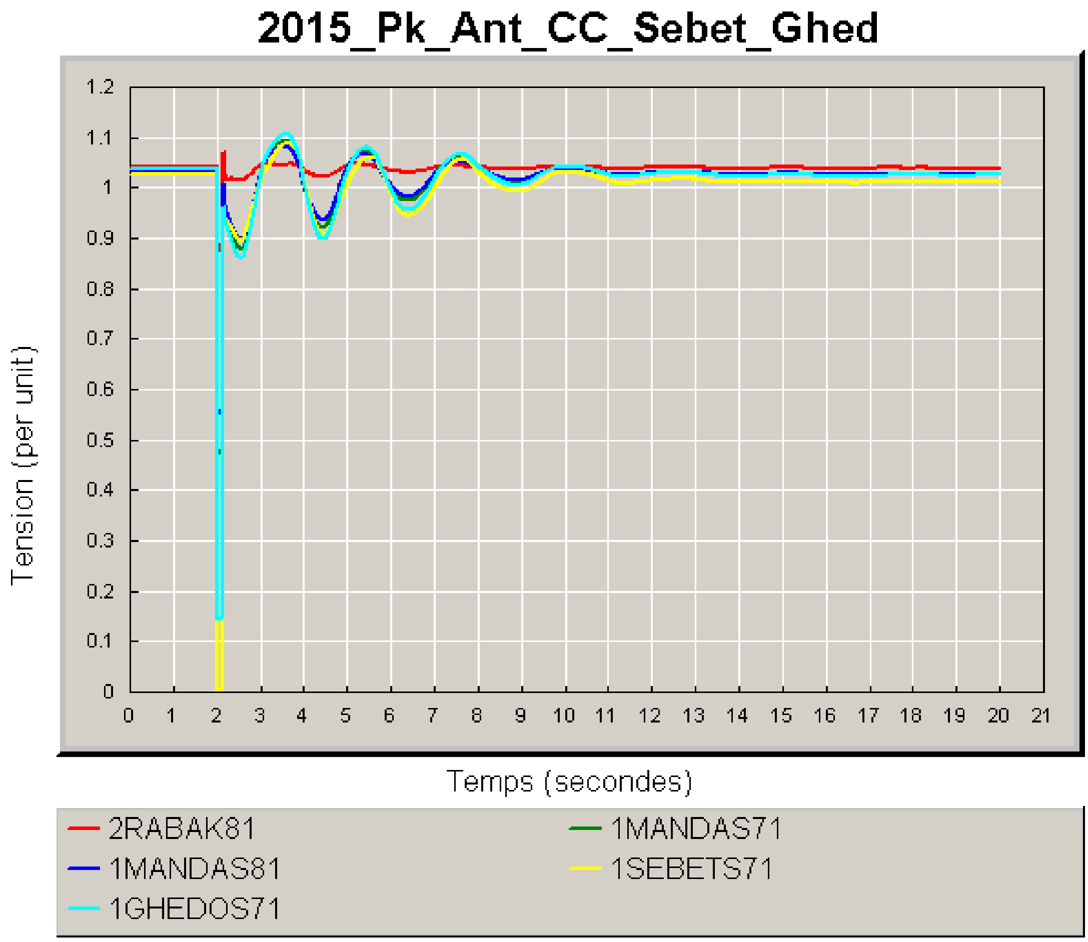


GG2 is Gigel Gibe II
GG3 is Gibe III

2.7.2 POWER FLOW VARIATION ON THE INTERCONNECTION AND ON SEBETA - GHEDO



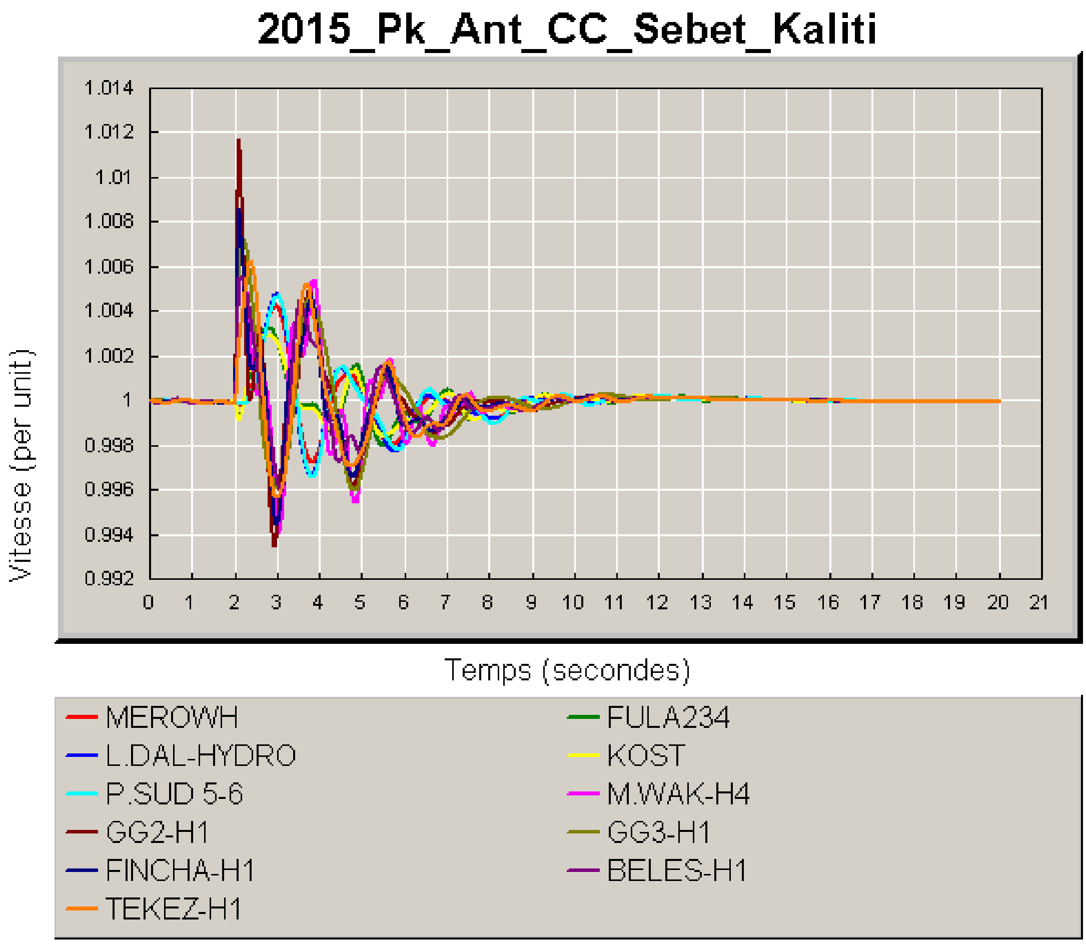
2.7.3 VOLTAGE VARIATION ON THE 400 AND 500 KV



2.8 SHORT-CIRCUIT AT SEBETA ON THE 400 KV SEBETA - KALITI CIRCUIT

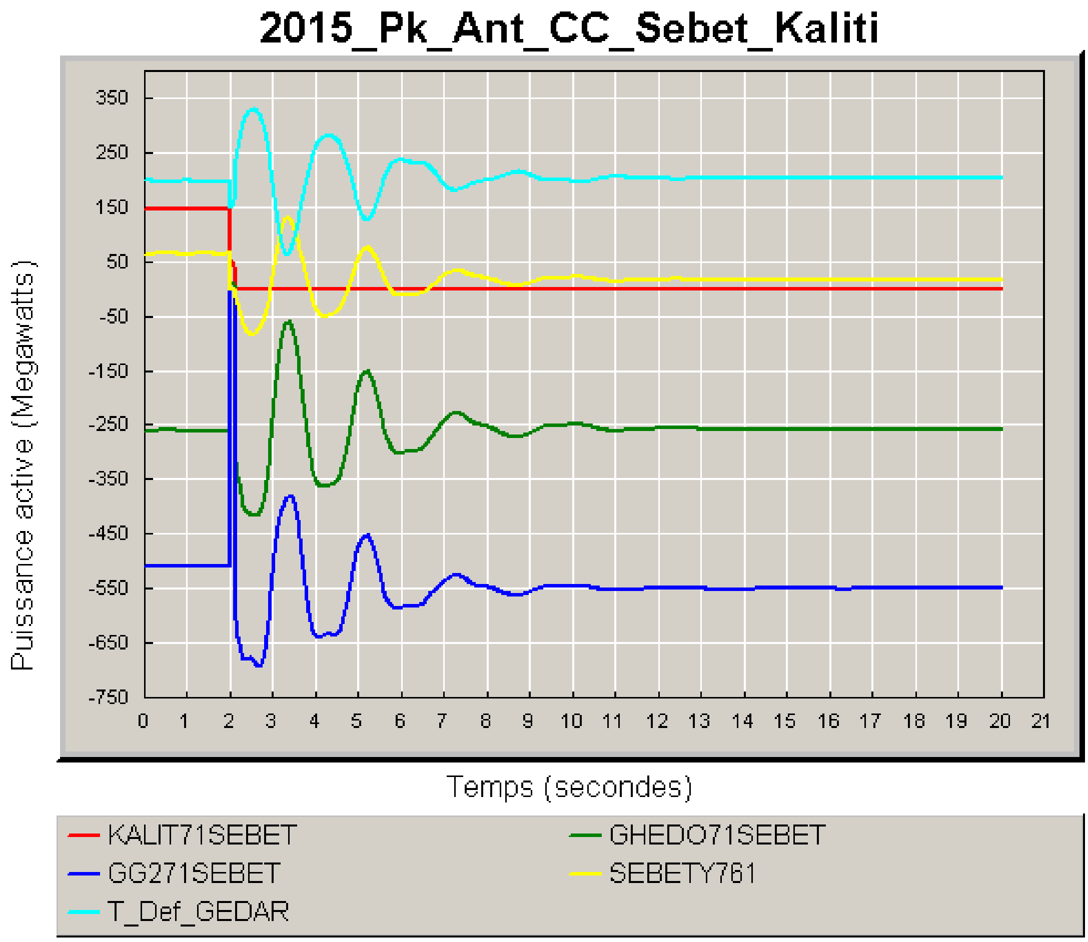
Event : a 3 phase short-circuit at Sebeta end, on the Sebeta - Kaliti circuits, cleared in 100 ms by the opening of the circuit breakers.

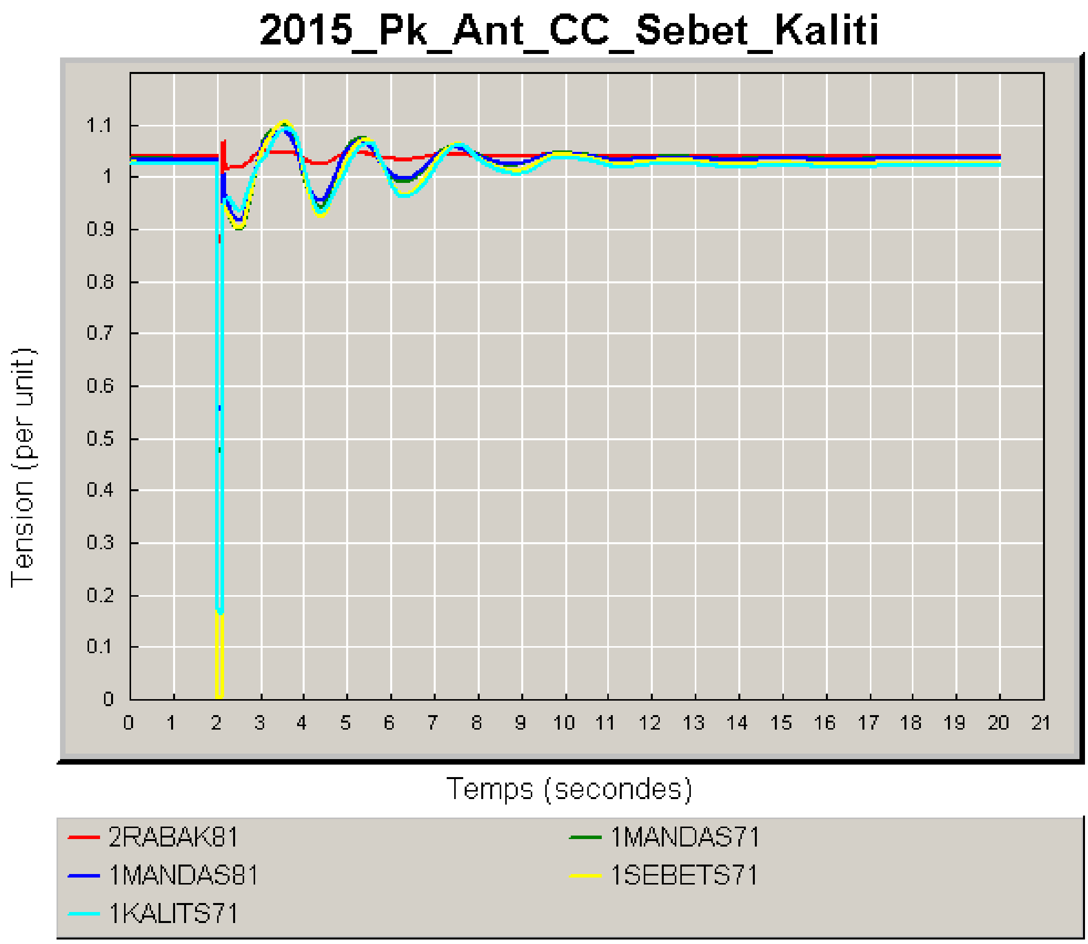
2.8.1 GENERATORS FREQUENCY VARIATION



GG2 is Gigel Gibe II
GG3 is Gibe III

2.8.2 POWER FLOW VARIATION ON THE INTERCONNECTION AND ON SEBETA CIRCUITS

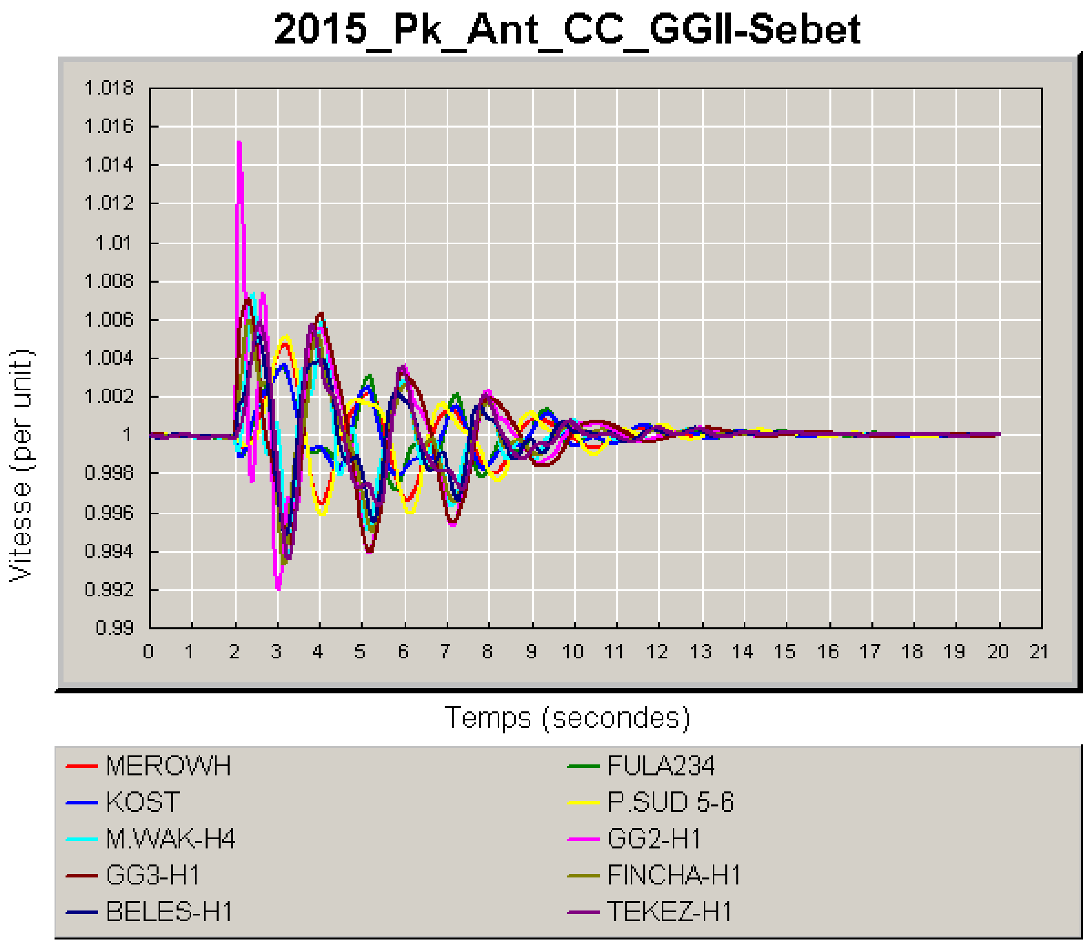



2015_Pk_Ant_CC_Sebet_Kaliti
Tension (per unit)
Temps (secondes)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21
2RABAK81
1MANDAS71
1MANDAS81
1SEBETS71
1KALITS71

2.9 SHORT-CIRCUIT AT GIGEL GIBE II ON THE SEBETA - GIGEL GIBE II CIRCUIT

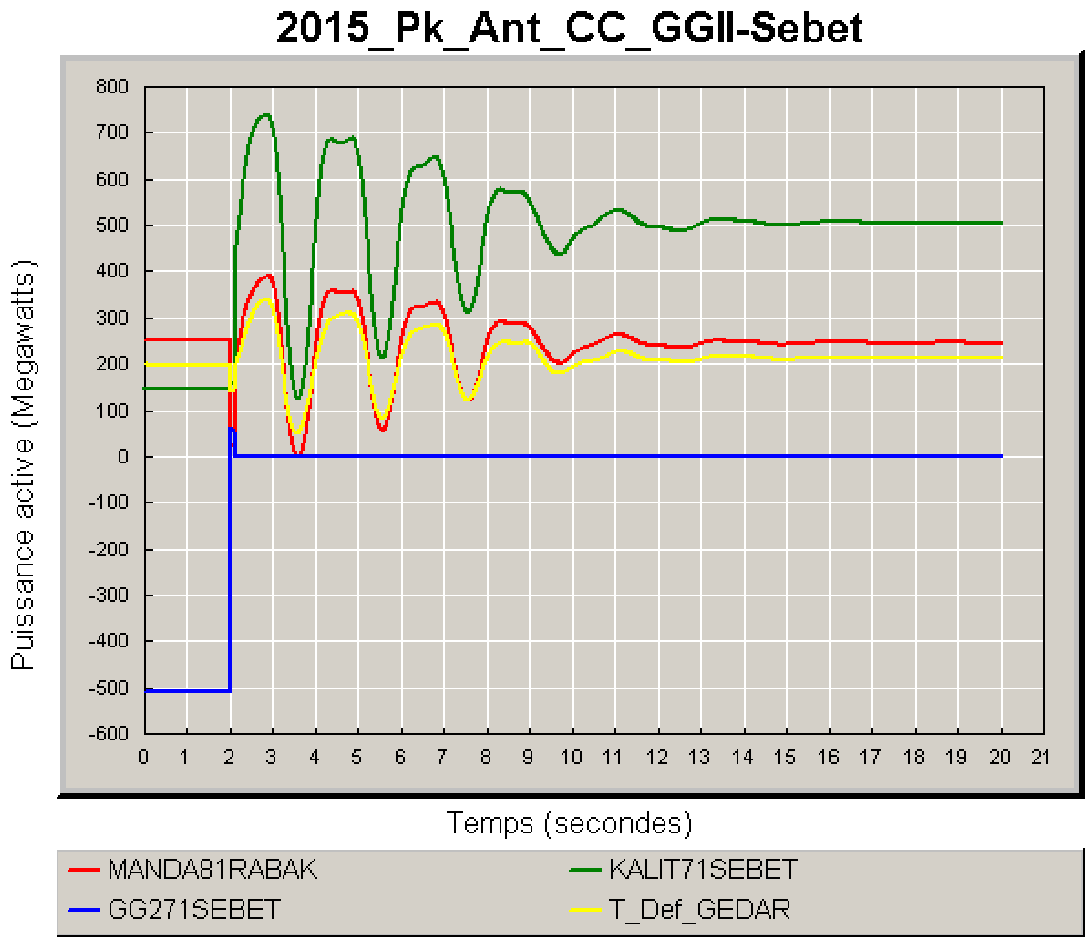
Event : a 3 phase short-circuit at Gigel Gibe II end, on the Sebeta - Gigel Gibe II circuit, cleared in 100 ms by the opening of the circuit breakers.

2.9.1 GENERATORS FREQUENCY VARIATION

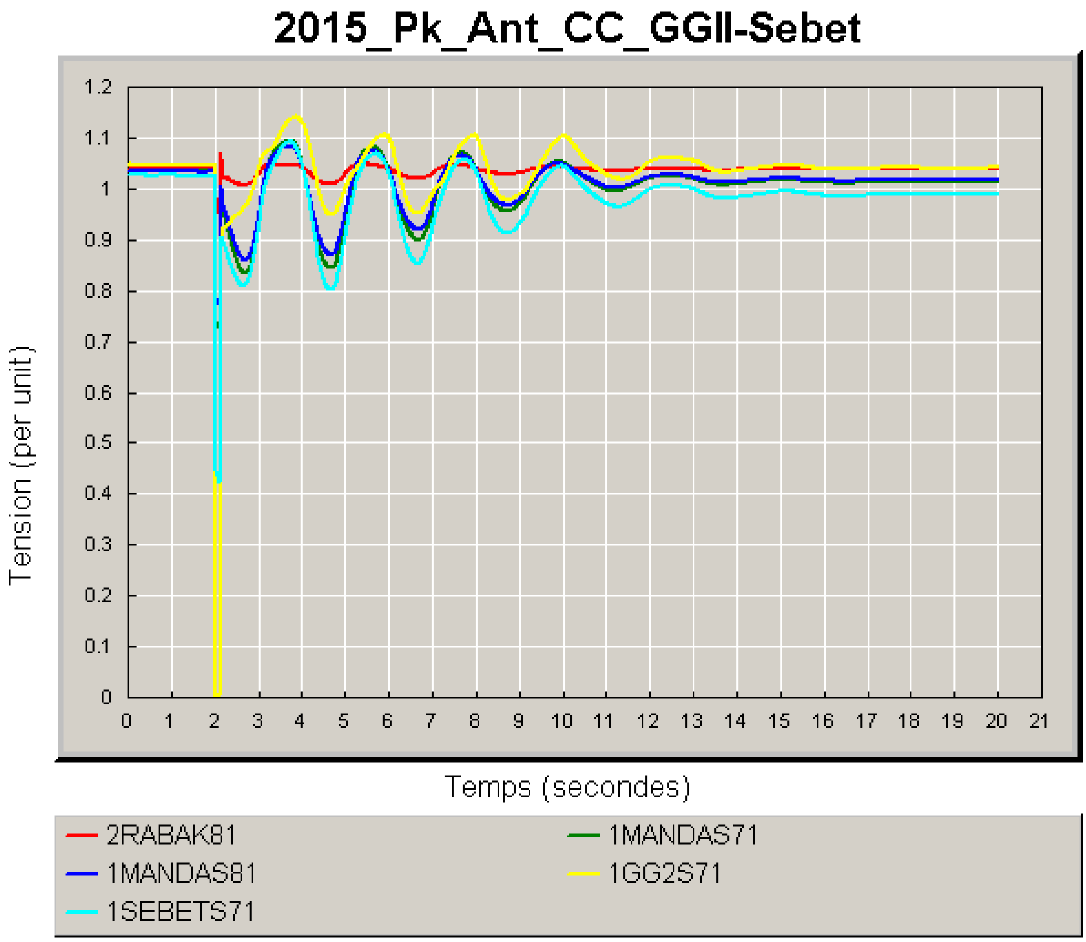


GG2 is Gigel Gibe II
GG3 is Gibe III

2.9.2 POWER FLOW VARIATION ON THE INTERCONNECTION AND ON SEBETA CIRCUITS



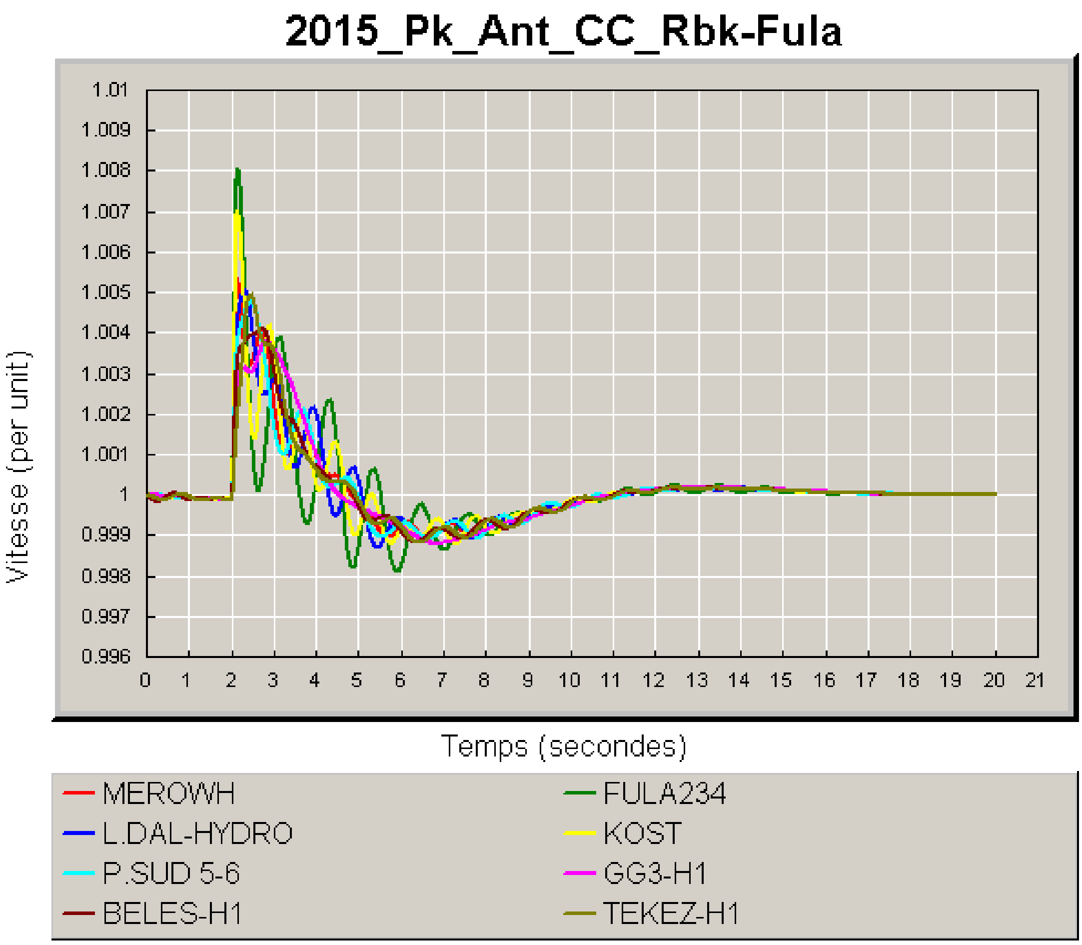
2.9.3 VOLTAGE VARIATION ON THE 400 AND 500 KV



2.10 SHORT-CIRCUIT AT KOSTI ON KOSTI - FULA

Event : a 3 phase short-circuit at Kosti end, on one of the 2 circuits Kosti - Fula, cleared in 120 ms by the opening of the circuit breakers.

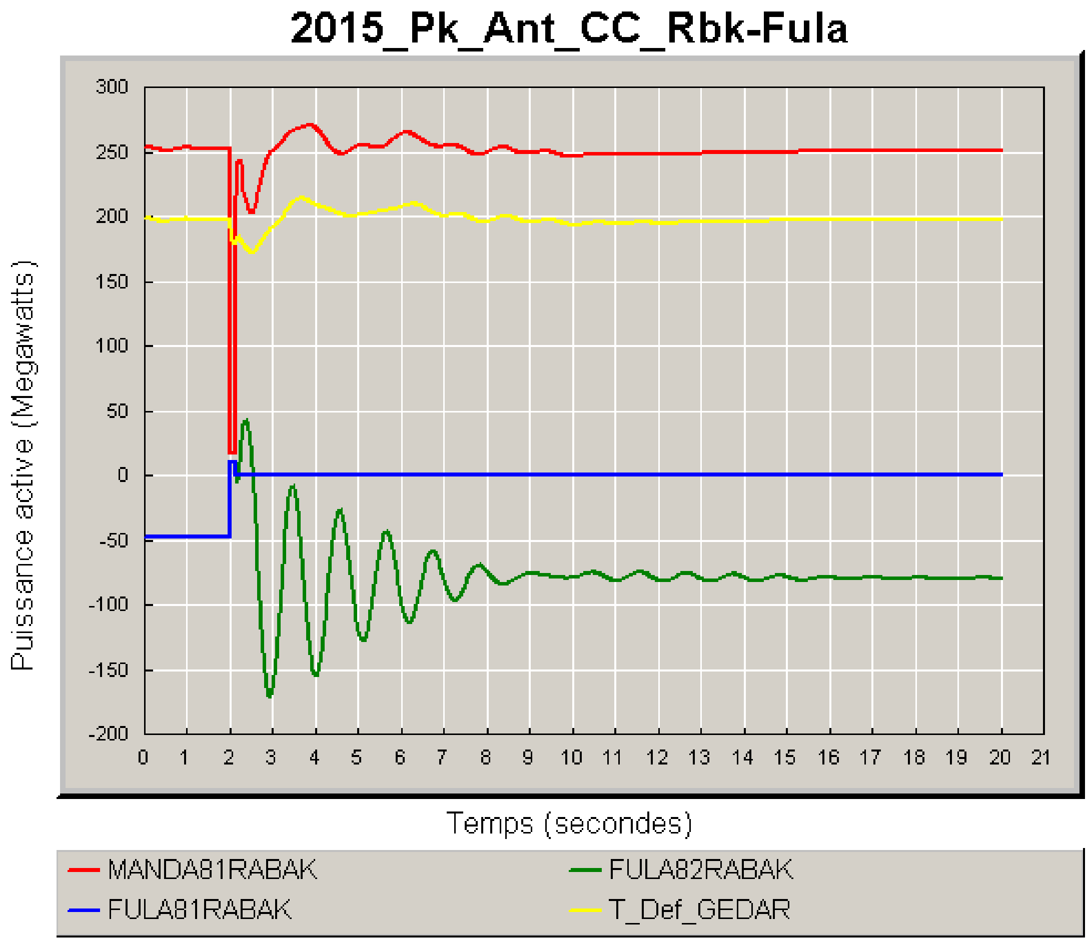
2.10.1 GENERATORS FREQUENCY VARIATION



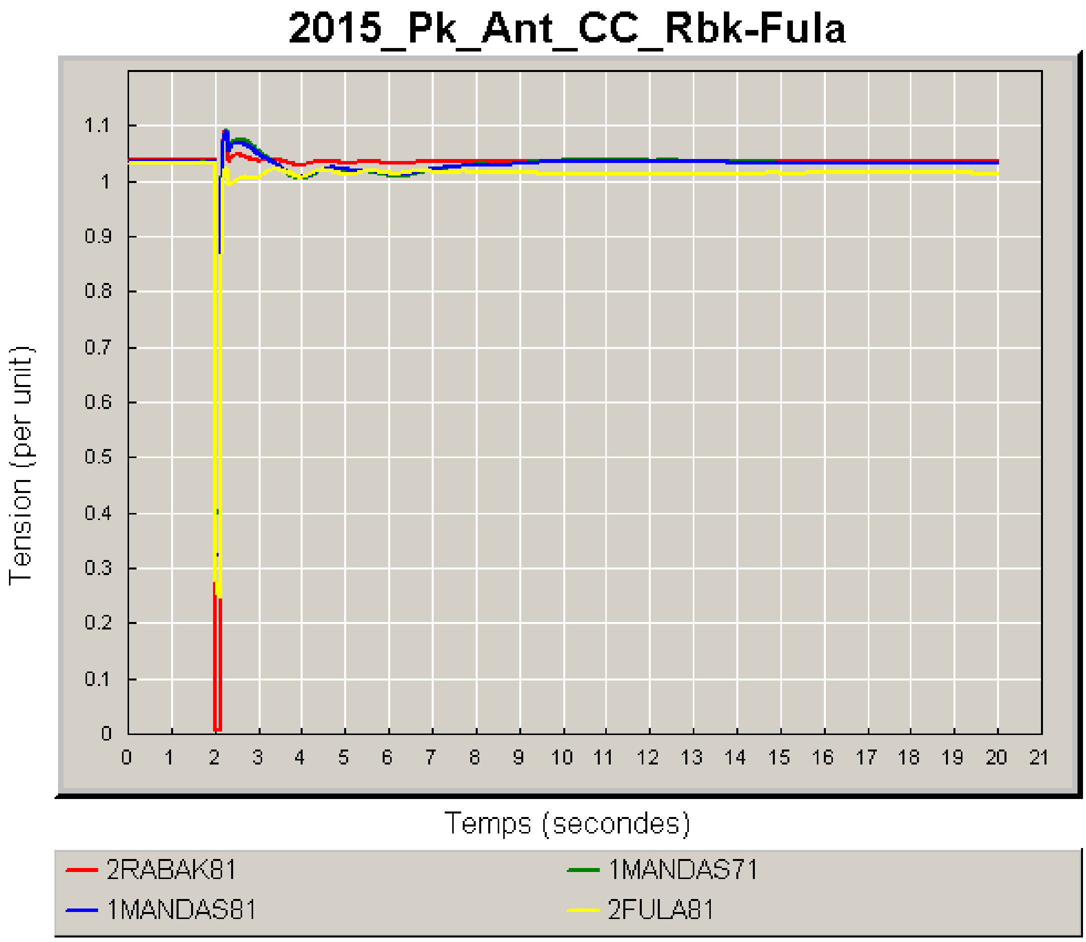
GG3 is Gibe III

Fula234 are Fula 128 MW steam units

2.10.2 POWER FLOW VARIATION ON ENTRO INTERCONNECTION



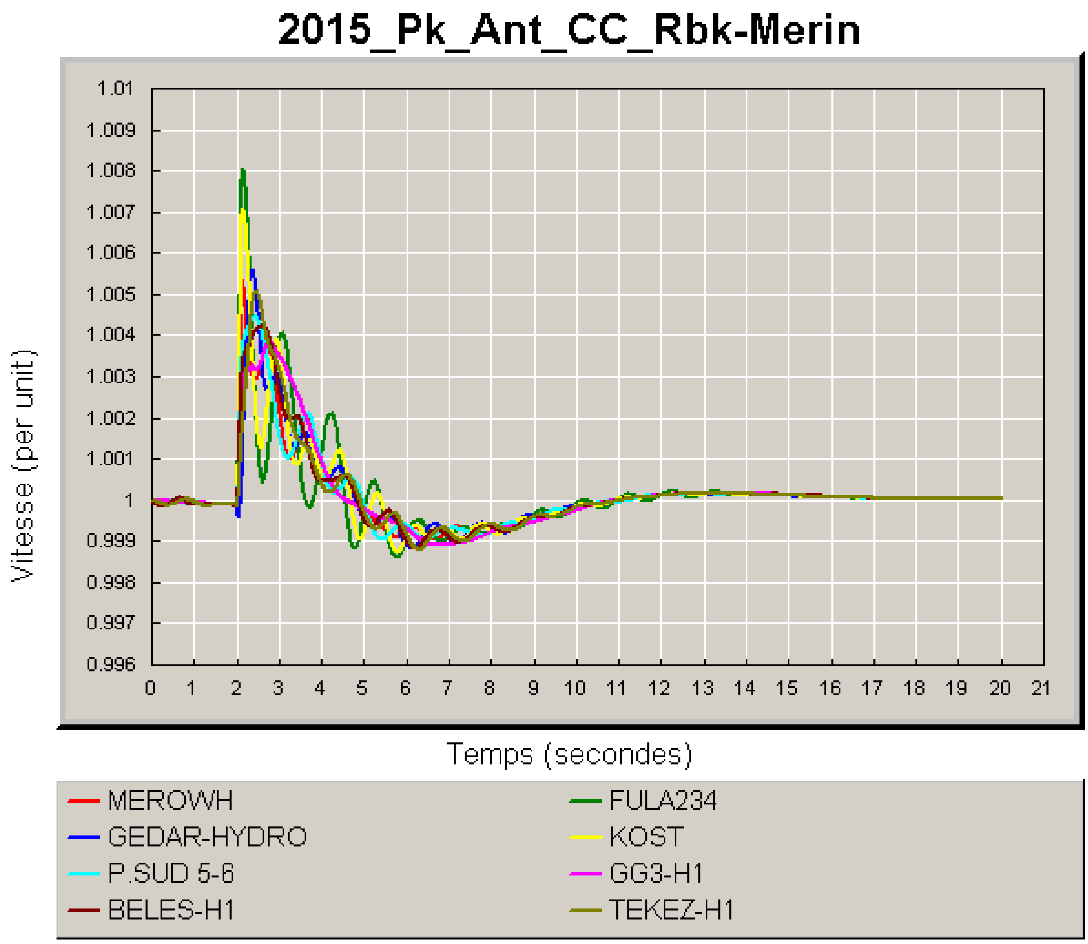
2.10.3 VOLTAGE VARIATION ON THE 400 AND 500 KV



2.11 SHORT-CIRCUIT AT KOSTI ON KOSTI - MERINGAN

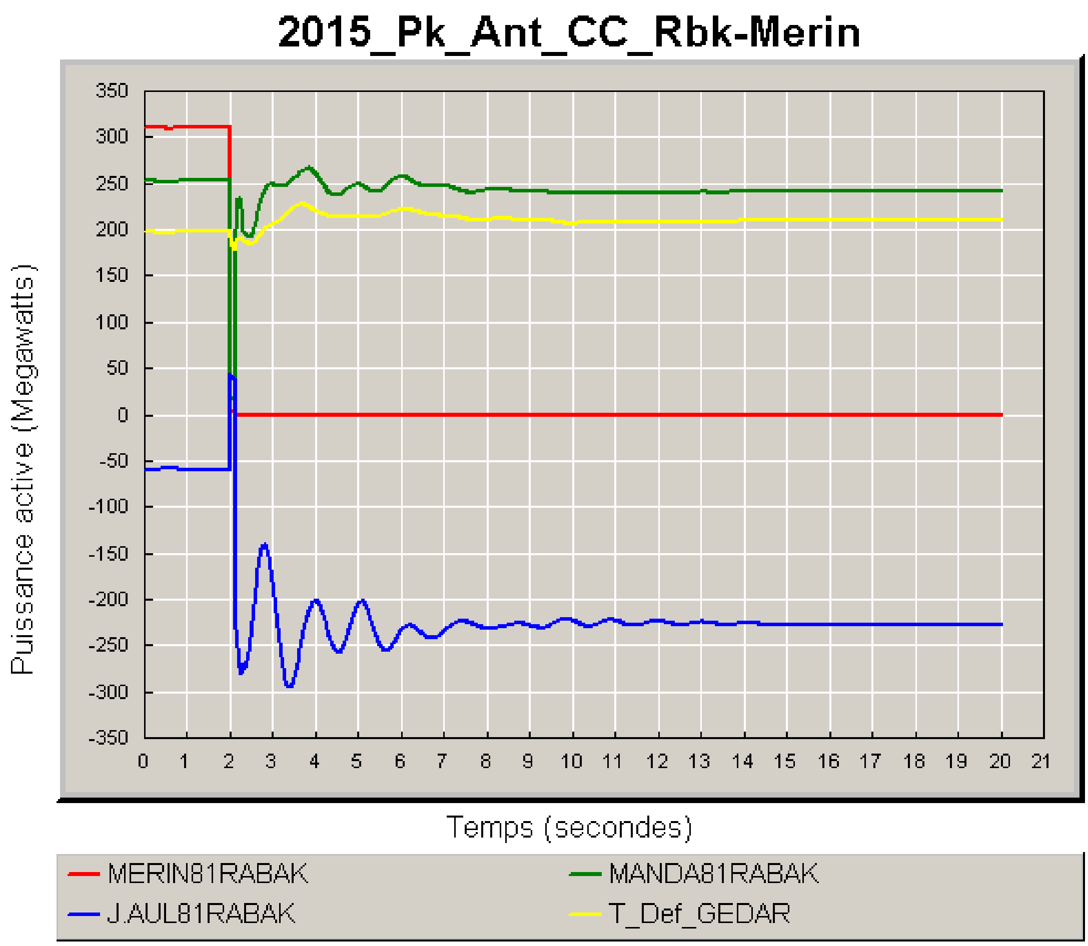
Event : a 3 phase short-circuit at Kosti end, on the circuit Kosti - Meringan, cleared in 120 ms by the opening of the circuit breakers.

2.11.1 GENERATORS FREQUENCY VARIATION

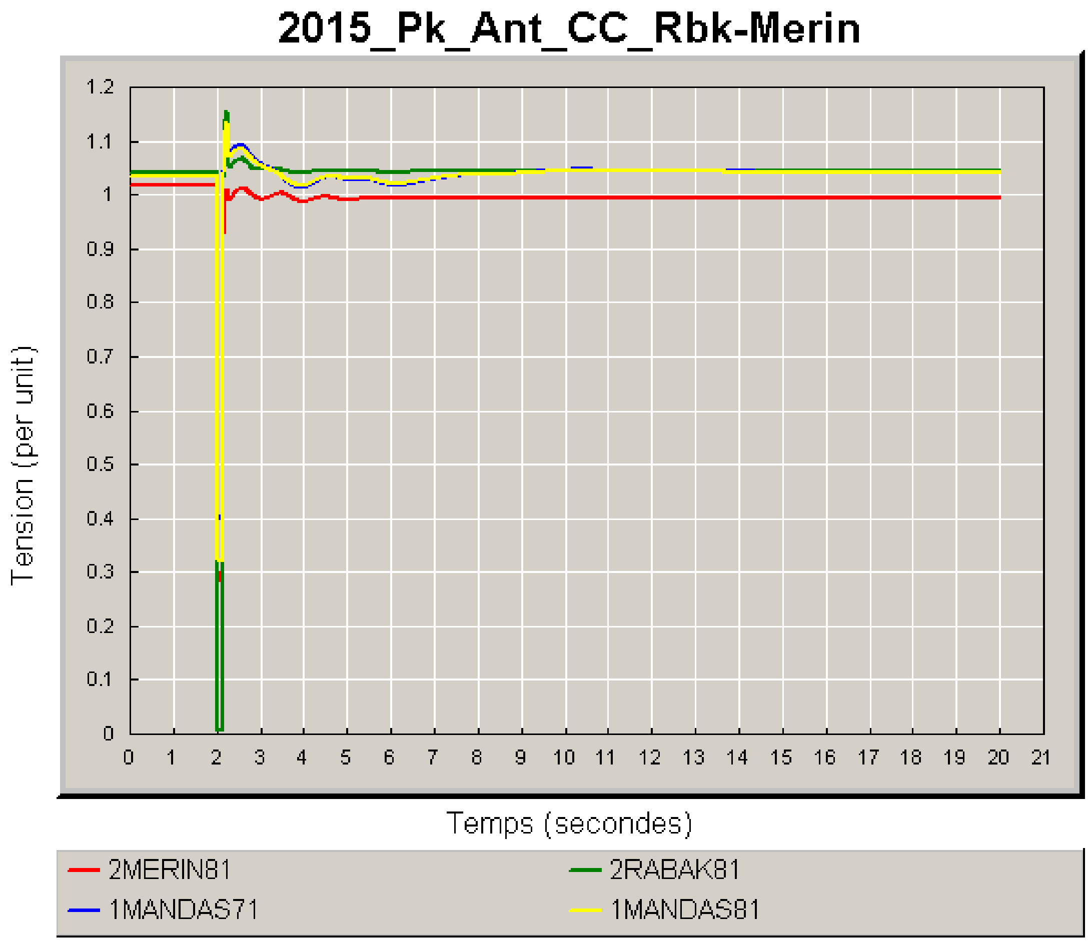


GG3 is Gibe III

2.11.2 POWER FLOW VARIATION ON ENTRO INTERCONNECTION AND ON KOSTI - MERINGAN, KOSTI - FULA AND KOSTI - J. AULIA



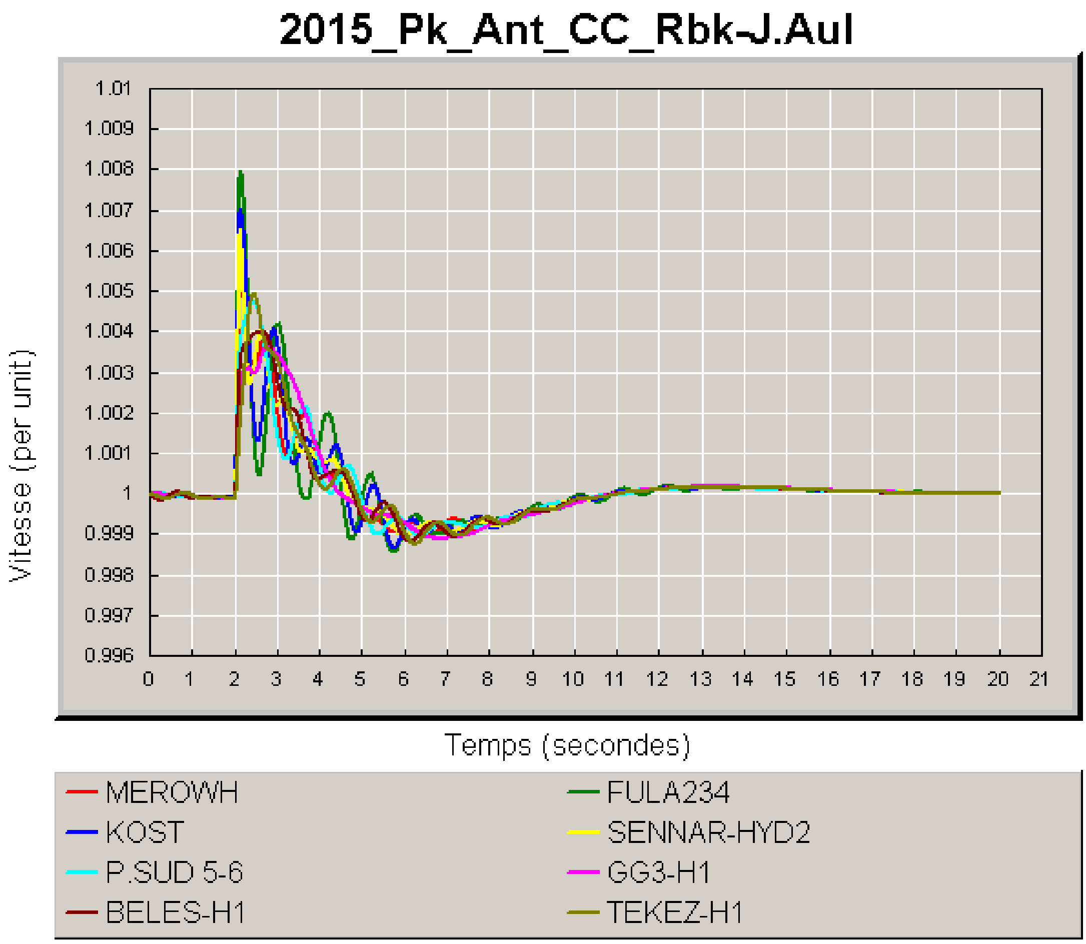
2.11.3 VOLTAGE VARIATION ON THE 400 AND 500 KV



2.12 SHORT-CIRCUIT AT KOSTI ON KOSTI - JEBEL AULIA

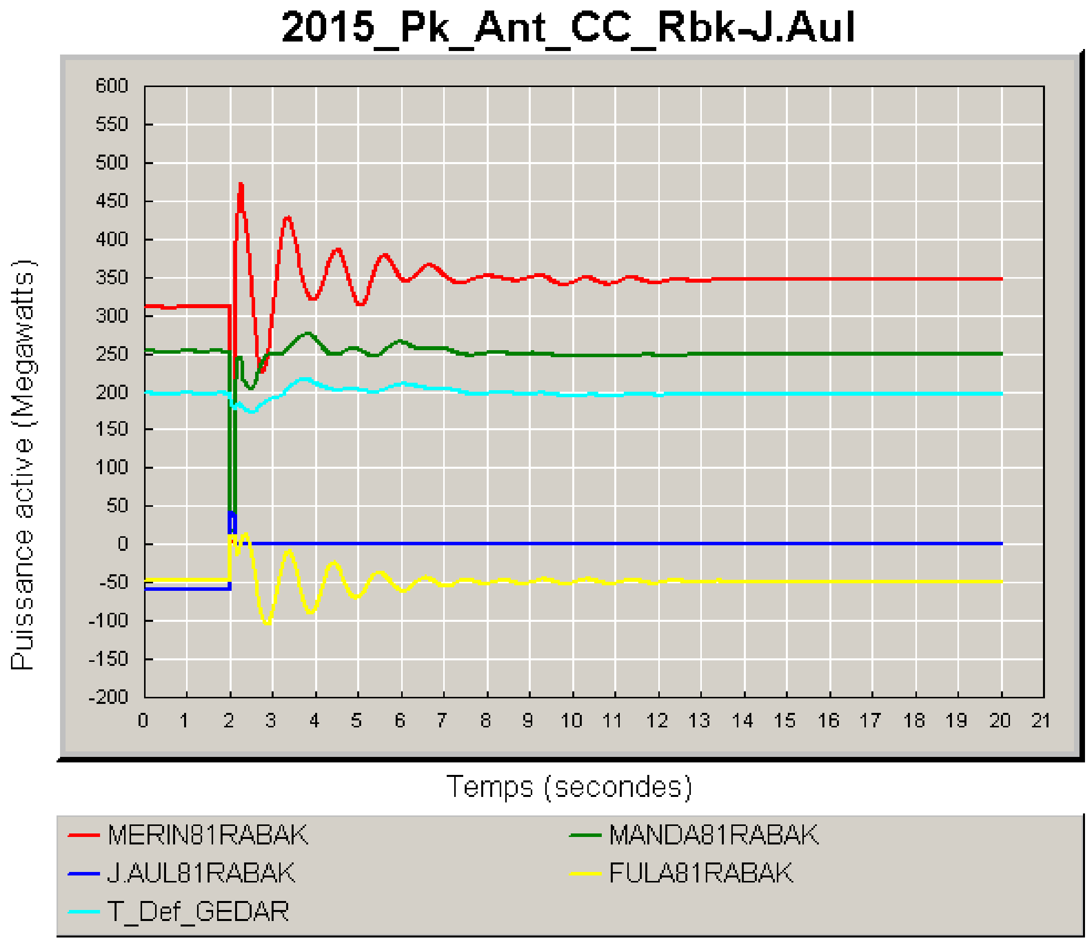
Event : a 3 phase short-circuit at Kosti end, on the circuit Kosti - Jebel Aulia, cleared in 120 ms by the opening of the circuit breakers.

2.12.1 GENERATORS FREQUENCY VARIATION

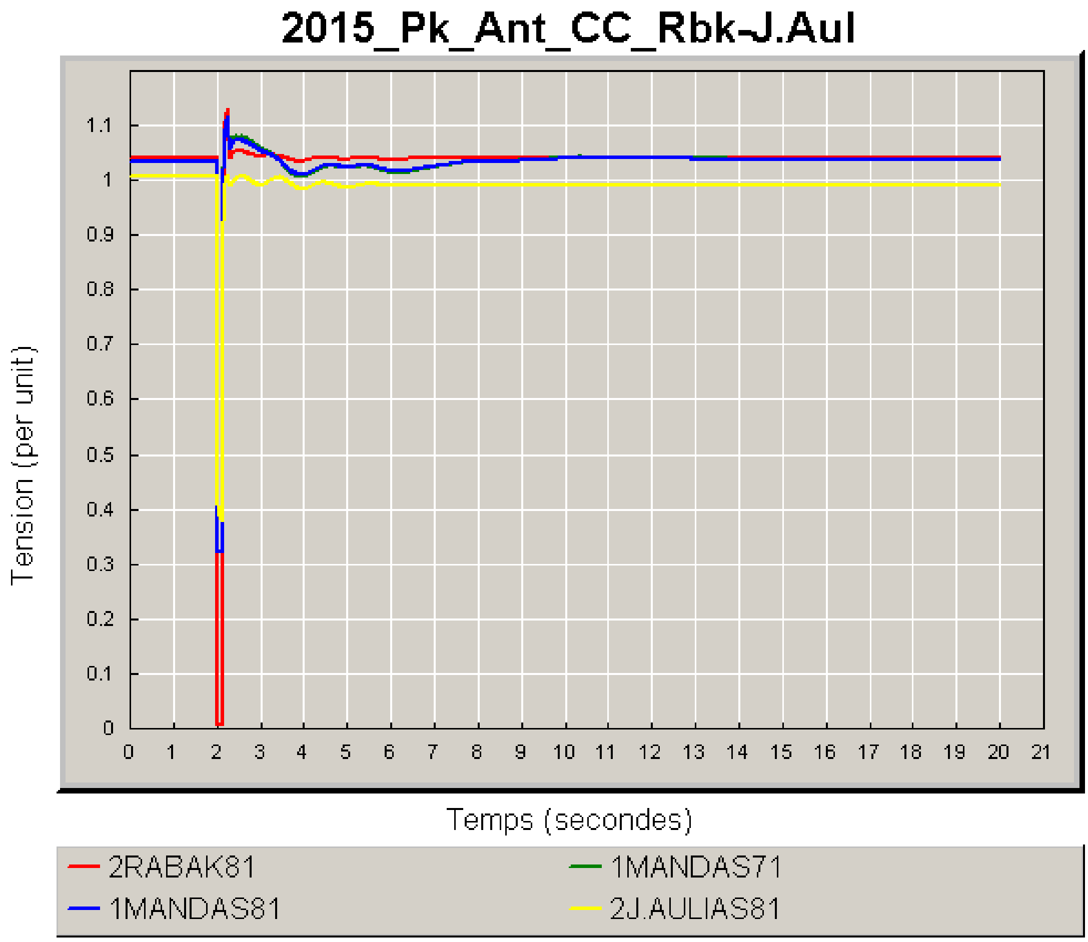


GG3 is Gibe III

2.12.2 POWER FLOW VARIATION ON THE INTERCONNECTION AND ON KOSTI - JEBEL AULIA AND KOSTI - MERINGAN



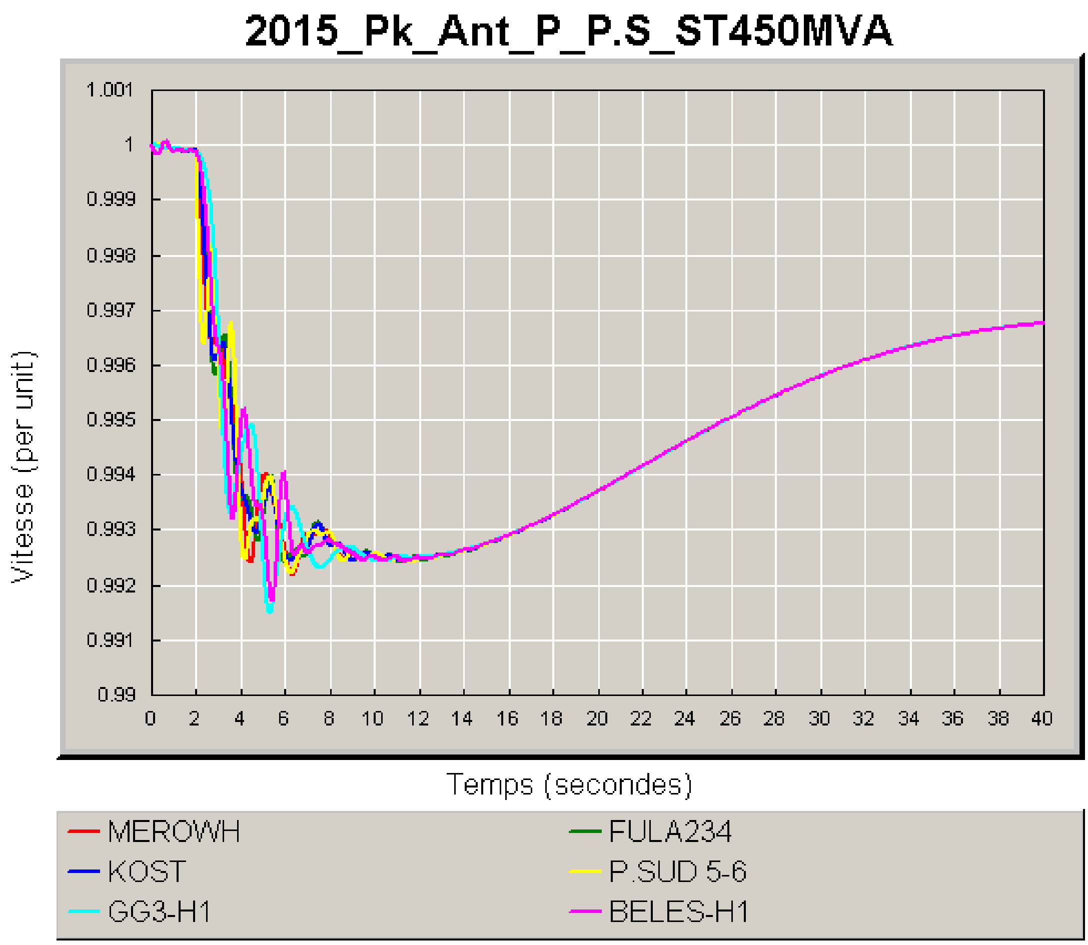
2.12.3 VOLTAGE VARIATION ON THE 400 AND 500 KV



2.13 TRIPPING OF THE MAIN UNIT IN SUDAN : PORT SUDAN 380 MW STEAM TURBINE

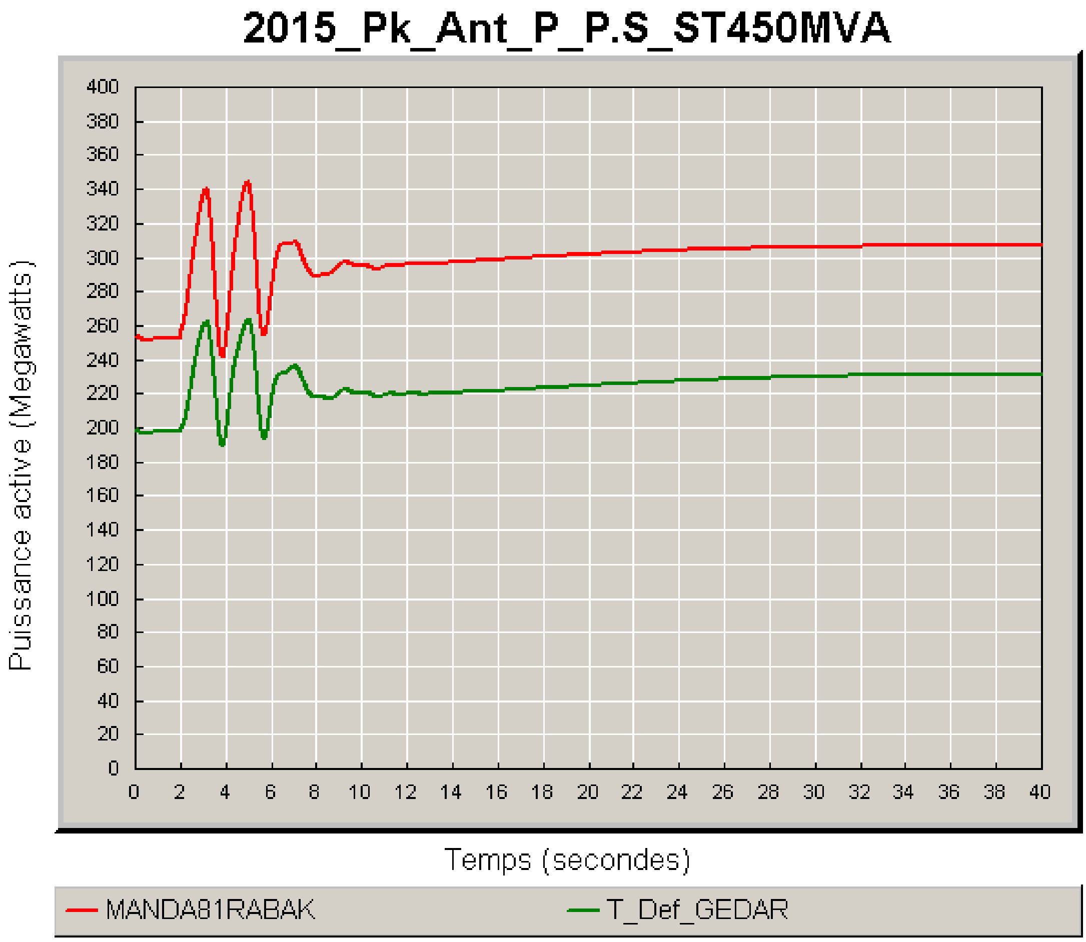
Event : the 450 MVA steam unit of Port-Sudan (the main unit in Sudan) is tripped.

2.13.1 GENERATORS FREQUENCY VARIATION

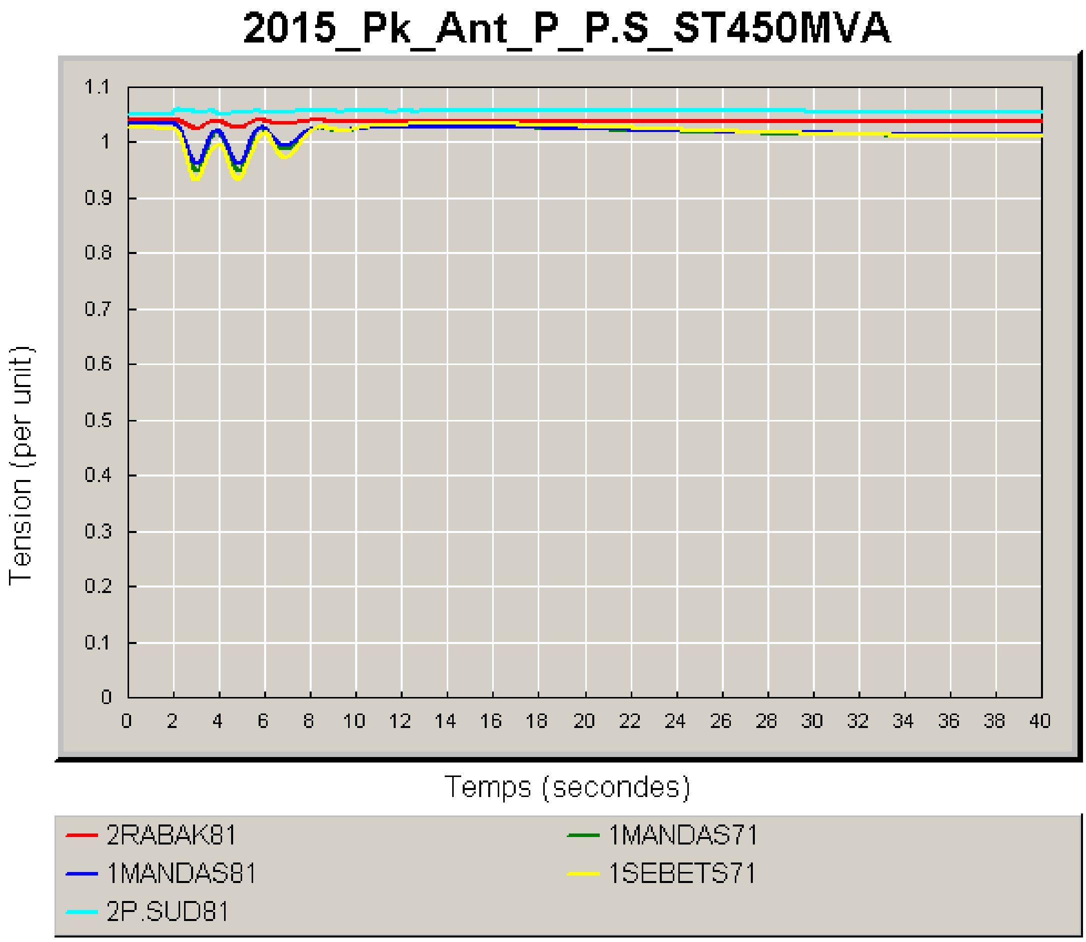


GG3 is Gibe III

2.13.2 POWER FLOW VARIATION ON THE INTERCONNECTION

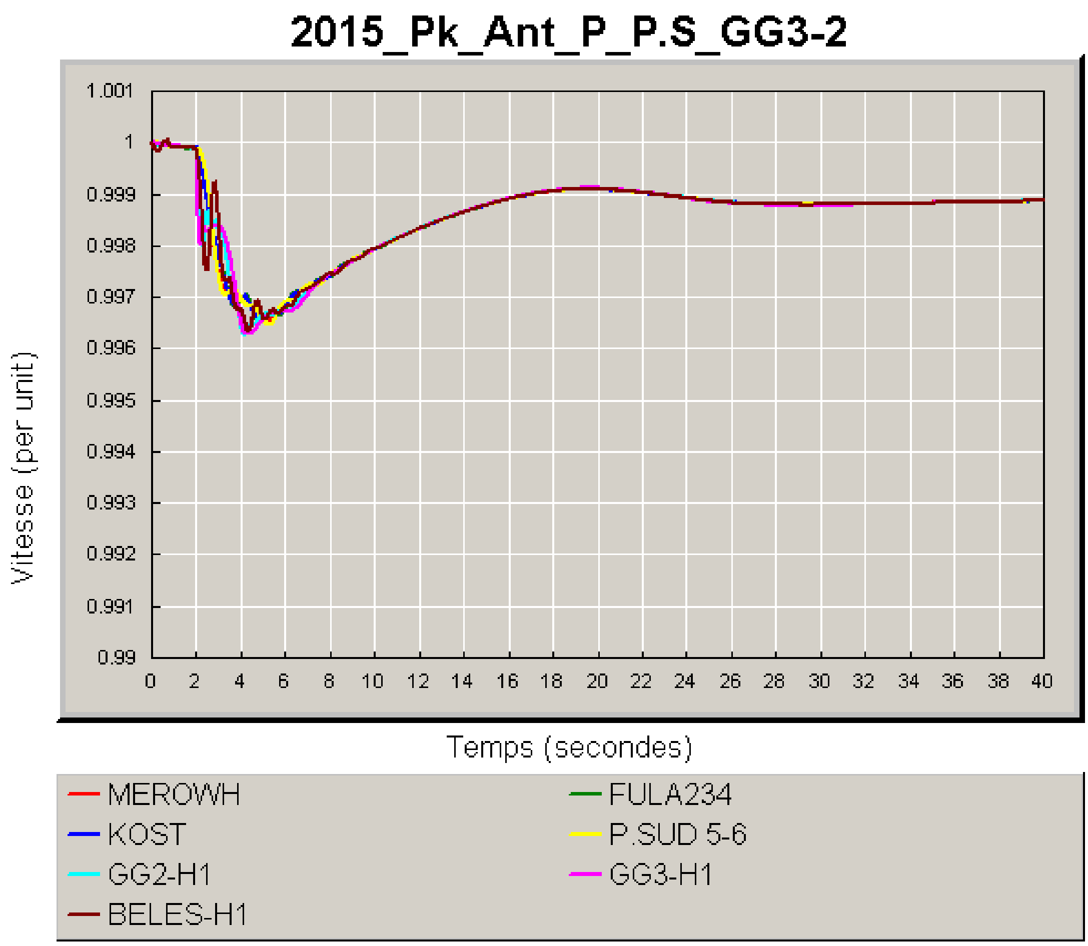


2.13.3 VOLTAGE VARIATION



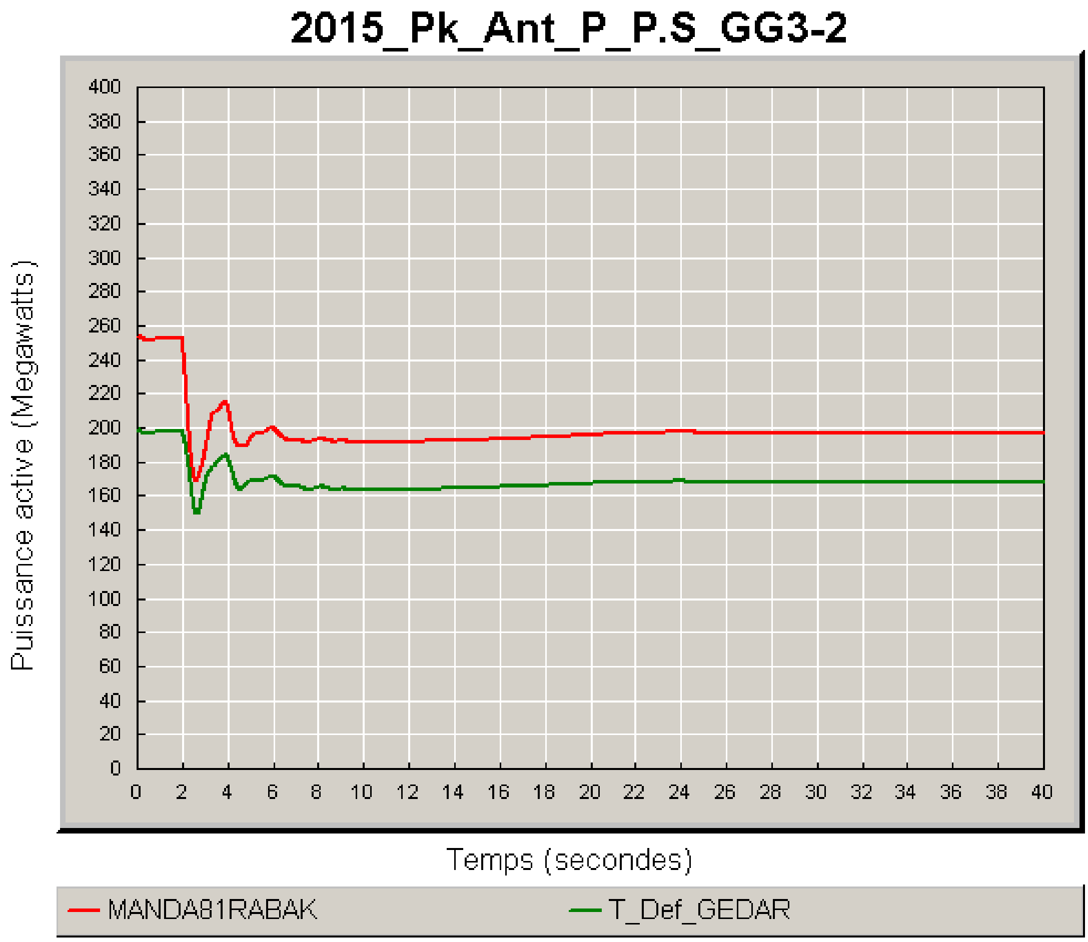
2.14 TRIPPING OF THE MAIN UNIT IN ETHIOPIA : GIBE III 225 MW UNIT

2.14.1 GENERATORS FREQUENCY VARIATION

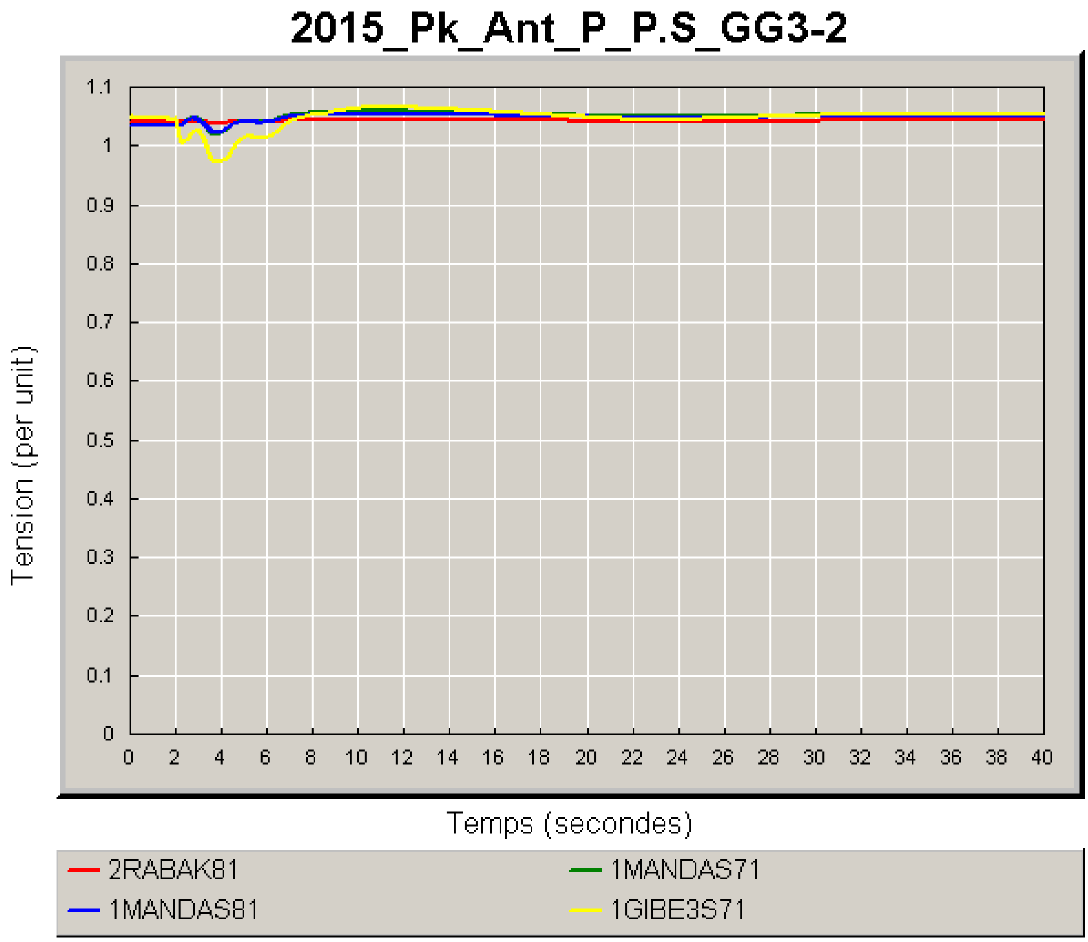


GG3 is Gibe III

2.14.2 POWER FLOW VARIATION ON THE INTERCONNECTION



2.14.3 VOLTAGE VARIATION

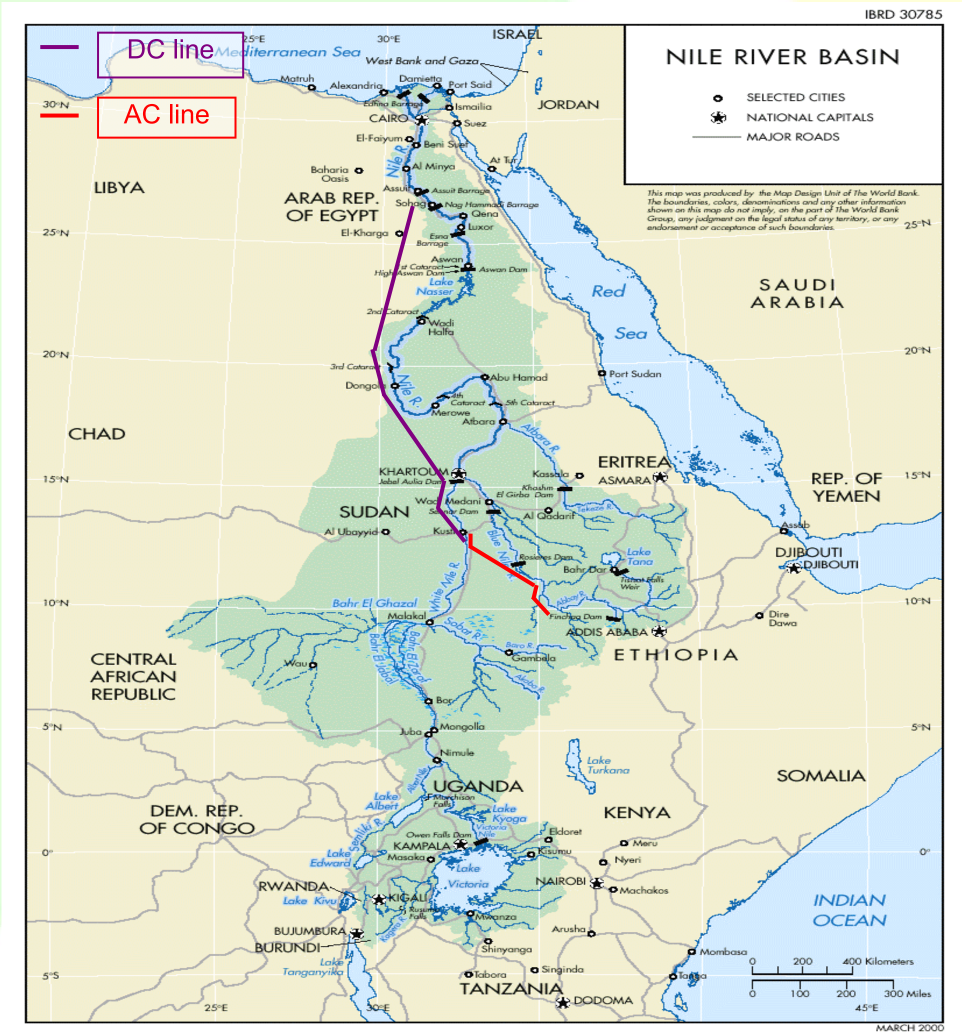


Nile Basin Initiative

Eastern Nile Subsidiary Action Program

Eastern Nile Technical Regional Office

EASTERN NILE POWER TRADE PROGRAM STUDY



M1 - 2020 APPENDIX - STABILITY STUDY

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LIST OF FIGURES

ABBREVIATIONS AND ACRONYMS

AC	Alternative Current
CCG	Combined Cycle Gas turbine
DC	Direct Current
ENPTPS	Eastern Nile Power Trade Program Study
EDF	Electricité de France
EN	Eastern Nile
ENTRO	Eastern Nile Technical Regional Office
GEP	Generation Expansion Plan
HPP	Hydro Power Plant
HD	High Dam
HV	High Voltage
HVDC	High Voltage Direct Current
NBI	Nile Basin Initiative
NH	Nag Hammadi
p.u	per unit
ST	Steam Turbine
SVC	Static Voltage Compensator
SW	Scott Wilson
TPP	Thermal Power Plant

1 TRANSIENT STABILITY ANALYSIS HYPOTHESIS

<u>The volume of spinning reserve</u> set as followed :

- Libya : 50 MW
- Jordan and Syria : 100 MW
- Egypt : 404 MW (104 MW on hydropower plants + 300 MW on thermal plants)
- Sudan : 420 MW
- Ethiopia : 697 MW (hydropower plant only)

Load voltage and frequency dependency coefficients

	dP/dV	dP/df	dQ/dV	dQ/df
Egypt	0.83	1.46	4.01	-0.88
Ethiopia	0.94	1.26	3.67	-1.29
Sudan	0.79	1.53	4.14	-0.72

<u>Load of Libya, Jordan and Syria</u>

The 2020 peak load forecast for Libya reached 7100 MW.

The 2020 peak load forecast for Jordan and Syria reached 15000 MW.

<u>Calculation of the damping magnitude of the power oscillations</u>

The power oscillations evolve according to the formula :

$$\mathbf{A.e^{-\alpha t}.cos(\omega t+\varphi)} \quad \text{with } \omega=2\pi f_x$$

From the curves it is possible to measure the frequency, f_x of the oscillations. (generally a low value close to 0.3Hz or 0.5Hz)

The apparent damping coefficient D of the oscillation mode is equal to :

$$\mathbf{D}=\frac{\boldsymbol{\alpha}}{\sqrt{(\alpha^2+\beta^2)}} \qquad \text{with } \beta = 2\pi f$$

and α is like that $e^{-\alpha t}=0.05$ with ***t*** is the damping duration.

The international literature concerning the inter-area oscillations, indicates that an inter-area oscillation mode is acceptably damped if the damping coefficient is close to 5% and it is well damped if the damping coefficient is higher than 5%.

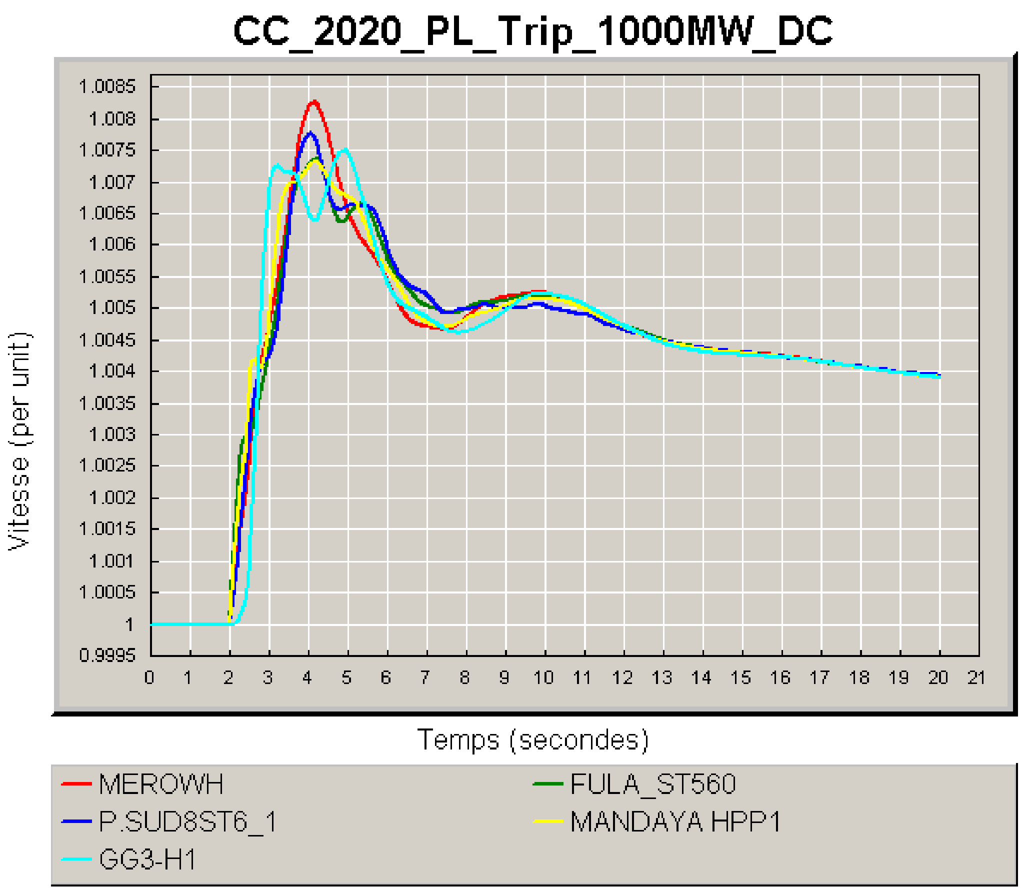
According to the above formula, the apparent damping coefficient for the average frequency was estimated from the curves and the results.

2 2020 PEAK LOAD SITUATION

2.1 TRIPPING OF ONE OF THE 2 POLES OF THE DC INTERCONECTION

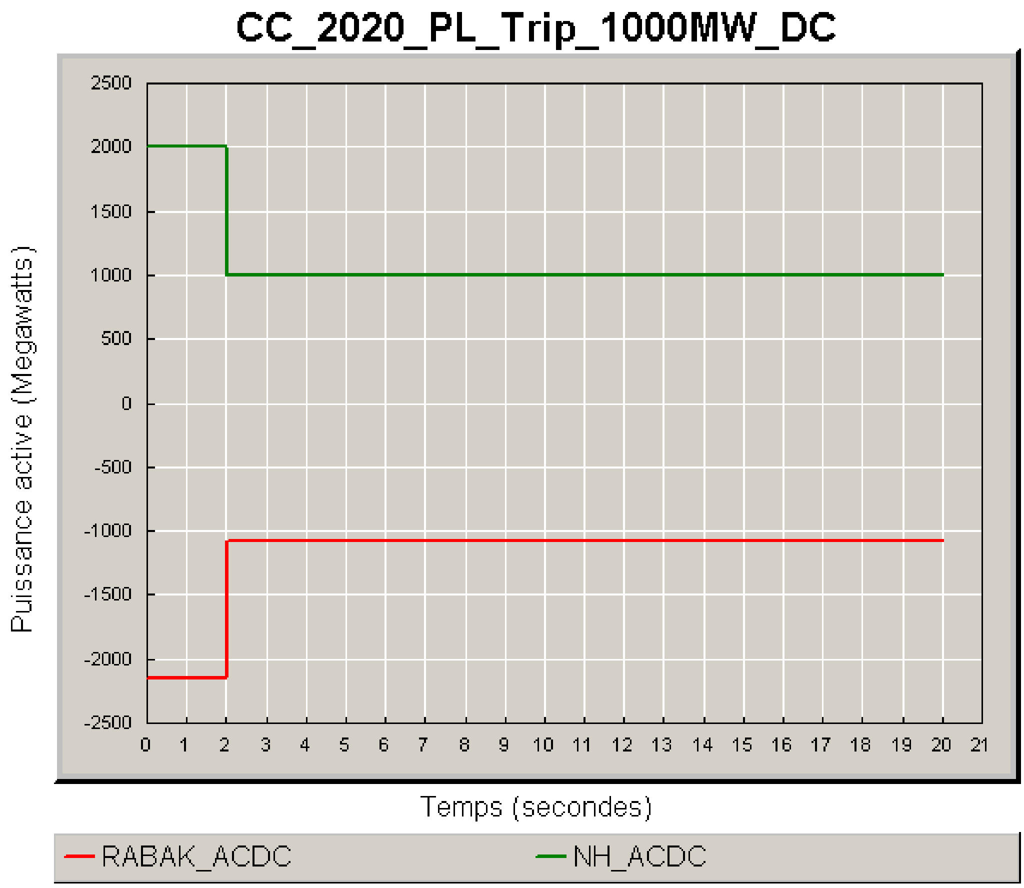
Event : one of the 2 poles was tripped following an internal fault. 200 ms after, half of the capacitor banks of each HVDC substations were disconnected.

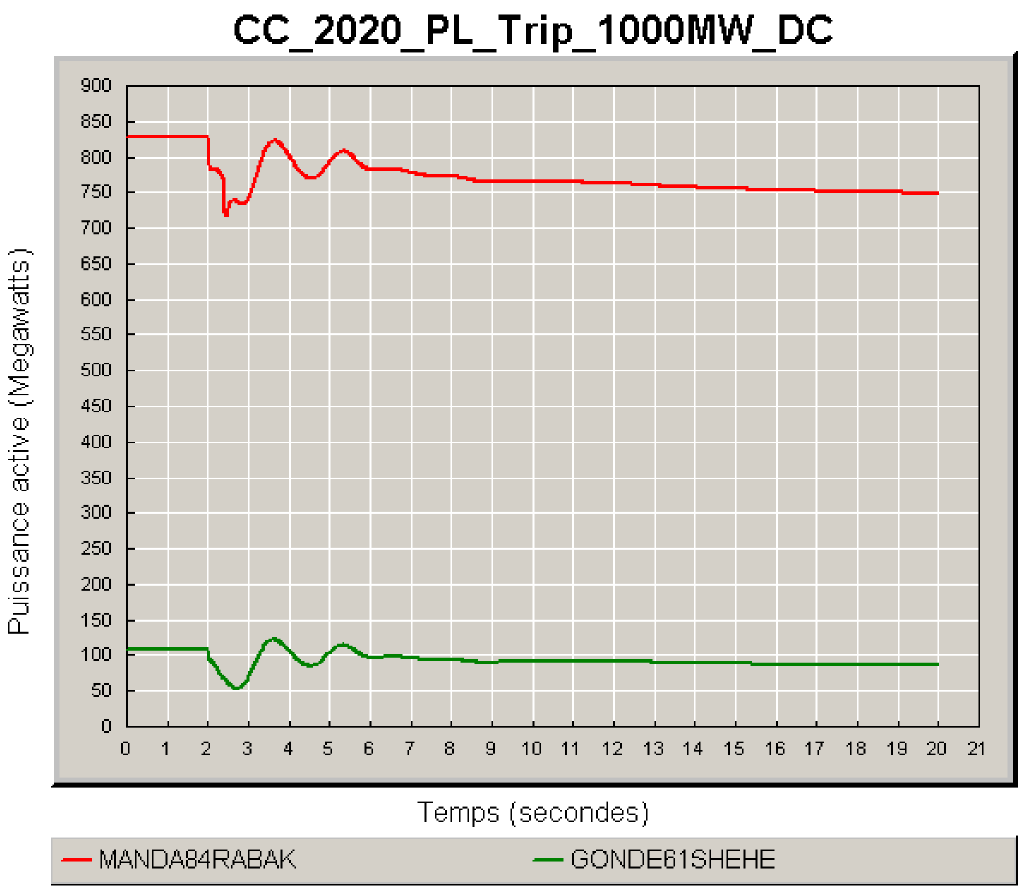
2.1.1 GENERATORS FREQUENCY VARIATION



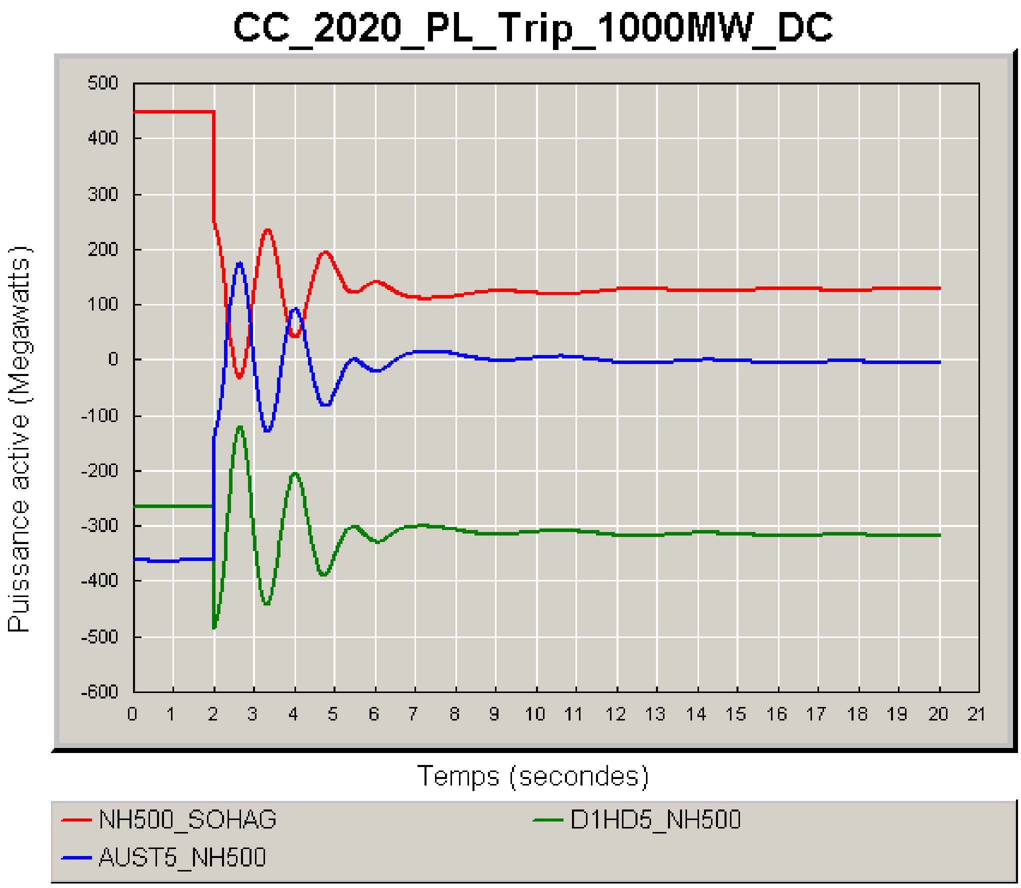
*GG3 is Gibe 3

2.1.2 POWER FLOW VARIATION ON INTERCONNECTION

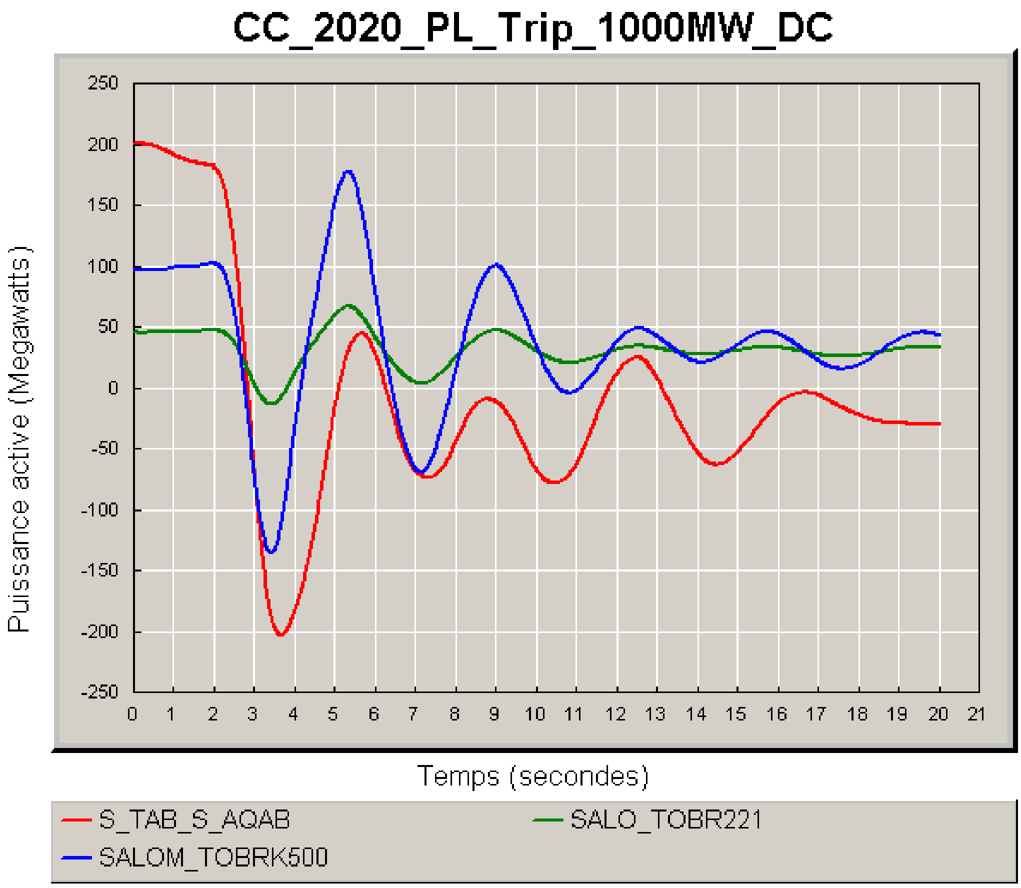



CC_2020_PL_Trip_1000MW_DC
Puissance active (Megawatts)
Temps (secondes)
MANDA84RABAK
GONDE61SHEHE

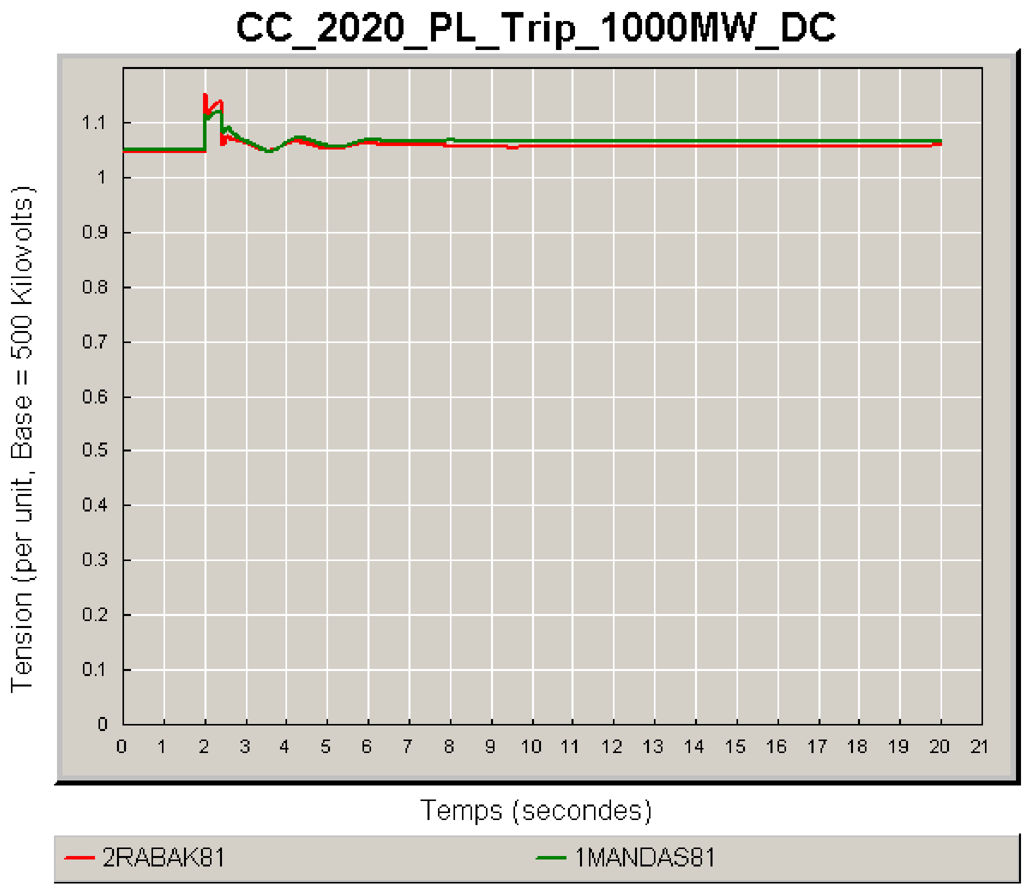
2.1.3 POWER FLOW VARIATION ON NAG HAMMADI 500 KV CIRCUITS



2.1.4 POWER FLOW VARIATION ON EGYPT INTERCONNECTIONS



2.1.5 VOLTAGE VARIATION ON THE 500 KV



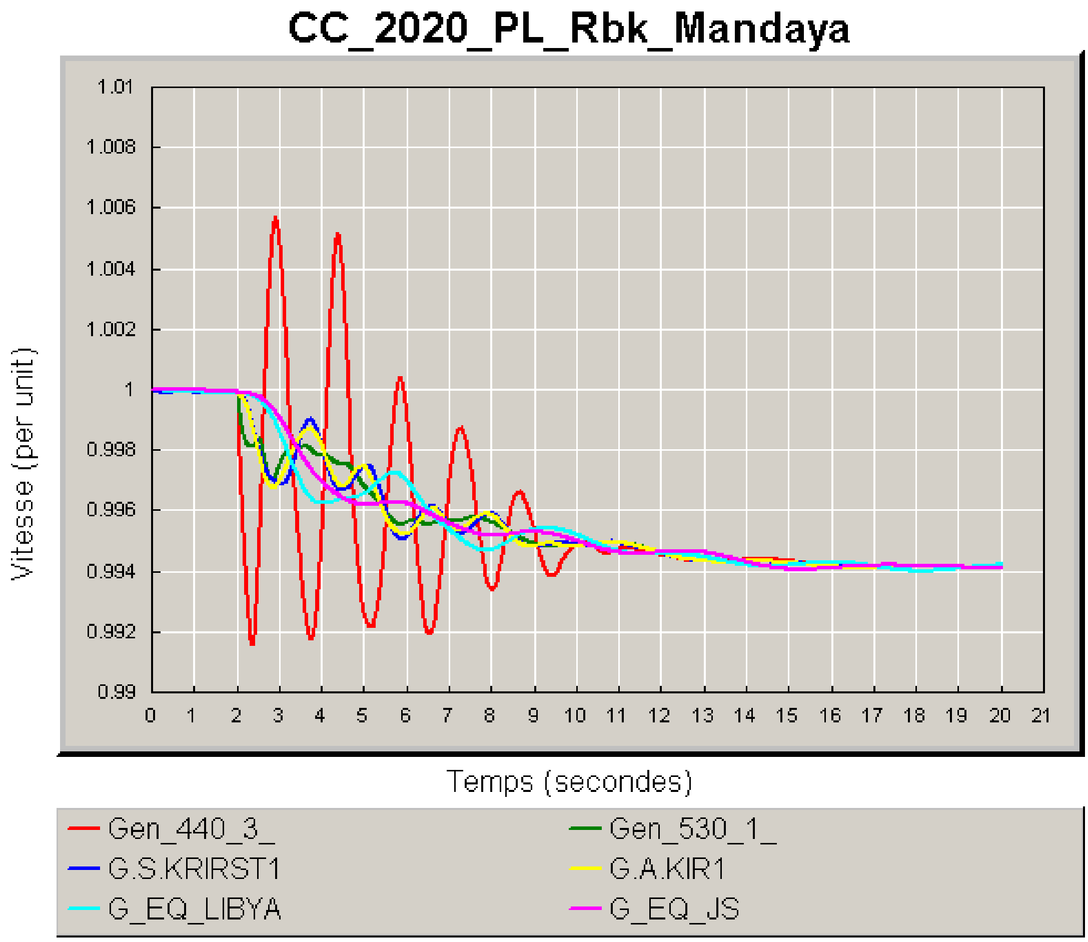
2.2 SHORT-CIRCUIT AT RABAK ON ONE OF THE 4 RABAK - MANDAYA CIRCUITS

Event : a 3 phase short-circuit at Rabak end, on one of the 4 circuits Mandaya - Rabak, cleared in 120 ms by the opening of the circuit breakers.

The voltage drop in Rabak (0 pu) led to a transitory blocking of commutation of the inverter station at Rabak. The flow on the DC interconnection is transitory reduced to 0, before recovering to half of its initial value. At the same time, half of the capacitor banks were triped.

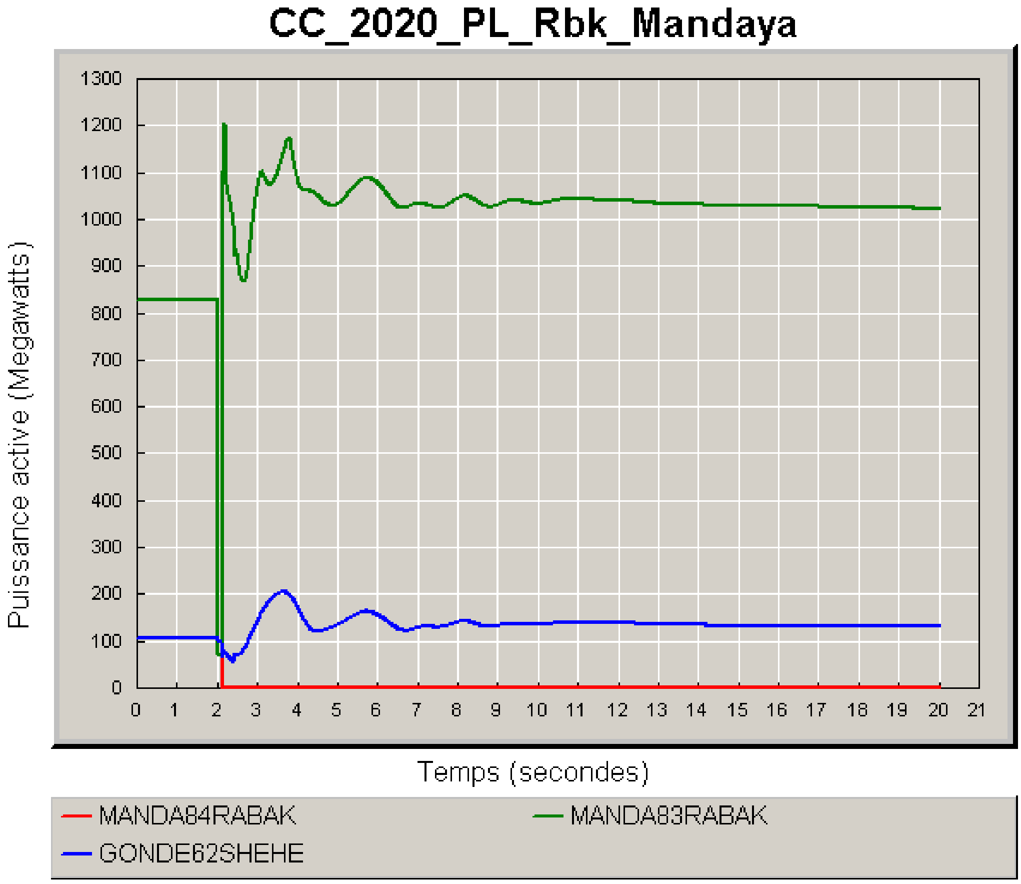
During the transitory blocking of the DC stations, the capacitors bank remained connected.

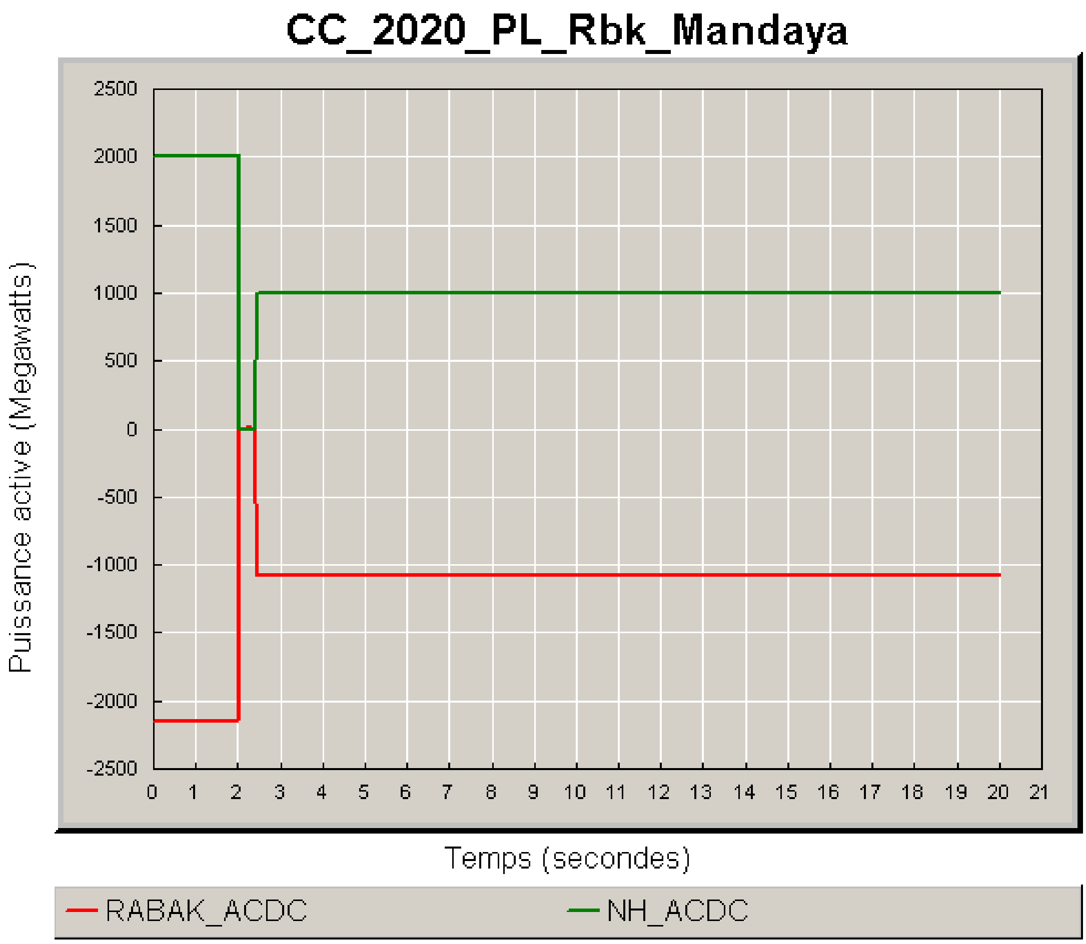
2.2.1 GENERATORS FREQUENCY VARIATION



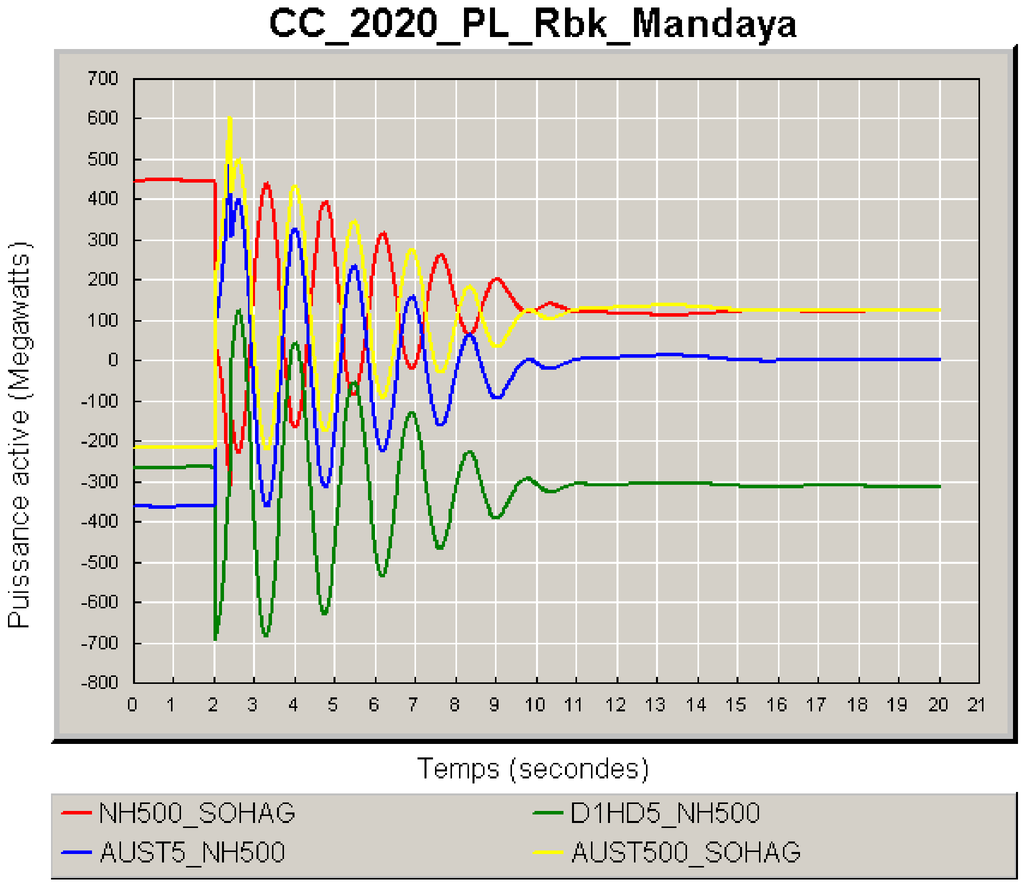
Gen_440_3 is a group of High Dam
Gen_530_1 is group 1 of Kurimat existing steam
GG3 is Gibe III

2.2.2 POWER FLOW VARIATION ON ENTRO INTERCONNECTION

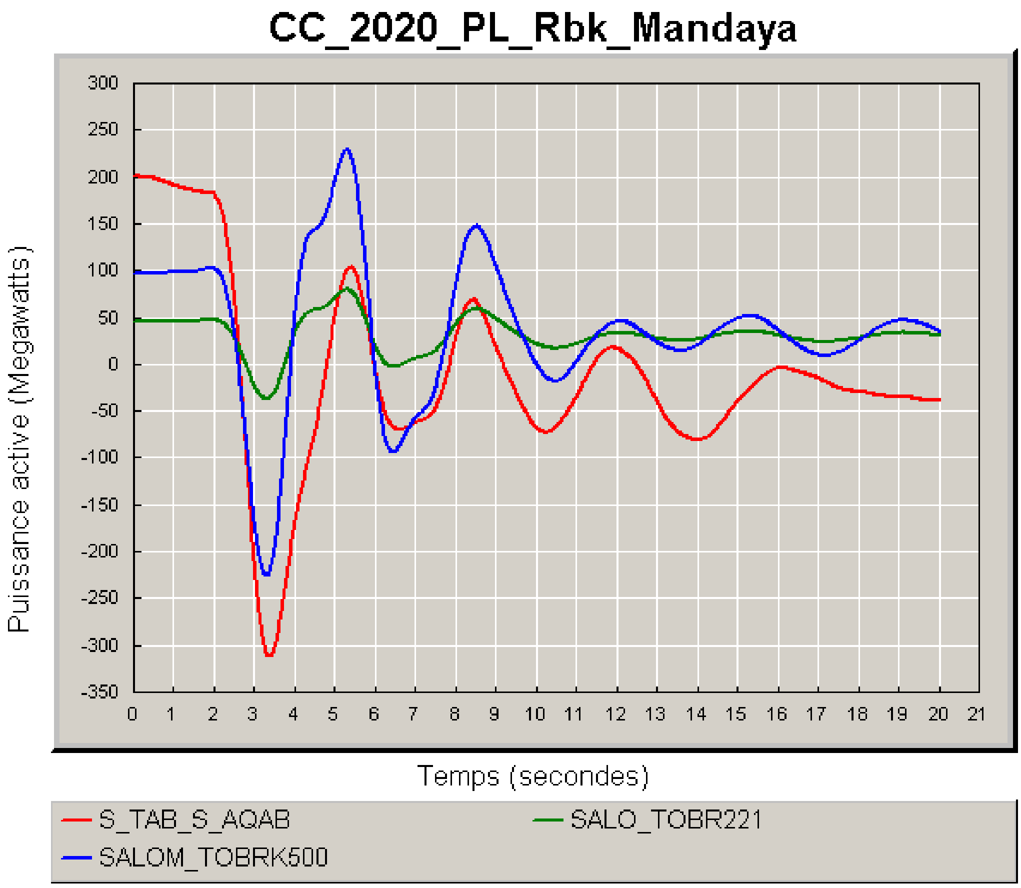



CC_2020_PL_Rbk_Mandaya
Puissance active (Megawatts)
2500
2000
1500
1000
500
0
-500
-1000
-1500
-2000
-2500
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21
Temps (secondes)
RABAK_ACDC
NH_ACDC

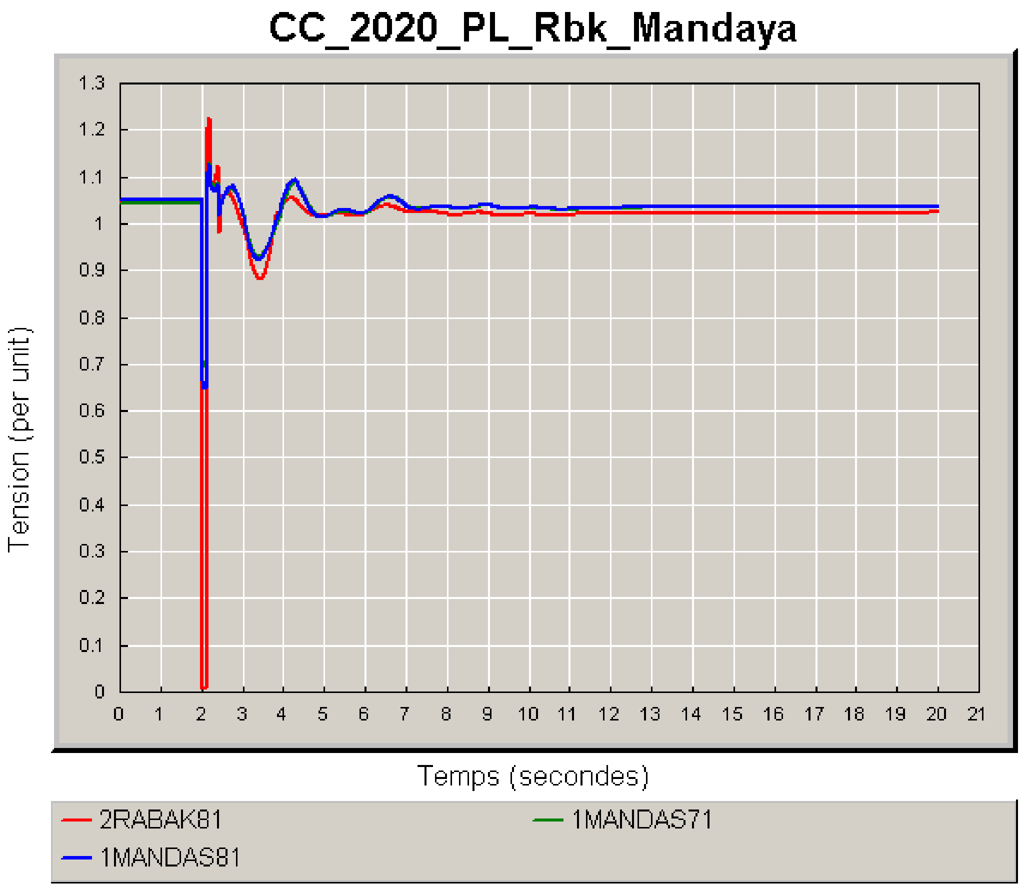
2.2.3 POWER FLOW VARIATION ON NAG HAMMADI 500 KV CIRCUITS

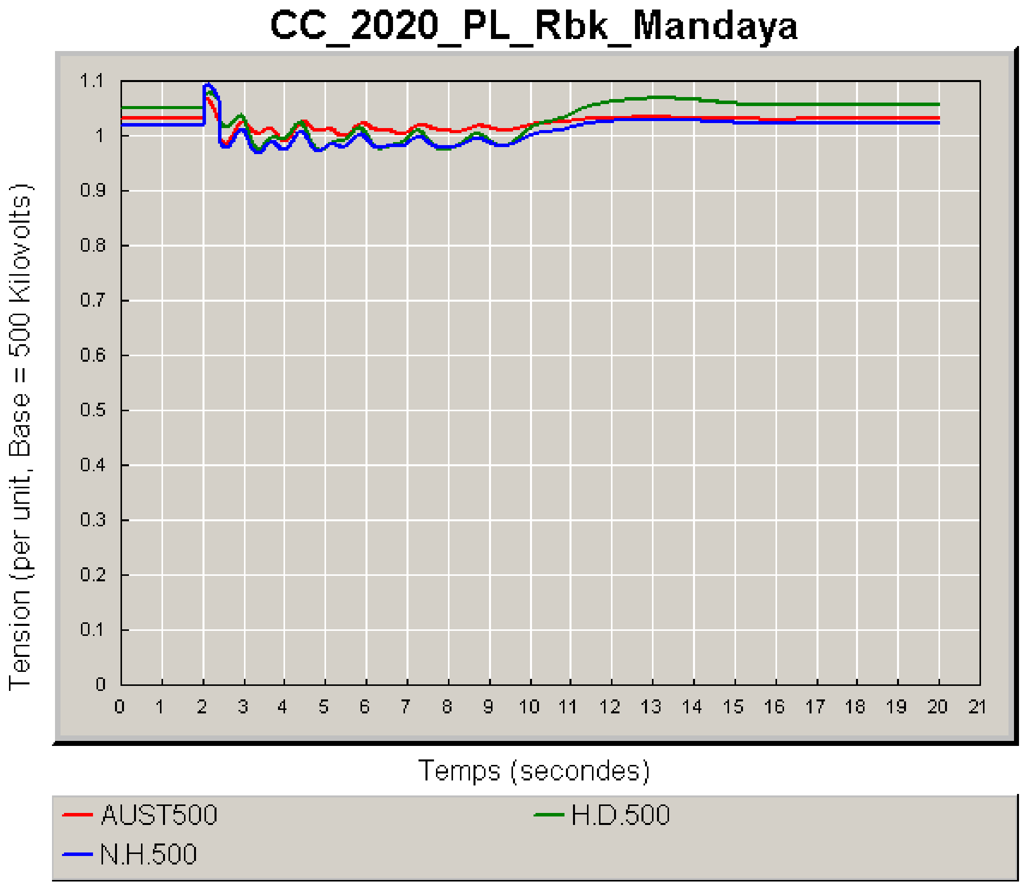


2.2.4 POWER FLOW VARIATION ON EGYPT INTERCONNECTIONS



2.2.5 VOLTAGE VARIATION ON THE 500 KV




CC_2020_PL_Rbk_Mandaya
Tension (per unit, Base = 500 Kilovolts)
Temps (secondes)
AUST500
H.D.500
N.H.500

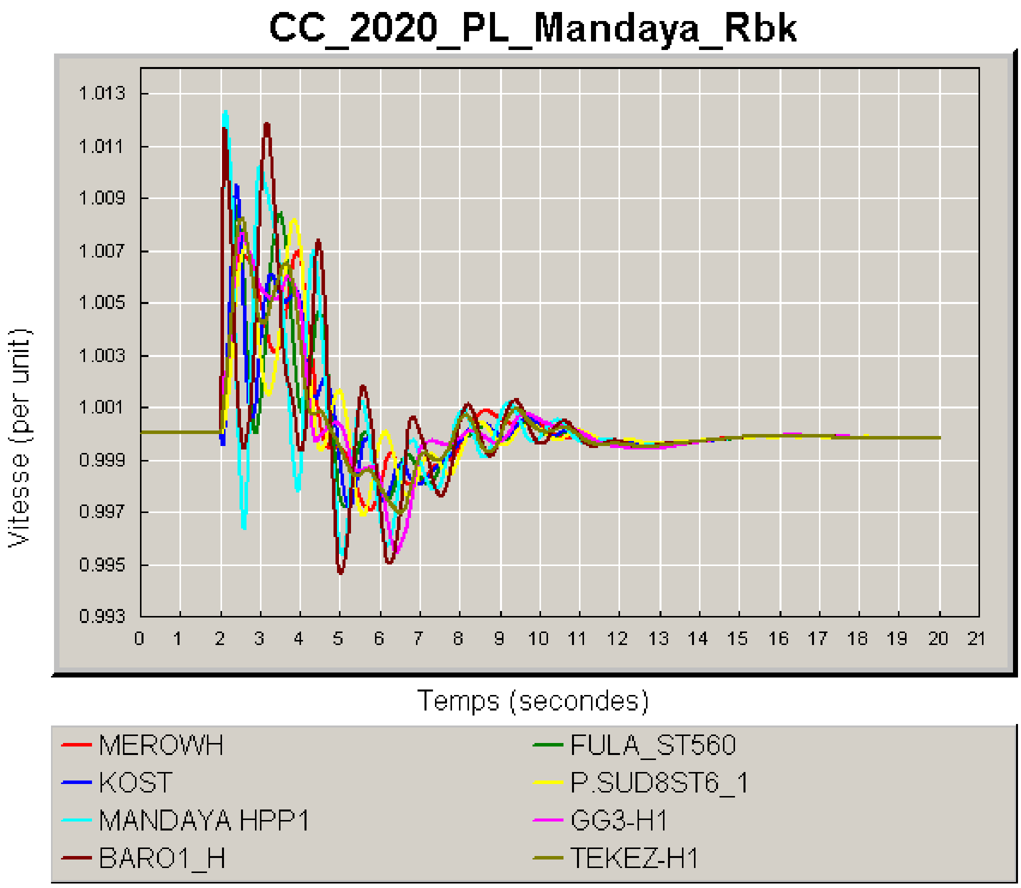
2.3 SHORT-CIRCUIT AT MANDAYA ON MANDAYA - RABAK WITH FULL RECOVERY OF THE DC EXCHANGE

Event : a 3 phase short-circuit at Mandaya end, on one of the 4 circuits Mandaya - Rabak, cleared in 120 ms by the opening of the circuit breakers.

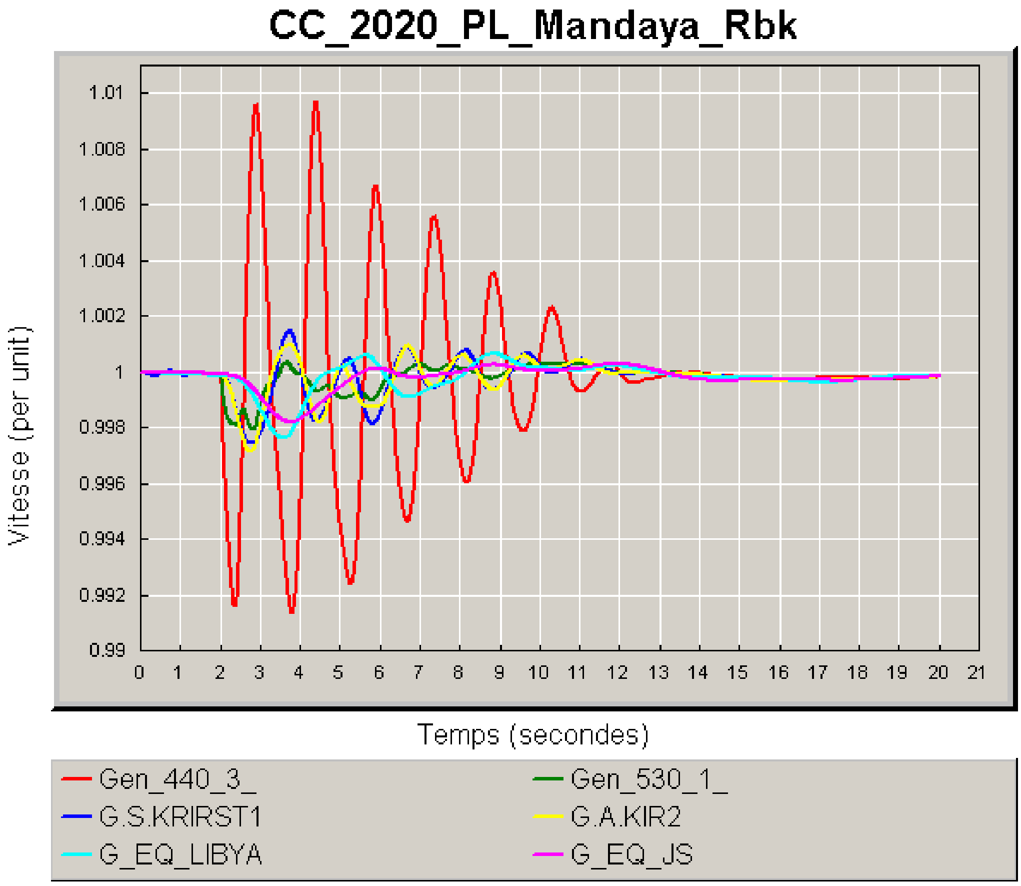
The voltage drop in Rabak (0.4 pu) led to a transitory blocking of commutation of the inverter station at Rabak. The flow on the DC interconnection is transitory reduced to 0, before recovering to its initial value 300 ms after the clearing of the fault.

During the transitory blocking of the DC stations, the capacitors bank remained connected.

2.3.1 GENERATORS FREQUENCY VARIATION

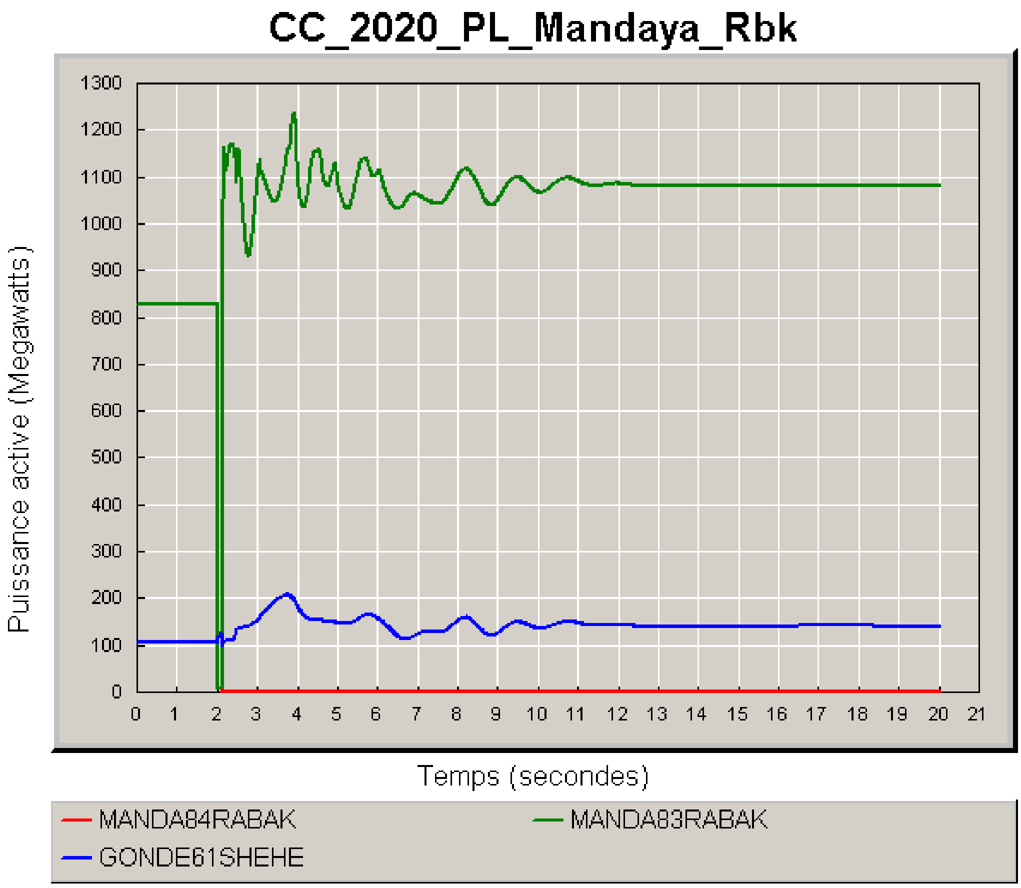


GG3 is Gibe III

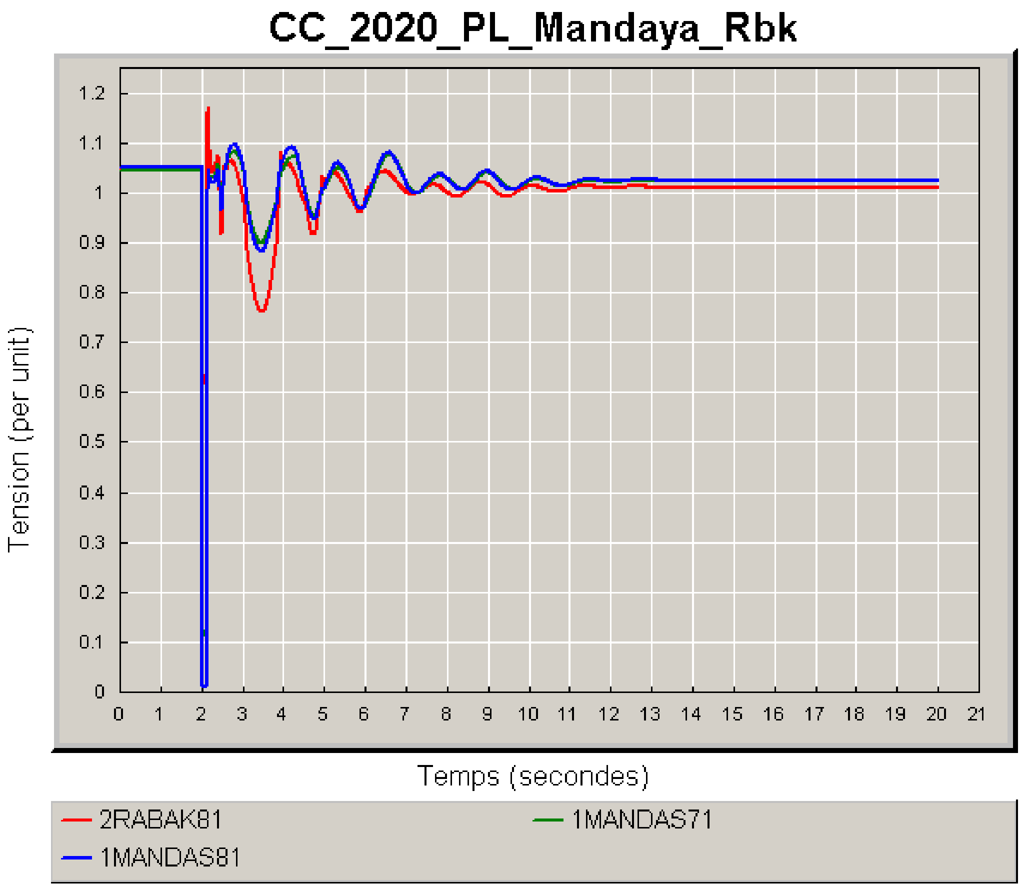


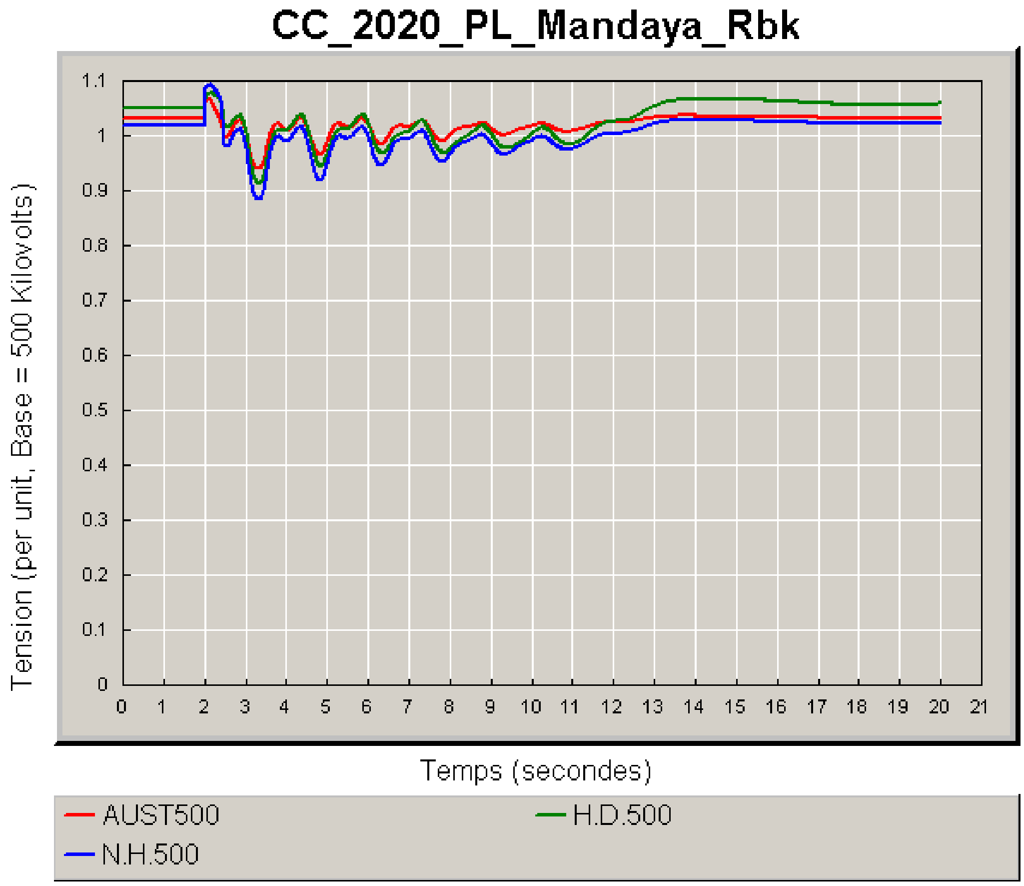
Gen_440_3 is a group of High Dam
Gen_530_1 is group 1 of Kurimat existing steam

2.3.2 POWER FLOW VARIATION ON ENTRO INTERCONNECTION



2.3.3 VOLTAGE VARIATION ON THE 500 KV



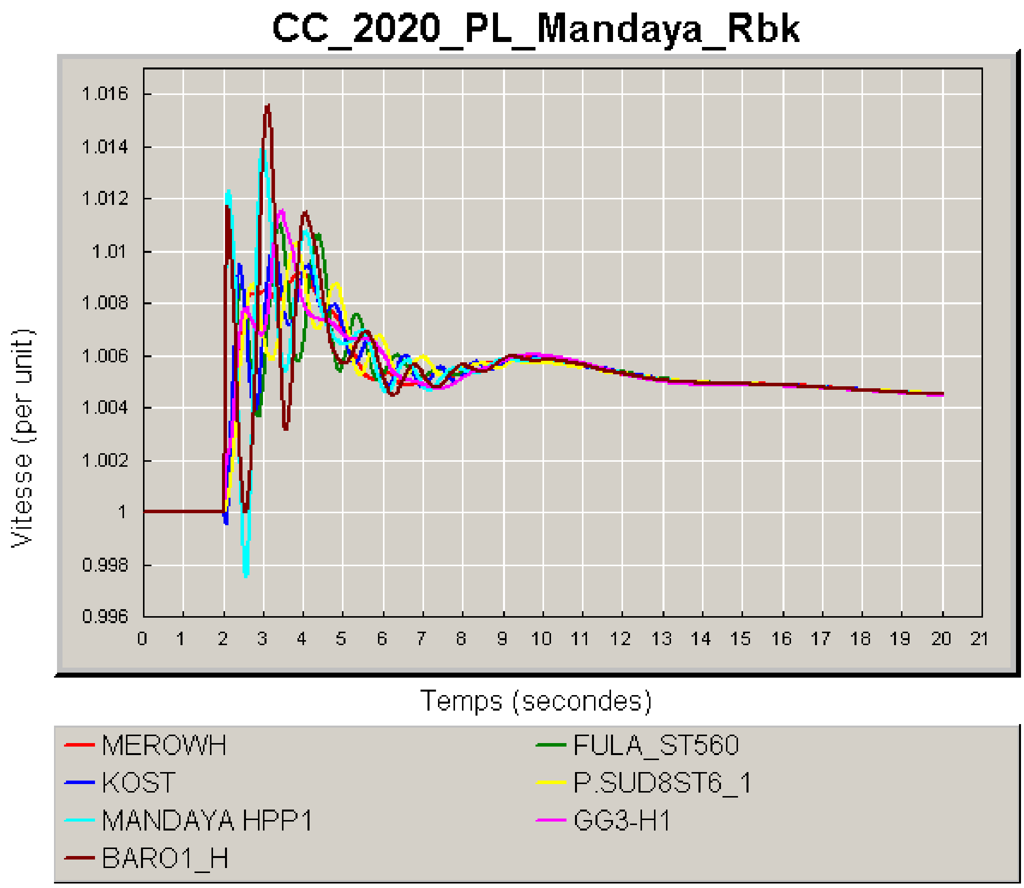

CC_2020_PL_Mandaya_Rbk
Tension (per unit, Base = 500 Kilovolts)
1.1
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21
Temps (secondes)
AUST500
H.D.500
N.H.500

2.4 SHORT-CIRCUIT AT MANDAYA ON MANDAYA - RABAK WITH HALF RECOVERY OF THE DC EXCHANGE

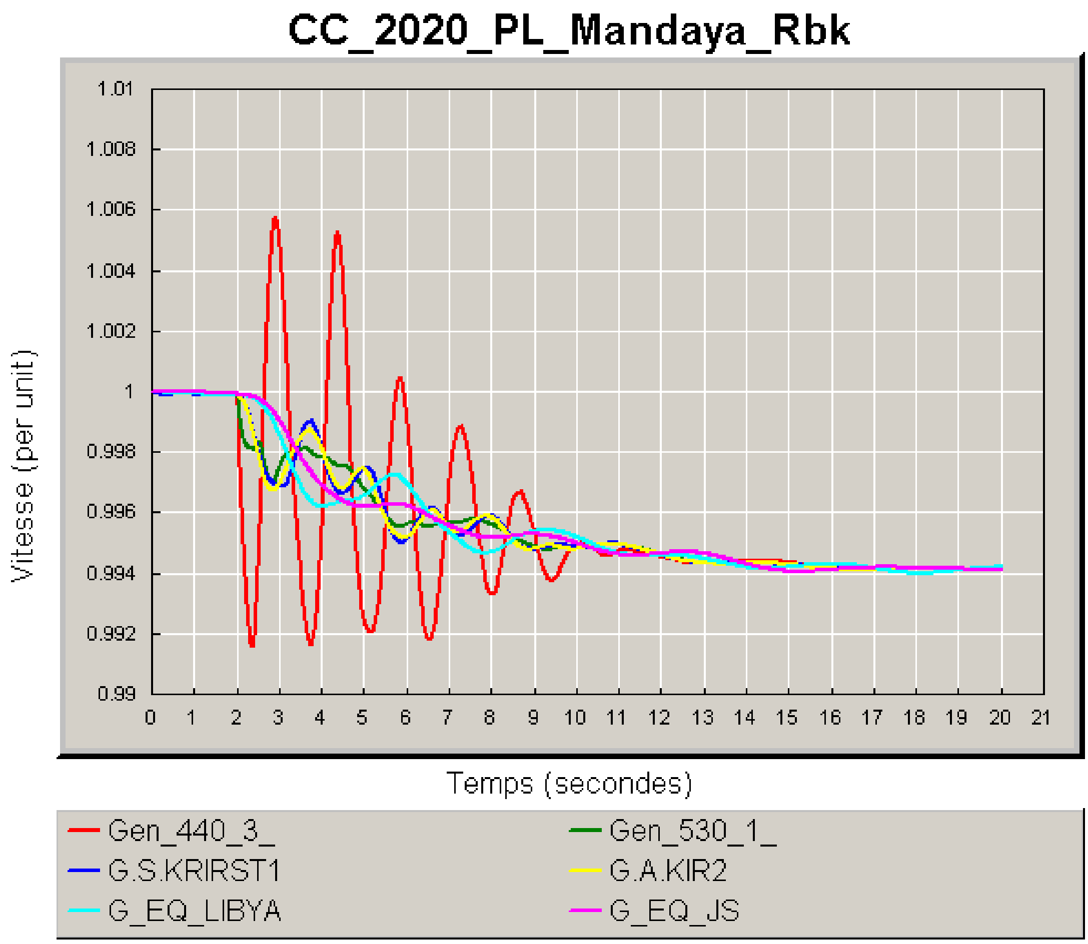
Event : a 3 phase short-circuit at Mandaya end, on one of the 4 circuits Mandaya - Rabak, cleared in 120 ms by the opening of the circuit breakers.

The voltage drop in Rabak (0.4 pu) led to a transitory blocking of commutation of the inverter station at Rabak. The flow on the DC interconnection is transitory reduced to 0, before recovering to half of its initial value 300 ms after the clearing of the fault. At the same time, half of the capacitors banks are disconnected at the same time.

2.4.1 GENERATORS FREQUENCY VARIATION

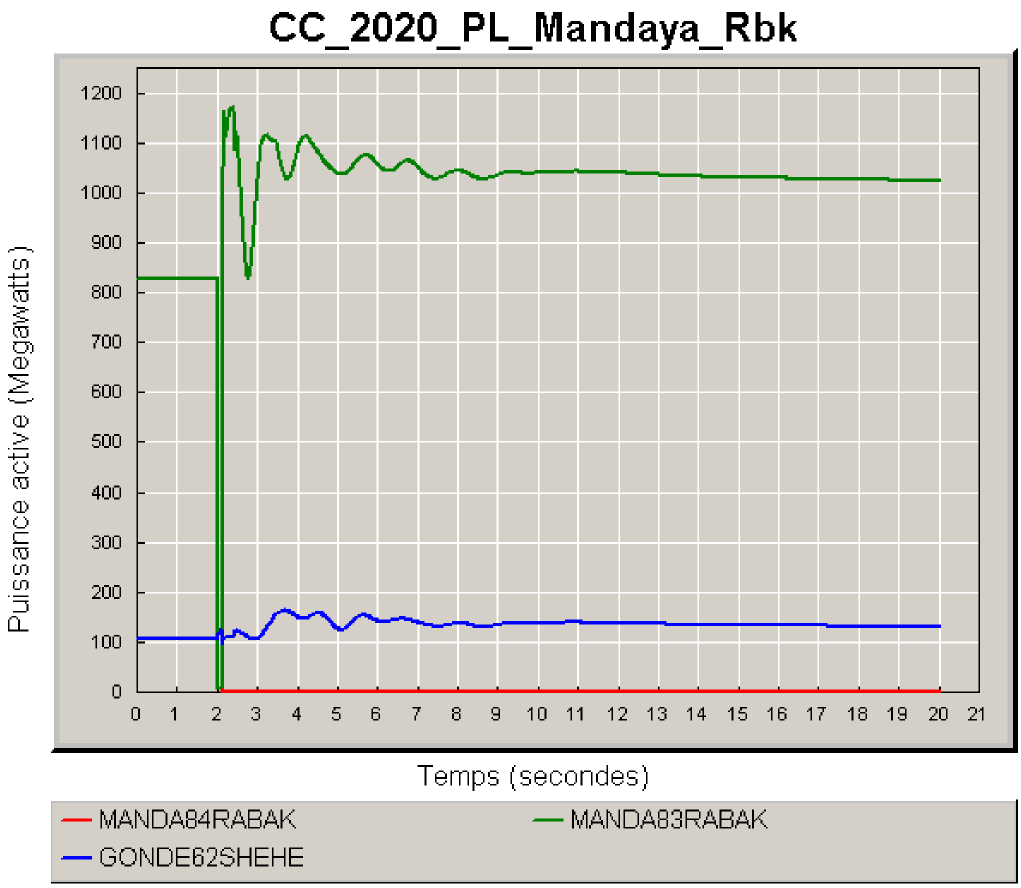


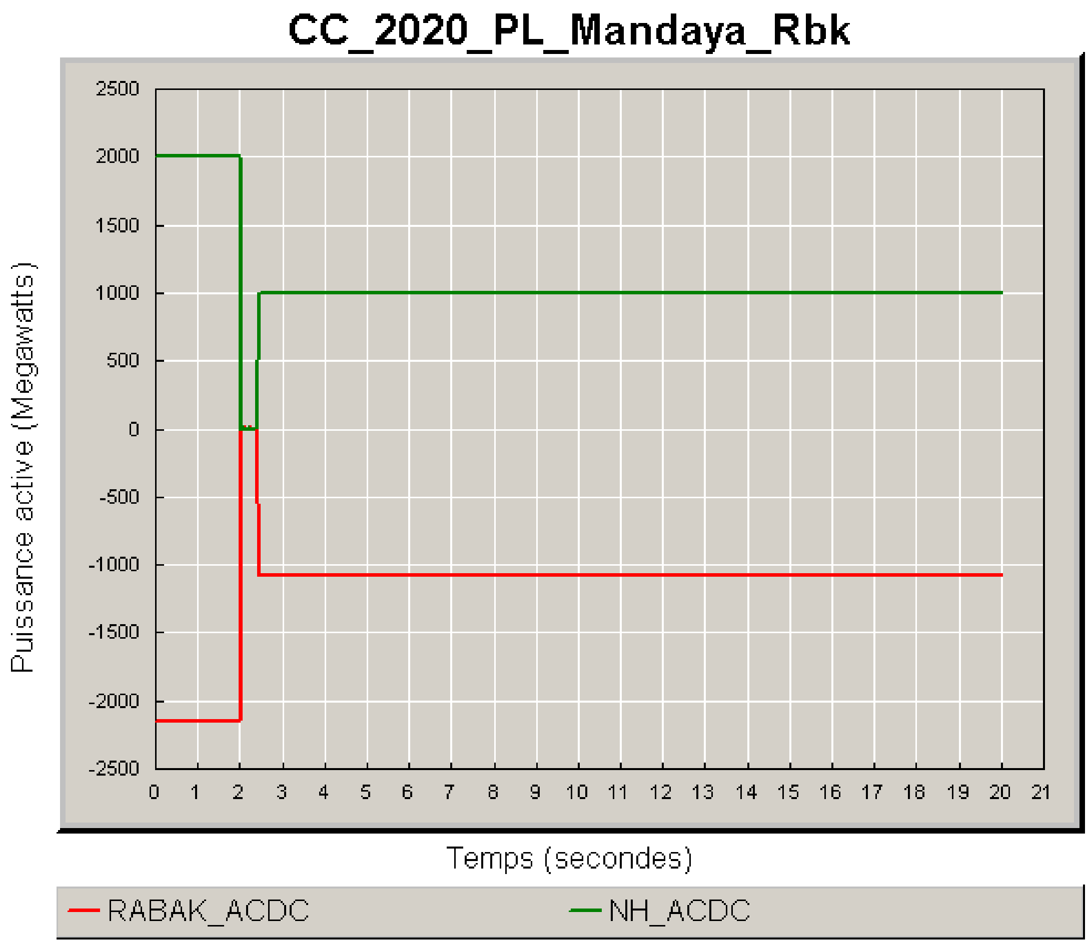
GG3 is Gibe III



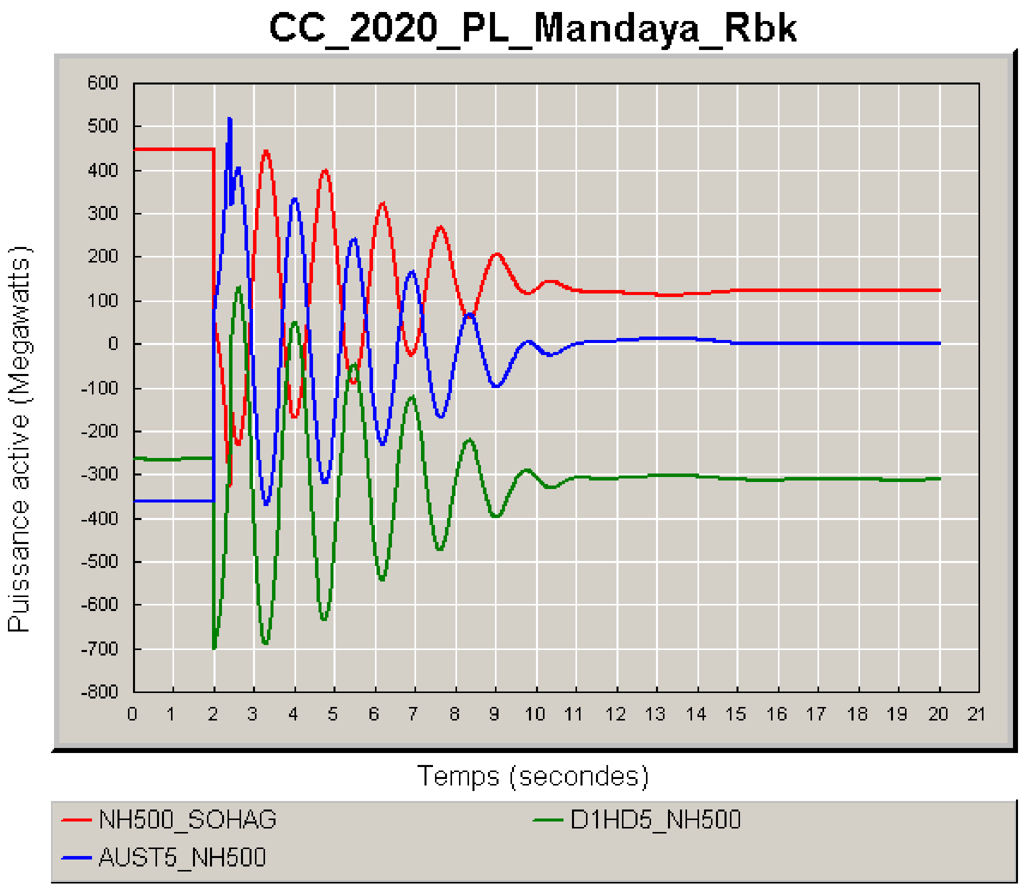
Gen_440_3 is a group of High Dam
Gen_530_1 is group 1 of Kurimat existing steam

2.4.2 POWER FLOW VARIATION ON ENTRO INTERCONNECTION

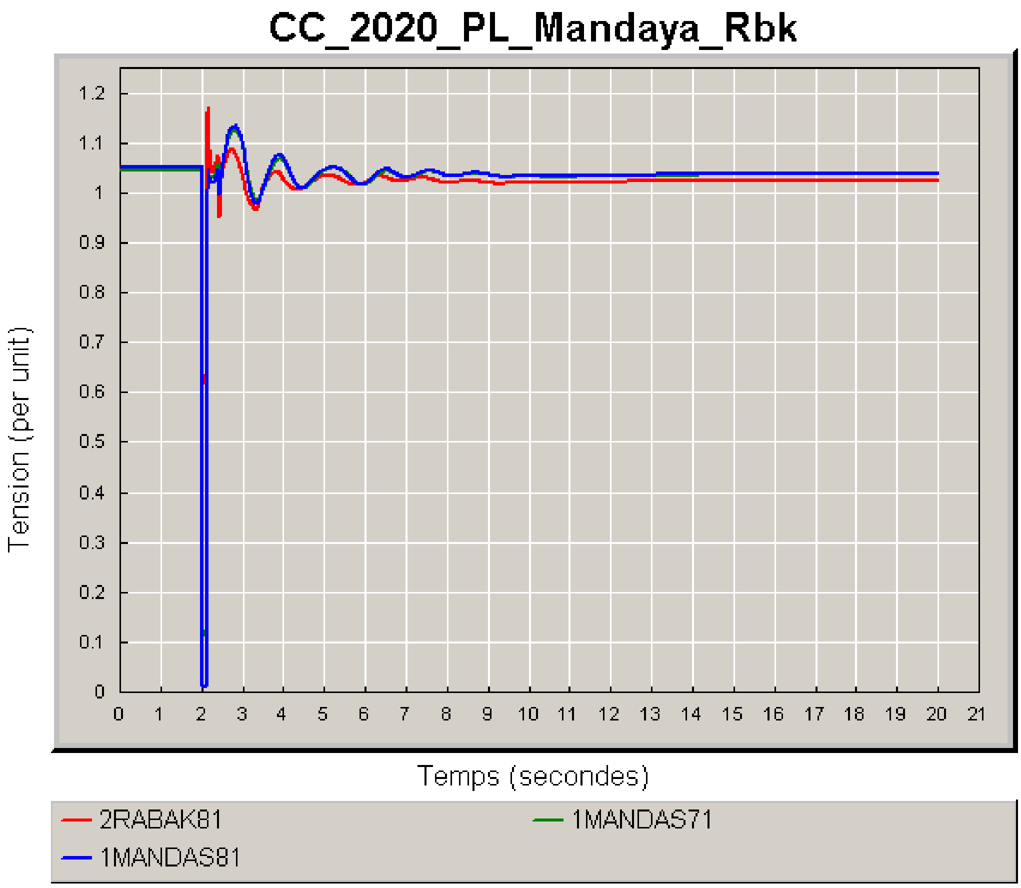


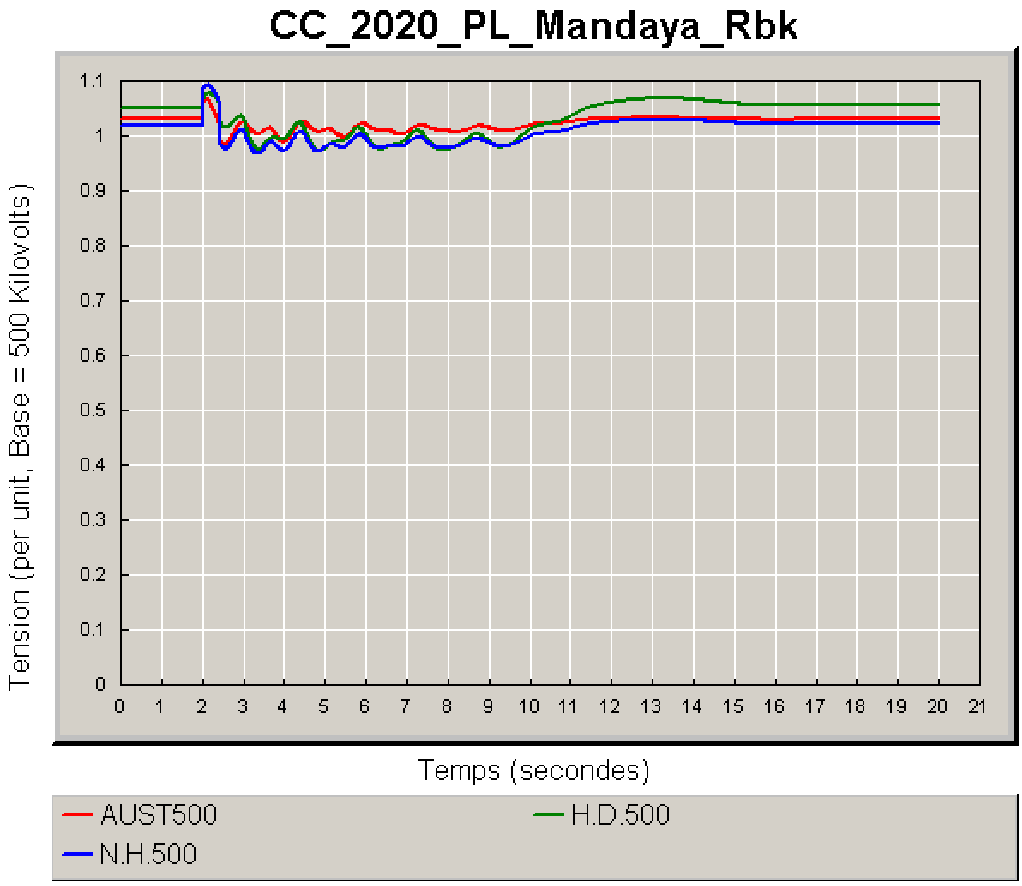

CC_2020_PL_Mandaya_Rbk
Puissance active (Megawatts)
2500
2000
1500
1000
500
0
-500
-1000
-1500
-2000
-2500
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21
Temps (secondes)
RABAK_ACDC
NH_ACDC

2.4.3 POWER FLOW VARIATION ON NAG HAMMADI 500 KV CIRCUITS



2.4.4 VOLTAGE VARIATION ON THE 500 KV



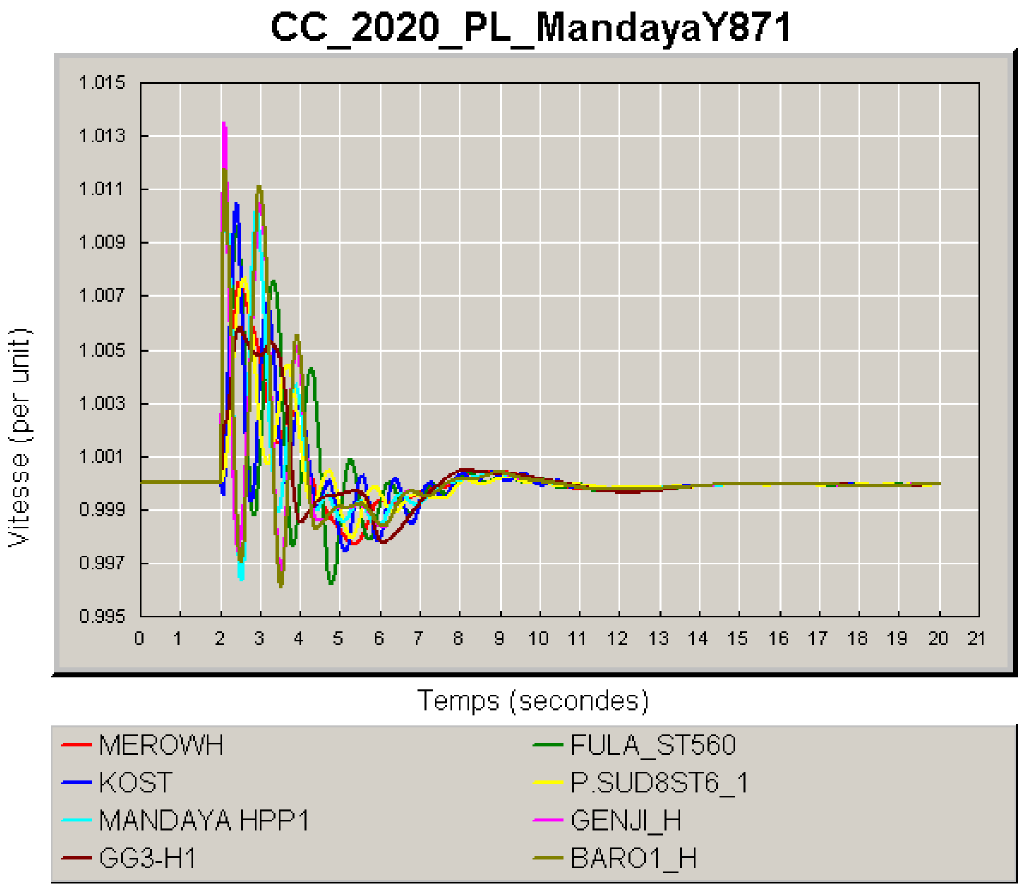

CC_2020_PL_Mandaya_Rbk
Tension (per unit, Base = 500 Kilovolts)
1.1
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21
Temps (secondes)
AUST500
H.D.500
N.H.500

2.5 SHORT-CIRCUIT ON ONE OF THE FOUR 400/500 KV TRANSFORMERS AT MANDAYA

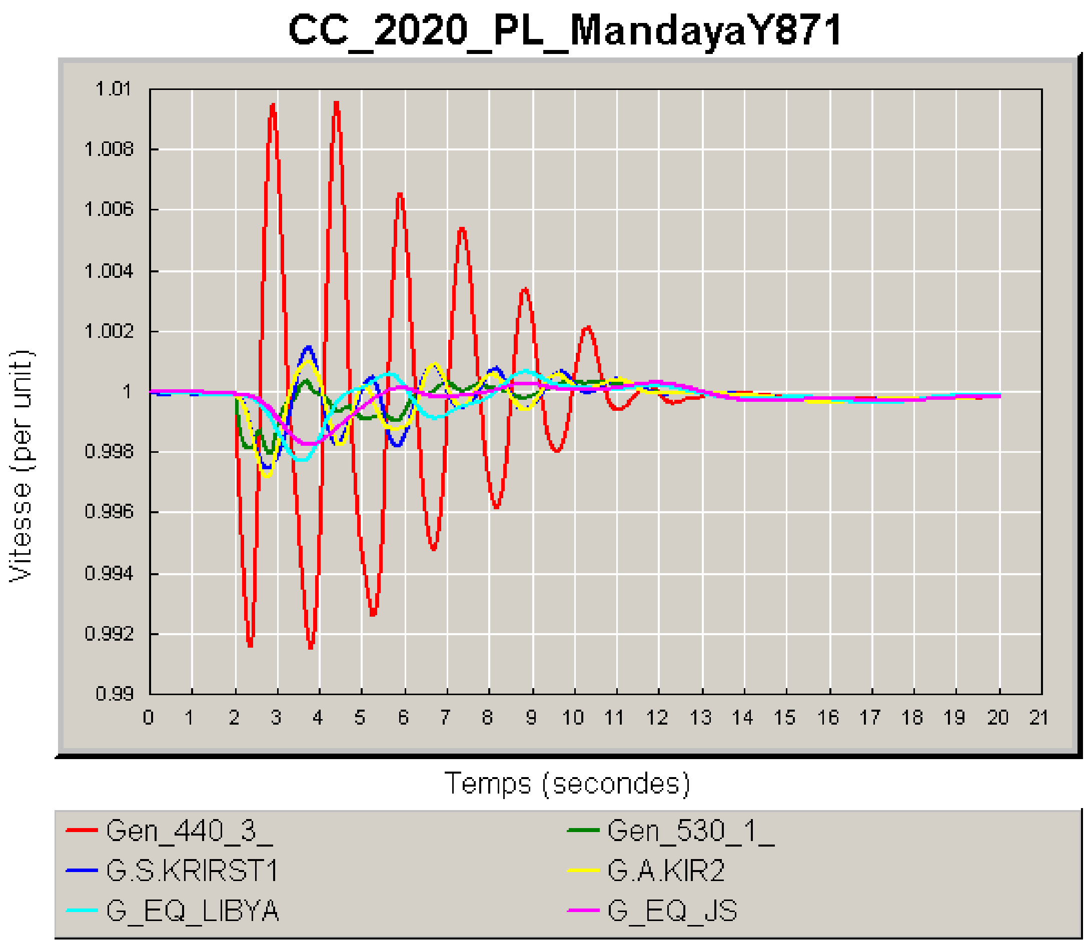
Event : a 3 phase short-circuit at the 500 kV side on one of the four 500/400 kV transformers at Mandaya, cleared in 120 ms by the opening of the circuit breakers.

The voltage drop in Rabak (0.5 pu) led to a transitory blocking of commutation of the inverter station at Rabak. The flow on the DC interconnection is transitory reduced to 0, before recovering to half of its initial value 300 ms after the clearing of the fault. At the same time, half of the capacitors banks are disconnected at the same time.

2.5.1 GENERATORS FREQUENCY VARIATION

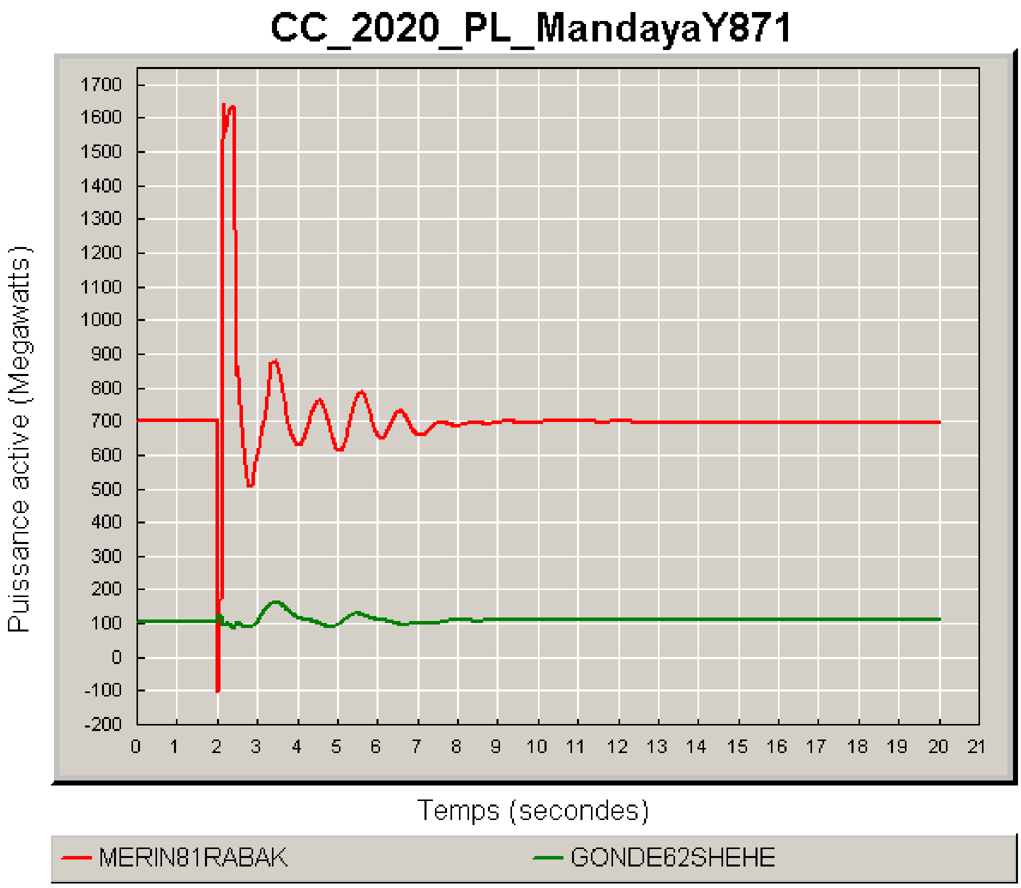


GG3 is Gibe III

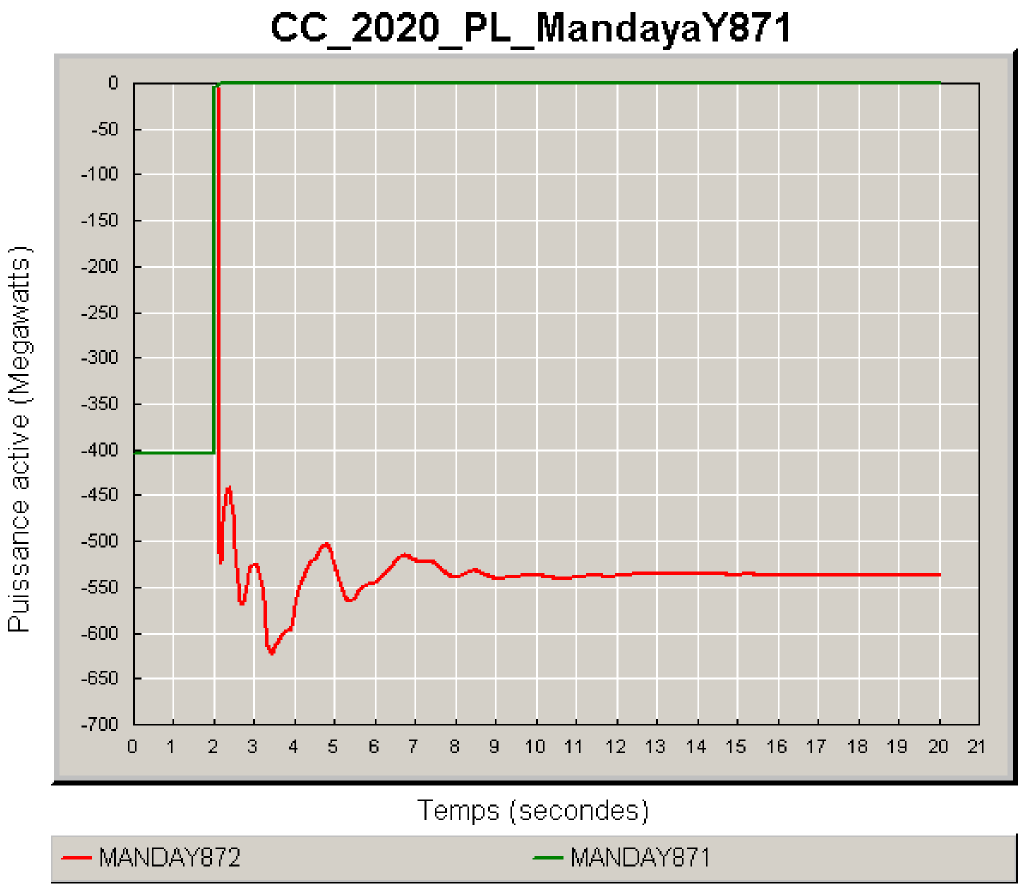


Gen_440_3 is a group of High Dam
Gen_530_1 is group 1 of Kurimat existing steam

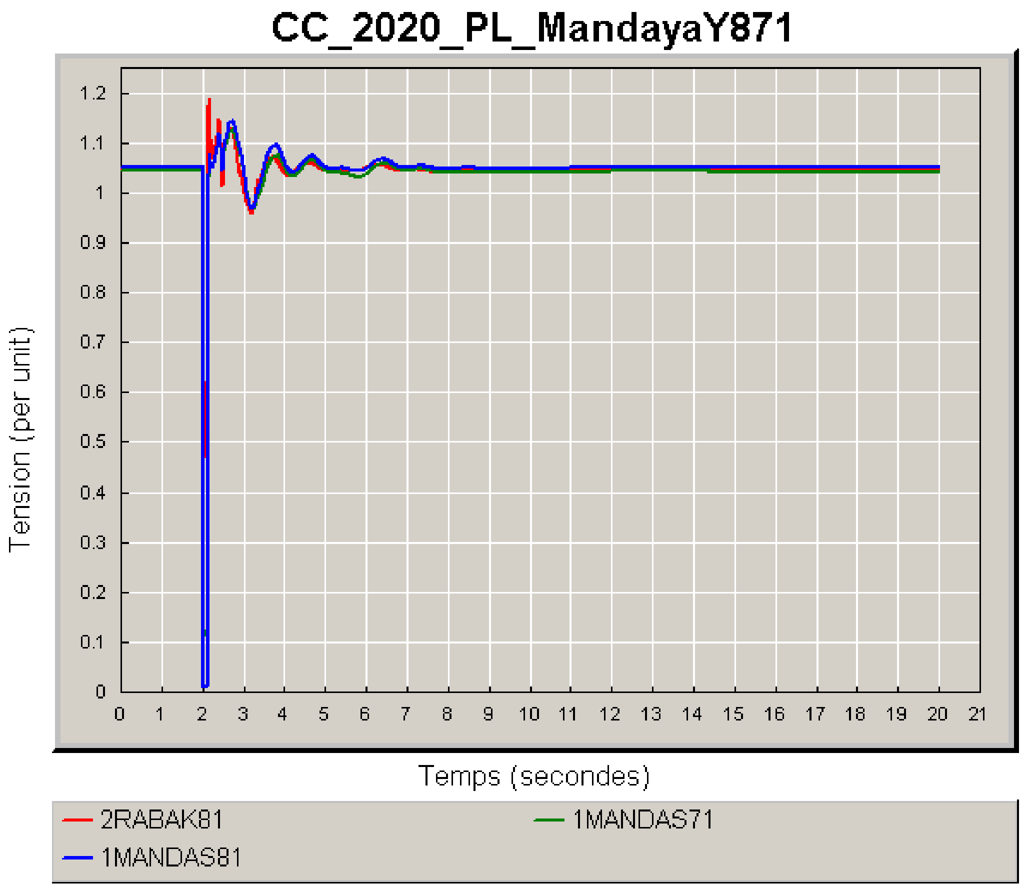
2.5.2 POWER FLOW VARIATION ON ENTRO INTERCONNECTION

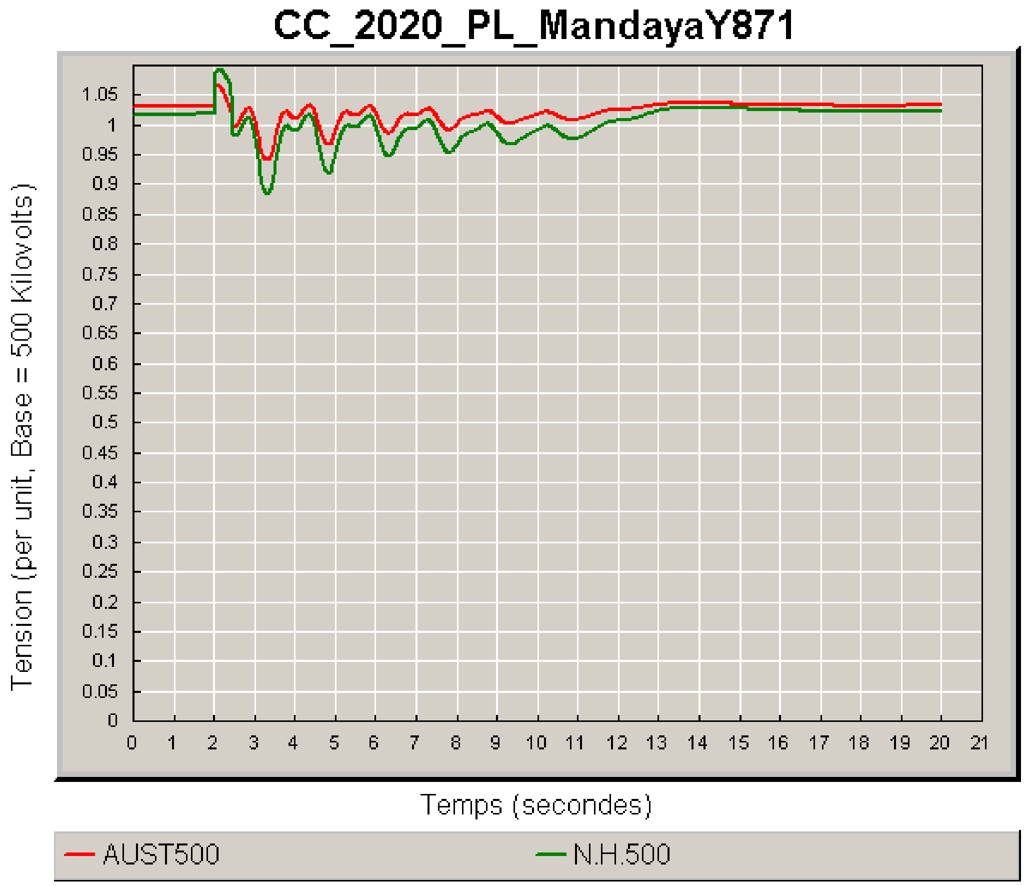


2.5.3 POWER FLOW VARIATION MANDAYA 500/400 KV TRANSFORMERS



2.5.4 VOLTAGE VARIATION ON THE 500 KV

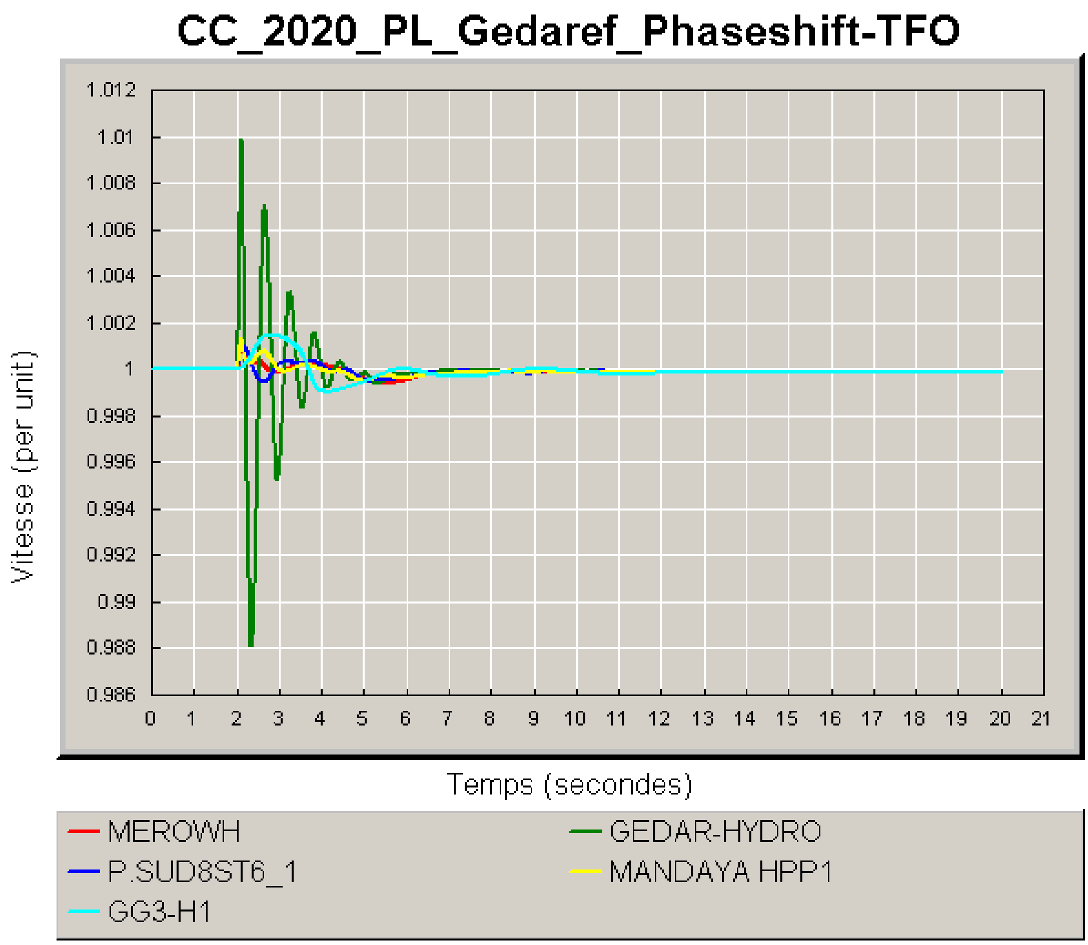



CC_2020_PL_MandayaY871
Tension (per unit, Base = 500 Kilovolts)
1.05
1
0.95
0.9
0.85
0.8
0.75
0.7
0.65
0.6
0.55
0.5
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21
Temps (secondes)
AUST500
N.H.500

2.6 SHORT-CIRCUIT AT GEDAREF, ON THE 220 KV PHASE-SHIFT TRANSFORMER

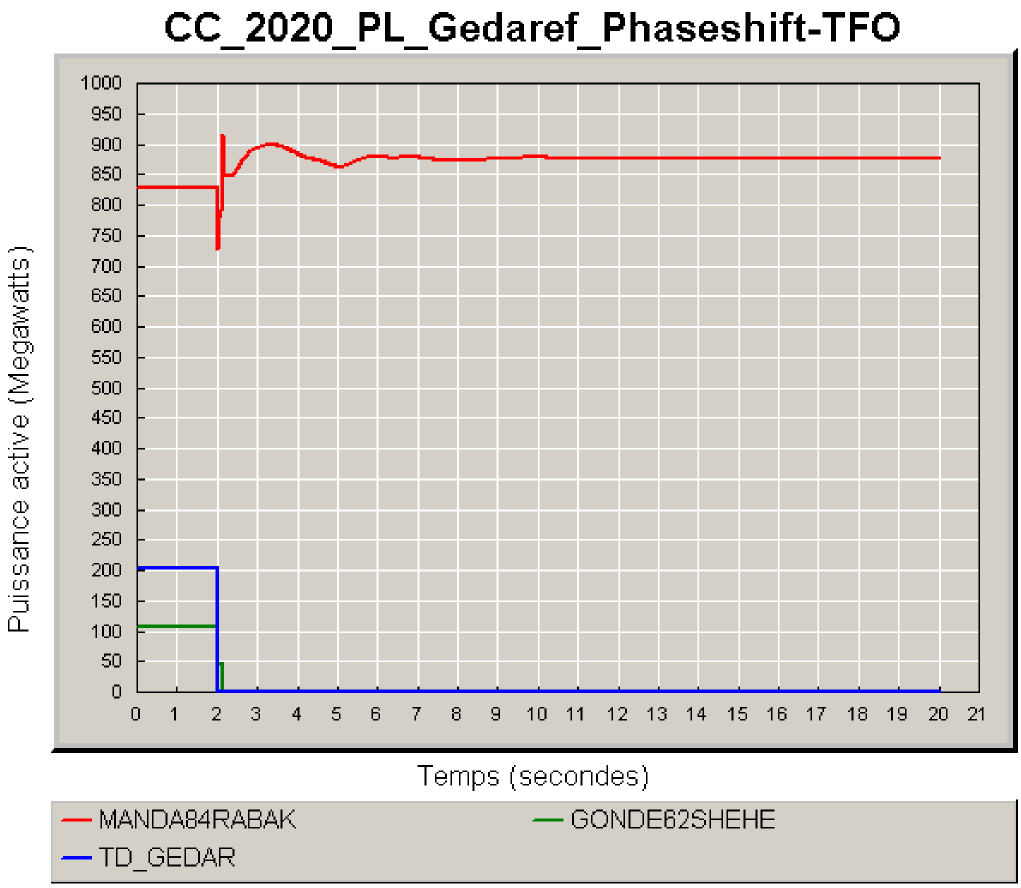
Event : a 3 phase short-circuit at Gedaref 220 kV end, on the 220 kV phase shift transformer, cleared in 120 ms by the opening of the circuit breakers.

2.6.1 GENERATORS FREQUENCY VARIATION

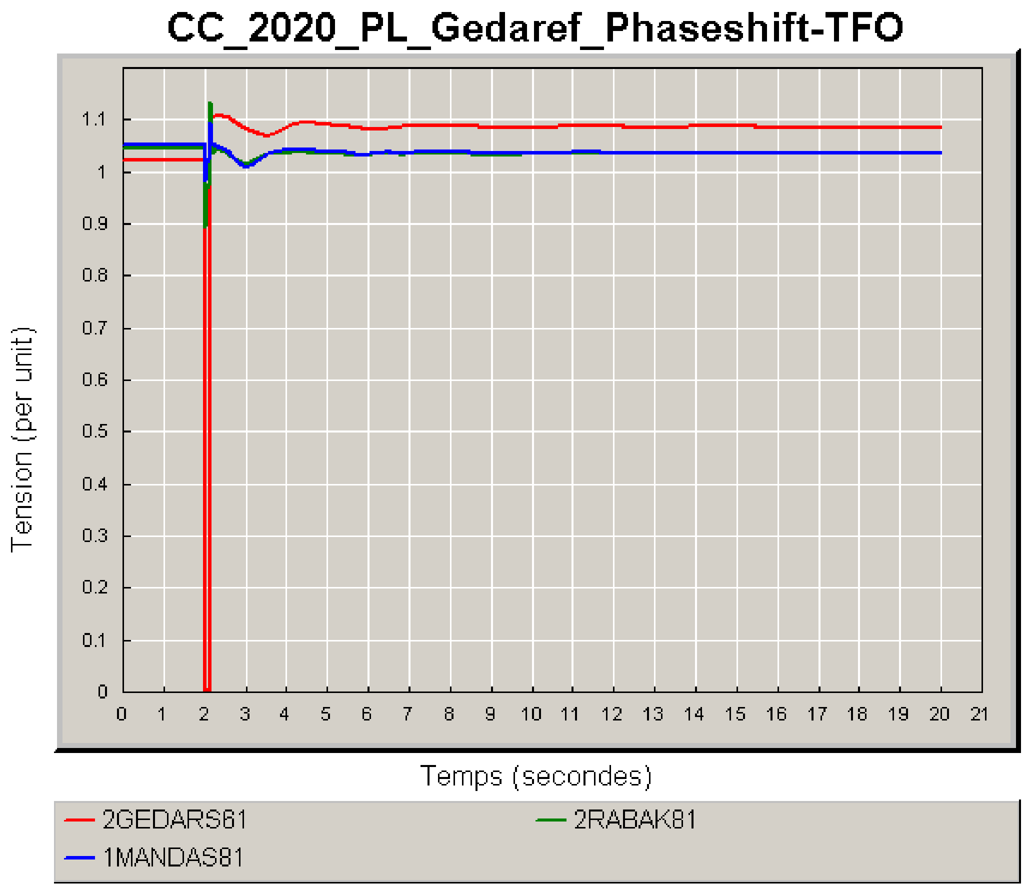


GG3 is Gibe III

2.6.2 POWER FLOW VARIATION ON ENTRO INTERCONNECTION



2.6.3 VOLTAGE VARIATION ON THE 500 KV

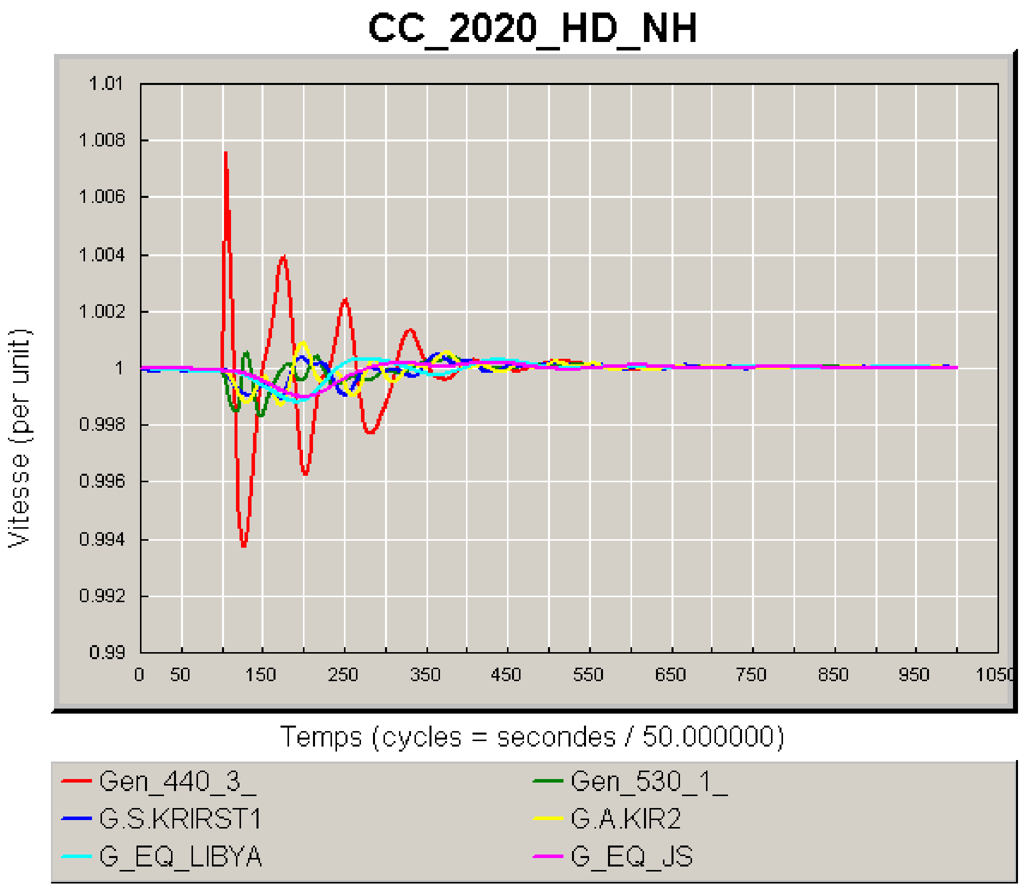


2.7 SHORT-CIRCUIT AT HIGH DAM SIDE, ON ONE OF THE 2 CIRCUITS HIGH DAM - NAG HAMMADI

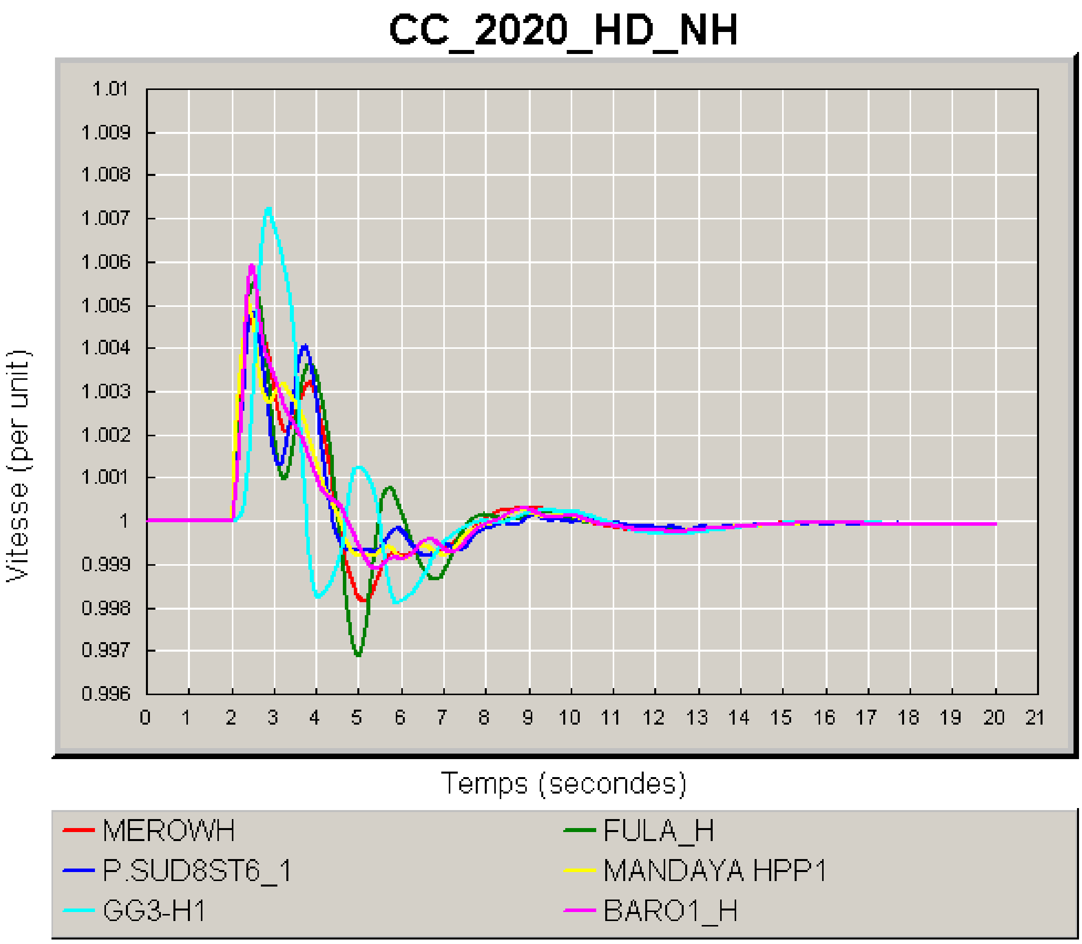
Event : a 3 phase short-circuit at High Dam end, on one of the 2 circuits High Dam - Nag Hammadi, cleared in 100 ms by the opening of the circuit breakers.

The voltage drop in Nag Hammadi (~60%) led to a transitory blocking of commutation of the inverter station at Nag Hammadi. The flow on the DC interconnection is transitory reduced to 0, before starting, 300 ms after the voltage return, its recovery to its initial value.
During the transitory blocking of the DC stations, the capacitors bank remained connected.

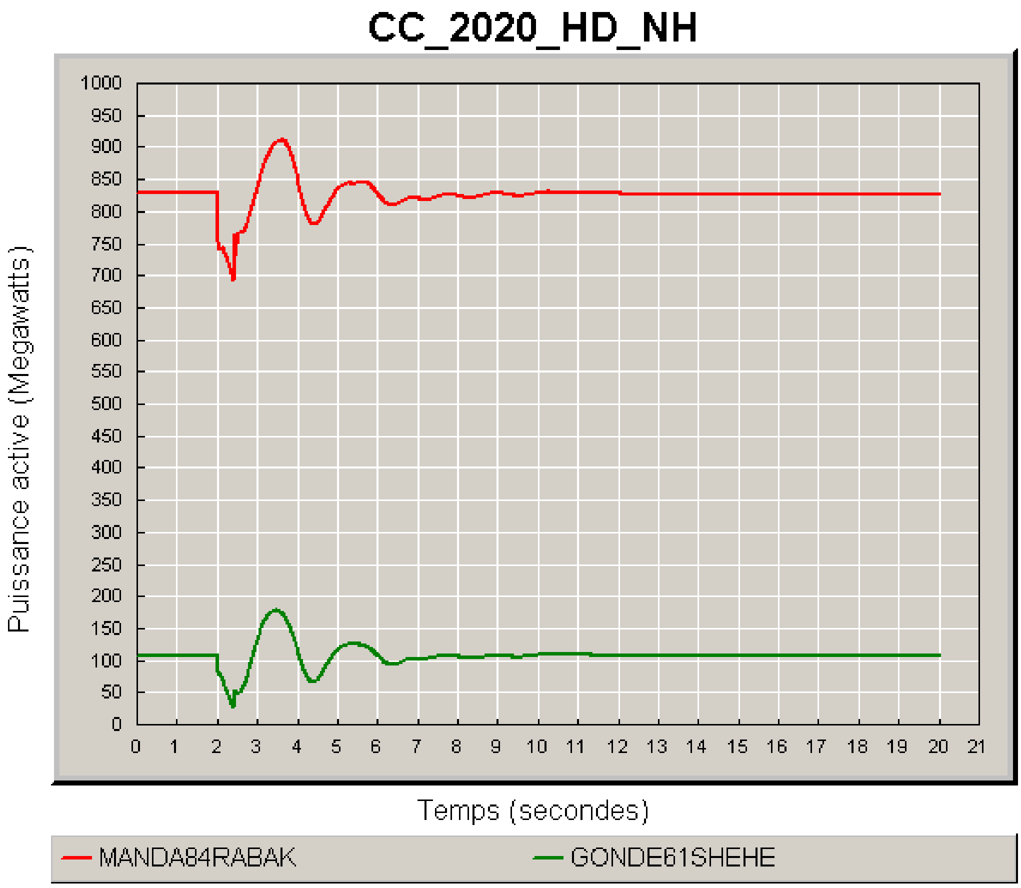
2.7.1 GENERATORS FREQUENCY VARIATION

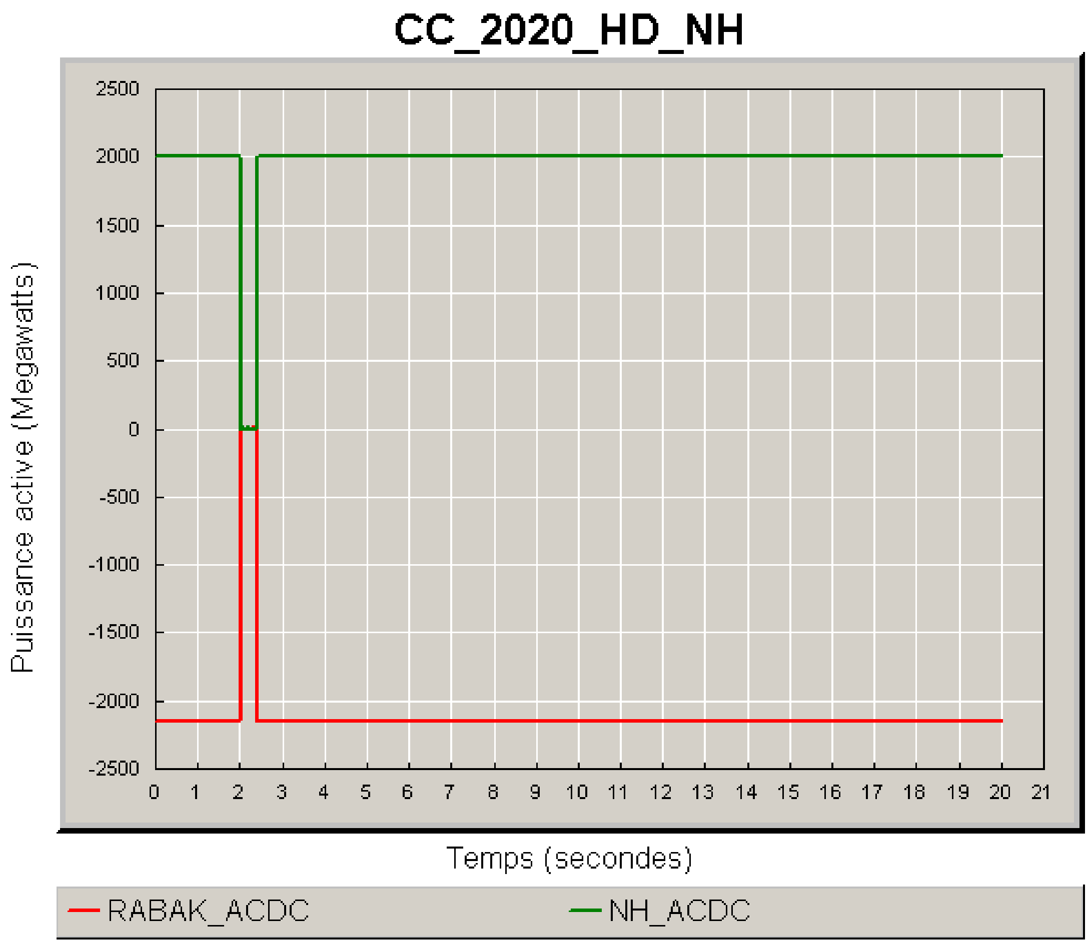


Gen_440_3 is a group of High Dam
Gen_530_1 is group 1 of Kurimat existing steam

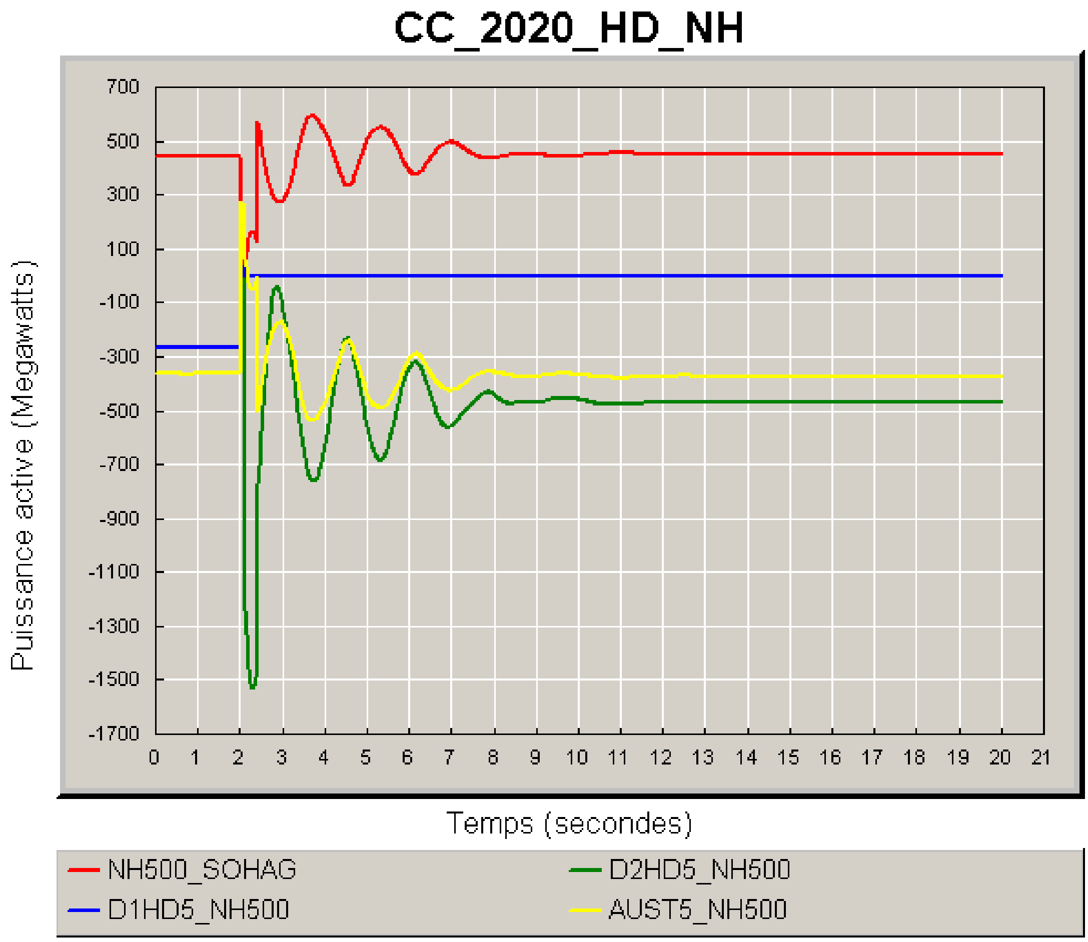

CC_2020_HD_NH
1.01
1.009
1.008
1.007
1.006
1.005
1.004
1.003
1.002
1.001
1
0.999
0.998
0.997
0.996
Vitesse (per unit)
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21
Temps (secondes)
MEROWH
FULA_H
P.SUD8ST6_1
MANDAYA HPP1
GG3-H1
BARO1_H

2.7.2 POWER FLOW VARIATION ON ENTRO INTERCONNECTION

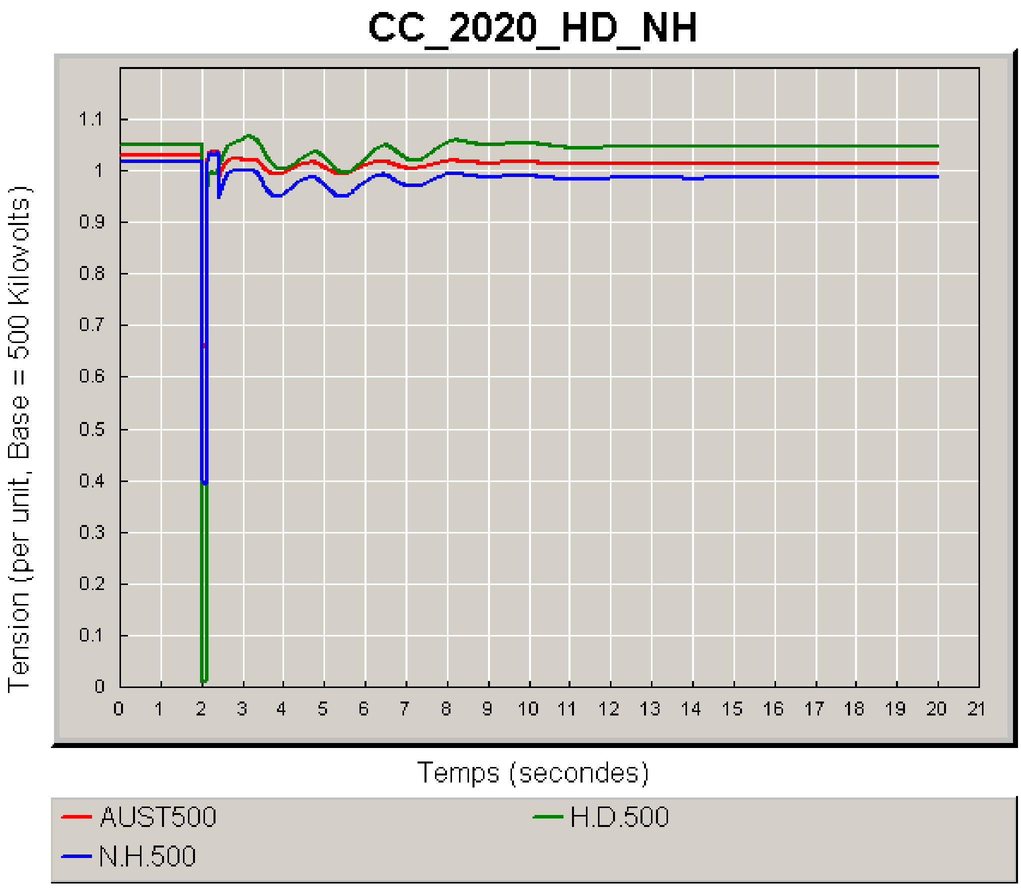


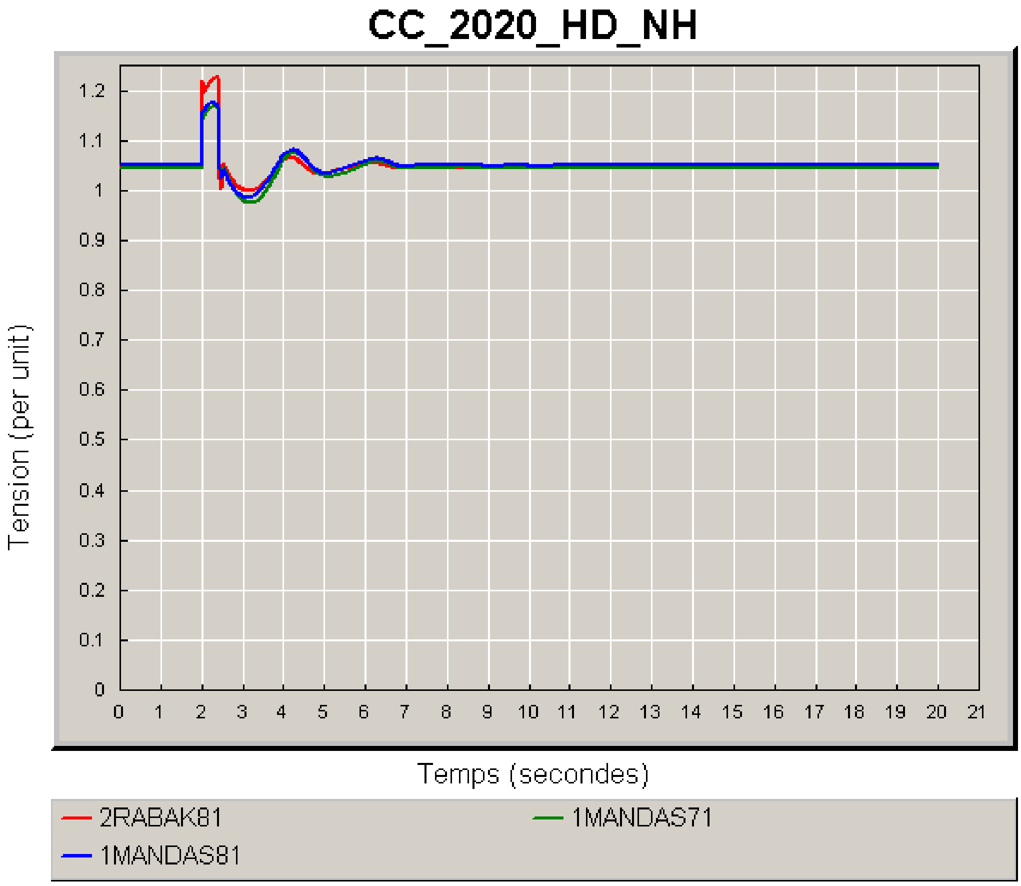

CC_2020_HD_NH
Puissance active (Megawatts)
2500
2000
1500
1000
500
0
-500
-1000
-1500
-2000
-2500
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
Temps (secondes)
RABAK_ACDC
NH_ACDC

2.7.3 POWER FLOW VARIATION ON HIGH DAM - NAG HAMMADI - ASSIUT



2.7.4 VOLTAGE VARIATION ON THE 500 KV




CC_2020_HD_NH
Tension (per unit)
1.2
1.1
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21
Temps (secondes)
2RABAK81
1MANDAS71
1MANDAS81

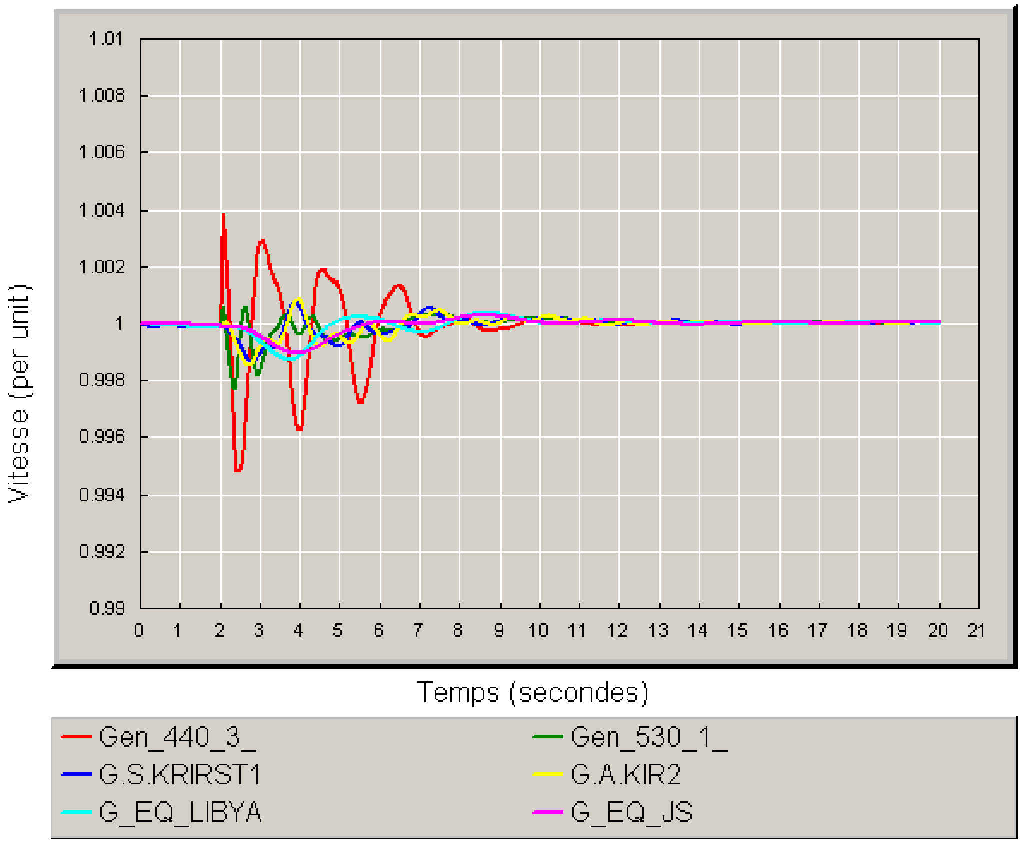
2.8 SHORT-CIRCUIT AT NAG HAMMADI ON NAG HAMMADI - HIGH DAM

Event : a 3 phase short-circuit at Nag Hammadi end, on one of the 2 circuits High Dam - Nag Hammadi, cleared in 100 ms by the opening of the circuit breakers.

The voltage drop in Nag Hammadi (to 0 pu) led to a transitory blocking of commutation of the inverter station at Nag Hammadi. The flow on the DC interconnection is transitory reduced to 0, The flow on the DC interconnection is transitory reduced to 0, before starting, 300 ms after the voltage return, its recovery to its initial value.
During the transitory blocking of the DC stations, the capacitors bank remained connected.

For the Ethiopian and Sudanese side, the impact on the system and its behaviour is very similar to the case of SC on High Dam - Nag Hammadi

2.8.1 GENERATORS FREQUENCY VARIATION

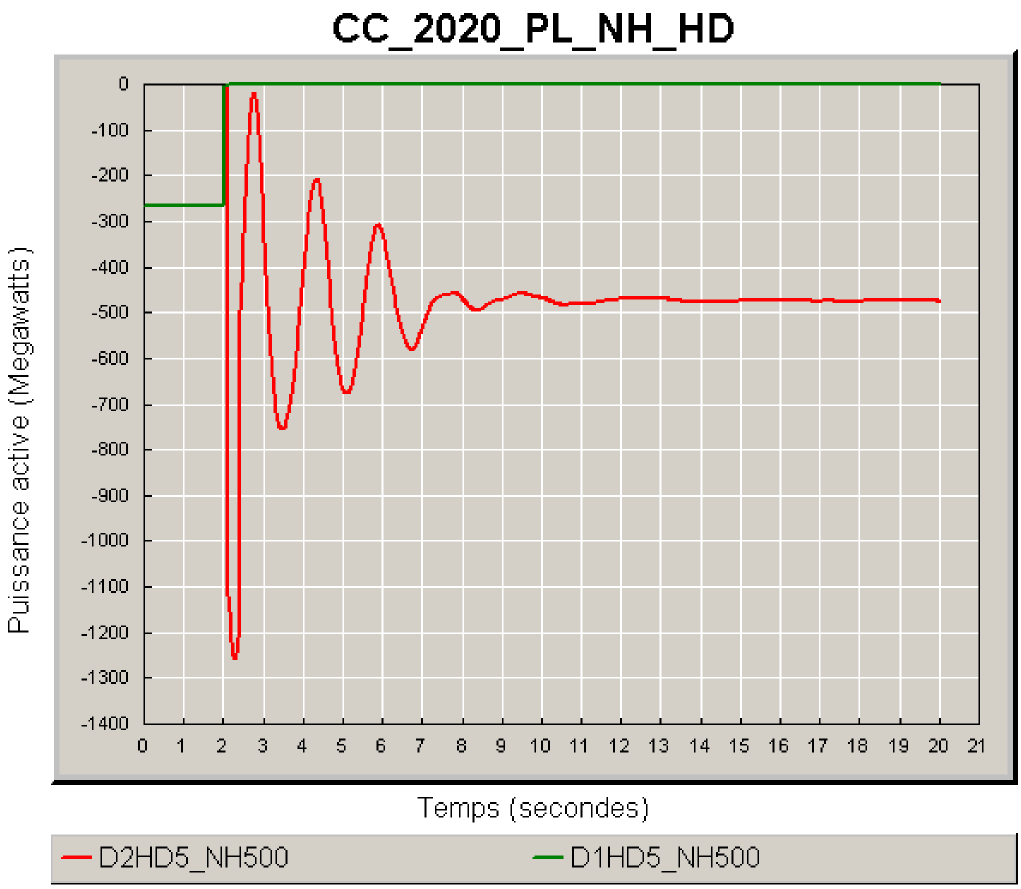


Gen_440_3 is a group of High Dam
Gen_530_1 is group 1 of Kurimat existing steam

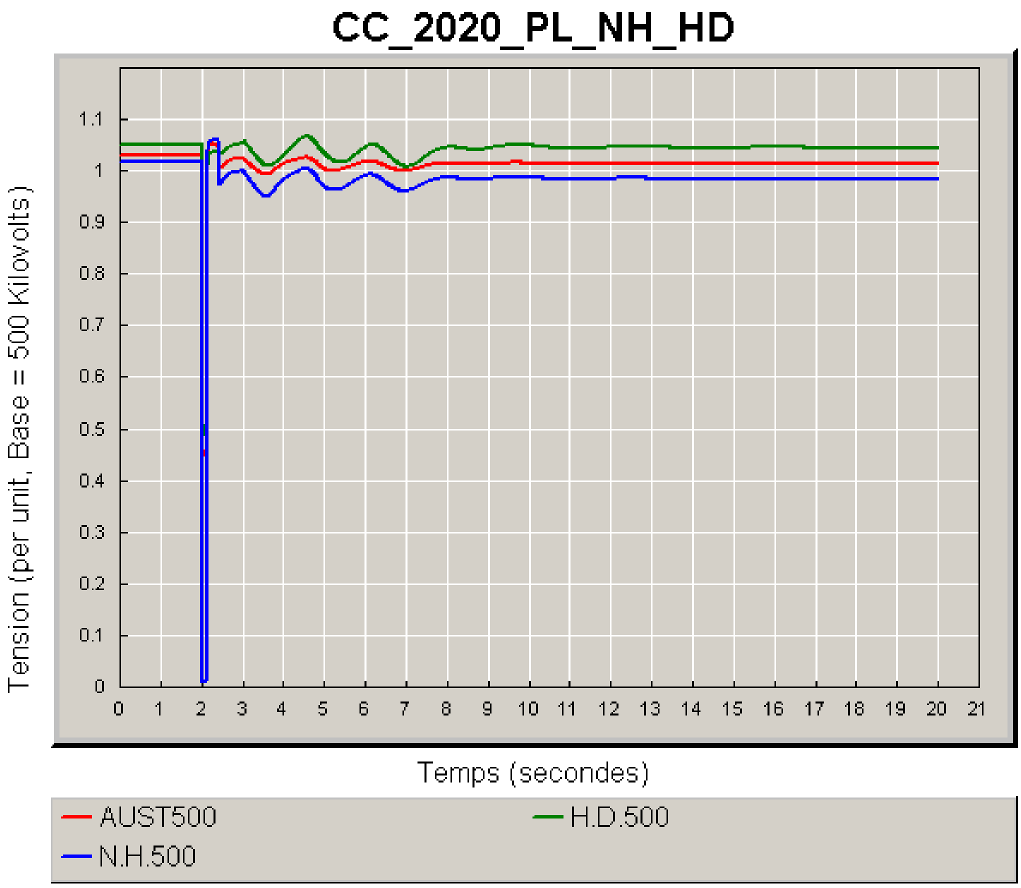
2.8.2 POWER FLOW VARIATION ON ENTRO INTERCONNECTION

For power flow variation on Ethiopia - Sudan interconneciton and on the DC interconnection between Sudan and Egypt, the situation is very similar to the case with trhe SC on High Dam - Nag Hammadi.

2.8.3 POWER FLOW VARIATION ON NAG - HAMMADI - HIGH DAM



2.8.4 VOLTAGE VARIATION ON THE 500 KV



2.9 SHORT-CIRCUIT AT NAG HAMMADI ON NH500 - SOHAG CIRCUIT

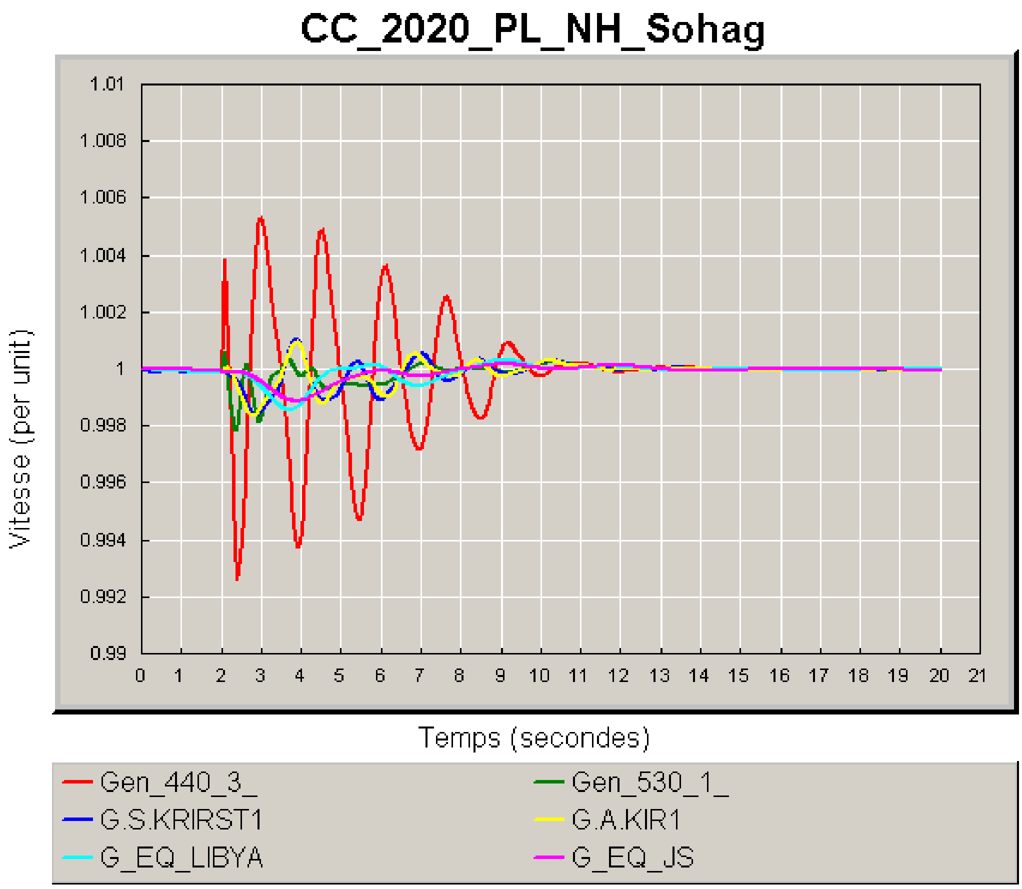
Event : a 3 phase short-circuit at Nag Hammadi end, on the circuit Nag Hammadi - Sohag, cleared in 100 ms by the opening of the circuit breakers.

The voltage drop in Nag Hammadi (to 0 pu) led to a transitory blocking of commutation of the inverter station at Nag Hammadi. The flow on the DC interconnection is transitory reduced to 0, before starting, 300 ms after the voltage return, its recovery to its initial value.

.
During the transitory blocking of the DC stations, the capacitors bank remained connected.

For the Ethiopian and Sudanese side, the impact on the system and its behaviour is very similar to the case of SC on High Dam - Nag Hammadi

2.9.1 GENERATORS FREQUENCY VARIATION

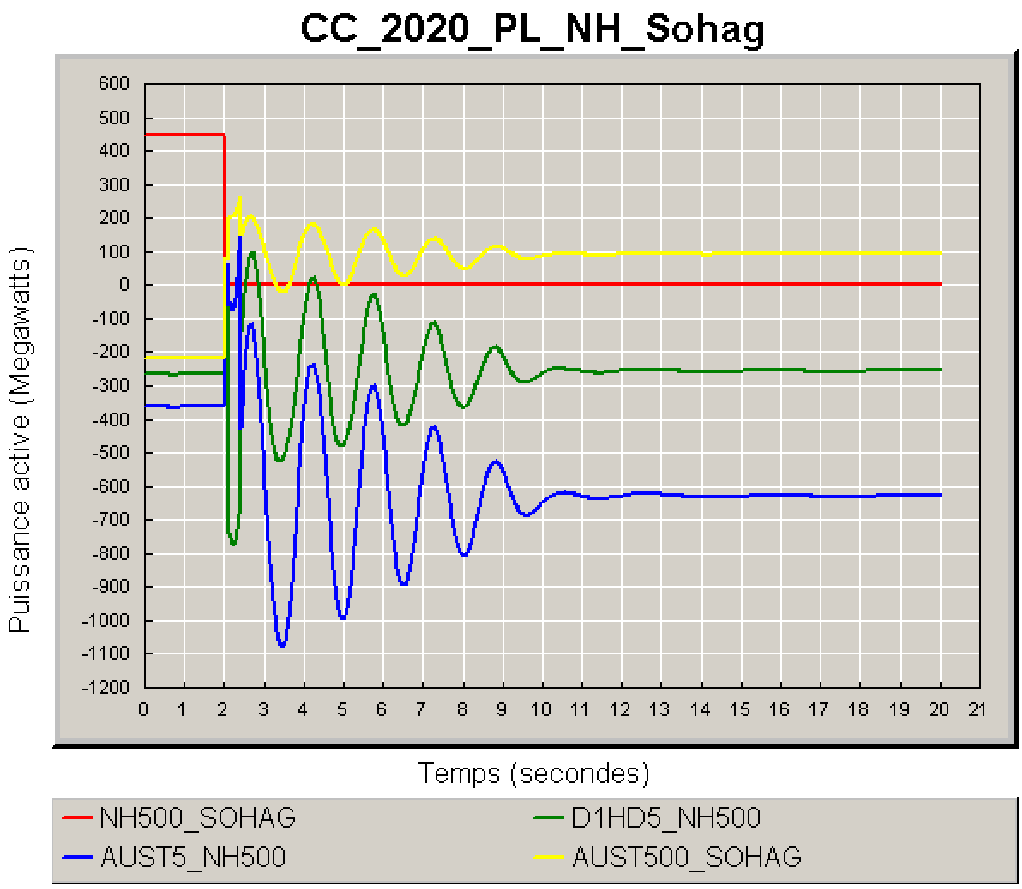


Gen_440_3 is a group of High Dam
Gen_530_1 is group 1 of Kurimat existing steam

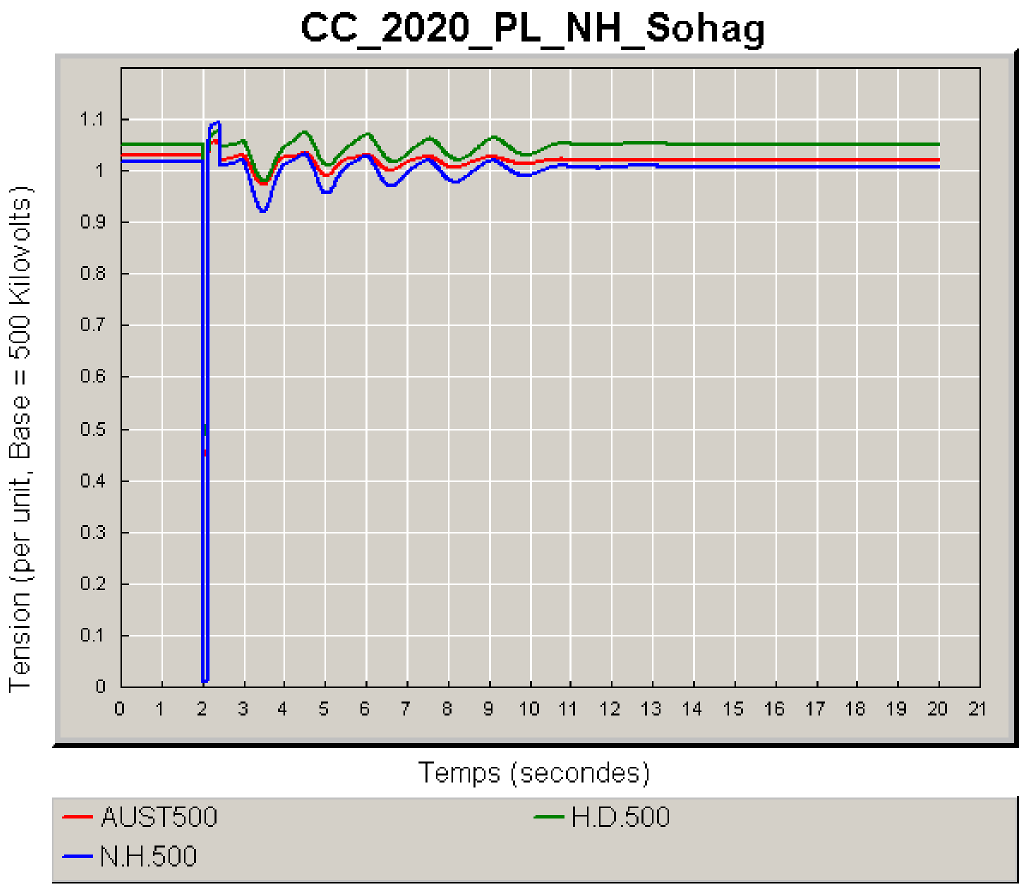
2.9.2 POWER FLOW VARIATION ON ENTRO INTERCONNECTION

For power flow variation on Ethiopia - Sudan interconneciton and on the DC interconnection between Sudan and Egypt, the situation is very similar to the case with trhe SC on High Dam - Nag Hammadi.

2.9.3 POWER FLOW VARIATION ON THE CIRCUIT HIGH DAM - NAG HAMMADI - ASSIUT



2.9.4 VOLTAGE VARIATION ON THE 500 KV



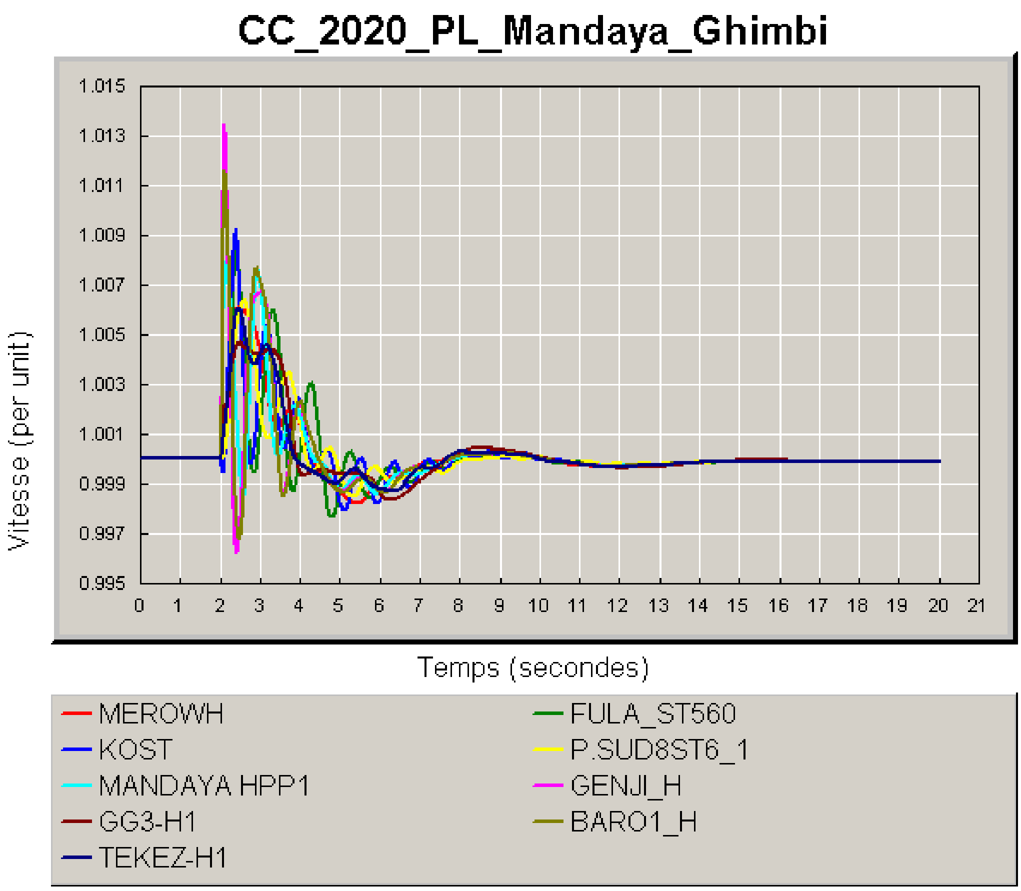
2.10 SHORT-CIRCUIT AT MANDAYA ON ONE OF THE 3 CIRCUITS MANDAYA - GHIMBI

Event : a 3 phase short-circuit at Mandaya end, on one of the 3 circuits Mandaya - Ghimbi, cleared in 100 ms by the opening of the circuit breakers.

The voltage drop in Rabak (to 0.6 pu) led to a transitory blocking of commutation of the rectifier station at Rabak. The flow on the DC interconnection is transitory reduced to 0, before starting, 300 ms after the voltage return, its recovery to its initial value.
During the transitory blocking of the DC stations, the capacitors bank remained connected.

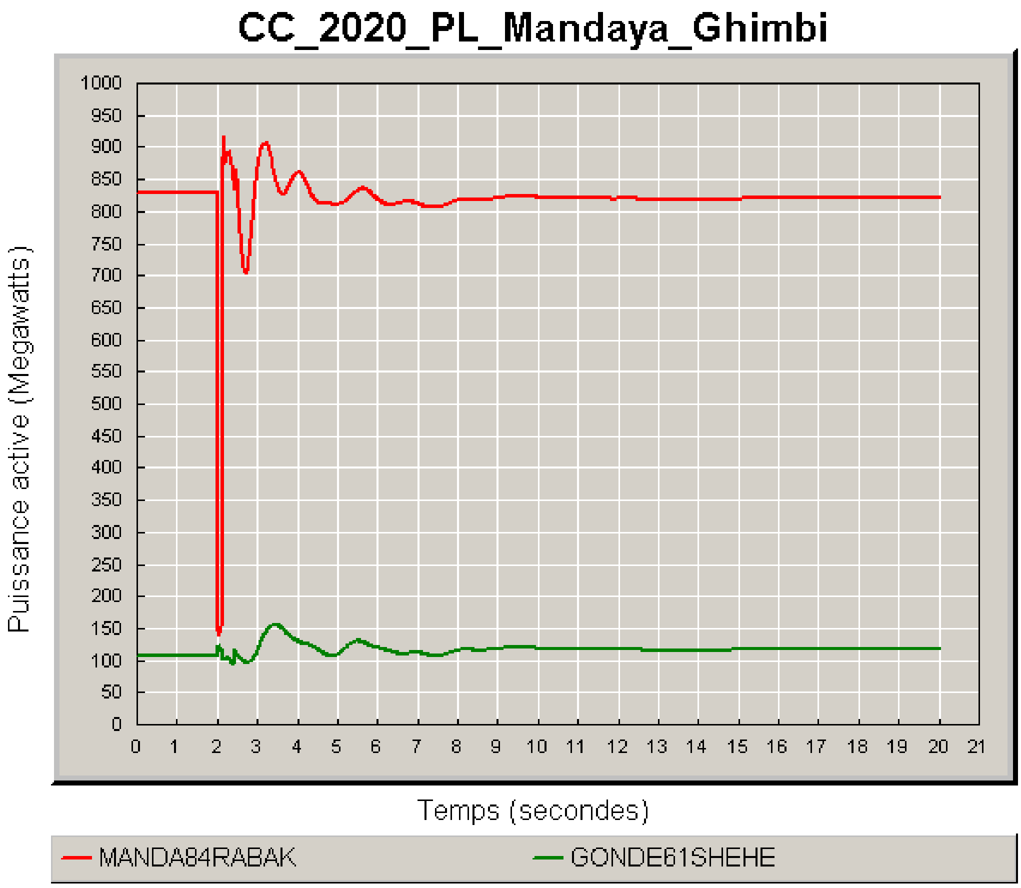
For the Egyptian side, the impact on the system and its behaviour is very similar to the case of SC on Rabak - Fula

2.10.1 GENERATORS FREQUENCY VARIATION

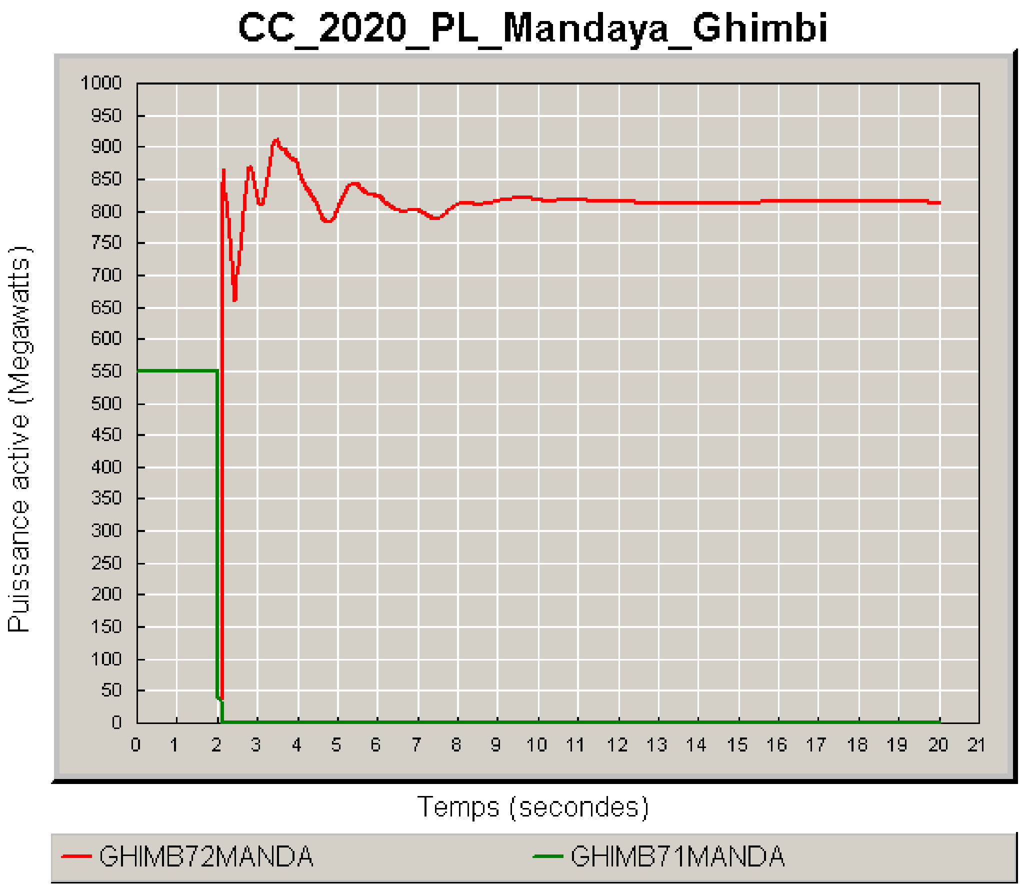


GG3 is Gibe III

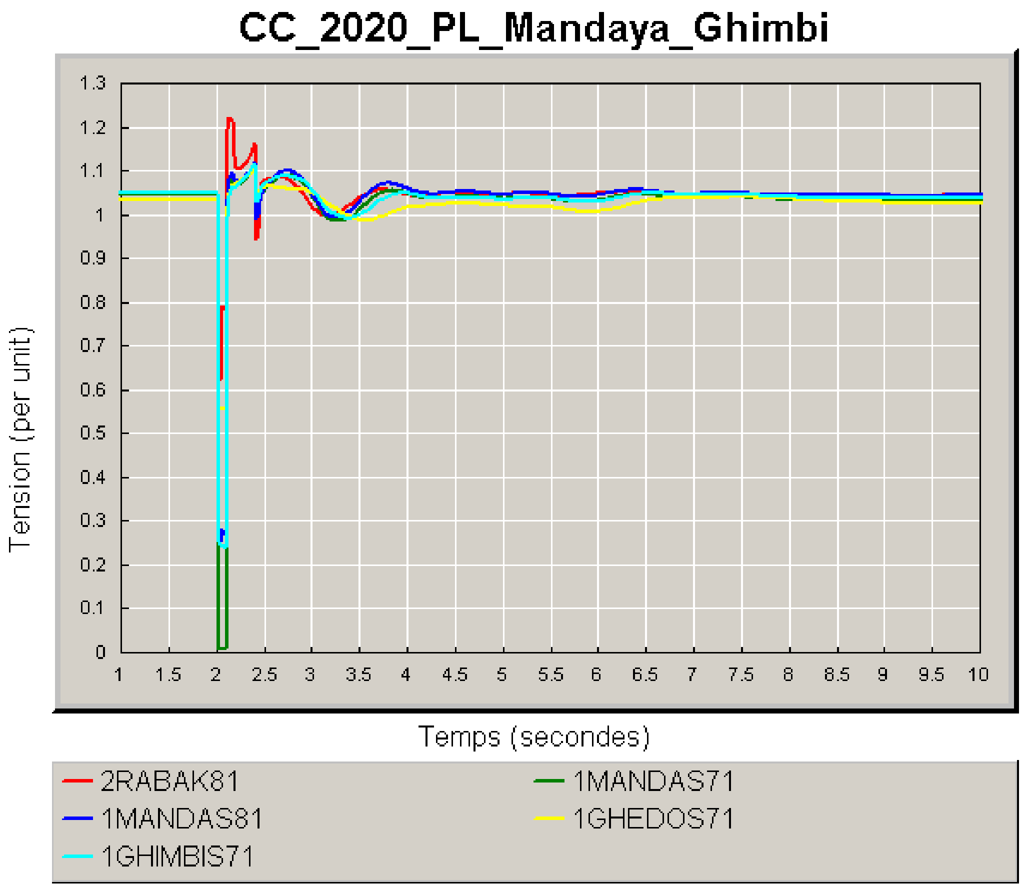
2.10.2 POWER FLOW VARIATION ON ENTRO INTERCONNECTION



2.10.3 POWER FLOW VARIATION ON MANDAYA - GHIMBI



2.10.4 VOLTAGE VARIATION ON THE 500 KV

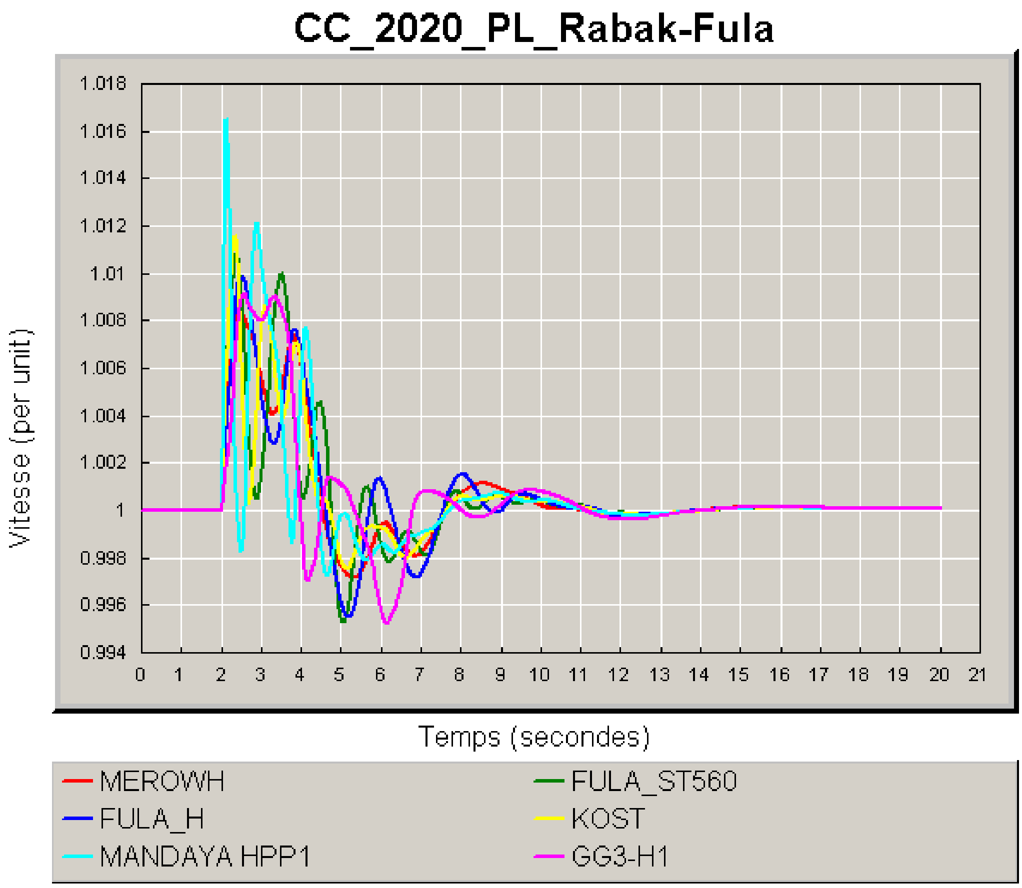


2.11 SHORT-CIRCUIT AT RABAK ON RABAK - FULA

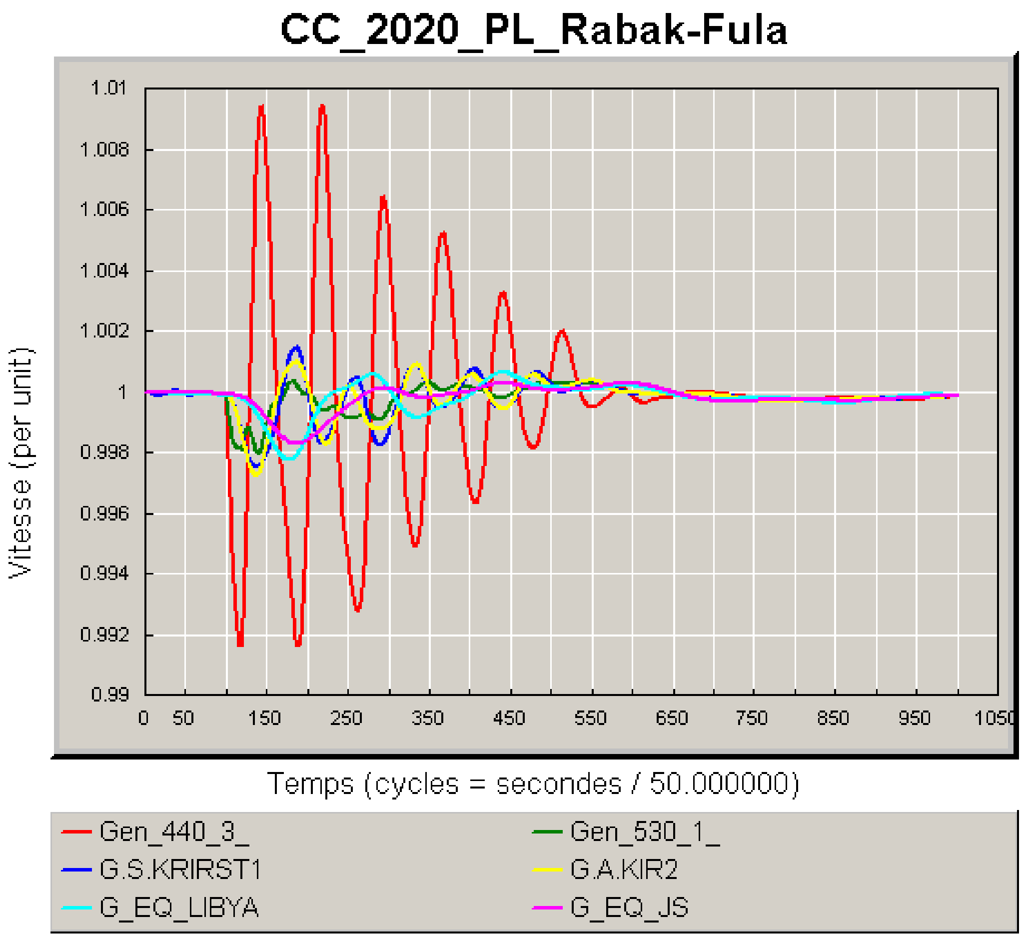
Event : a 3 phase short-circuit at Rabak end, on one of the 2 circuits Rabak - Fula, cleared in 120 ms by the opening of the circuit breakers.

The voltage drop in Rabak (to 0 pu) led to a transitory blocking of commutation of the rectifier station at Rabak. The flow on the DC interconnection is transitory reduced to 0, before starting, 300 ms after the voltage return, its recovery to its initial value.
During the transitory blocking of the DC stations, the capacitors bank remained connected.

2.11.1 GENERATORS FREQUENCY VARIATION



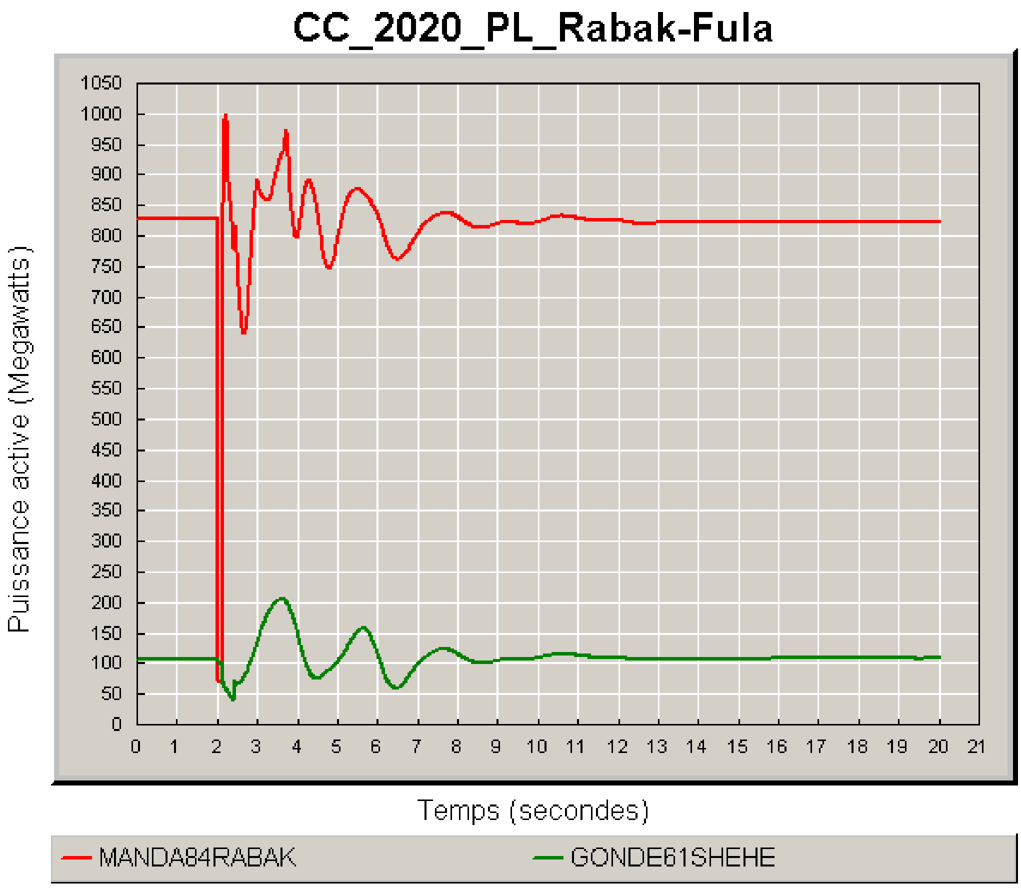
GG3 is Gibe III



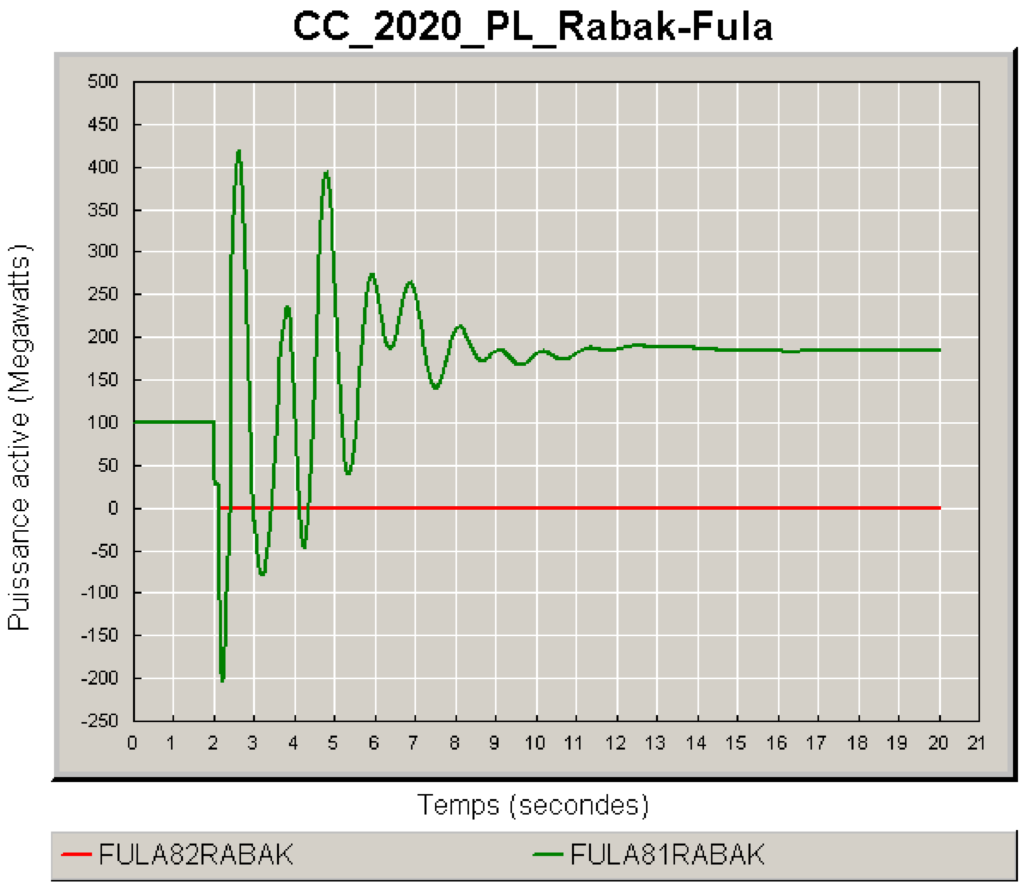
Gen_440_3 is a group of High Dam

Gen_530 is the existing steam turbine in Kurimat

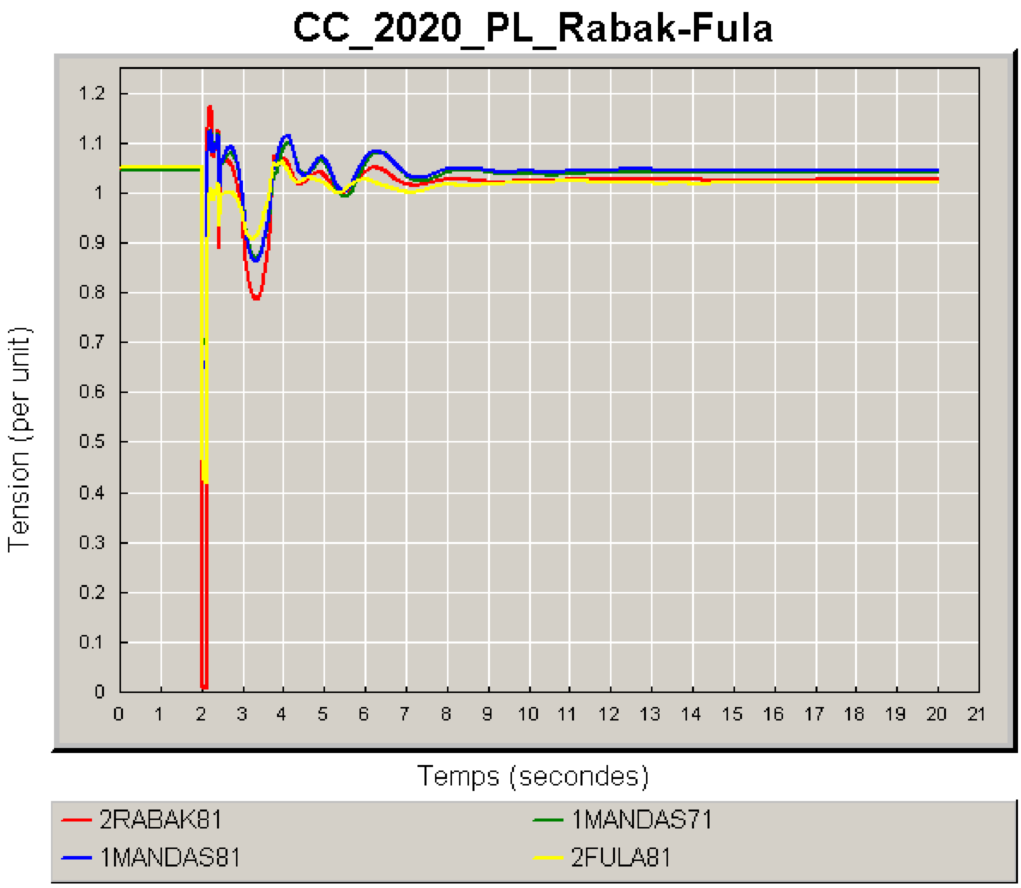
2.11.2 POWER FLOW VARIATION ON ENTRO INTERCONNECTION

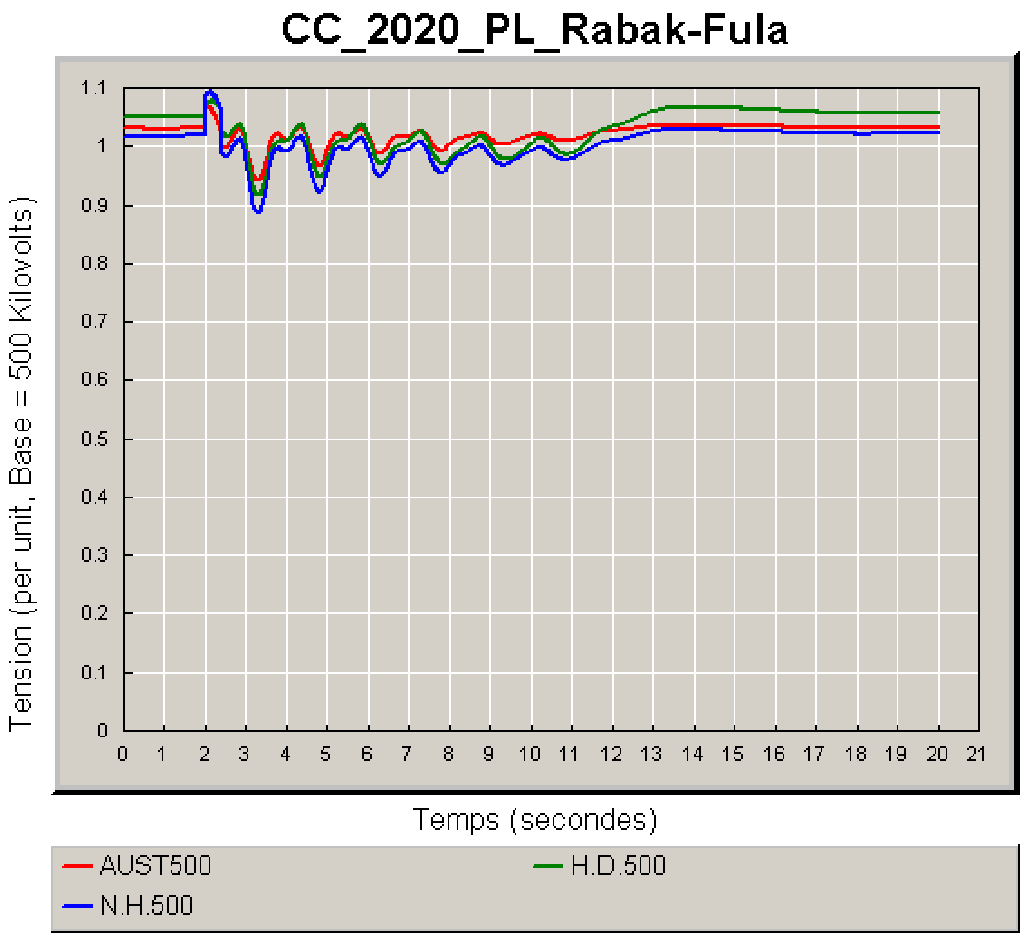


2.11.3 POWER FLOW VARIATION ON RABAK - FULA



2.11.4 VOLTAGE VARIATION ON THE 500 KV




CC_2020_PL_Rabak-Fula
Tension (per unit, Base = 500 Kilovolts)
1.1
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21
Temps (secondes)
AUST500
H.D.500
N.H.500

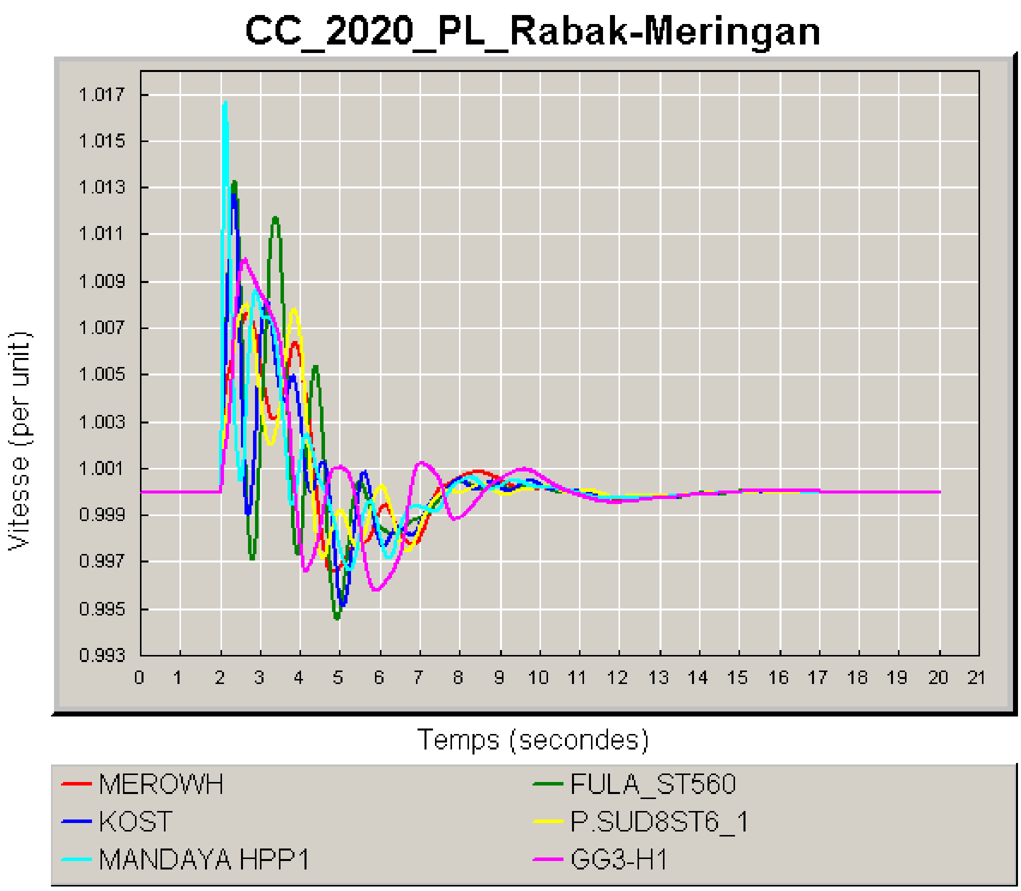
2.12 SHORT-CIRCUIT AT RABAK ON RABAK - MERINGAN

Event : a 3 phase short-circuit at Rabak end, on the circuit Rabak - Meringan, cleared in 120 ms by the opening of the circuit breakers.

The voltage drop in Rabak (to 0 pu) led to a transitory blocking of commutation of the rectifier station at Rabak. The flow on the DC interconnection is transitory reduced to 0, before starting, 300 ms after the voltage return, its recovery to its initial value.
During the transitory blocking of the DC stations, the capacitors bank remained connected.

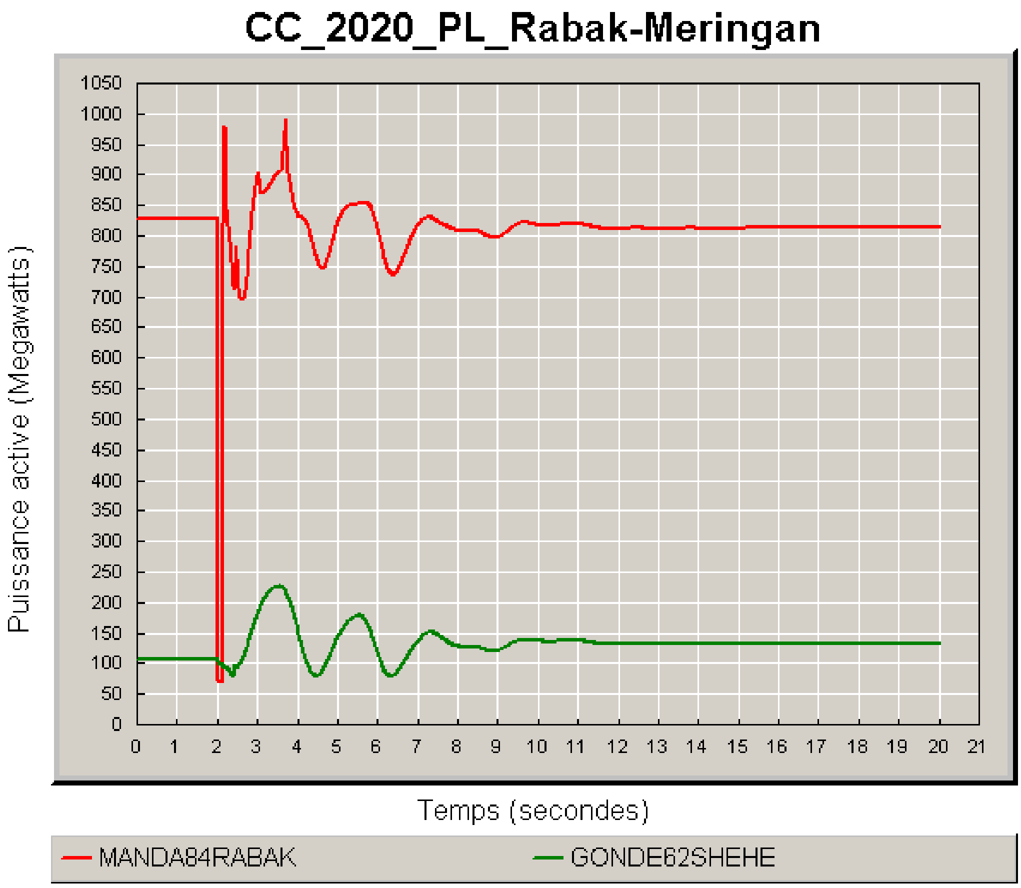
For the Egyptian side, the impact on the system and its behaviour is very similar to the case of SC on Rabak - Fula

2.12.1 GENERATORS FREQUENCY VARIATION

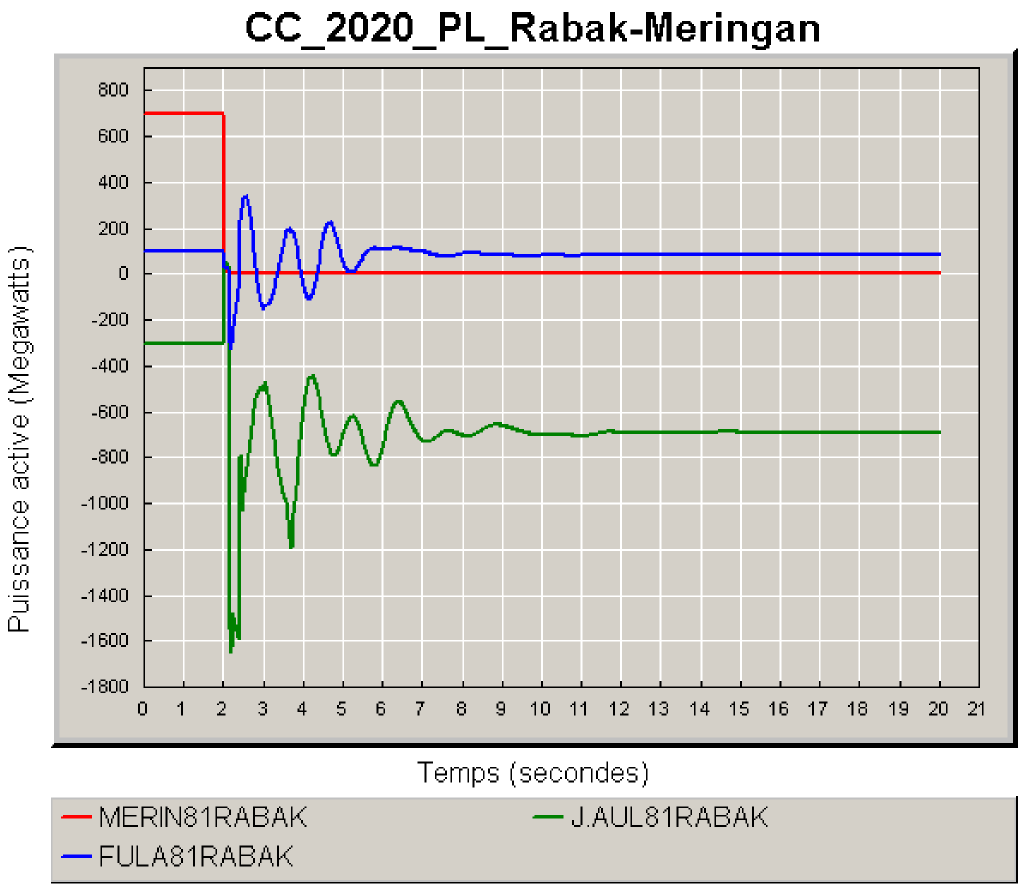


GG3 is Gibe III

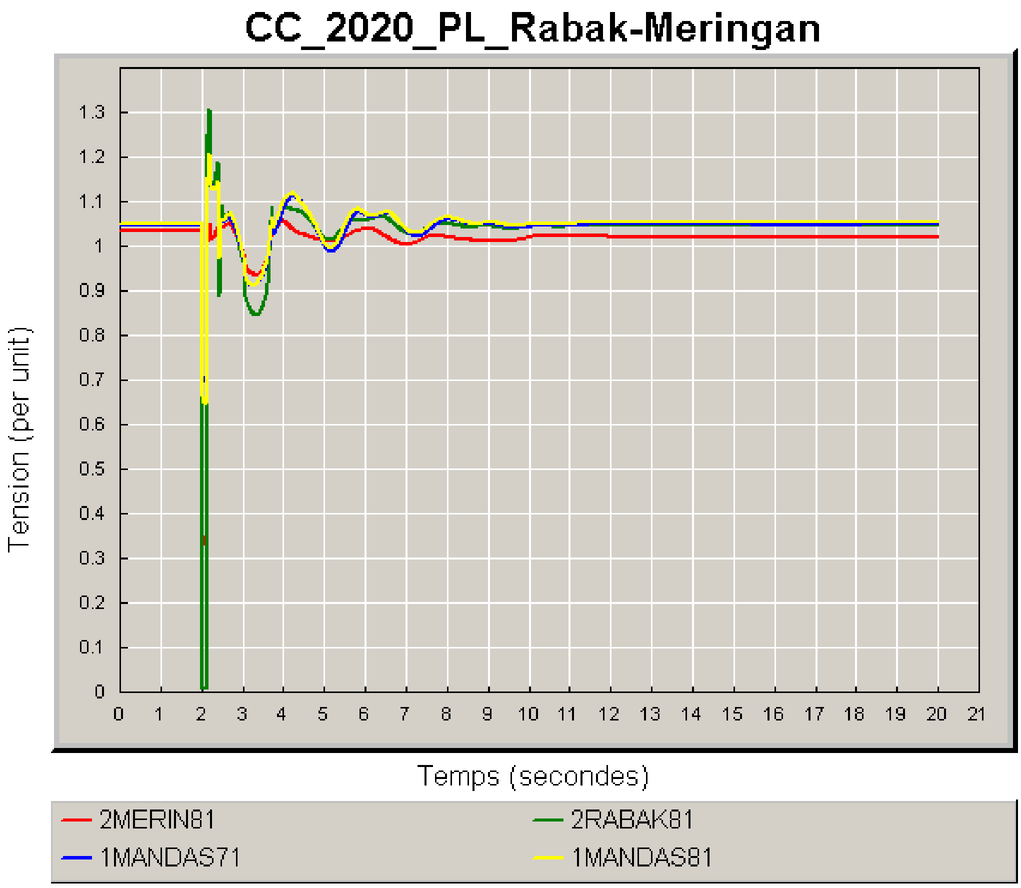
2.12.2 POWER FLOW VARIATION ON ENTRO INTERCONNECTION



2.12.3 POWER FLOW VARIATION ON RABAK - MERINGAN, RABAK - FULA AND RABAK - J. AULIA



2.12.4 VOLTAGE VARIATION ON THE 500 KV



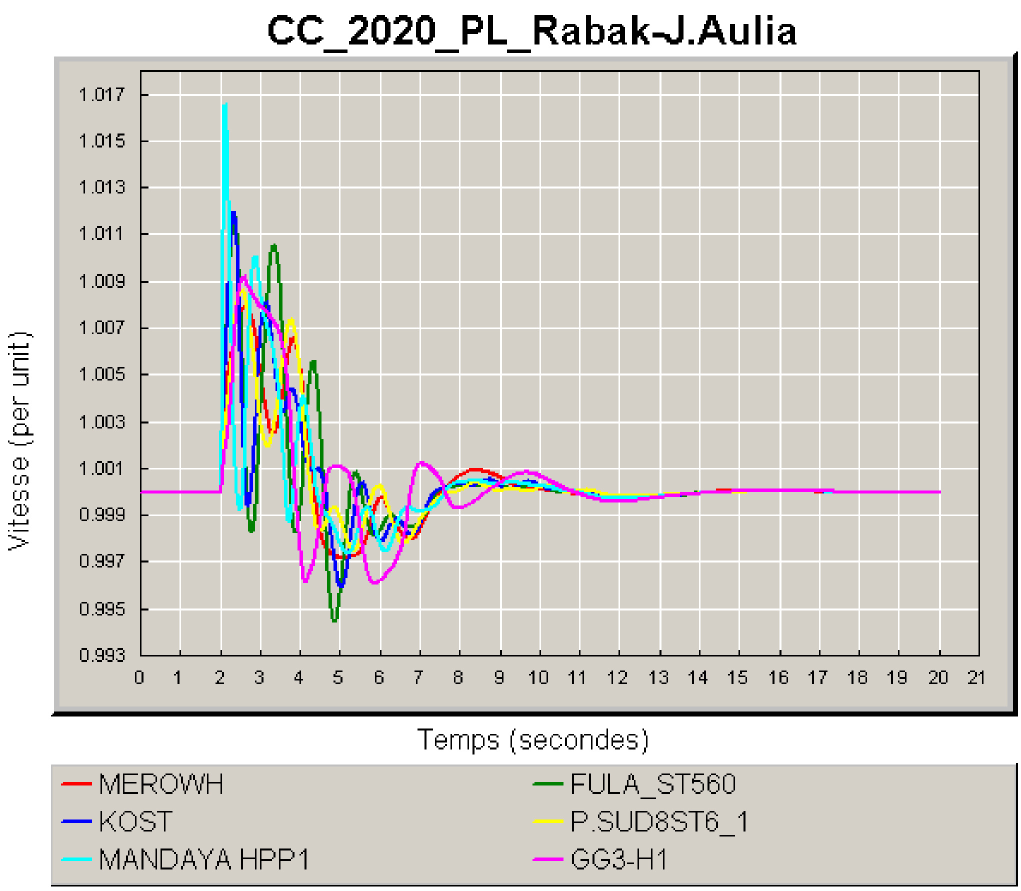
2.13 SHORT-CIRCUIT AT RABAK ON RABAK - JEBEL AULIA

Event : a 3 phase short-circuit at Rabak end, on the circuit Rabak – Jebel Aulia, cleared in 120 ms by the opening of the circuit breakers.

The voltage drop in Rabak (to 0 pu) led to a transitory blocking of commutation of the rectifier station at Rabak. The flow on the DC interconnection is transitory reduced to 0, before starting, 300 ms after the voltage return, its recovery to its initial value.
During the transitory blocking of the DC stations, the capacitors bank remained connected.

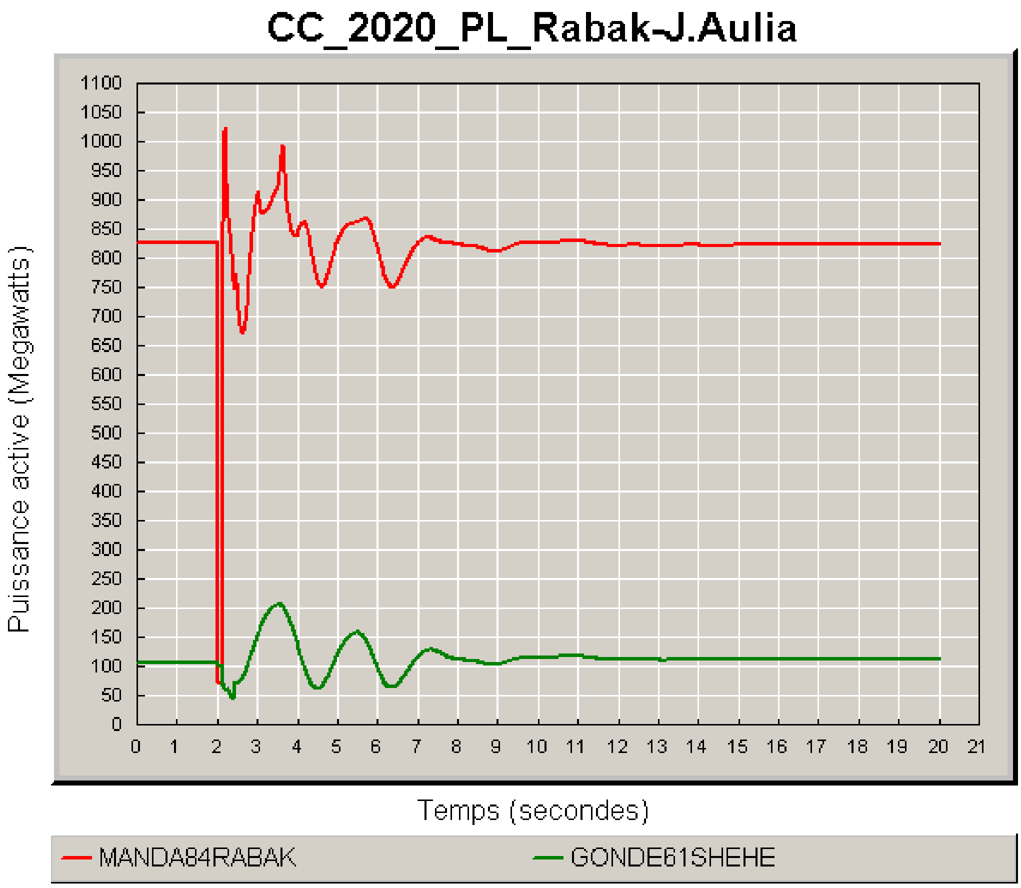
For the Egyptian side, the impact on the system and its behaviour is very similar to the case of SC on Rabak - Fula

2.13.1 GENERATORS FREQUENCY VARIATION

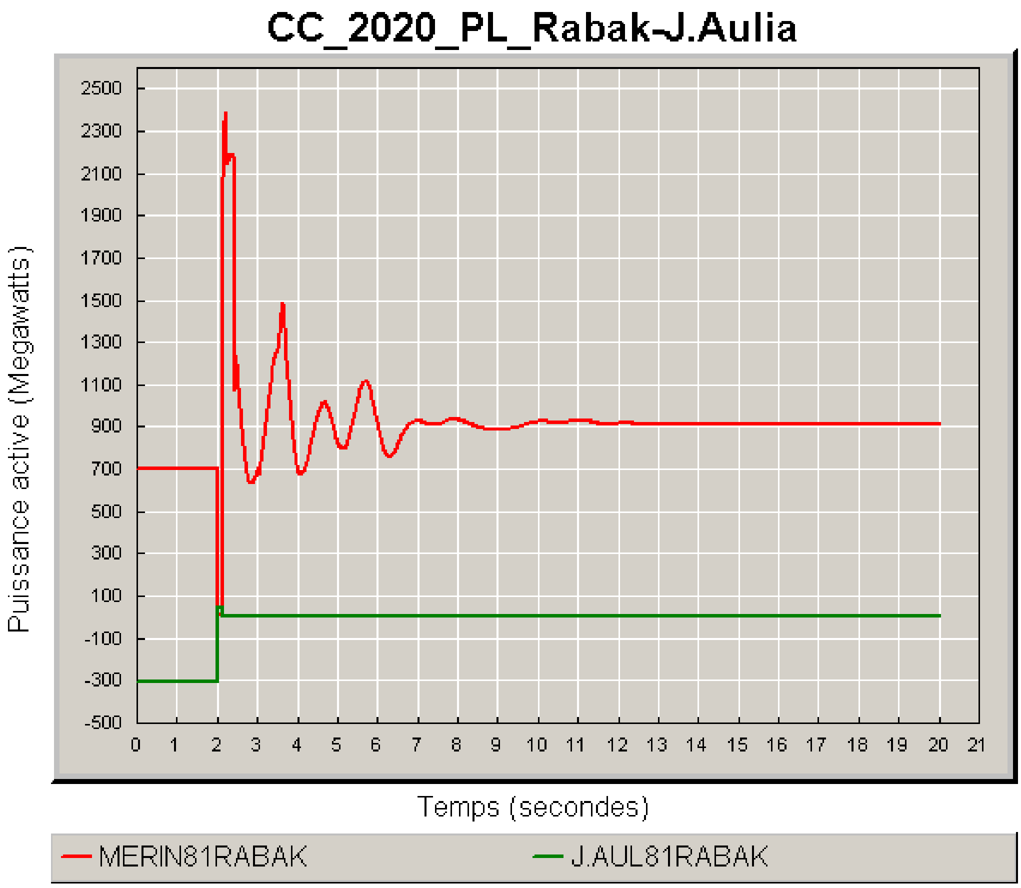


GG3 is Gibe III

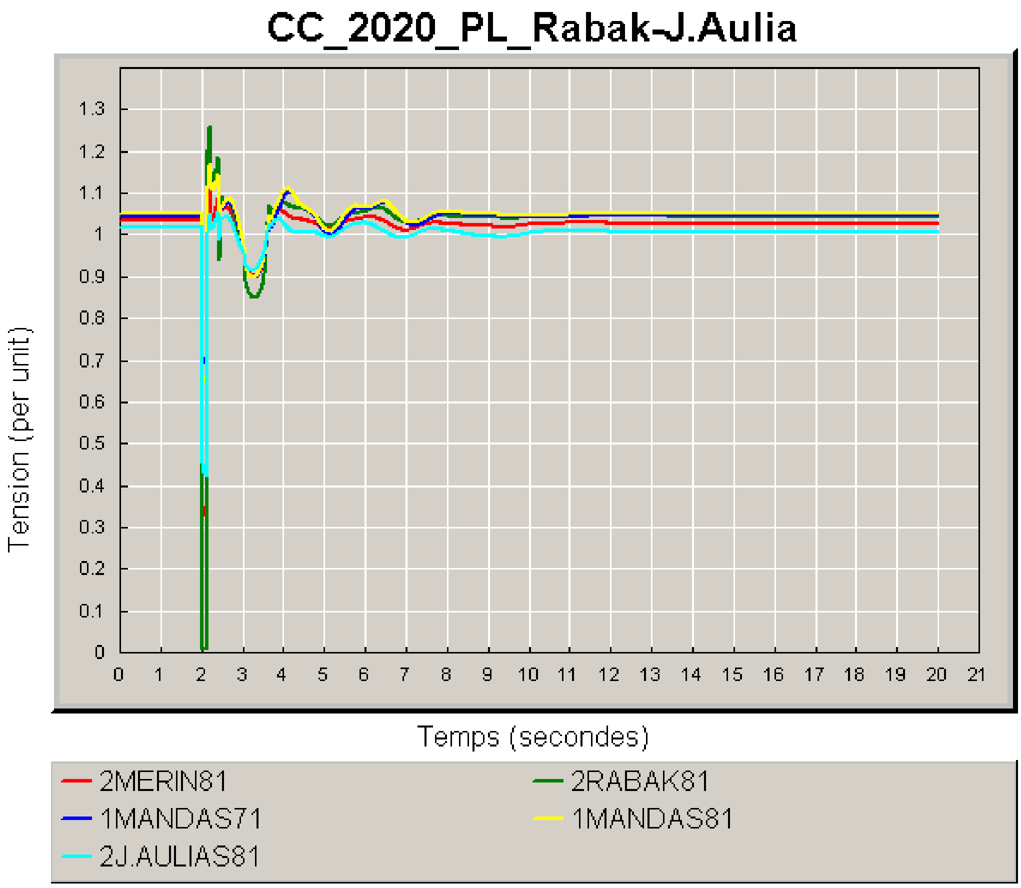
2.13.2 POWER FLOW VARIATION ON ENTRO INTERCONNECTION



2.13.3 POWER FLOW VARIATION ON RABAK - JEBEL AULIA AND RABAK - MERINGAN

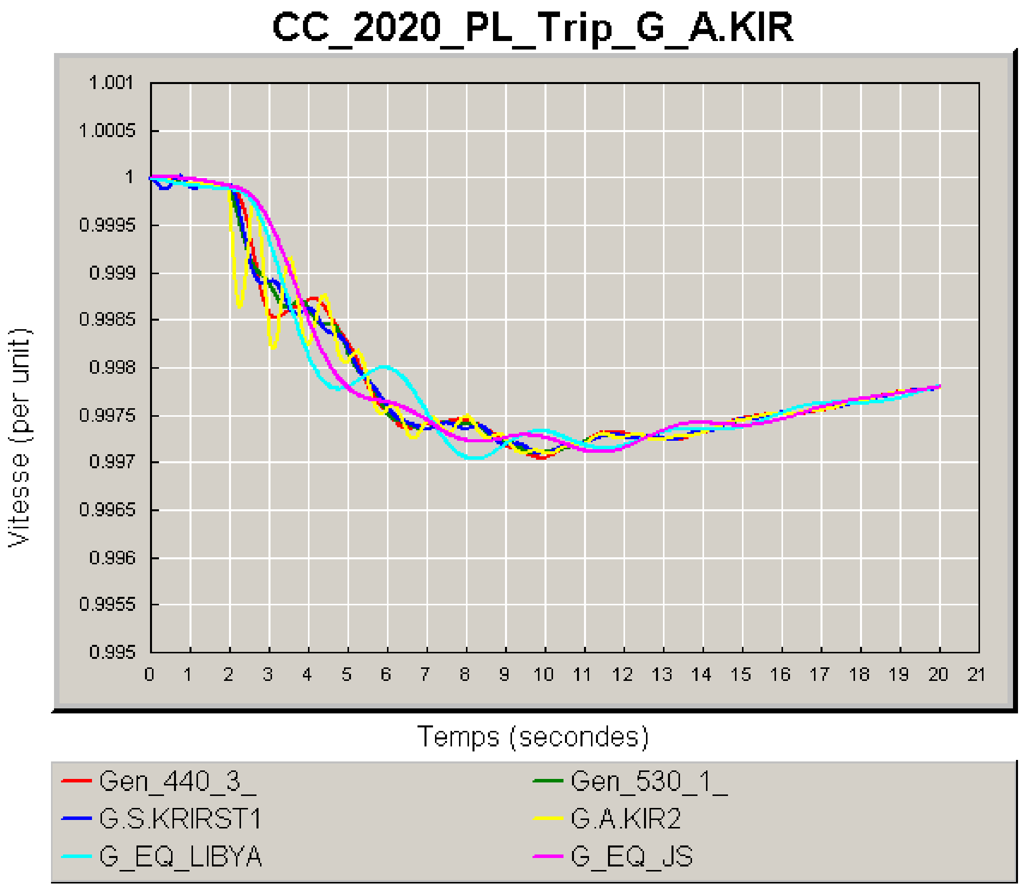


2.13.4 VOLTAGE VARIATION ON THE 500 KV



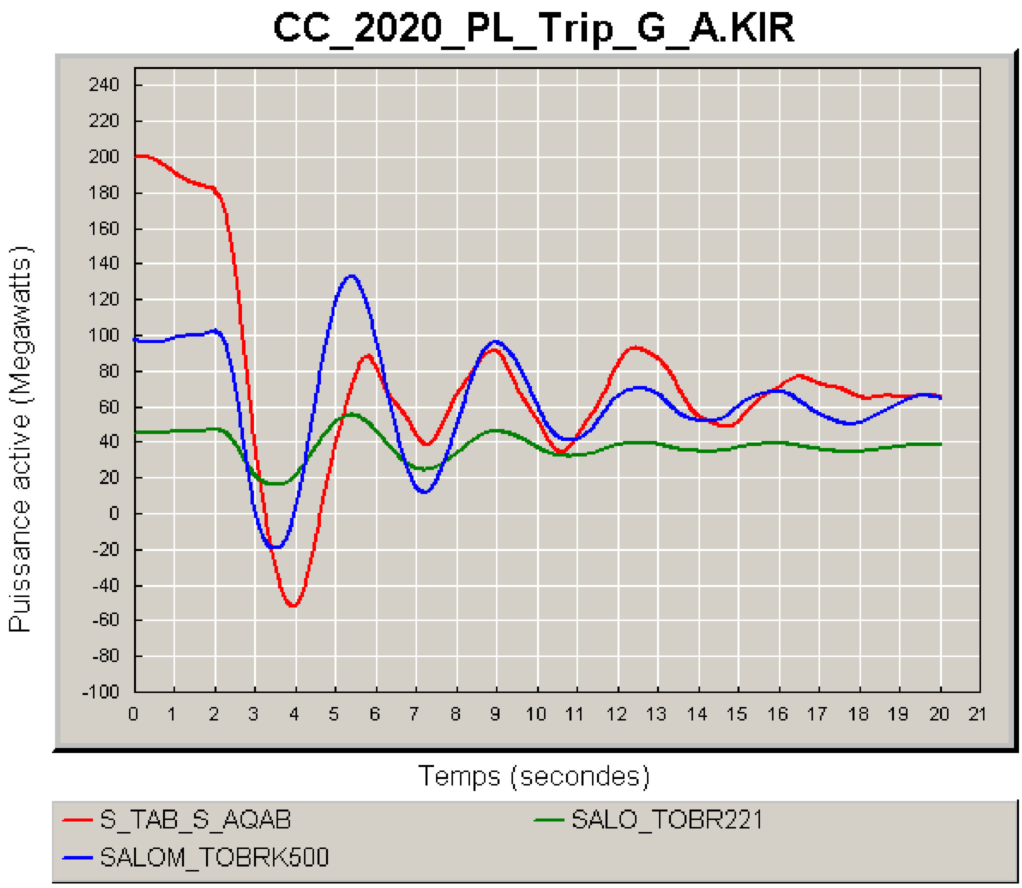
2.14 TRIPPING OF THE MAIN UNIT IN EGYPT : ABU KIR 650 MW STEAM TURBINE

2.14.1 GENERATORS FREQUENCY VARIATION

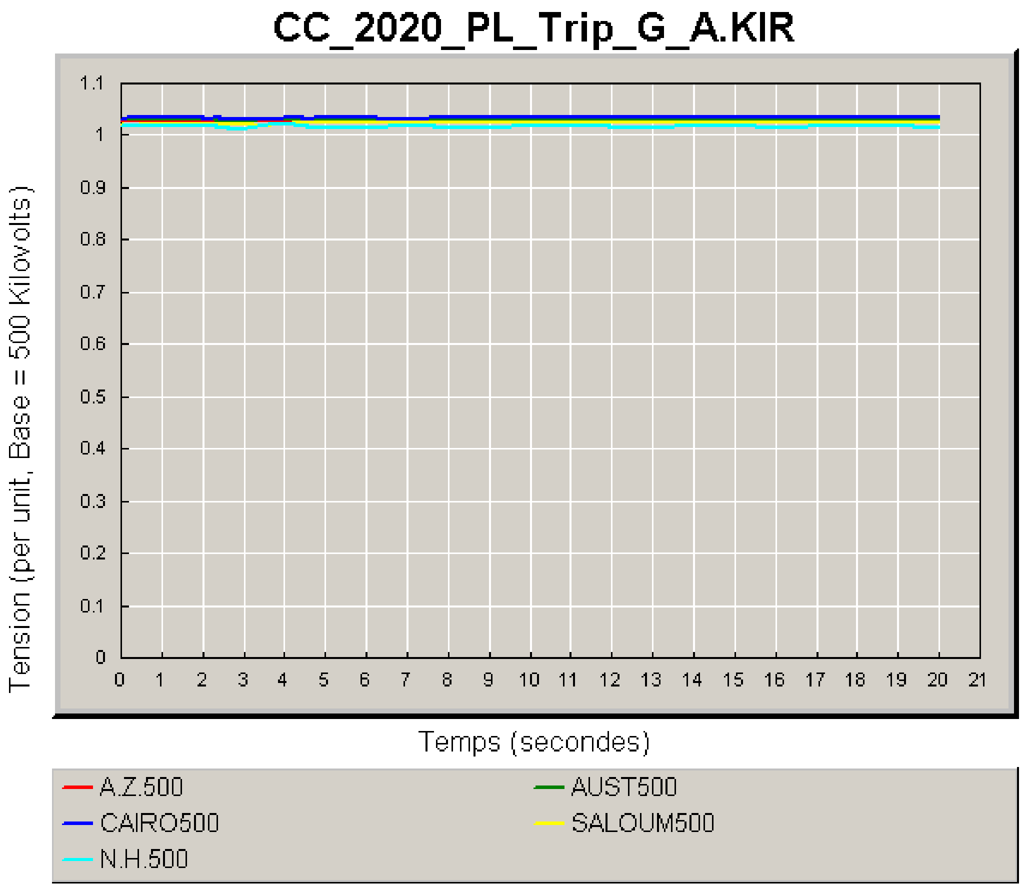


Gen_440_3 is a group of High Dam
Gen_530_1 is group 1 of Kurimat existing steam

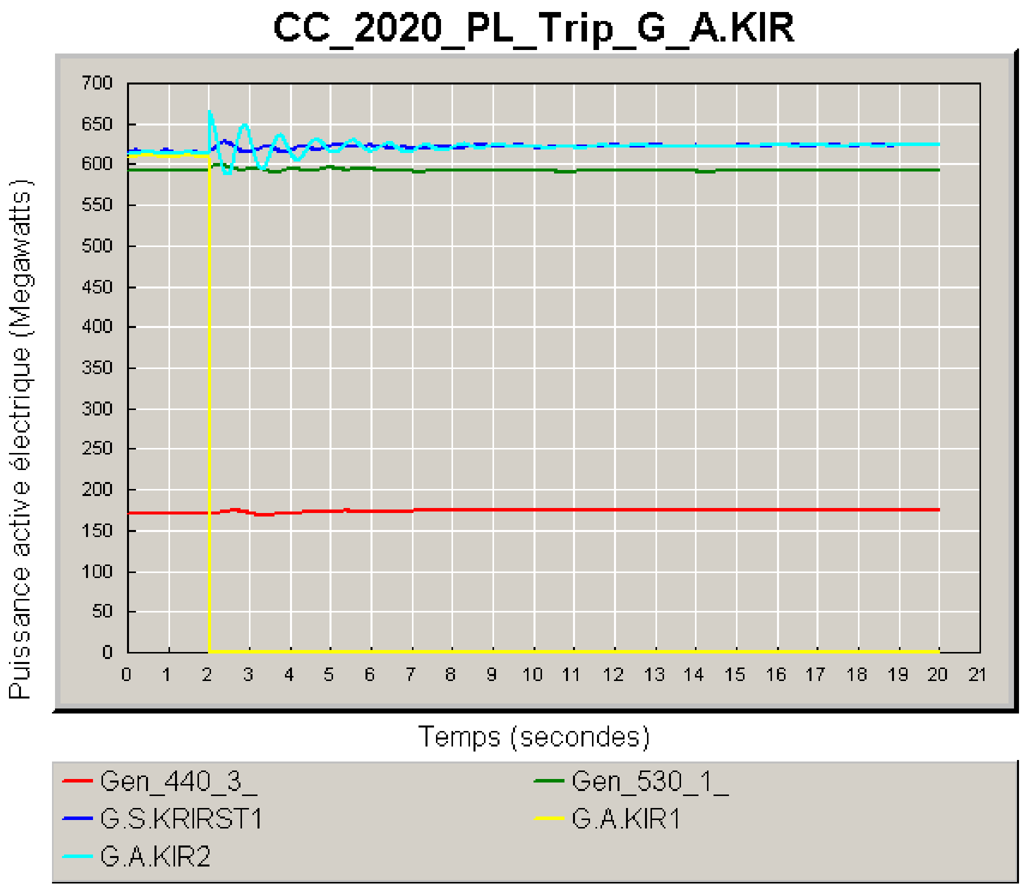
2.14.2 POWER FLOW VARIATION ON EGYPT - LIBYA AND EGYPT - JORDAN INTERCONNECTION



2.14.3 VOLTAGE VARIATION



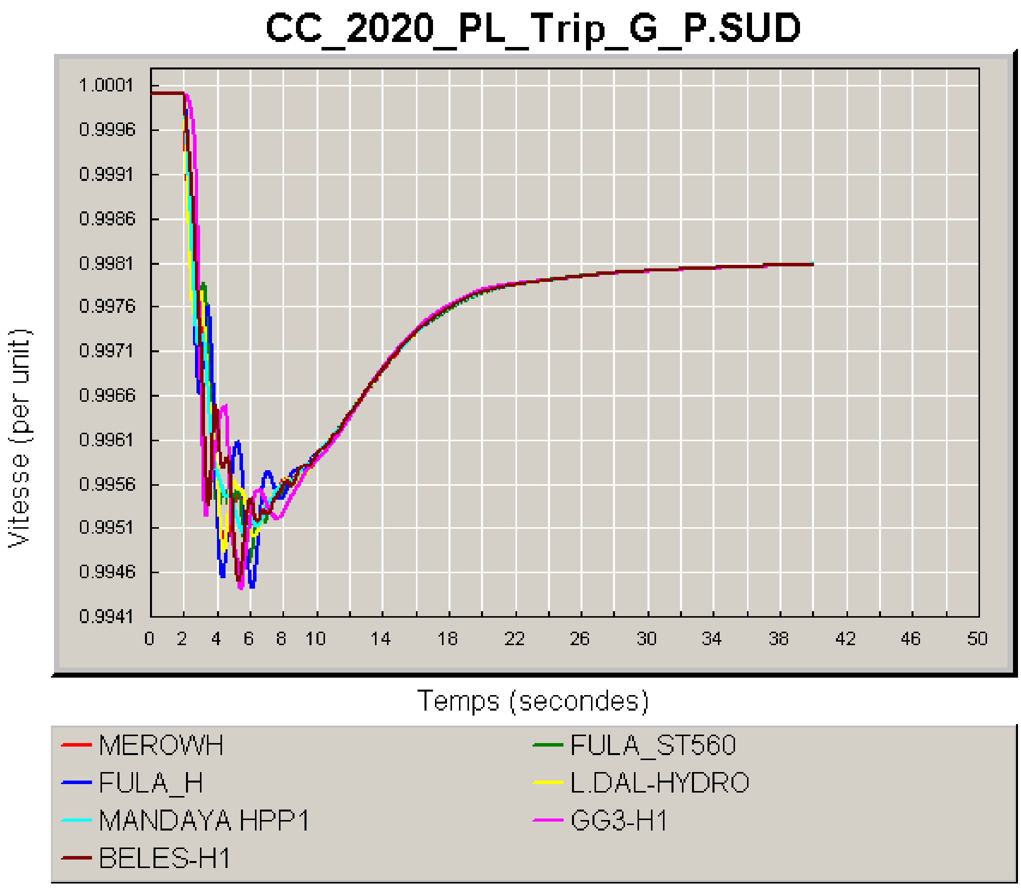
2.14.4 OUTPUT VARIATION OF SOME GENERATION UNITS



2.15 TRIPPING OF THE MAIN UNIT IN SUDAN : PORT SUDAN 530 MW STEAM TURBINE

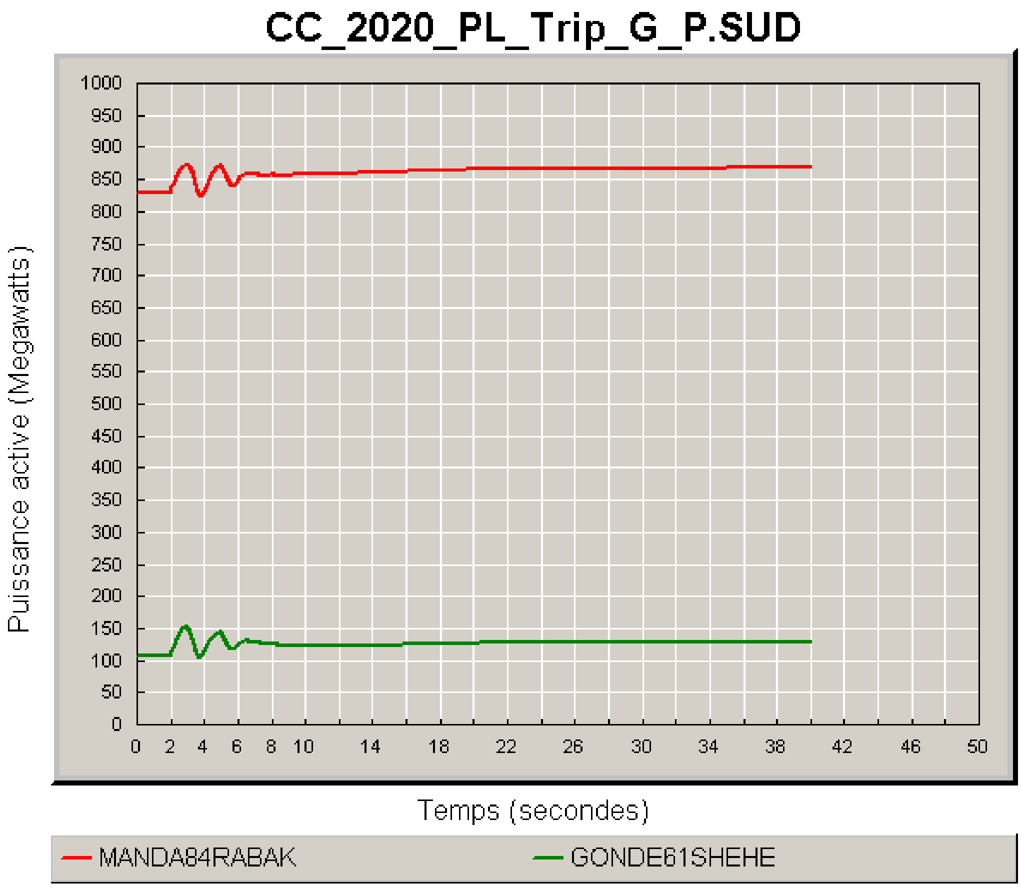
Event : the 670 MVA steam unit of Port-Sudan (the main unit in Sudan) is tripped.

2.15.1 GENERATORS FREQUENCY VARIATION

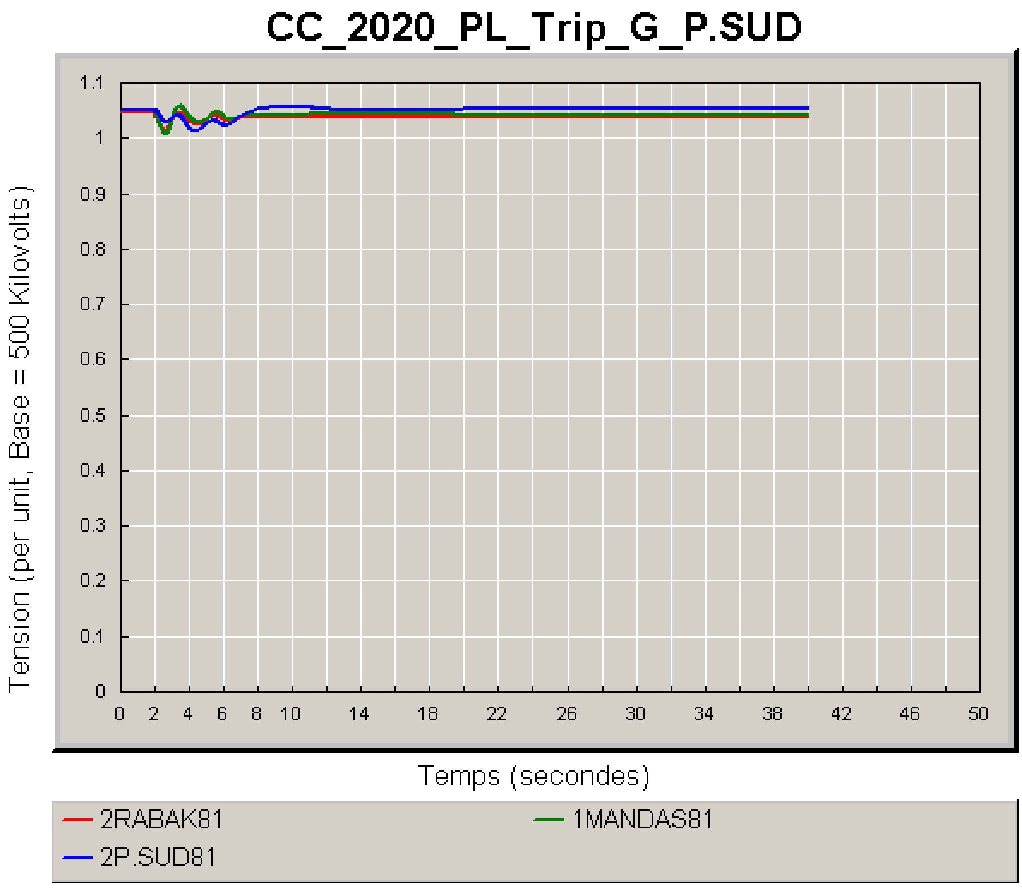


GG3 is Gibe III

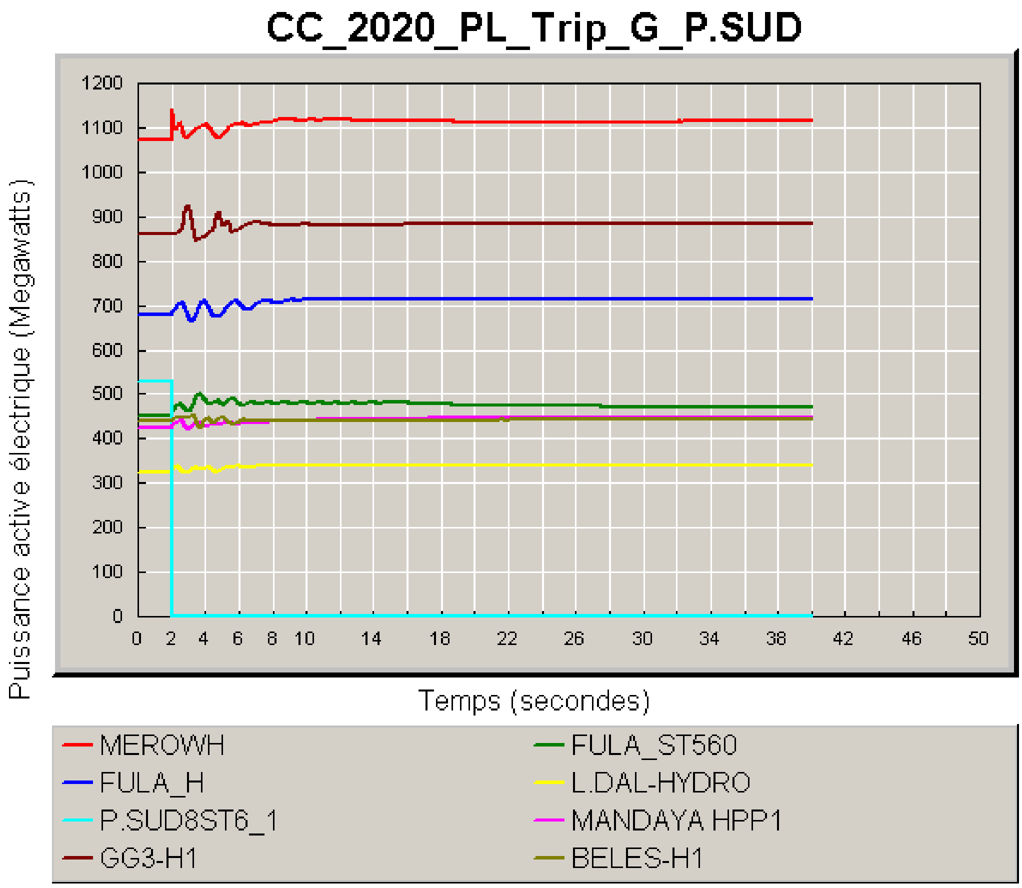
2.15.2 POWER FLOW VARIATION ON ENTRO INTERCONNECTION



2.15.3 VOLTAGE VARIATION

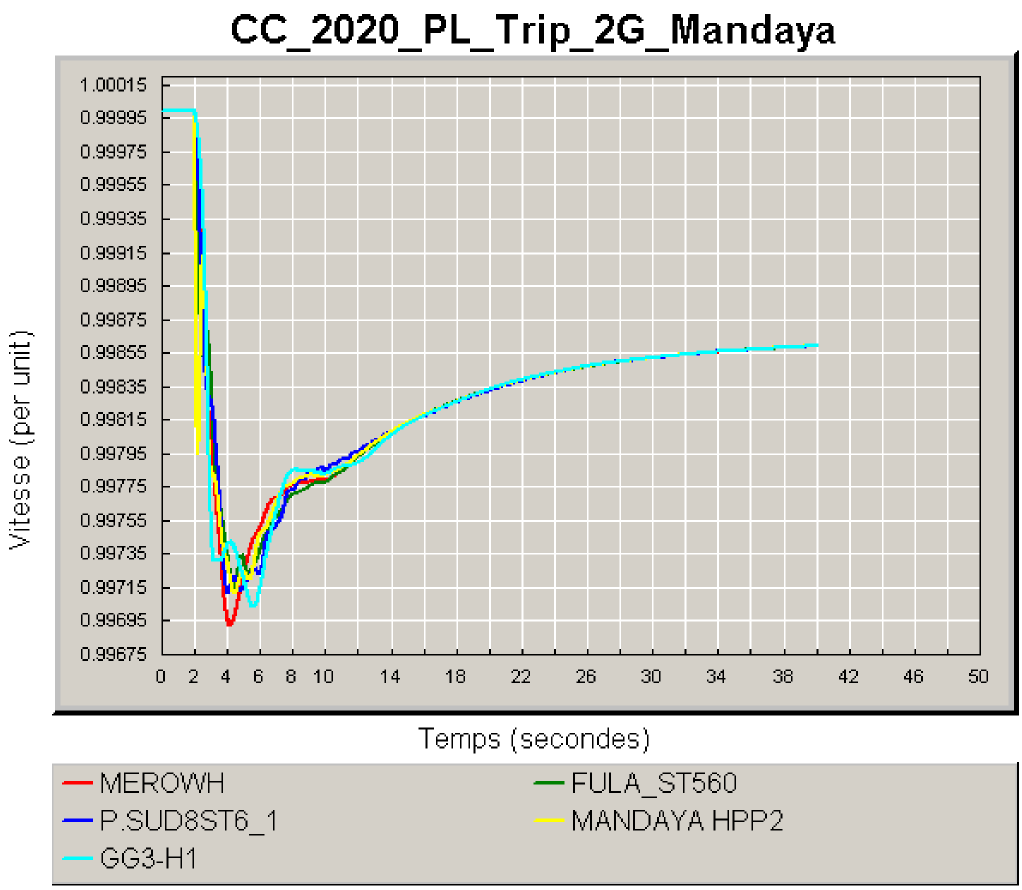


2.15.4 OUTPUT VARIATION FOR SOME GENERATION UNITS



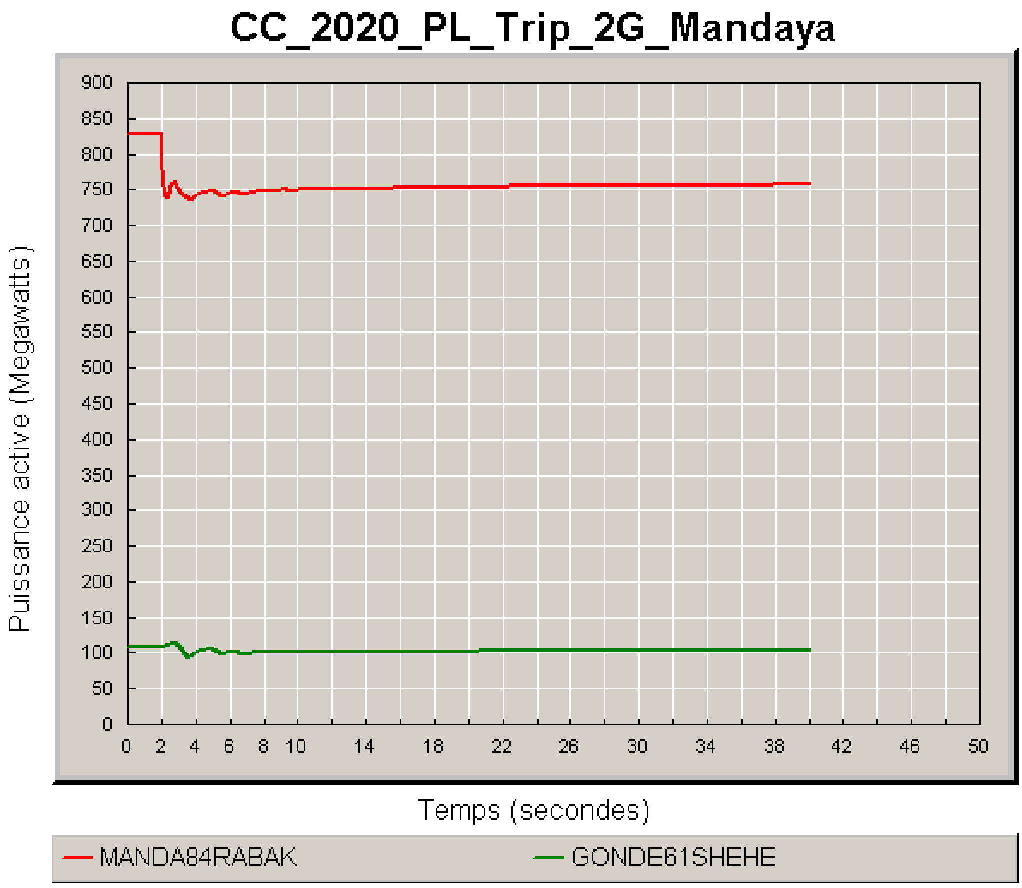
2.16 TRIPPING OF THE MAIN 2 UNITS IN ETHIOPIA : 2 UNITS OF 212.5 MW IN MANDAYA

2.16.1 GENERATORS FREQUENCY VARIATION

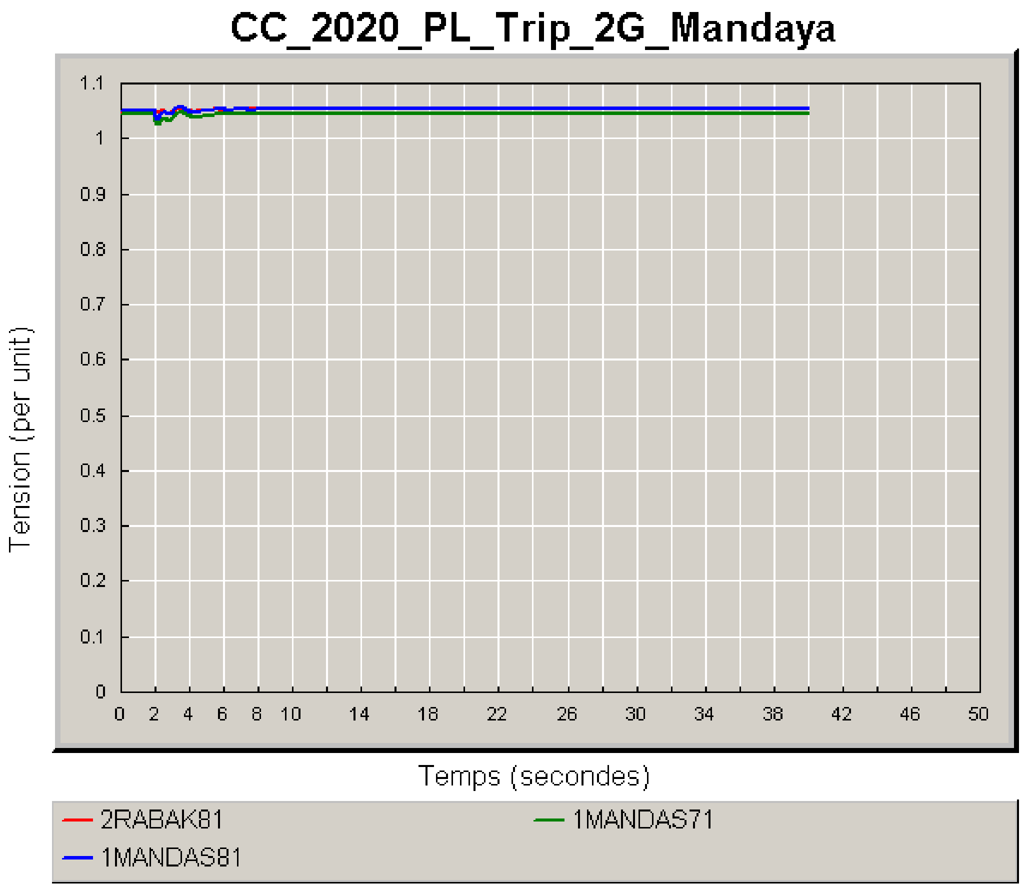


GG3 is Gibe III

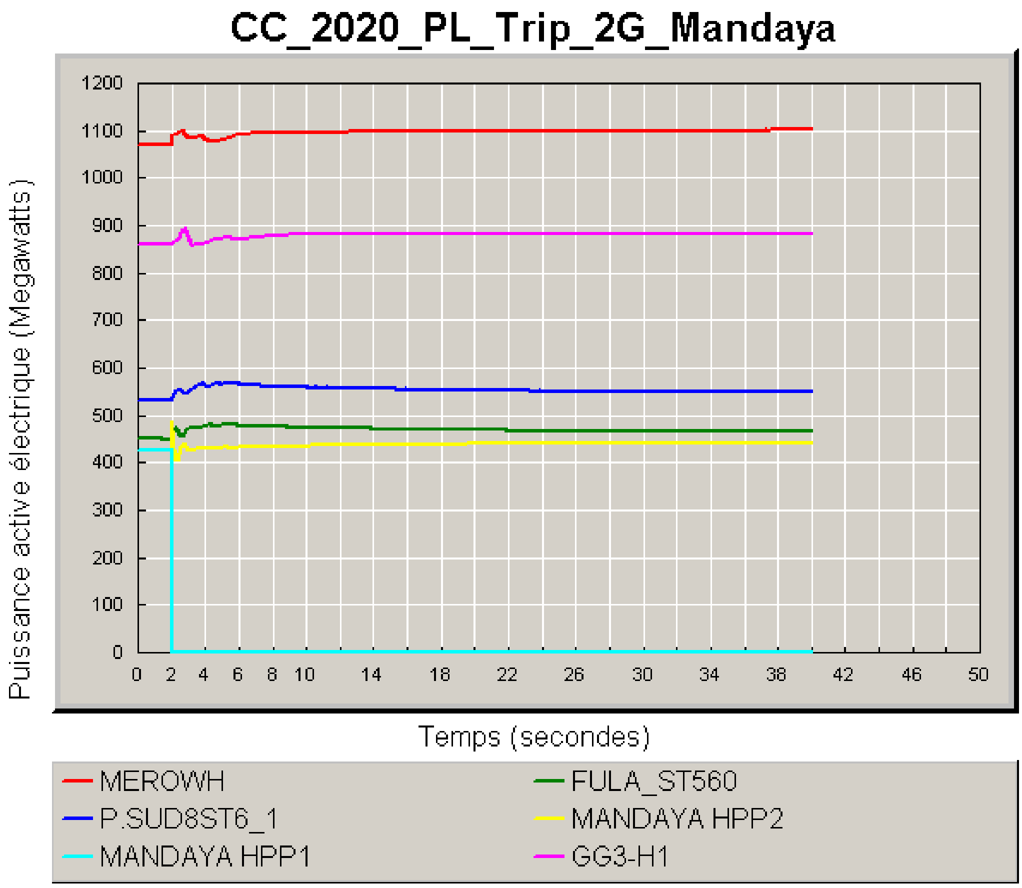
2.16.2 POWER FLOW VARIATION ON ENTRO INTERCONNECTION



2.16.3 VOLTAGE VARIATION



2.16.4 OUTPUT VARIATION FOR SOME GENERATION UNITS

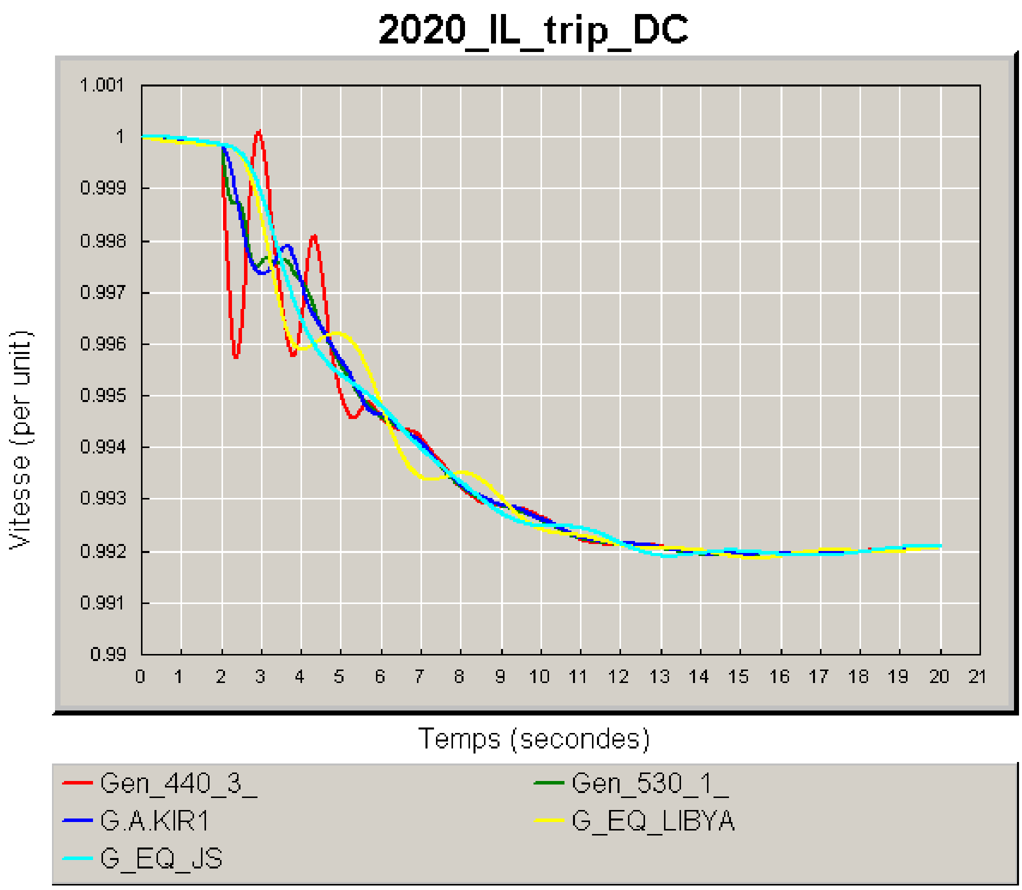


3 2020 INTERMEDIATE LOAD SITUATION

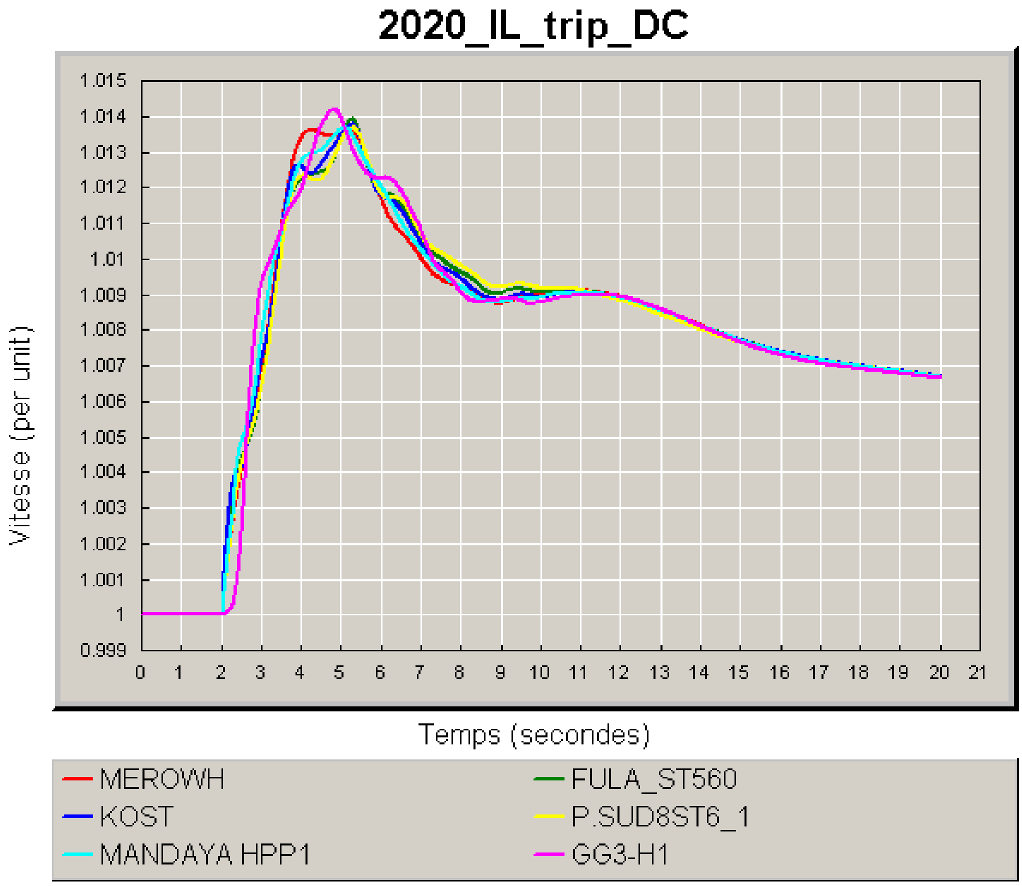
3.1 TRIPPING OF ONE OF THE 2 POLES OF THE DC INTERCONECTION

Event : one of the 2 poles was tripped following an internal fault. 300 ms after, half of the capacitor banks of each HVDC substations were disconnected.

3.1.1 GENERATORS FREQUENCY VARIATION

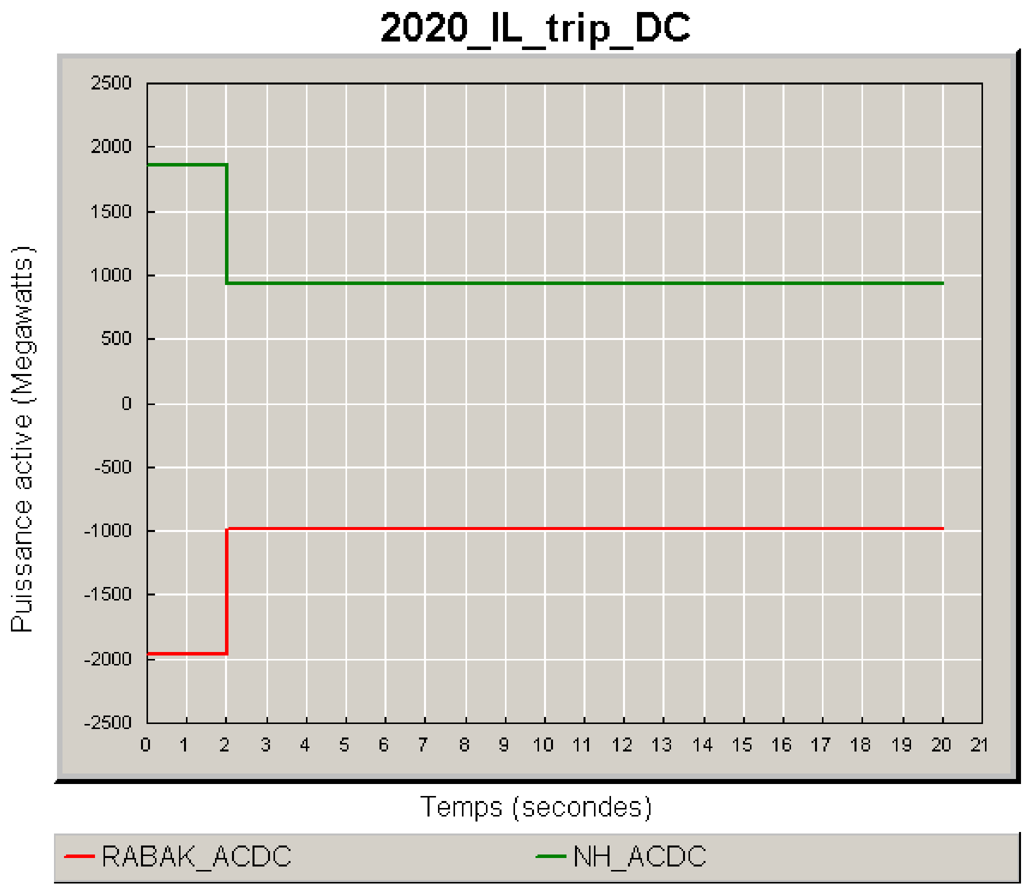


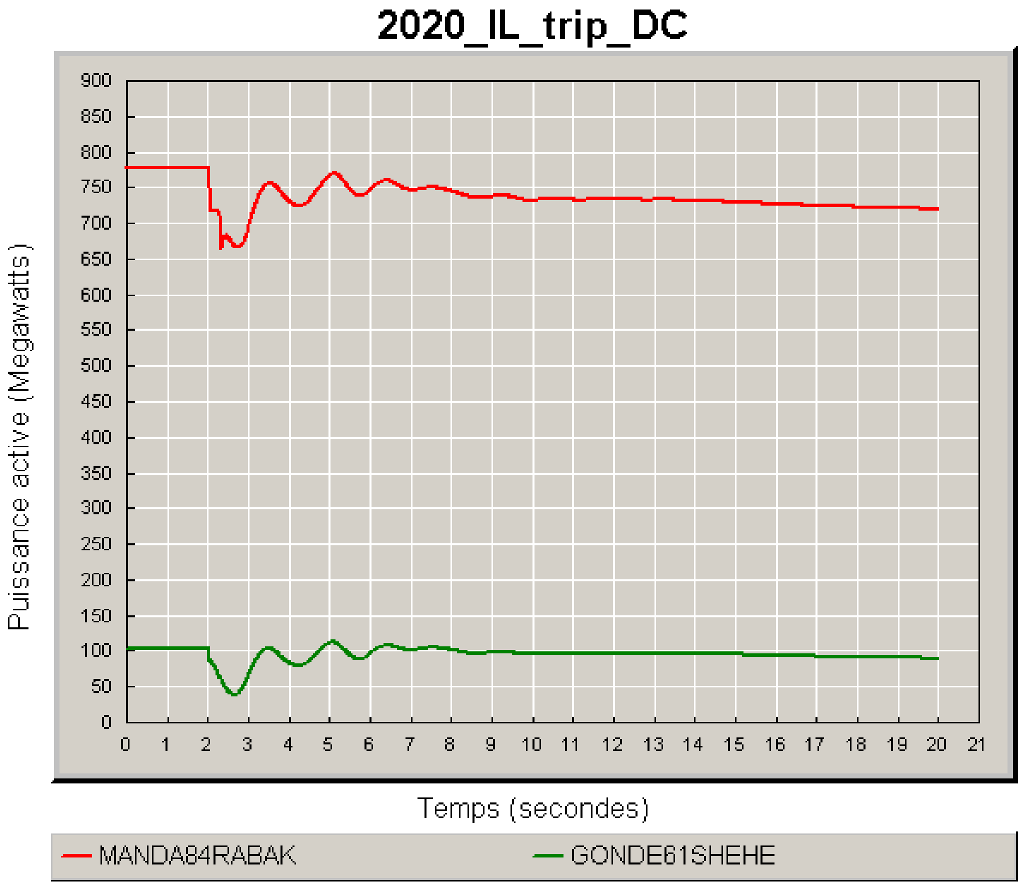
Gen_440_3 is a group of High Dam
Gen_530_1 is group 1 of Kurimat existing steam



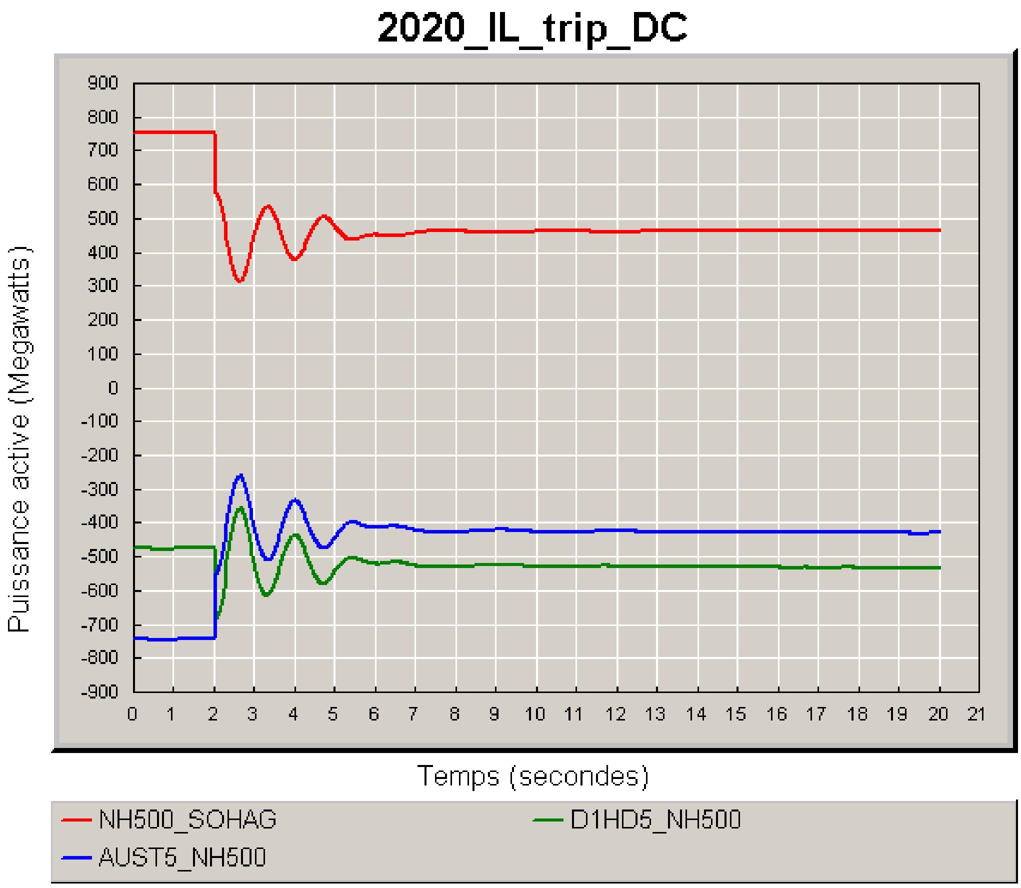
GG3 is Gibe III

3.1.2 POWER FLOW VARIATION ON ENTRO INTERCONNECTION

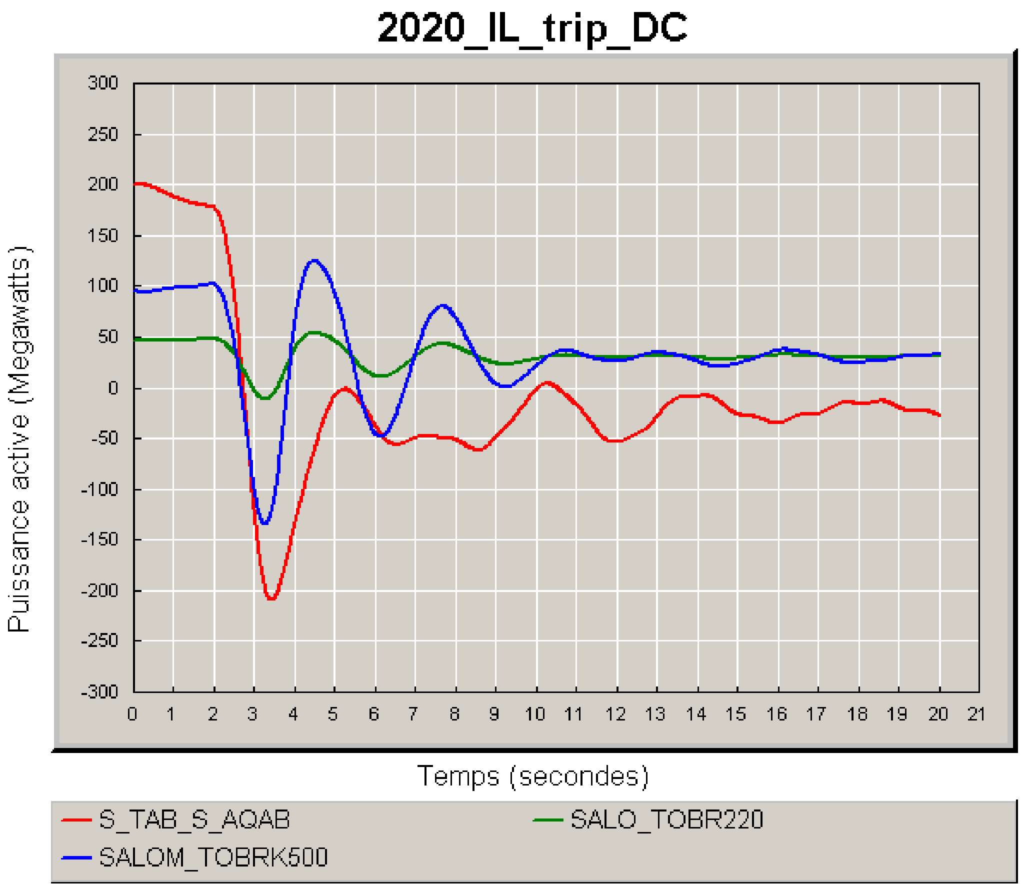



2020_IL_trip_DC
Puissance active (Megawatts)
900
850
800
750
700
650
600
550
500
450
400
350
300
250
200
150
100
50
0
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21
Temps (secondes)
MANDA84RABAK
GONDE61SHEHE

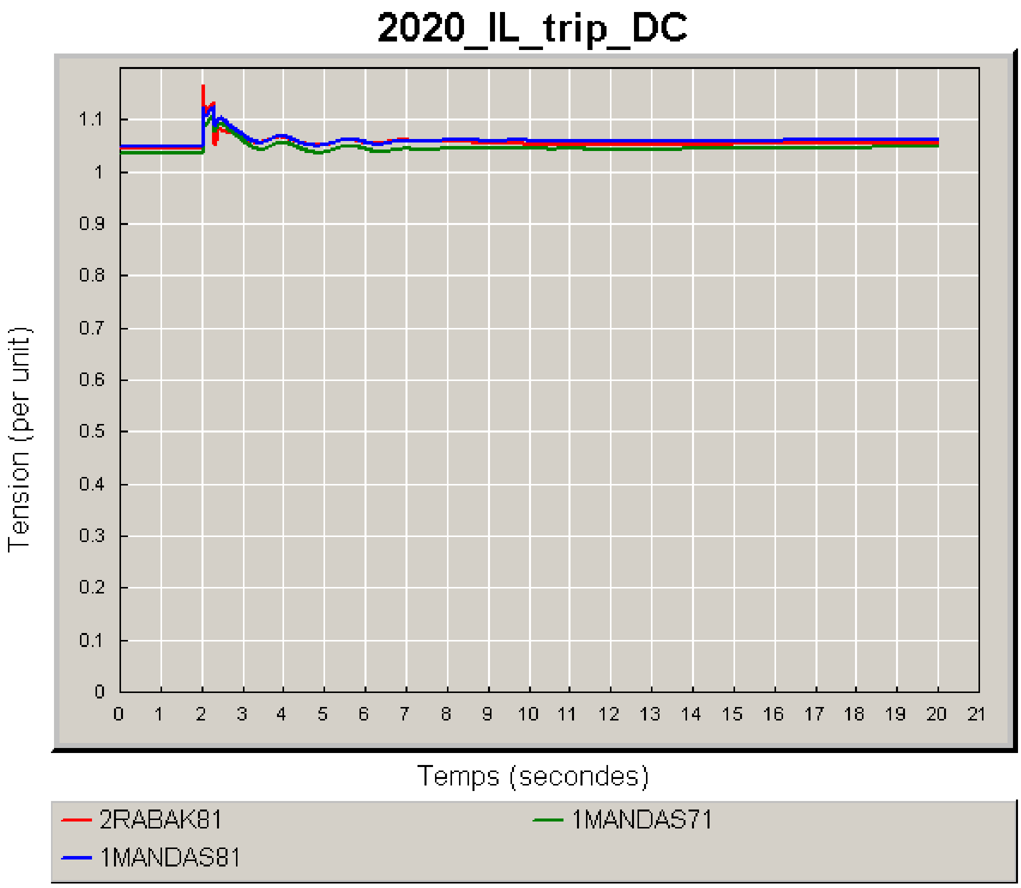
3.1.3 POWER FLOW VARIATION ON NAG HAMMADI 500 KV CIRCUITS

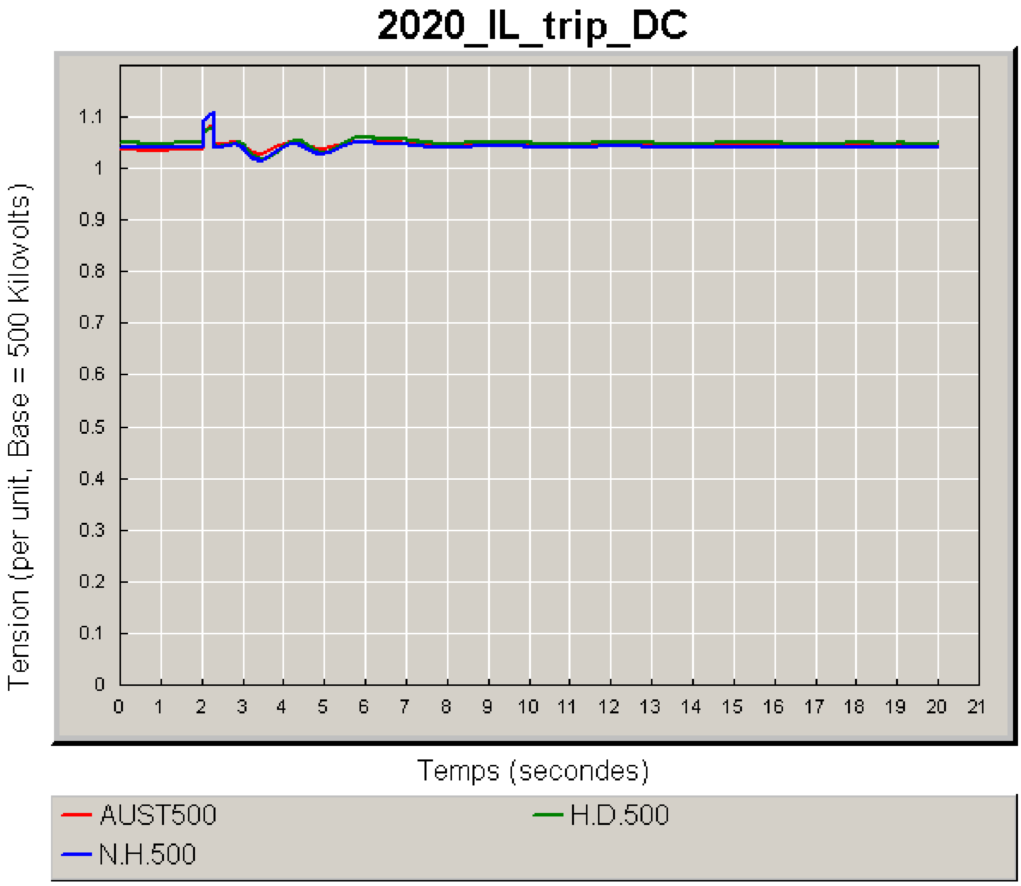


3.1.4 POWER FLOW VARIATION ON EGYPT INTERCONNECTIONS



3.1.5 VOLTAGE VARIATION ON THE 500 KV



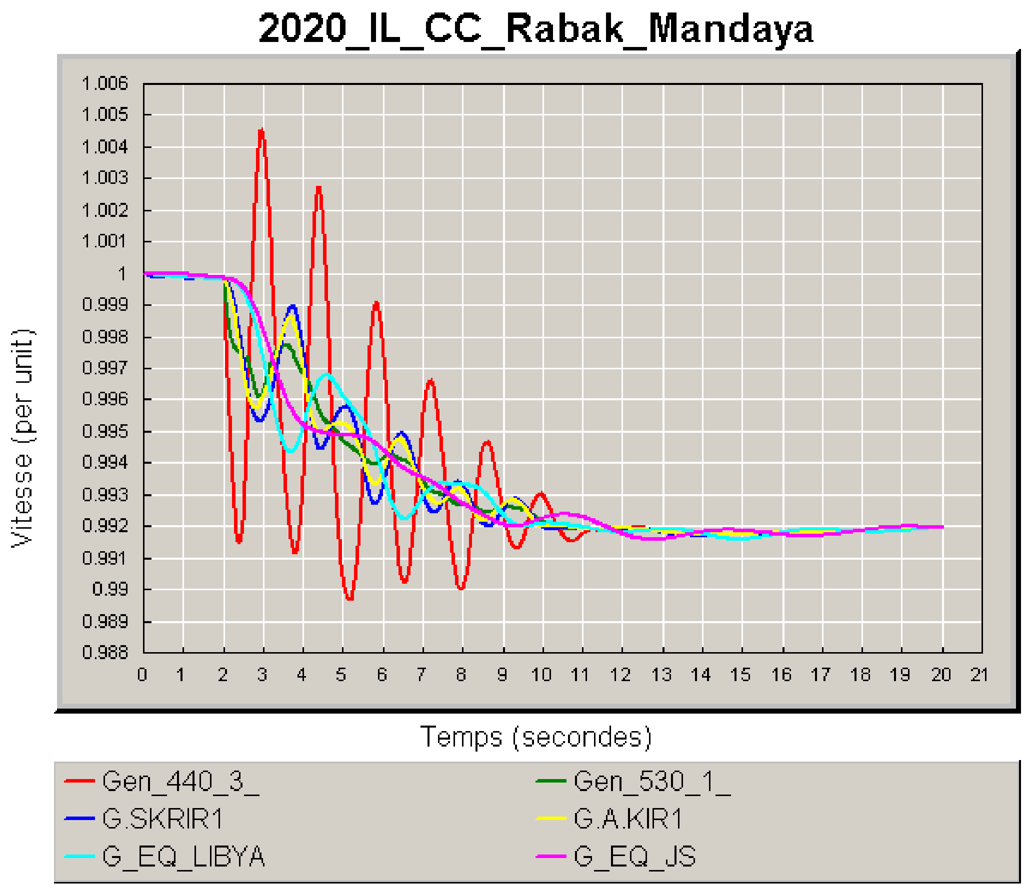

2020_IL_trip_DC
Tension (per unit, Base = 500 Kilovolts)
1.1
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21
Temps (secondes)
AUST500
H.D.500
N.H.500

3.2 SHORT-CIRCUIT AT RABAK ON ONE OF THE 4 RABAK - MANDAYA CIRCUITS

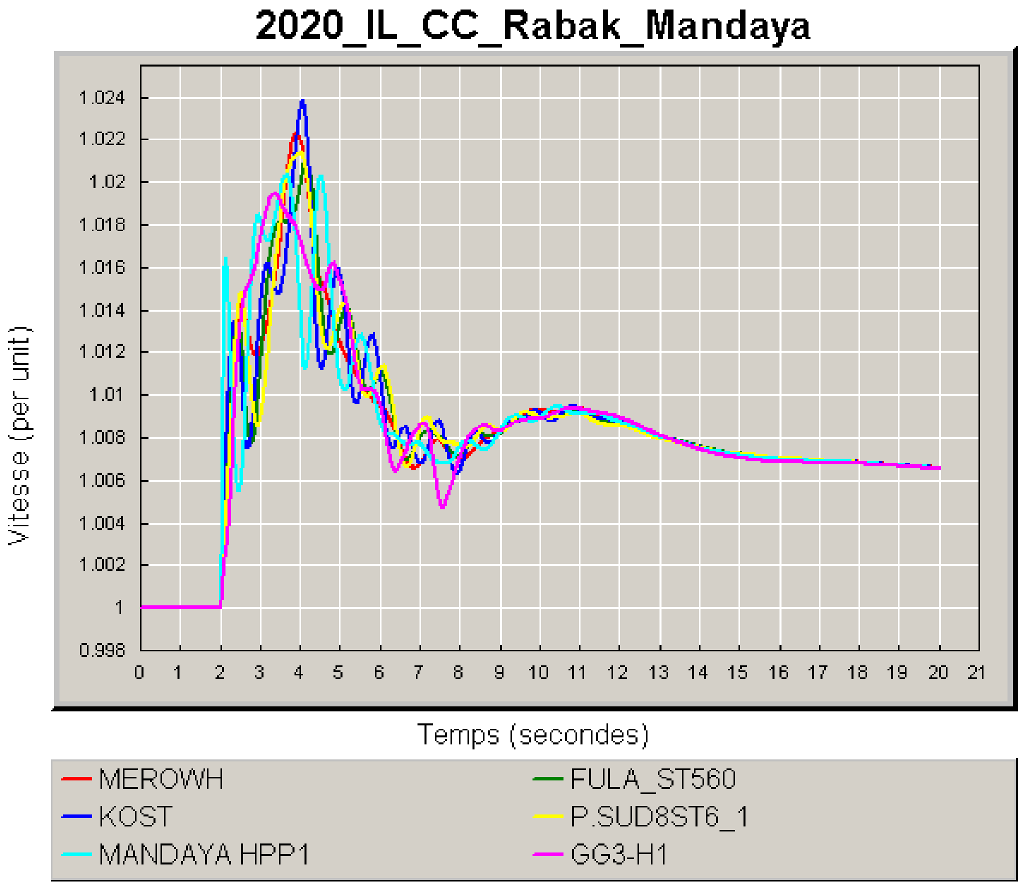
Event : a 3 phase short-circuit at Rabak end, on one of the 4 circuits Mandaya - Rabak, cleared in 120 ms by the opening of the circuit breakers.

The voltage drop in Rabak (0 pu) led to a transitory blocking of commutation of the inverter station at Rabak. The flow on the DC interconnection is transitory reduced to 0, before recovering to half of its initial value. At the same time, half of the capacitor banks were triped.
During the transitory blocking of the DC stations, the capacitors bank remained connected.

3.2.1 GENERATORS FREQUENCY VARIATION

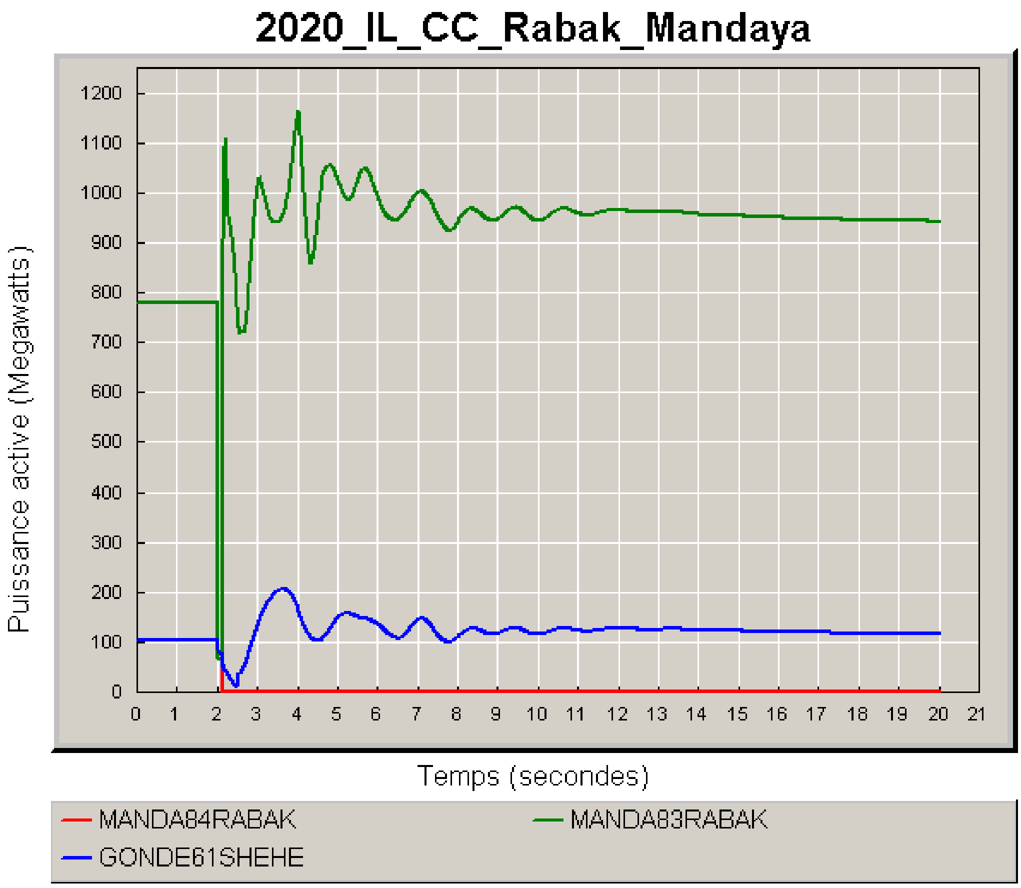


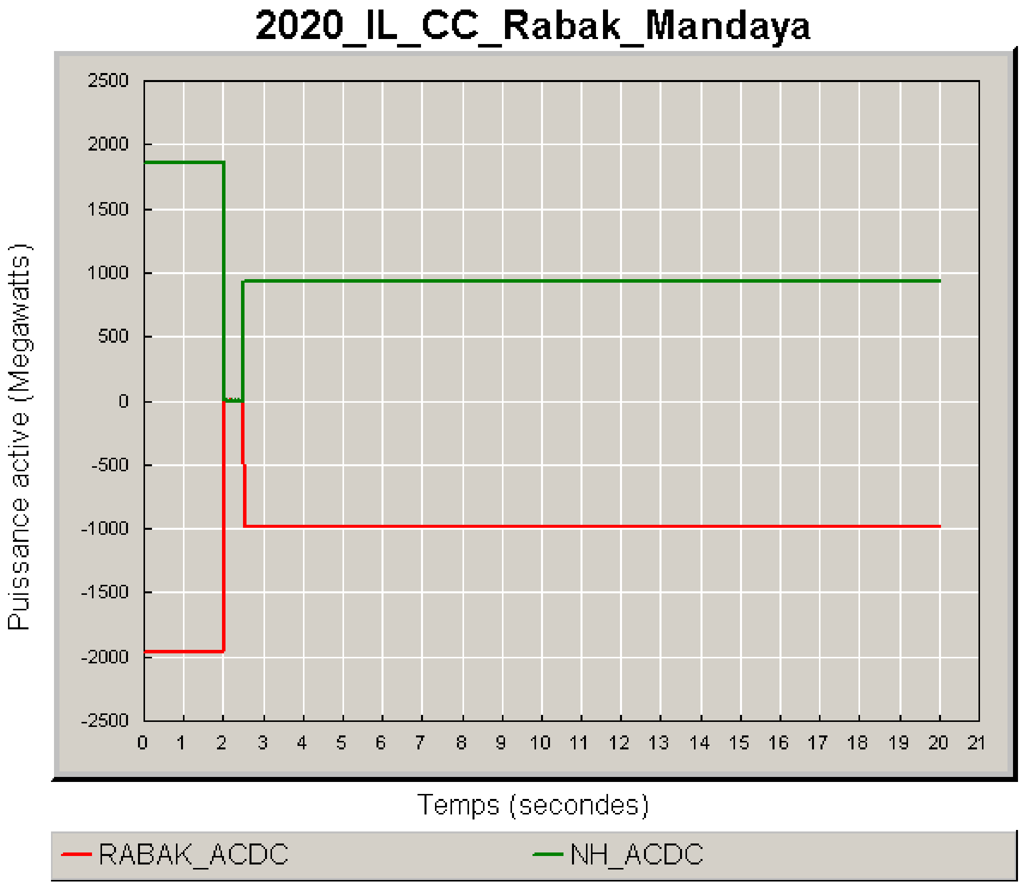
Gen_440_3 is a group of High Dam
Gen_530_1 is group 1 of Kurimat existing steam



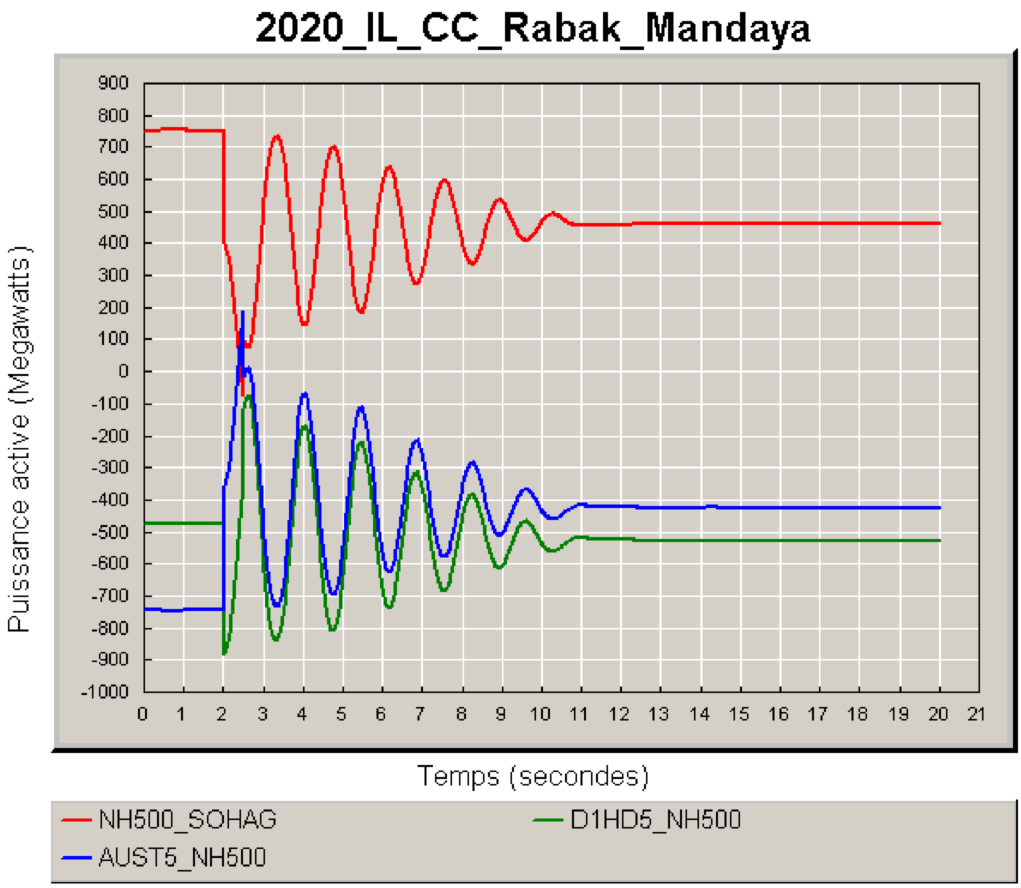
GG3 is Gibe III

3.2.2 POWER FLOW VARIATION ON ENTRO INTERCONNECTION

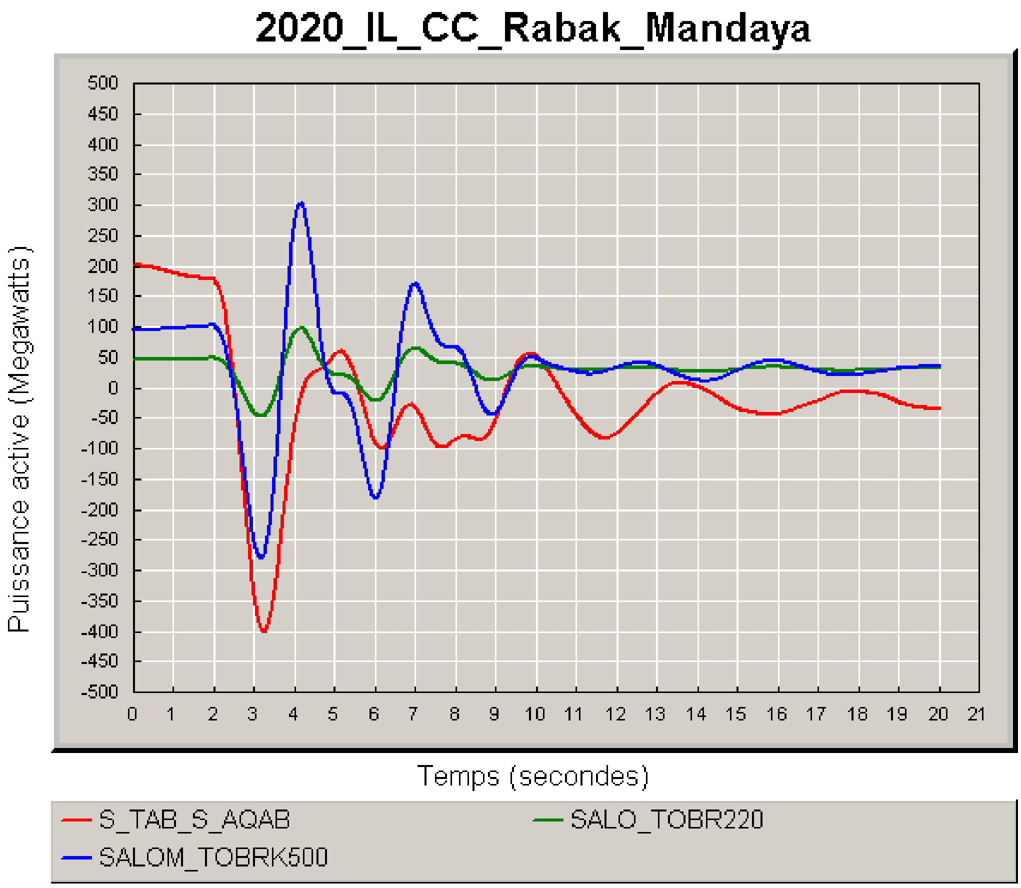



2020_IL_CC_Rabak_Mandaya
Puissance active (Megawatts)
2500
2000
1500
1000
500
0
-500
-1000
-1500
-2000
-2500
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21
Temps (secondes)
RABAK_ACDC
NH_ACDC

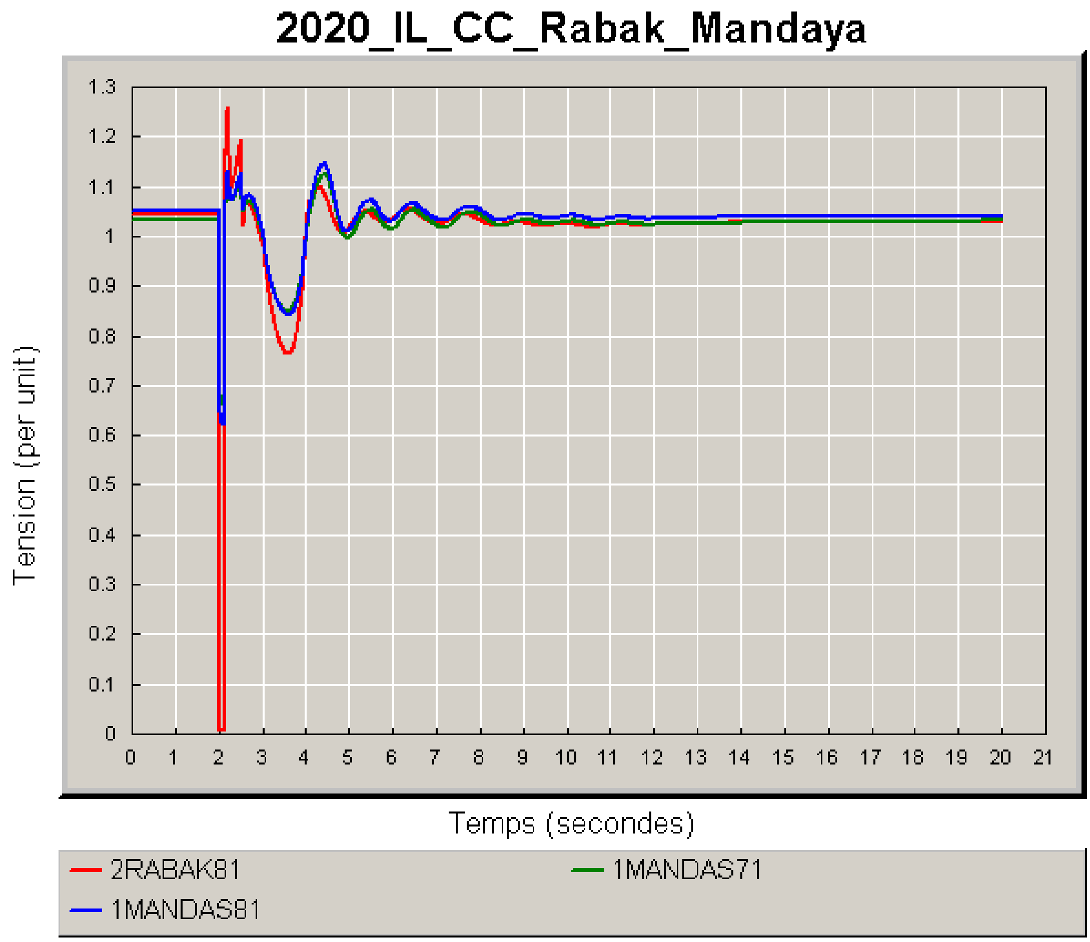
3.2.3 POWER FLOW VARIATION ON NAG HAMMADI 500 KV CIRCUITS

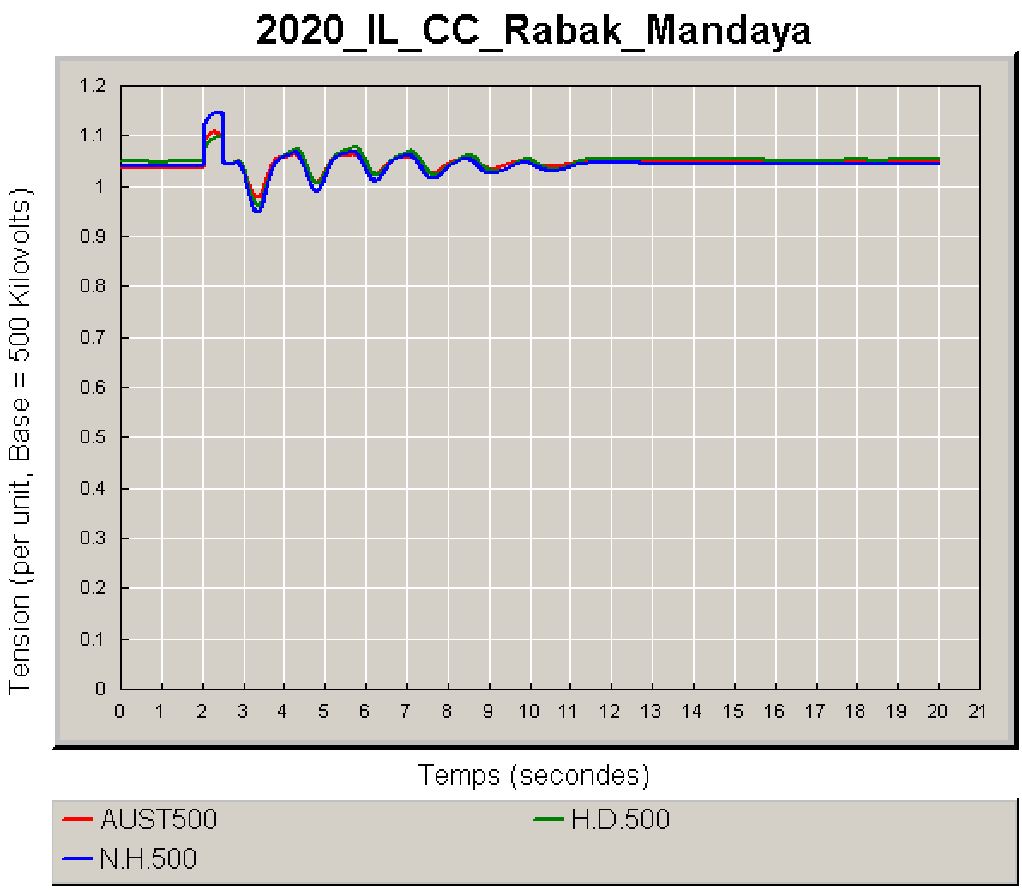


3.2.4 POWER FLOW VARIATION ON EGYPT INTERCONNECTIONS



3.2.5 VOLTAGE VARIATION ON THE 500 KV



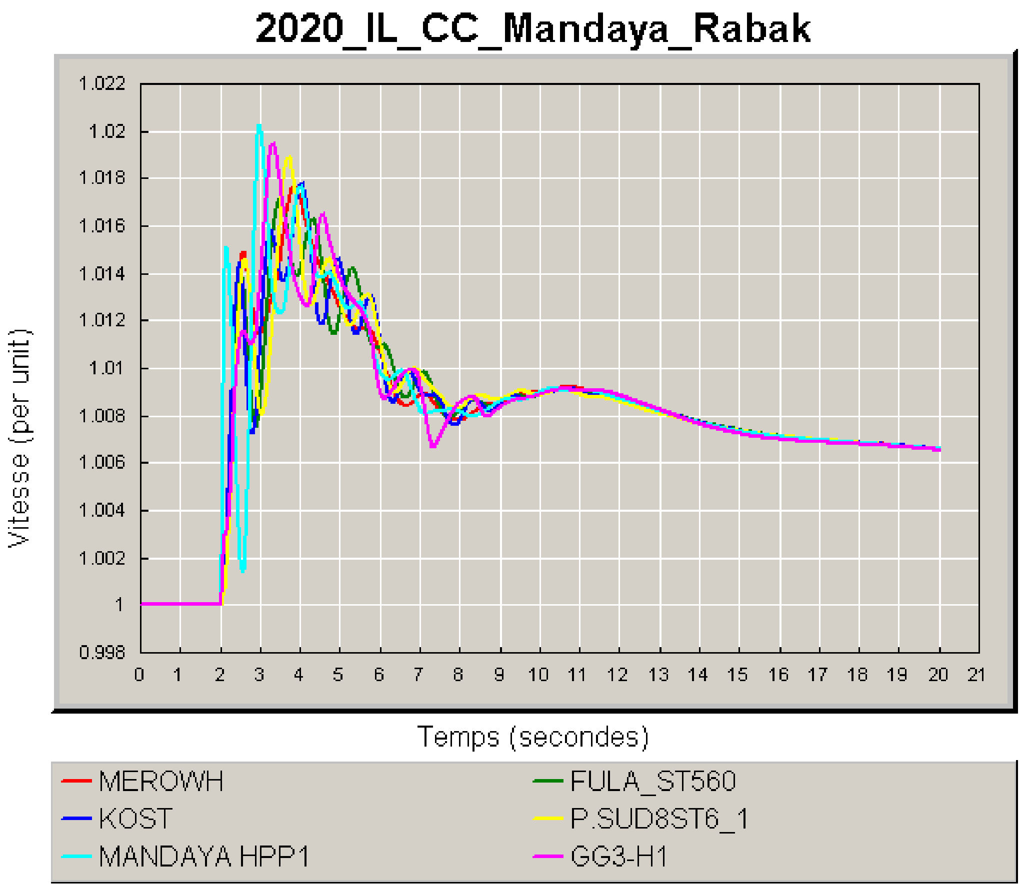

2020_IL_CC_Rabak_Mandaya
Tension (per unit, Base = 500 Kilovolts)
1.2
1.1
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21
Temps (secondes)
AUST500
H.D.500
N.H.500

3.3 SHORT-CIRCUIT AT MANDAYA ON MANDAYA - RABAK WITH HALF RECOVERY OF THE DC EXCHANGE

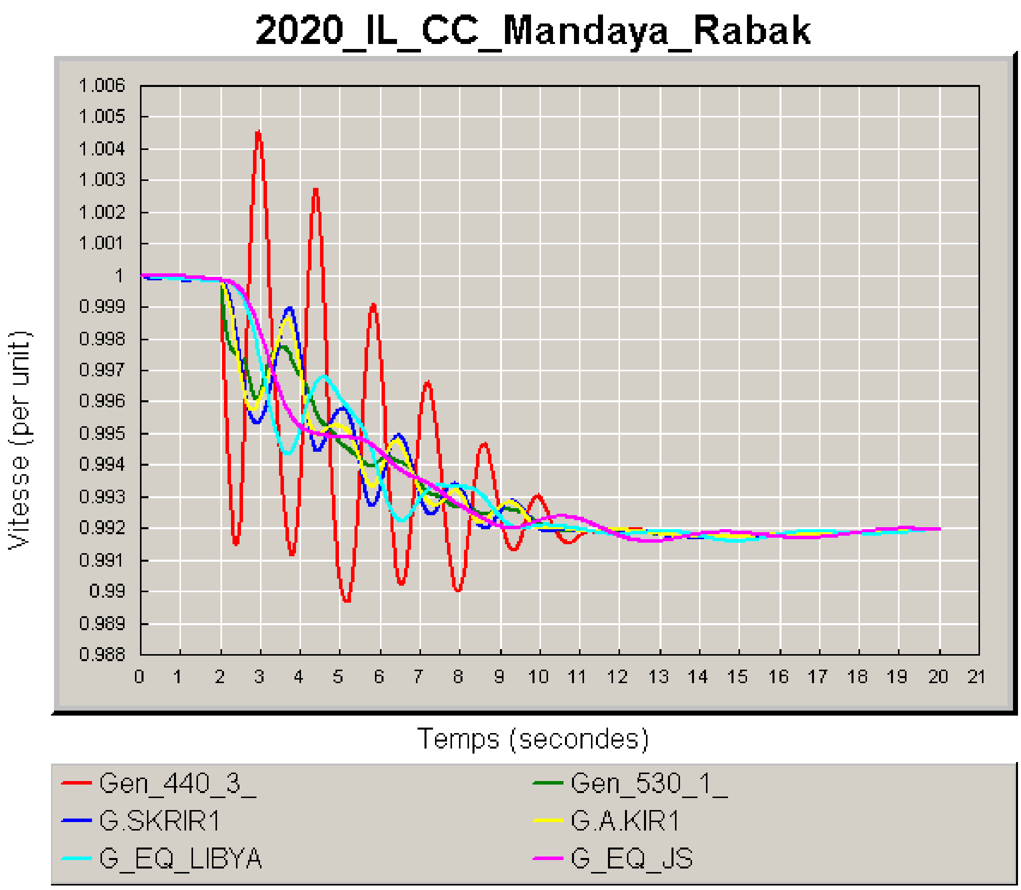
Event : a 3 phase short-circuit at Mandaya end, on one of the 4 circuits Mandaya - Rabak, cleared in 120 ms by the opening of the circuit breakers.

The voltage drop in Rabak (0.4 pu) led to a transitory blocking of commutation of the inverter station at Rabak. The flow on the DC interconnection is transitory reduced to 0, before recovering to half of its initial value 300 ms after the clearing of the fault. At the same time, half of the capacitors banks are disconnected at the same time.

3.3.1 GENERATORS FREQUENCY VARIATION

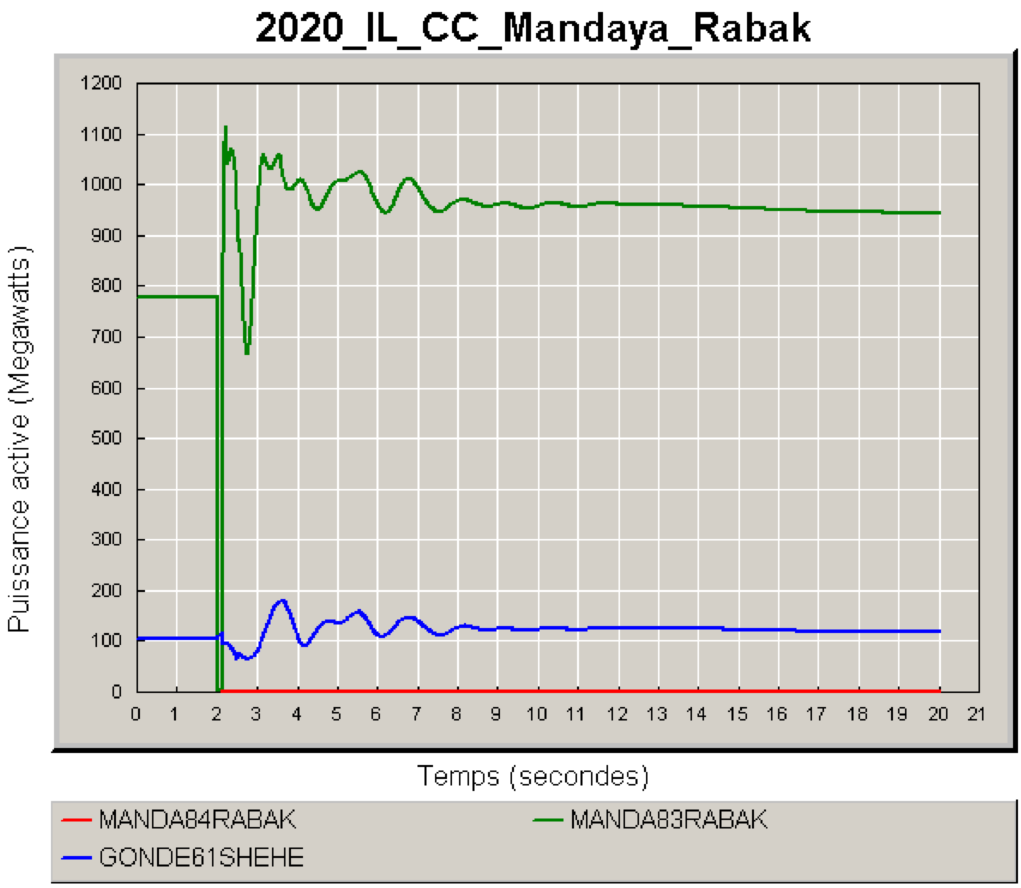


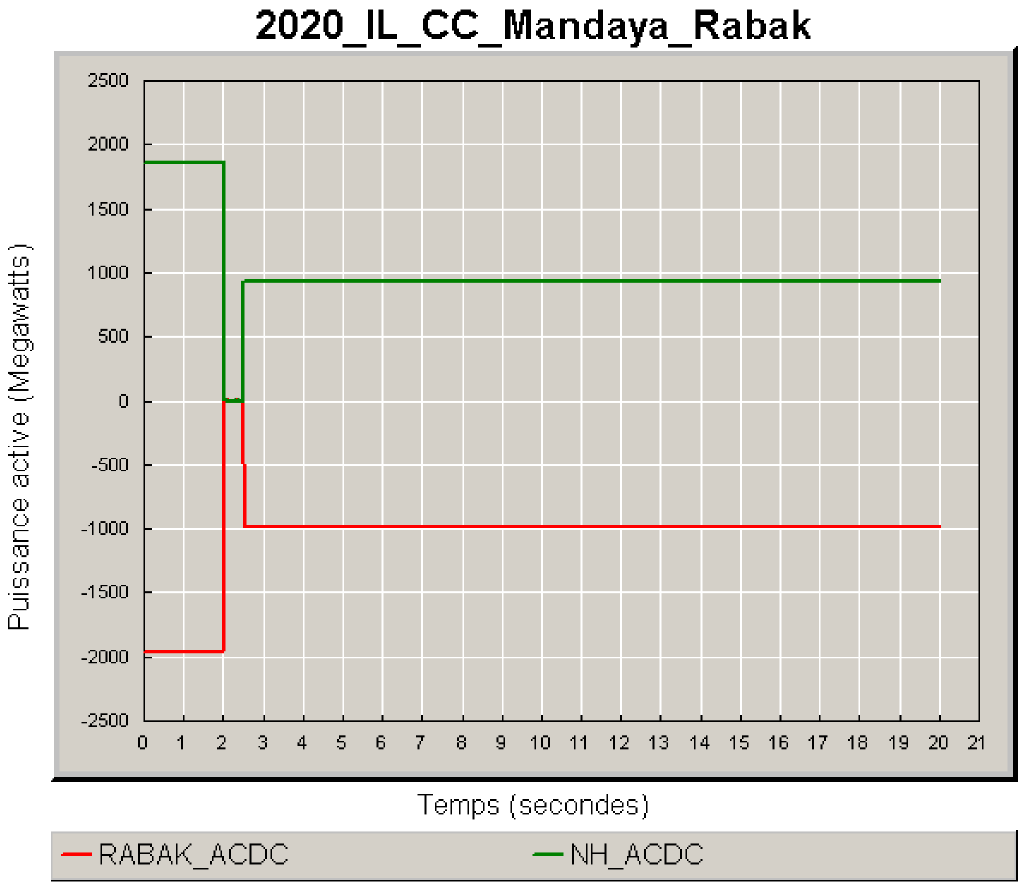
GG3 is Gibe III



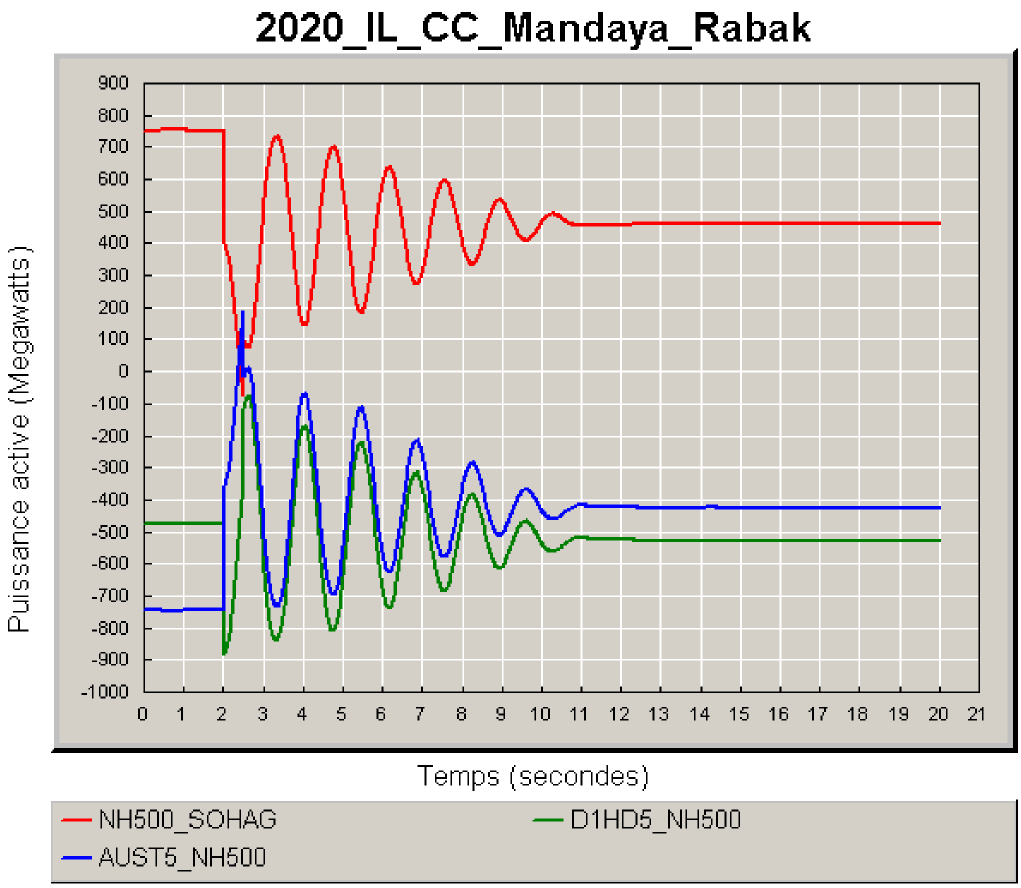
Gen_441_1 is a group of High Dam
Gen_530_1 is group 1 of Kurimat existing steam

3.3.2 POWER FLOW VARIATION ON ENTRO INTERCONNECTION

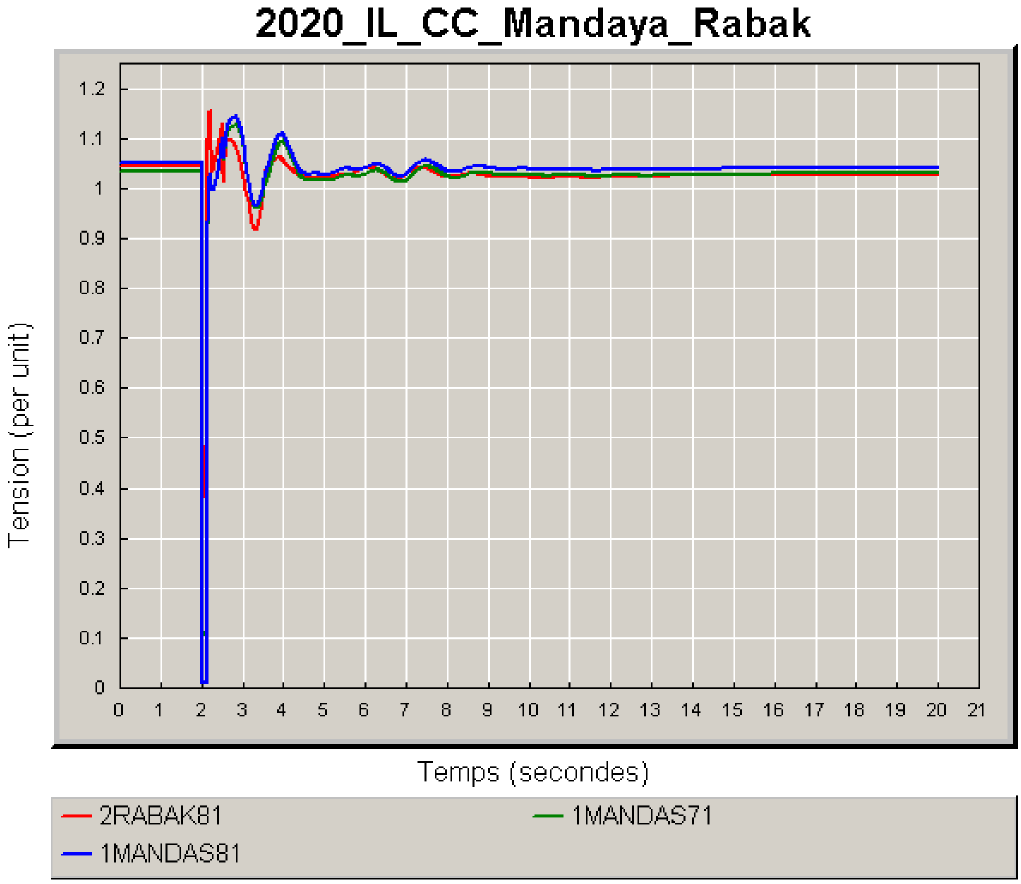


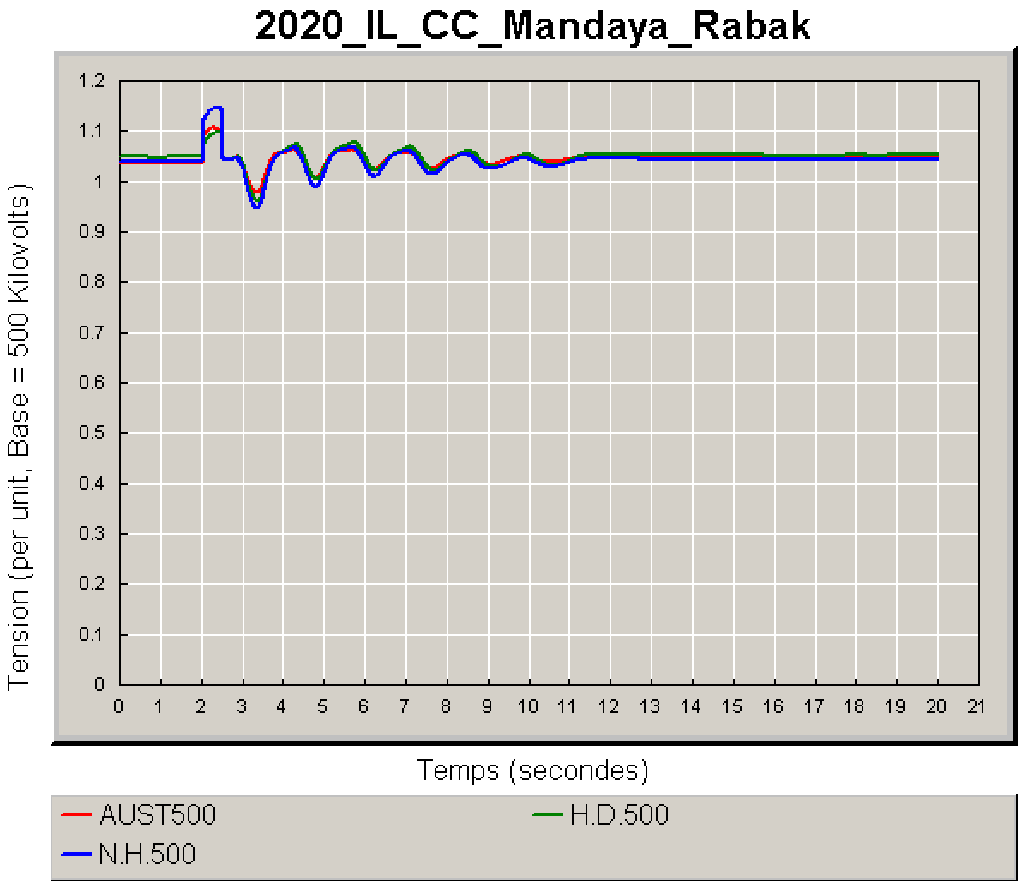

2020_IL_CC_Mandaya_Rabak
Puissance active (Megawatts)
2500
2000
1500
1000
500
0
-500
-1000
-1500
-2000
-2500
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21
Temps (secondes)
RABAK_ACDC
NH_ACDC

3.3.3 POWER FLOW VARIATION ON NAG HAMMADI 500 KV CIRCUITS



3.3.4 VOLTAGE VARIATION ON THE 500 KV



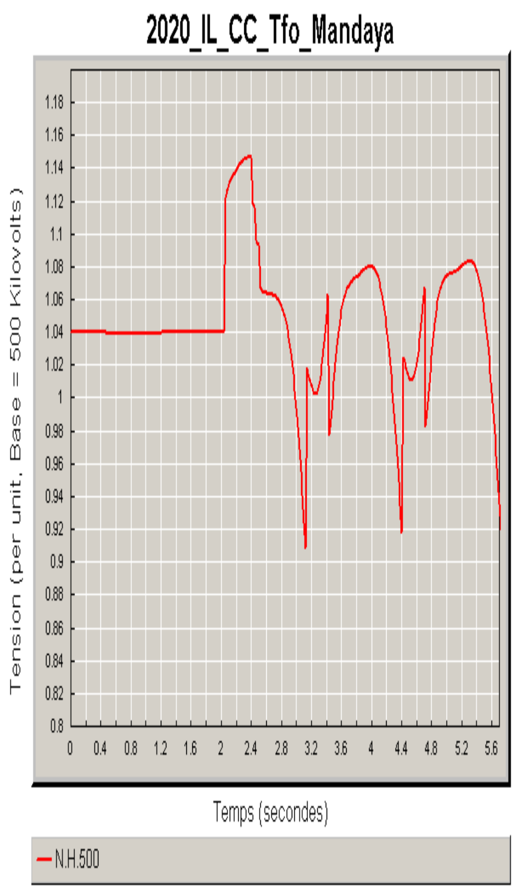

2020_IL_CC_Mandaya_Rabak
Tension (per unit, Base = 500 Kilovolts)
1.2
1.1
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21
Temps (secondes)
AUST500
H.D.500
N.H.500

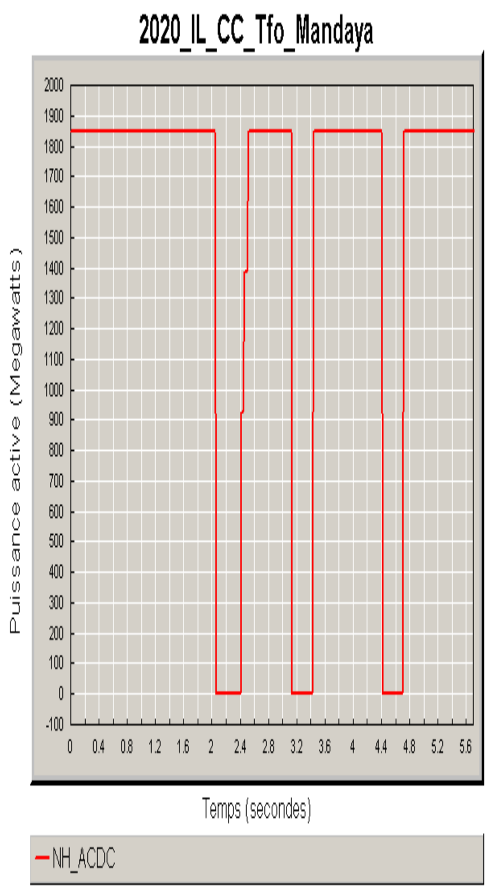
3.4 SHORT-CIRCUIT ON ONE OF THE FOUR 400/500 KV TRANSFORMERS AT MANDAYA

Event : a 3 phase short-circuit at the 500 kV side on one of the four 500/400 kV transformers at Mandaya, cleared in 120 ms by the opening of the circuit breakers.

The voltage drop in Rabak (0.5 pu) led to a transitory blocking of commutation of the inverter station at Rabak. The flow on the DC interconnection is transitory reduced to 0, before recovering to half of its initial value 300 ms after the clearing of the fault. At the same time, half of the capacitors banks are disconnected at the same time.

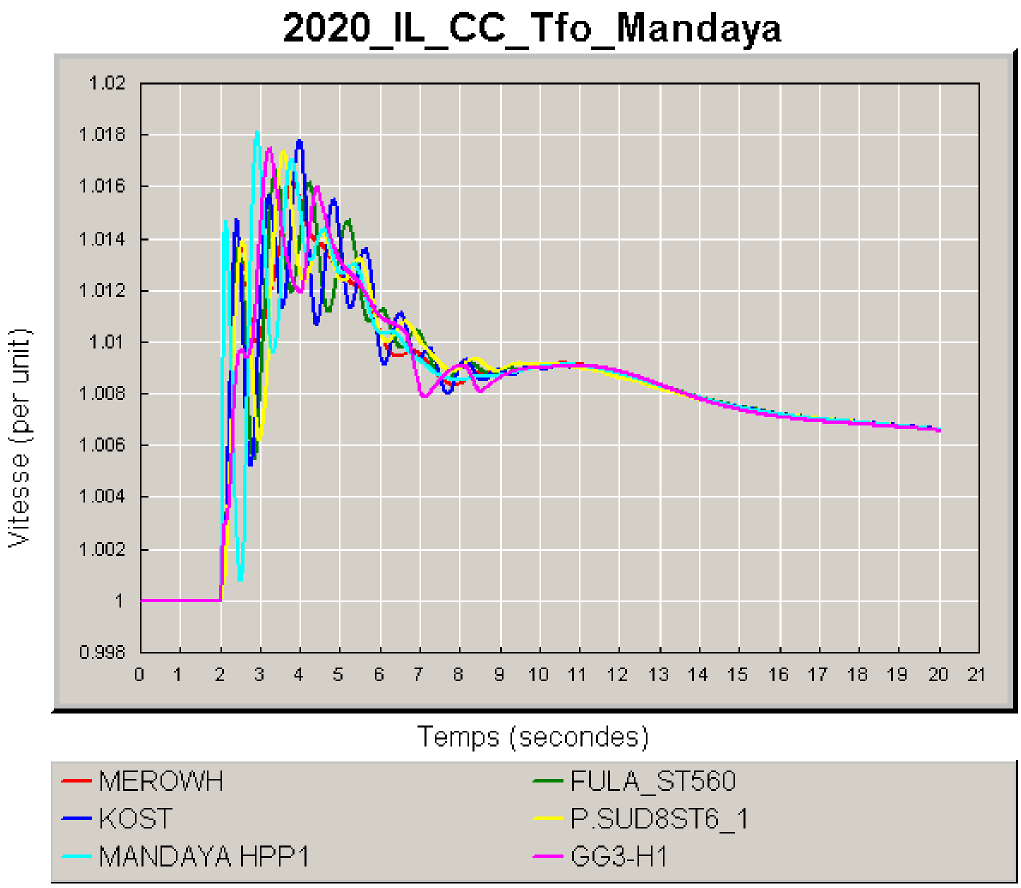
3.4.1 VOLTAGE AT NAG HAMMADI WITHOUT TRIPPING OF HALF OF THE DC POWER FLOW (OR ONE OF THE 2 POLES)



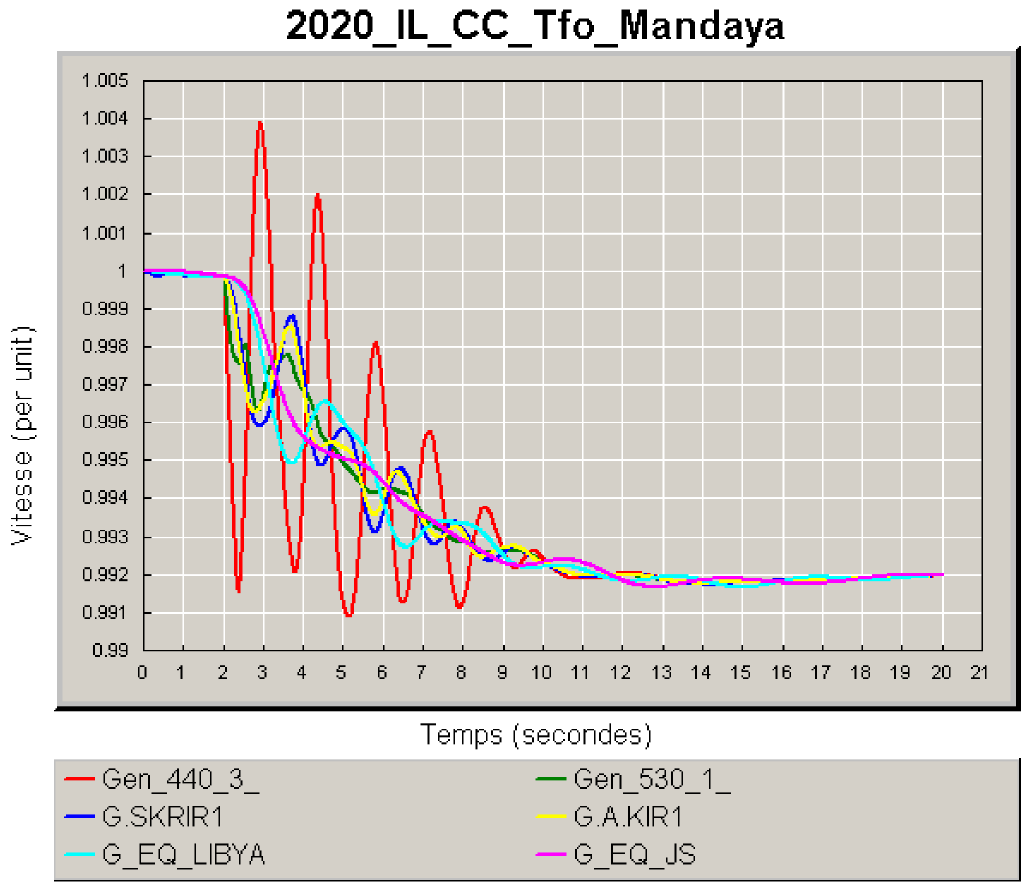


This event became acceptable on the Egypttian system with the installation of a 300 MVAr SVC at rabak.

3.4.2 GENERATORS FREQUENCY VARIATION

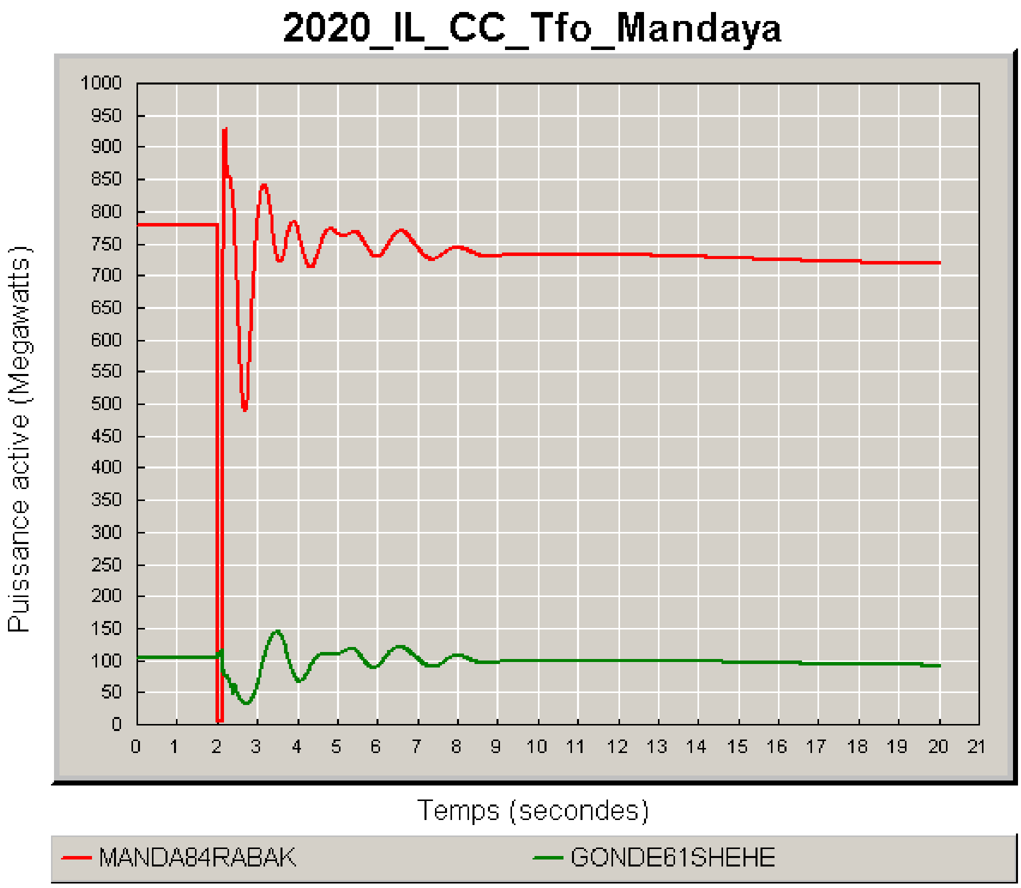


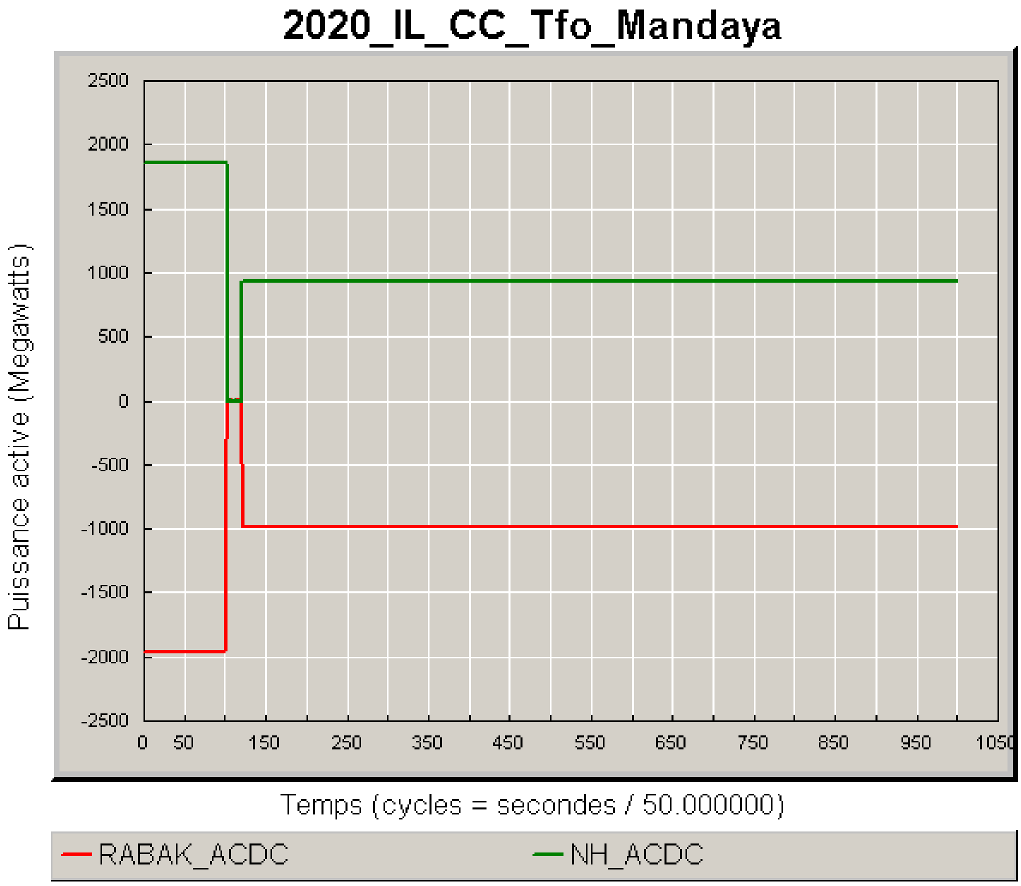
GG3 is Gibe III



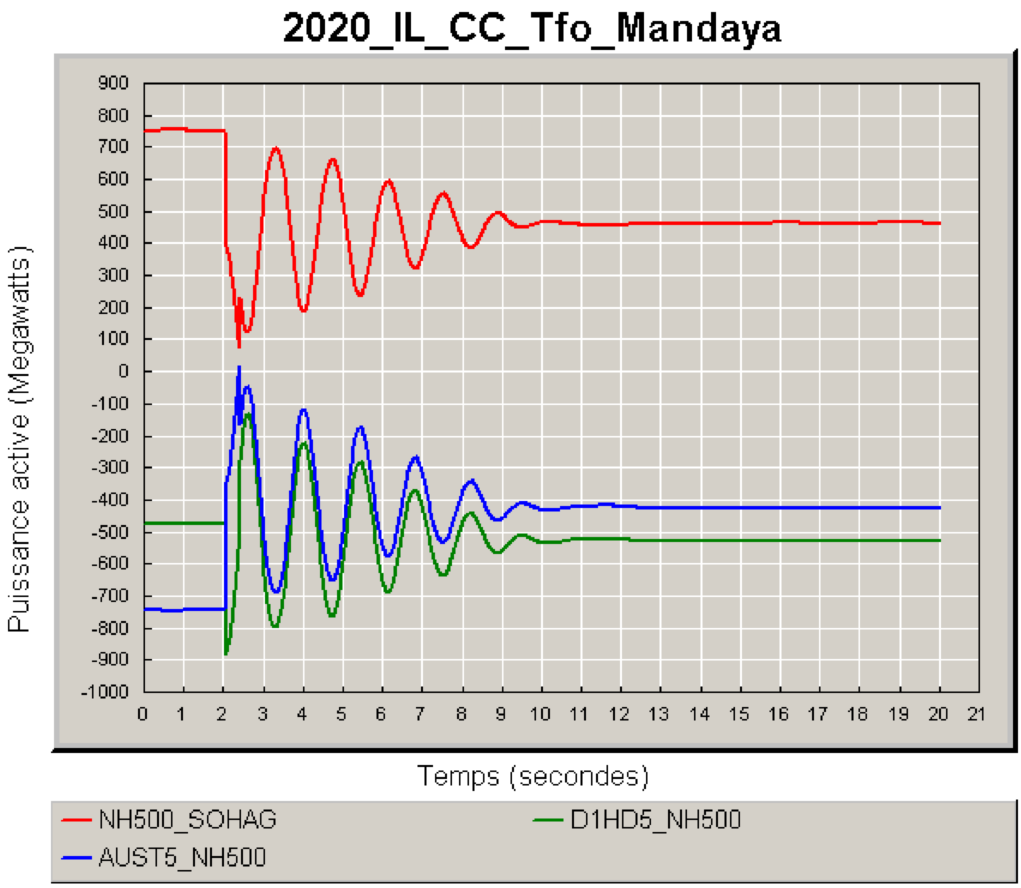
Gen_441_1 is a group of High Dam
Gen_530_1 is group 1 of Kurimat existing steam

3.4.3 POWER FLOW VARIATION ON ENTRO INTERCONNECTION

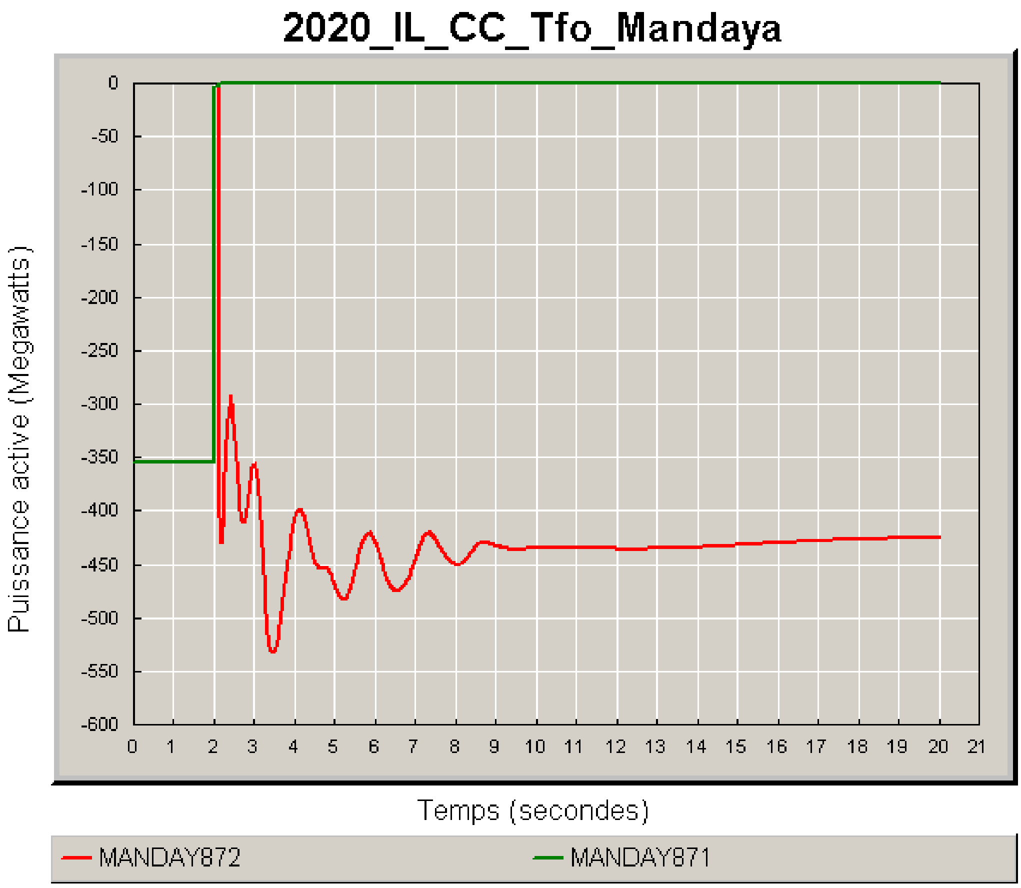



2020_IL_CC_Tfo_Mandaya
Puissance active (Megawatts)
2500
2000
1500
1000
500
0
-500
-1000
-1500
-2000
-2500
0
50
150
250
350
450
550
650
750
850
950
1050
Temps (cycles = secondes / 50.000000)
RABAK_ACDC
NH_ACDC

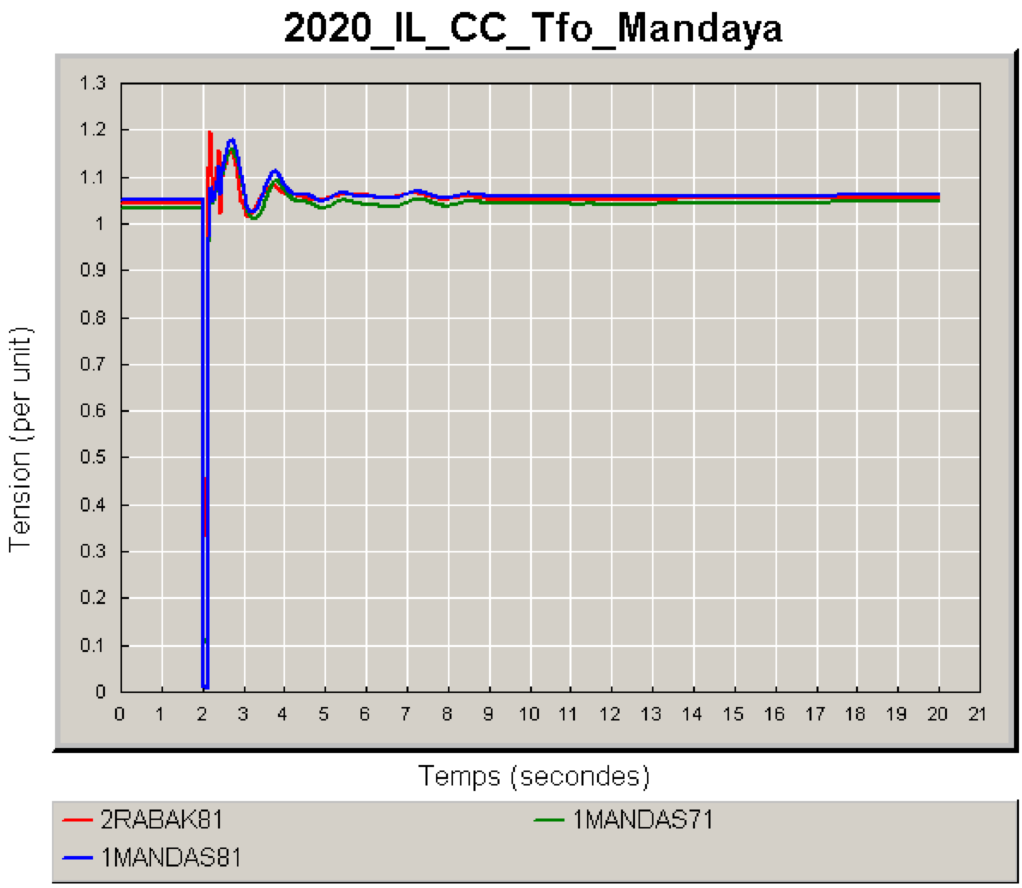
3.4.4 POWER FLOW VARIATION ON NAG HAMMADI 500 KV CIRCUITS

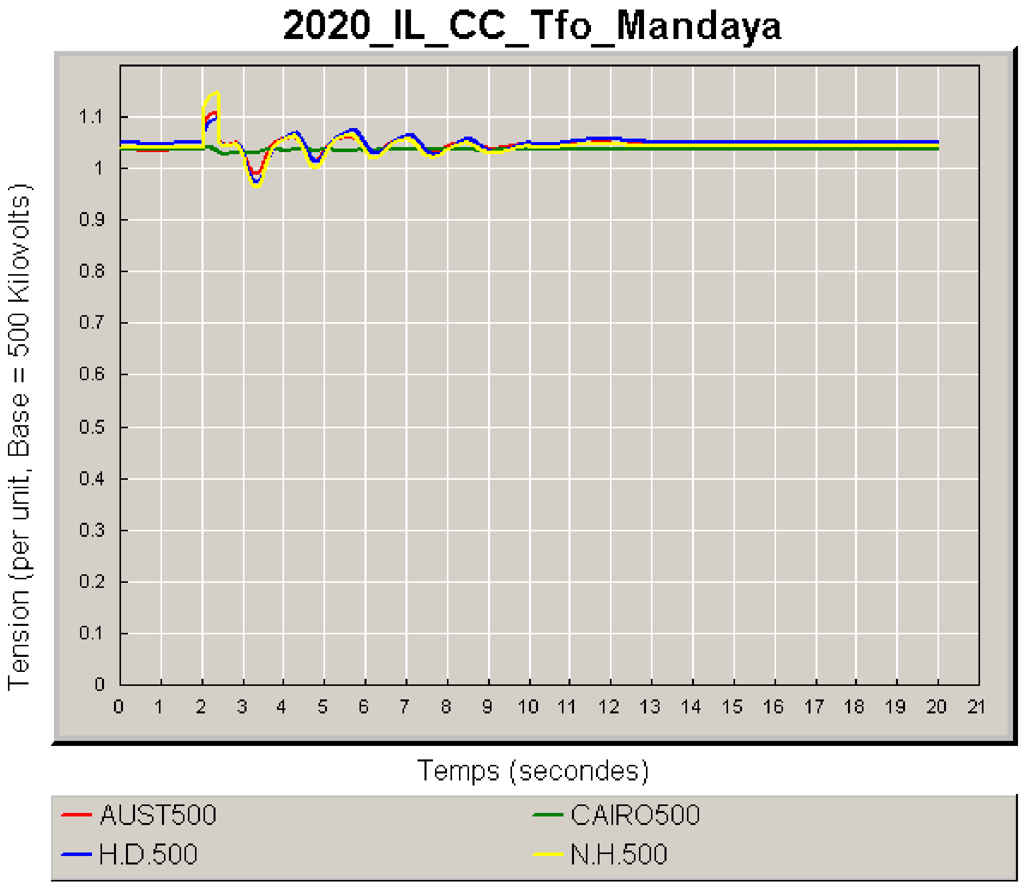


3.4.5 POWER FLOW VARIATION MANDAYA 500/400 KV TRANSFORMERS



3.4.6 VOLTAGE VARIATION ON THE 500 KV



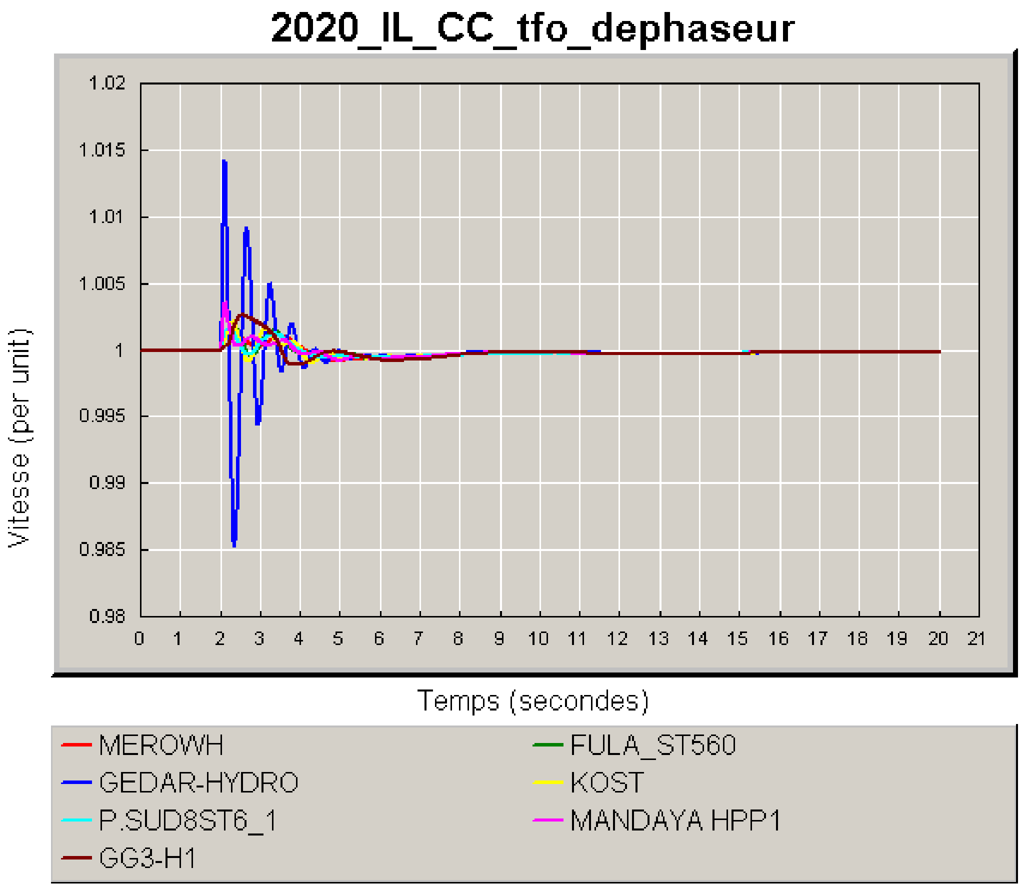

2020_IL_CC_Tfo_Mandaya
Tension (per unit, Base = 500 Kilovolts)
Temps (secondes)
AUST500
CAIRO500
H.D.500
N.H.500

3.5 SHORT-CIRCUIT AT GEDAREF, ON THE 220 KV PHASE-SHIFT TRANSFORMER

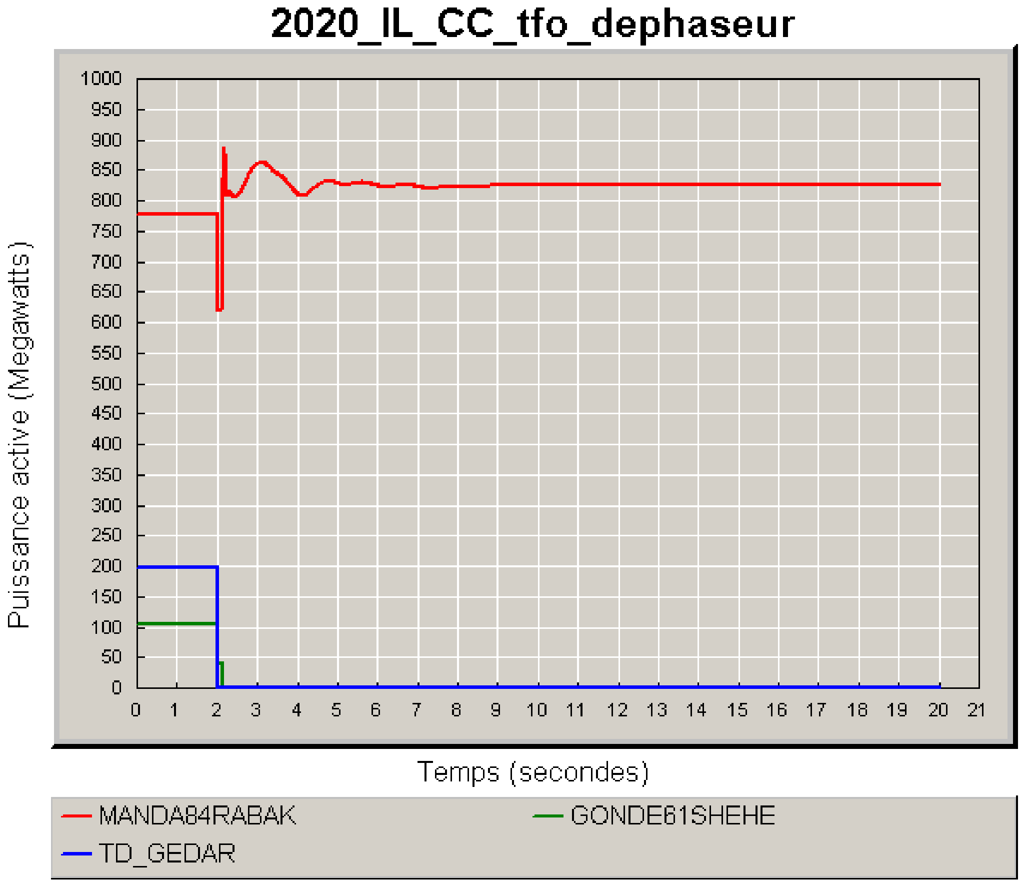
Event : a 3 phase short-circuit at Gedaref 220 kV end, on the 220 kV phase shift transformer, cleared in 120 ms by the opening of the circuit breakers.

The Egyptian system is not affected by the fault.

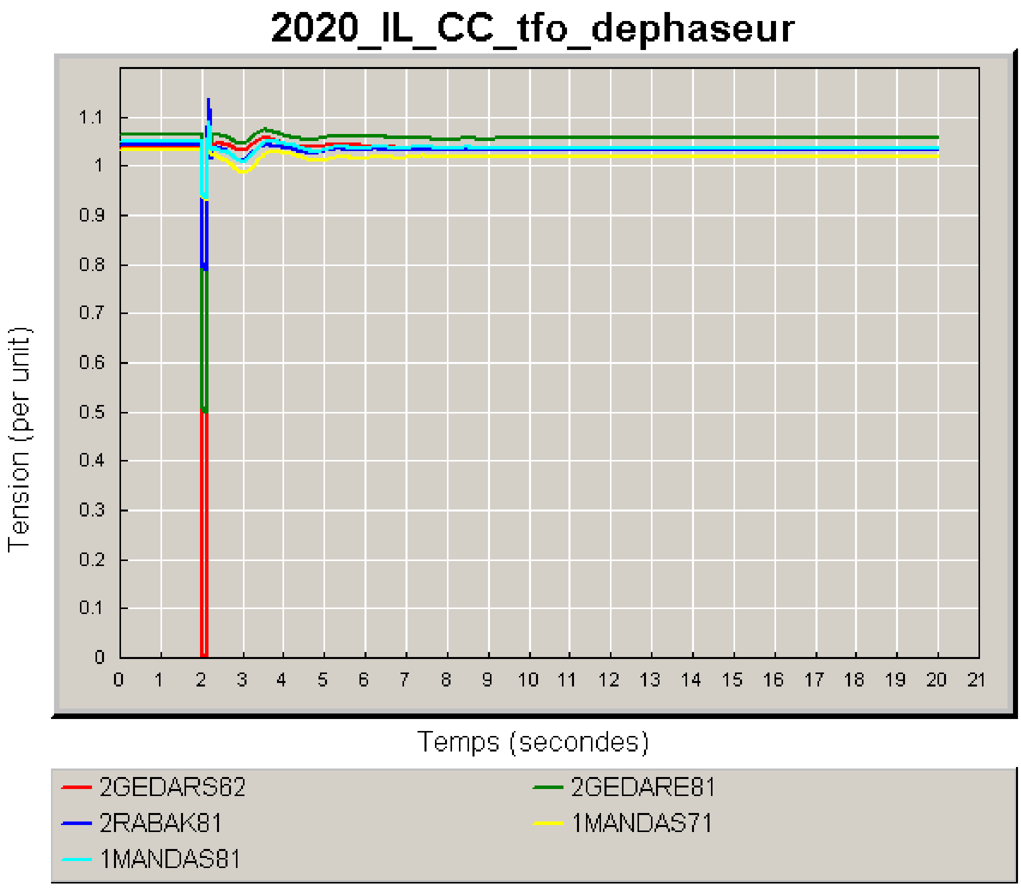
3.5.1 GENERATORS FREQUENCY VARIATION



3.5.2 POWER FLOW VARIATION ON ENTRO INTERCONNECTION



3.5.3 VOLTAGE VARIATION ON THE 500 KV

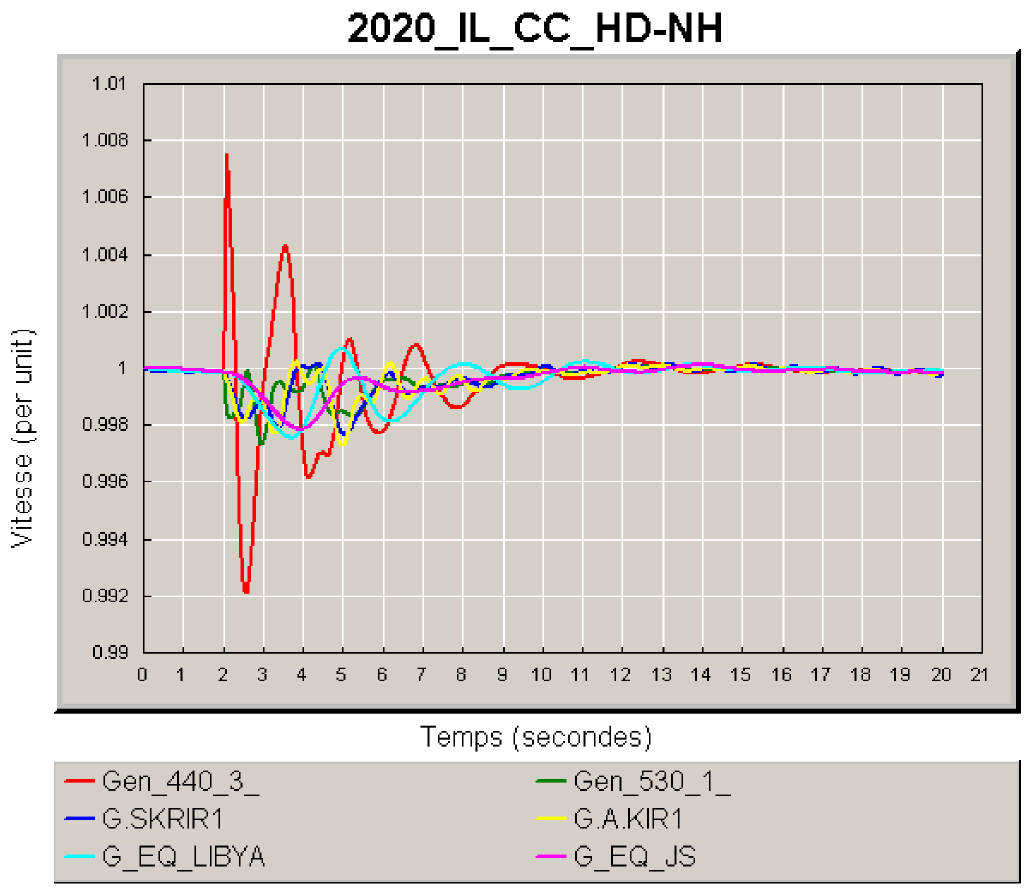


3.6 SHORT-CIRCUIT AT HIGH DAM SIDE, ON ONE OF THE 2 CIRCUITS HIGH DAM - NAG HAMMADI

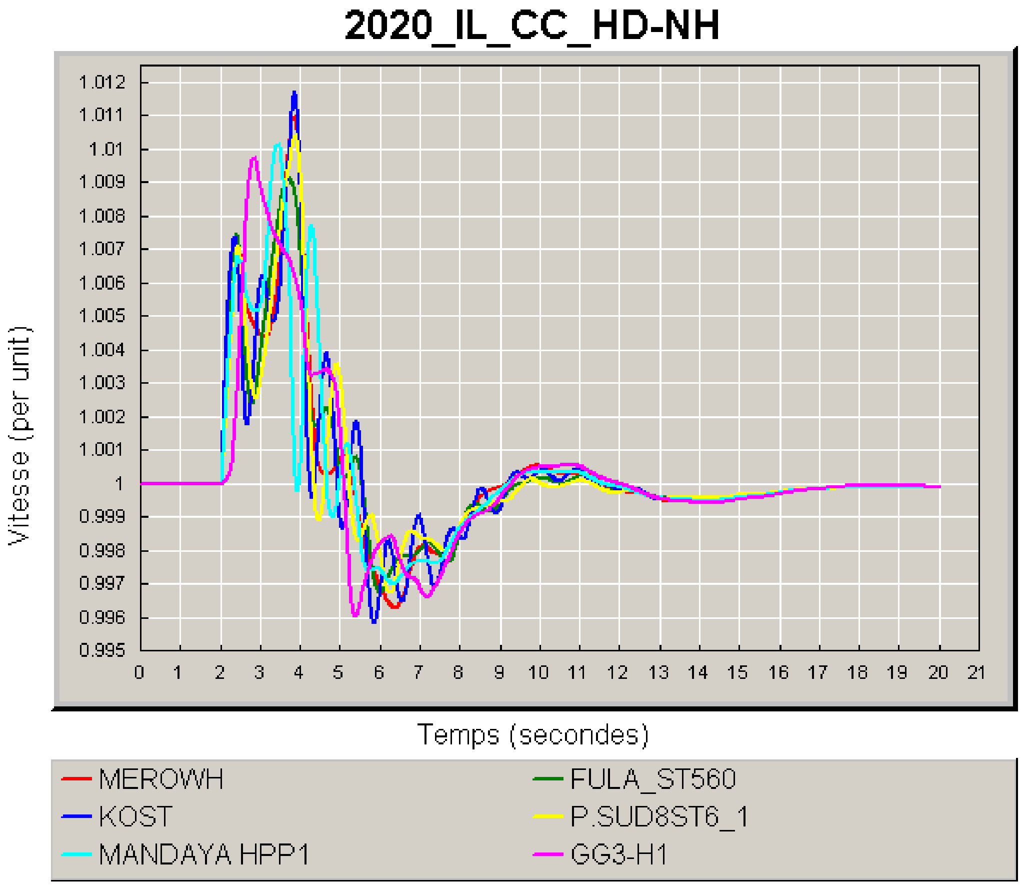
Event : a 3 phase short-circuit at High Dam end, on one of the 2 circuits High Dam - Nag Hammadi, cleared in 100 ms by the opening of the circuit breakers.

The voltage drop in Nag Hammadi (~60%) led to a transitory blocking of commutation of the inverter station at Nag Hammadi. The flow on the DC interconnection is transitory reduced to 0, before recovering to its initial value.
During the transitory blocking of the DC stations, the capacitors bank remained connected.

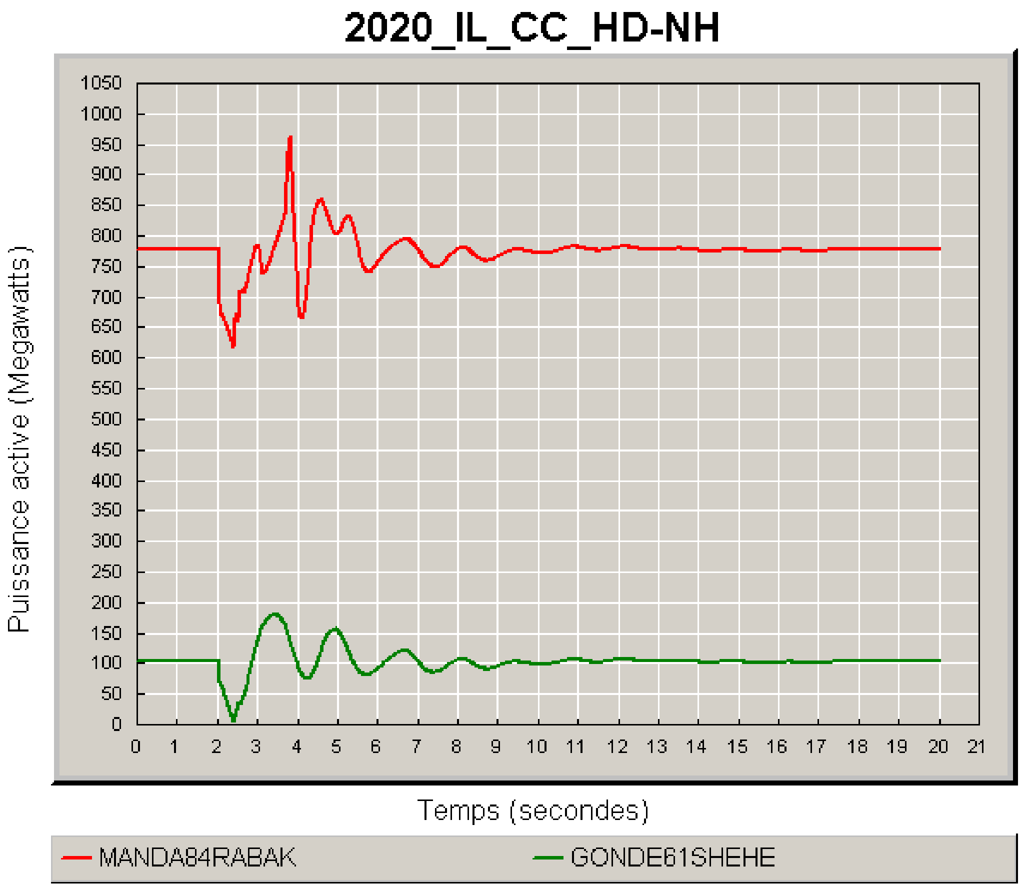
3.6.1 GENERATORS FREQUENCY VARIATION



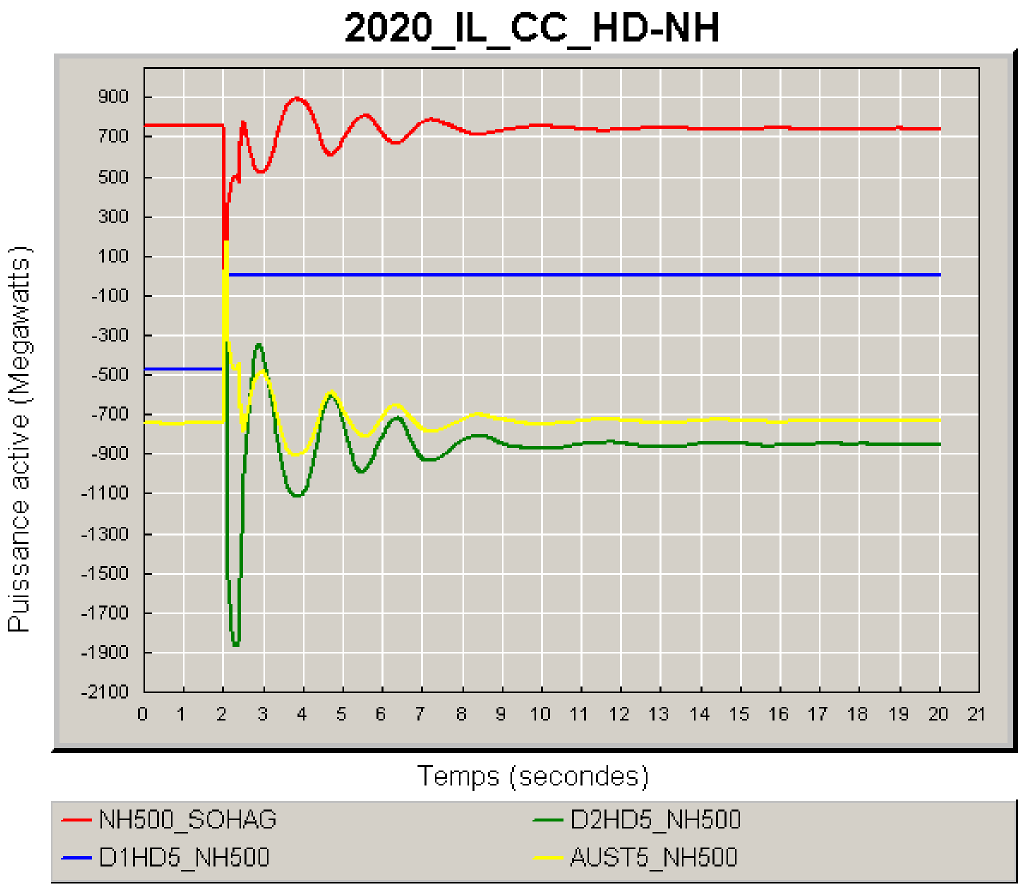
Gen_440_3 is a group of High Dam
Gen_530_1 is group 1 of Kurimat existing steam


2020_IL_CC_HD-NH
Vitesse (per unit)
1.012
1.011
1.01
1.009
1.008
1.007
1.006
1.005
1.004
1.003
1.002
1.001
1
0.999
0.998
0.997
0.996
0.995
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21
Temps (secondes)
MEROWH
KOST
MANDAYA HPP1
FULA_ST560
P.SUD8ST6_1
GG3-H1

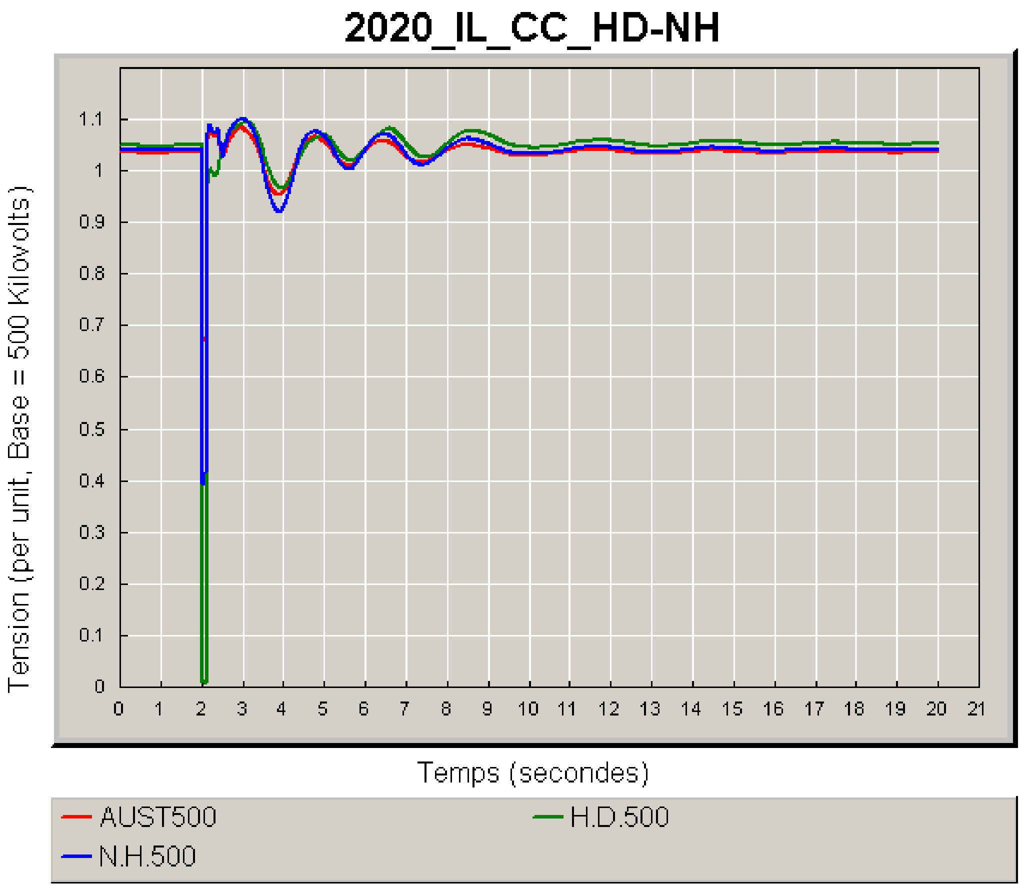
3.6.2 POWER FLOW VARIATION ON ENTRO INTERCONNECTION

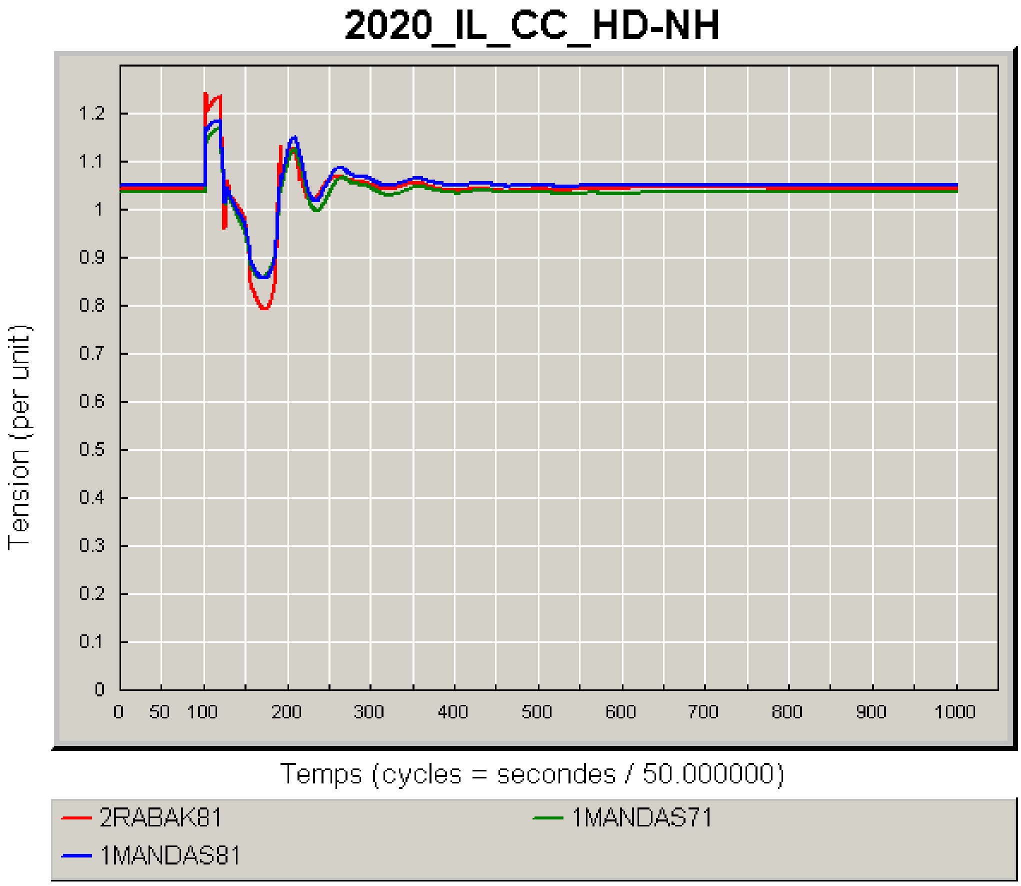


3.6.3 POWER FLOW VARIATION ON HIGH DAM – NAG HAMMADI - ASSIUT



3.6.4 VOLTAGE VARIATION ON THE 500 KV




2020_IL_CC_HD-NH
Tension (per unit)
1.2
1.1
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
50
100
200
300
400
500
600
700
800
900
1000
Temps (cycles = secondes / 50.000000)
2RABAK81
1MANDAS71
1MANDAS81

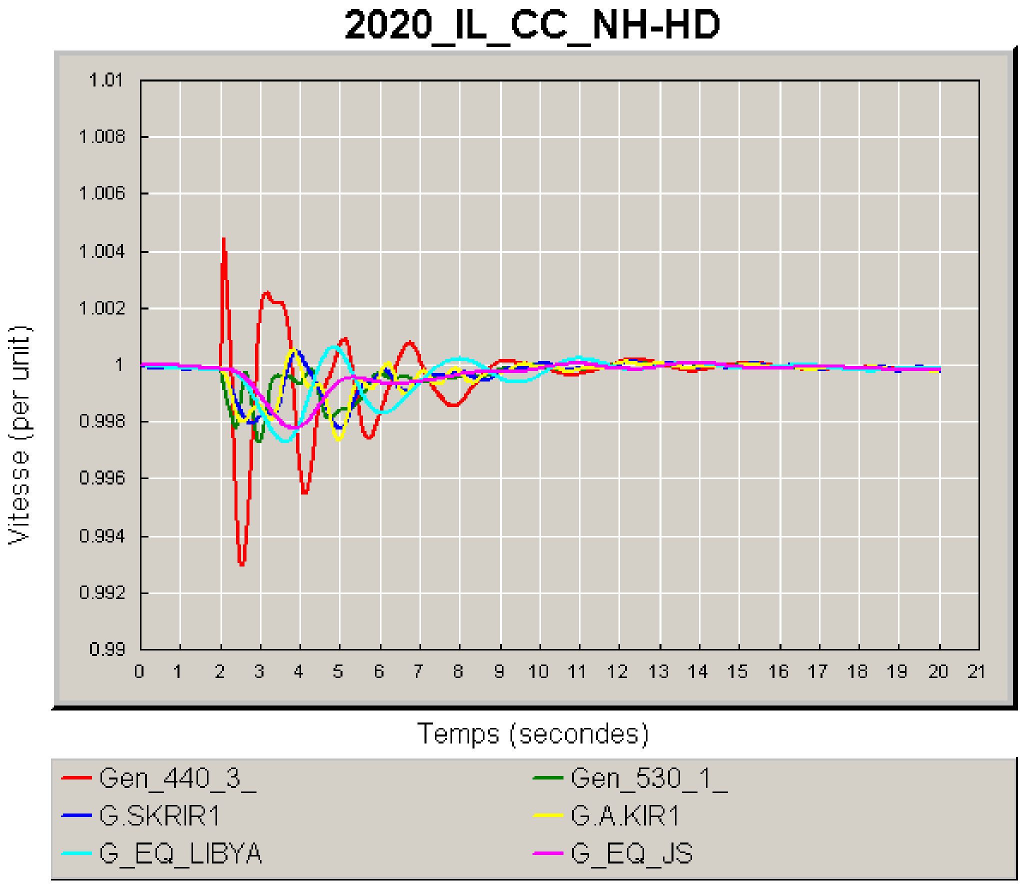
3.7 Short-circuit at Nag Hammadi on Nag Hammadi - High Dam

Event : a 3 phase short-circuit at Nag Hammadi end, on one of the 2 circuits High Dam - Nag Hammadi, cleared in 100 ms by the opening of the circuit breakers. The reactance in Nag Hammadi is tripped at the same time.

The voltage drop in Nag Hammadi (to 0 pu) led to a transitory blocking of commutation of the inverter station at Nag Hammadi. The flow on the DC interconnection is transitory reduced to 0, before recovering to its initial value.
During the transitory blocking of the DC stations, the capacitors bank remained connected.

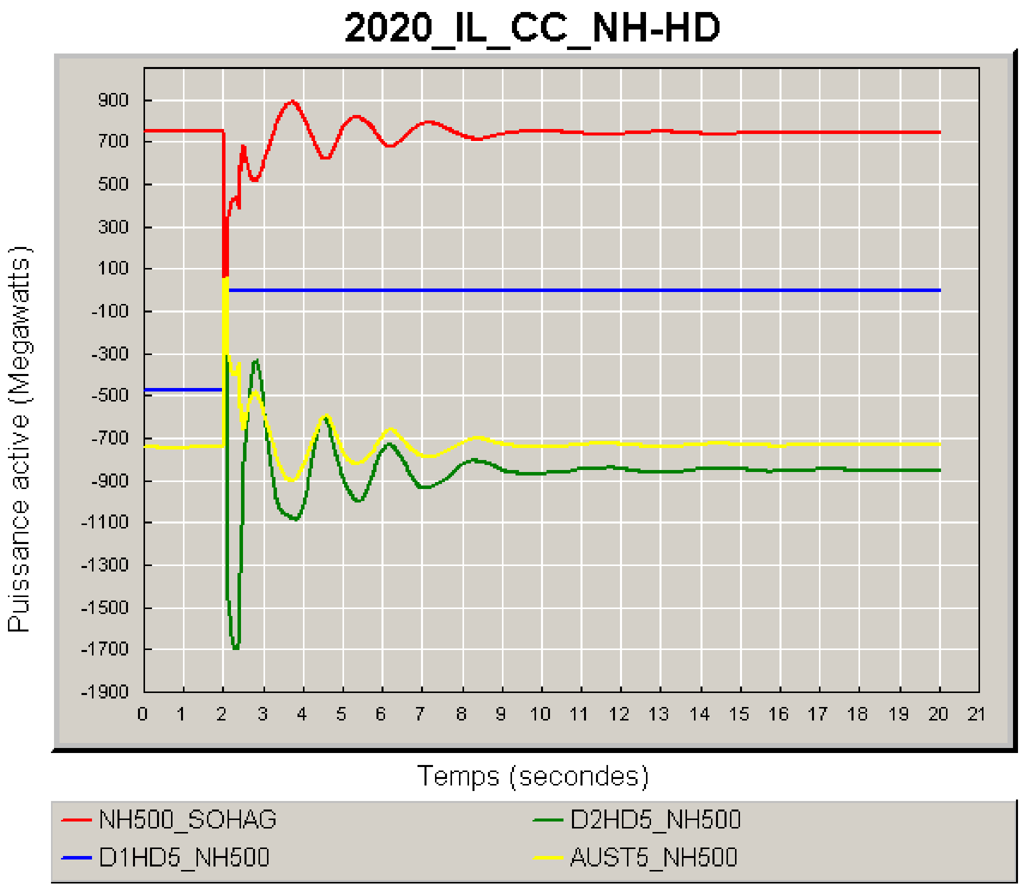
For the Ethiopian and Sudanese side, the impact on the system and its behaviour is very similar to the case of SC on High Dam - Nag Hammadi

3.7.1 Generators frequency variation

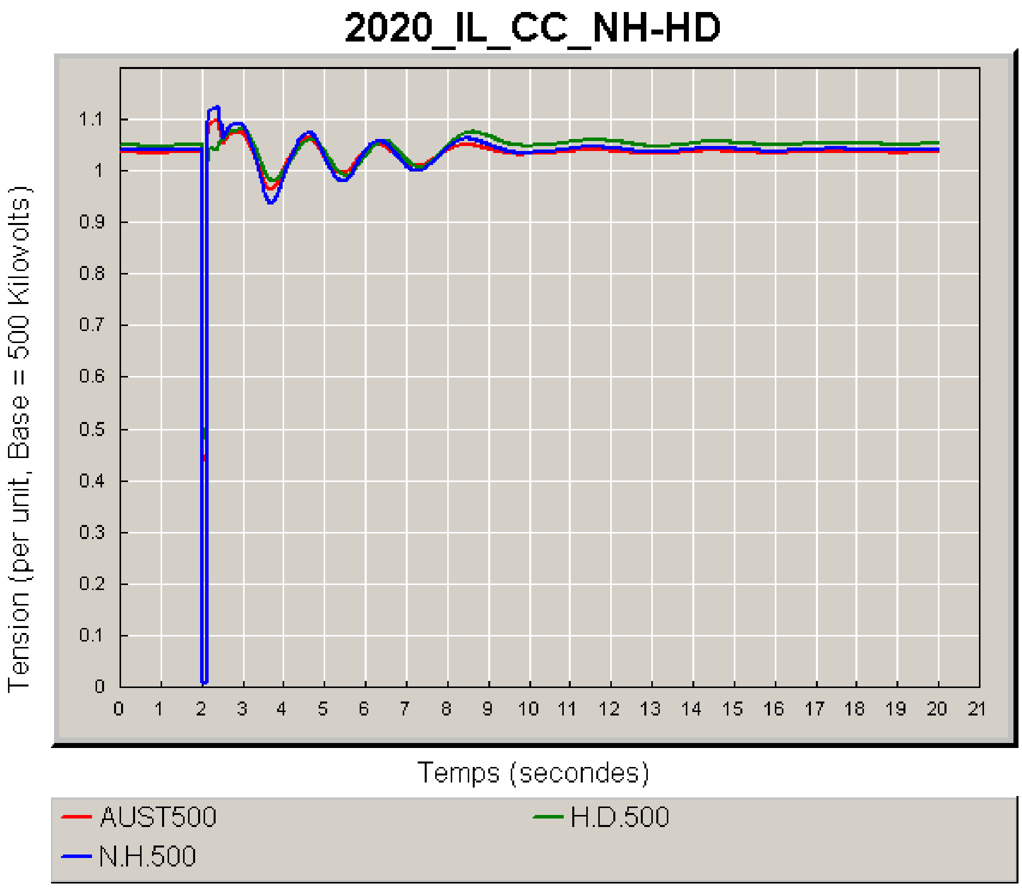


Gen_440_3 is a group of High Dam
Gen_530_1 is group 1 of Kurimat existing steam

3.7.2 POWER FLOW VARIATION ON HIGH DAM – NAG HAMMADI - ASSIUT



3.7.3 VOLTAGE VARIATION ON THE 500 KV



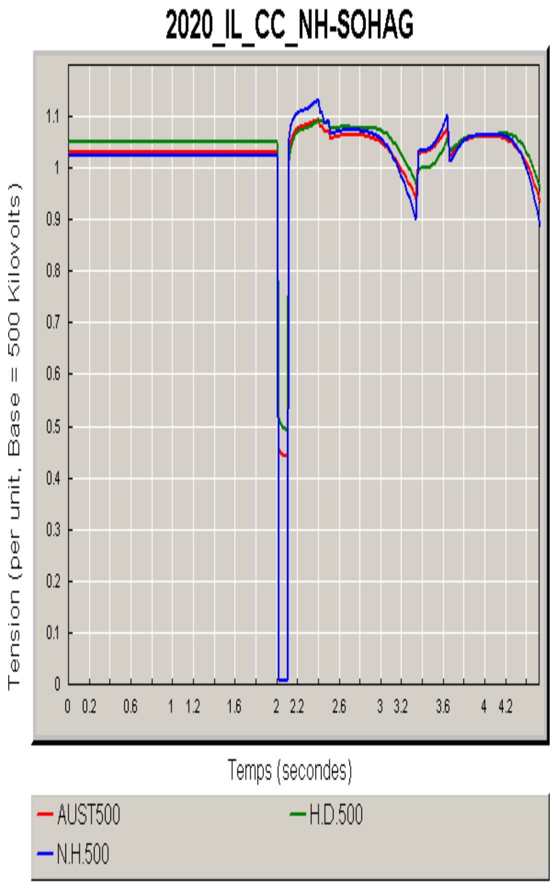
3.8 SHORT-CIRCUIT AT NAG HAMMADI ON NH500 - SOHAG CIRCUIT

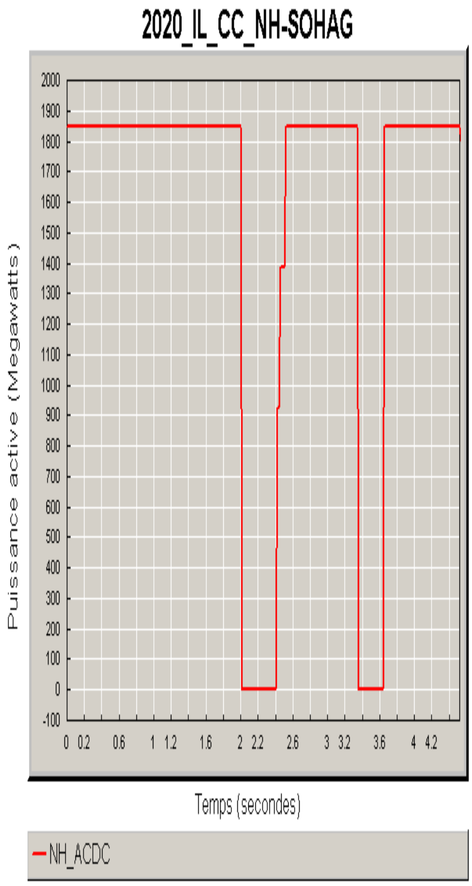
Event : a 3 phase short-circuit at Nag Hammadi end, on the circuit Nag Hammadi - Sohag, cleared in 100 ms by the opening of the circuit breakers.

The voltage drop in Nag Hammadi (to 0 pu) led to a transitory blocking of commutation of the inverter station at Nag Hammadi. The flow on the DC interconnection is transitory reduced to 0, before recovering to its initial value.
During the transitory blocking of the DC stations, the capacitors bank remained connected.

For the Ethiopian and Sudanese side, the impact on the system and its behaviour is very similar to the case of SC on High Dam - Nag Hammadi

3.8.1 VOLTAGE VARIATION AND DC POWER FLOW WITHOUT ANY ADDITIONAL DEVICE



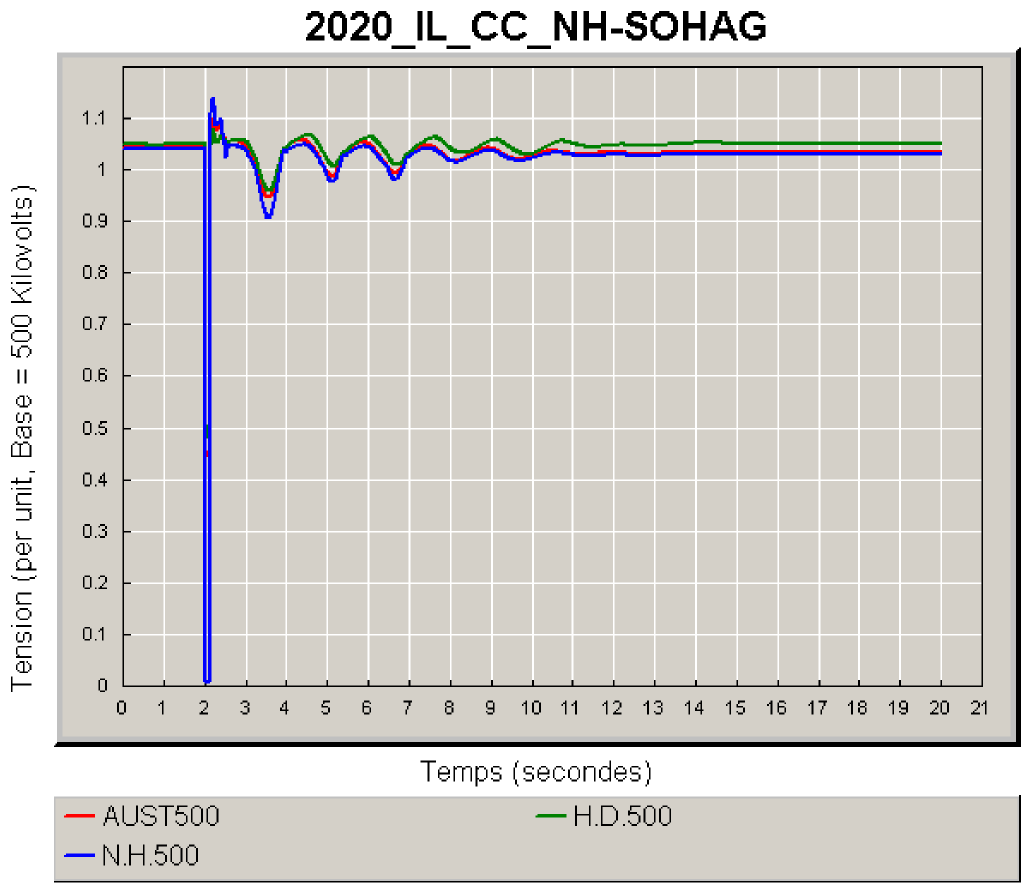


Without any additional divice, the DC substation would face several commutation failure before a complete blocking. This situation is not satisfying.

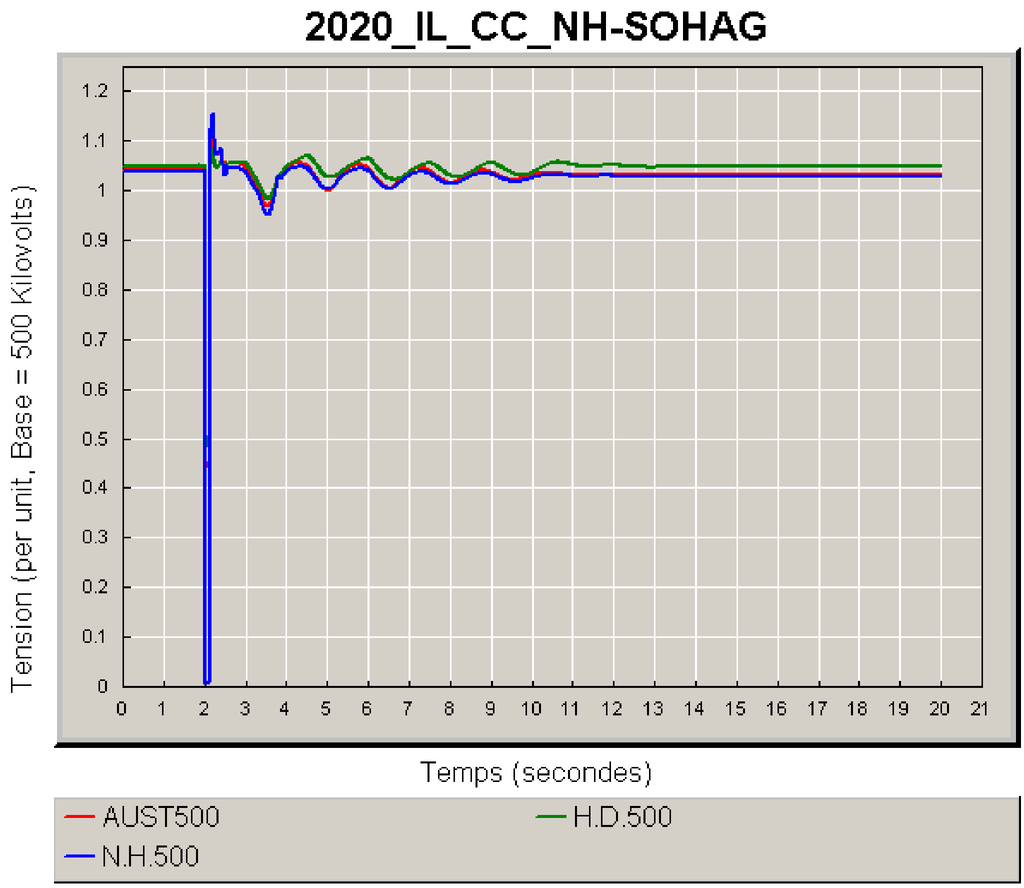
3.8.2 IMPLEMENTATION OF A SVC IN RABAK

3.8.2.1 Voltage variation on the 500 kV

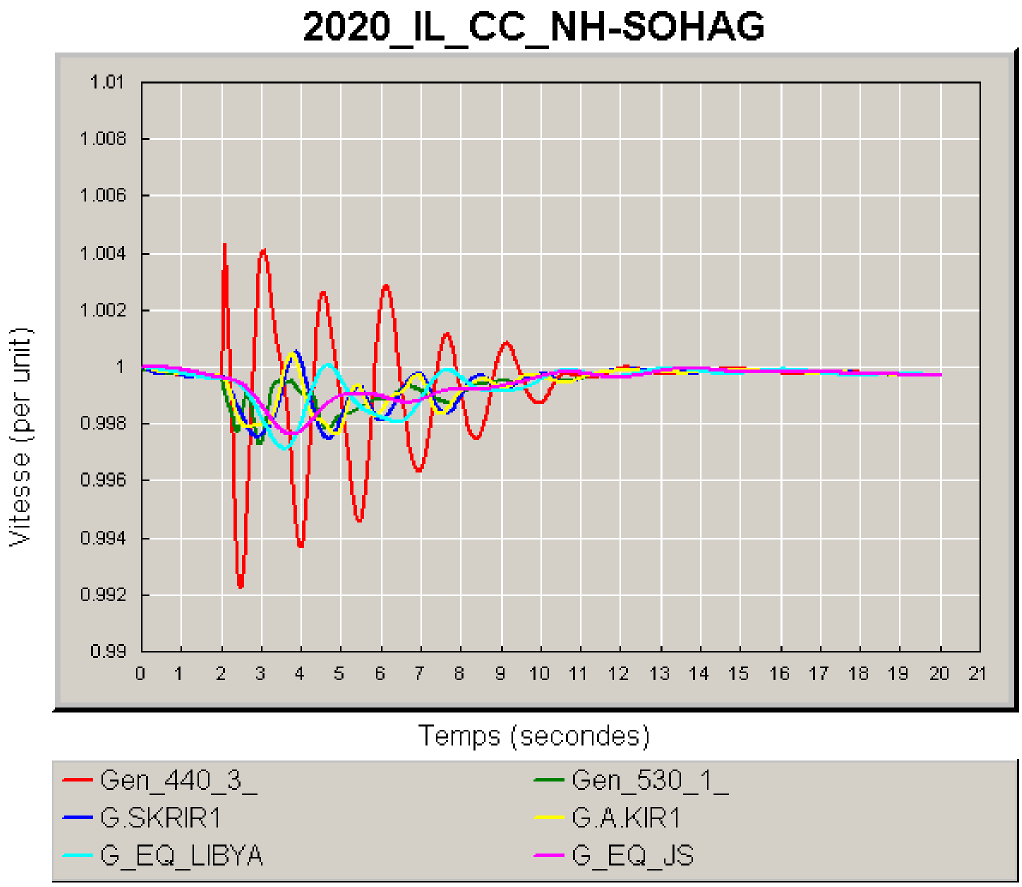
With a 200 MVAR SVC



With a 300 MVAR SVC

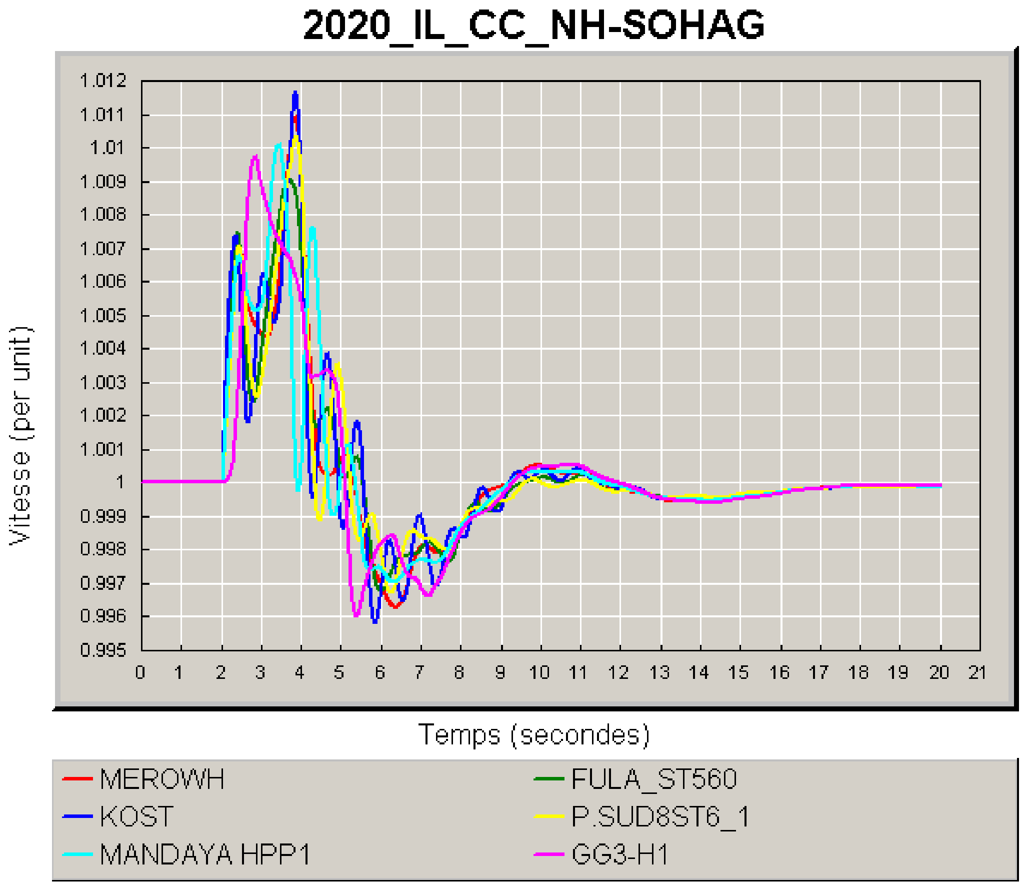


3.8.2.2 Frequency variation

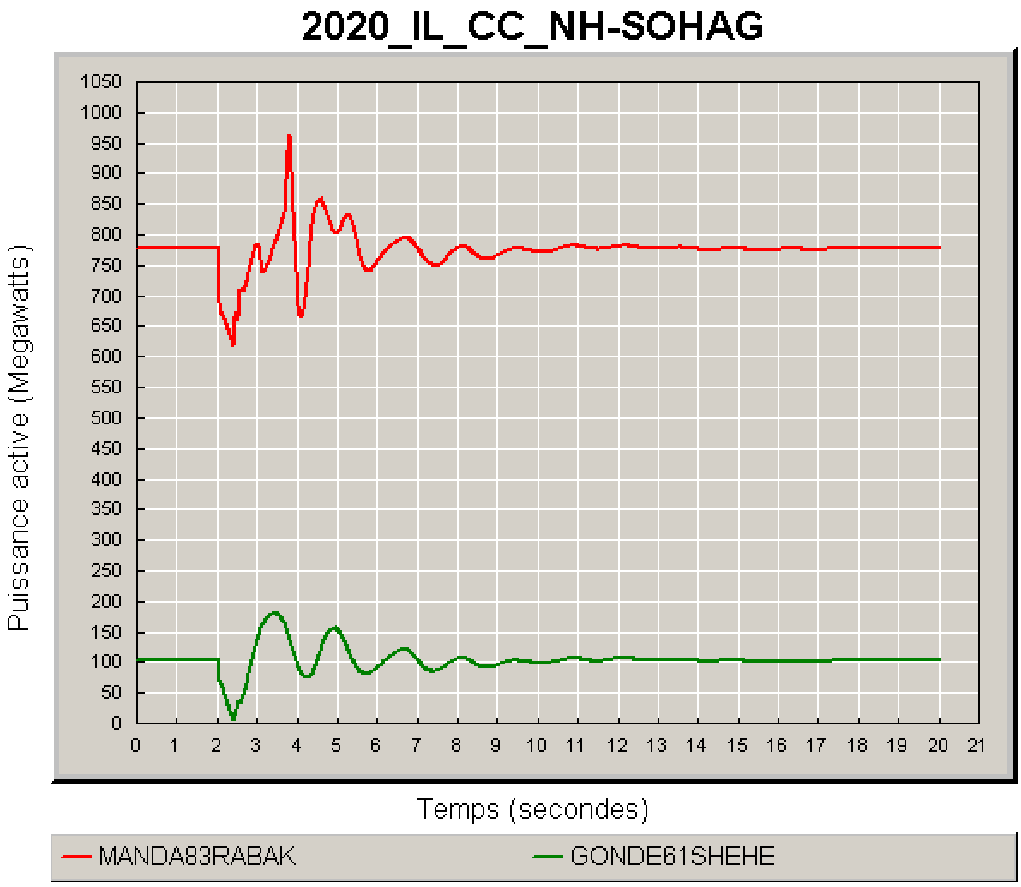


Gen_440_3 is a group of High Dam

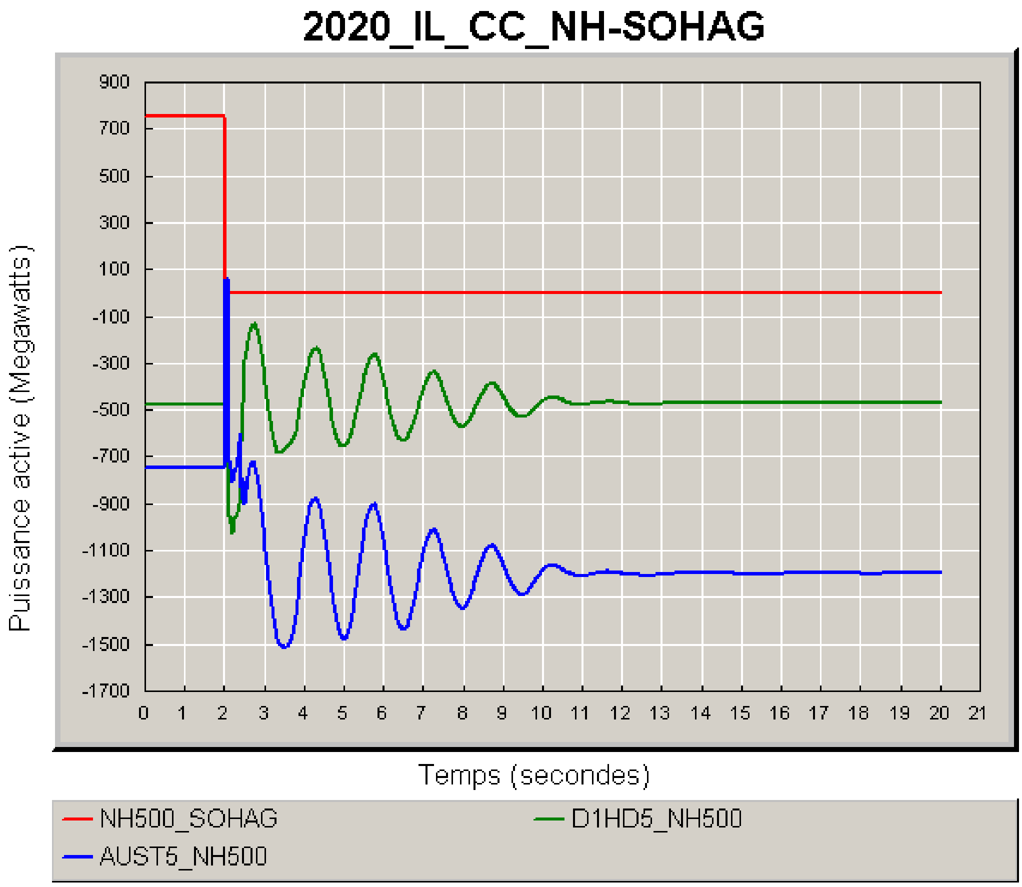
Gen_530_1 is group 1 of the existing steam turbine in Kurimat


2020_IL_CC_NH-SOHAG
Vitesse (per unit)
1.012
1.011
1.01
1.009
1.008
1.007
1.006
1.005
1.004
1.003
1.002
1.001
1
0.999
0.998
0.997
0.996
0.995
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21
Temps (secondes)
MEROWH
KOST
MANDAYA HPP1
FULA_ST560
P.SUD8ST6_1
GG3-H1

3.8.2.3 Power flow variation on ENTRO interconnection



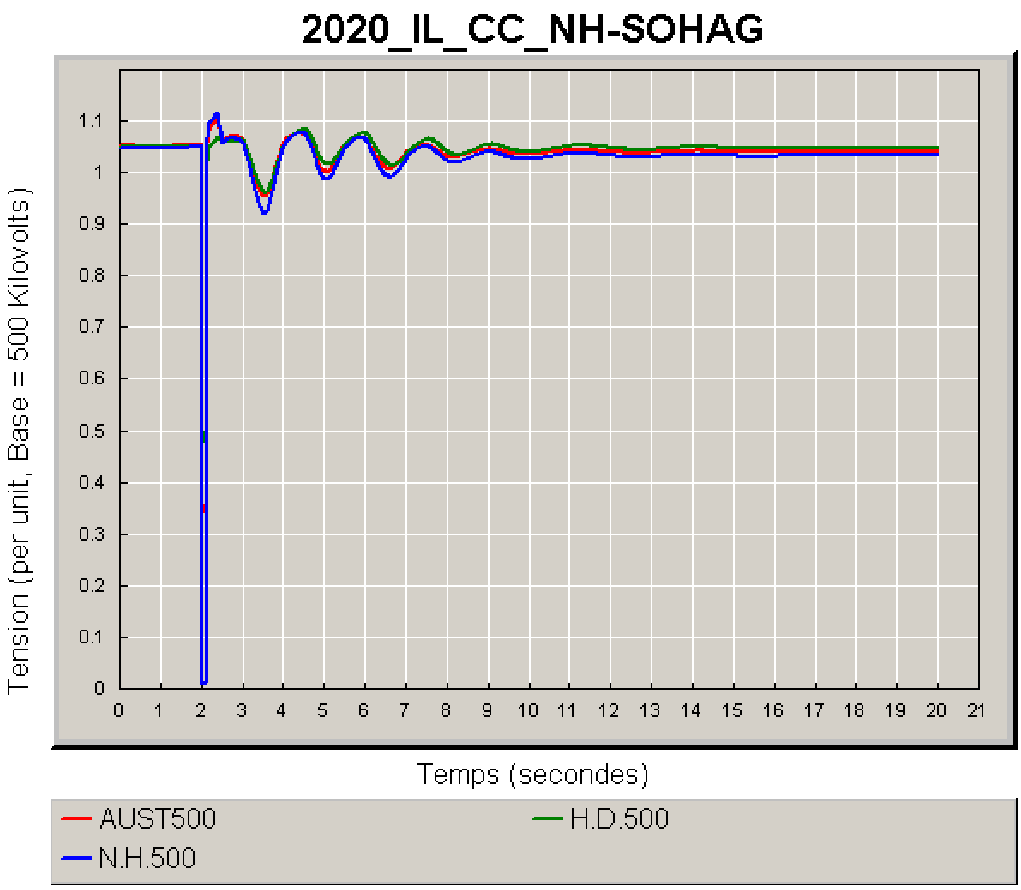
3.8.2.4 Power flow variation on the circuit High Dam - Nag Hammadi - Assiut



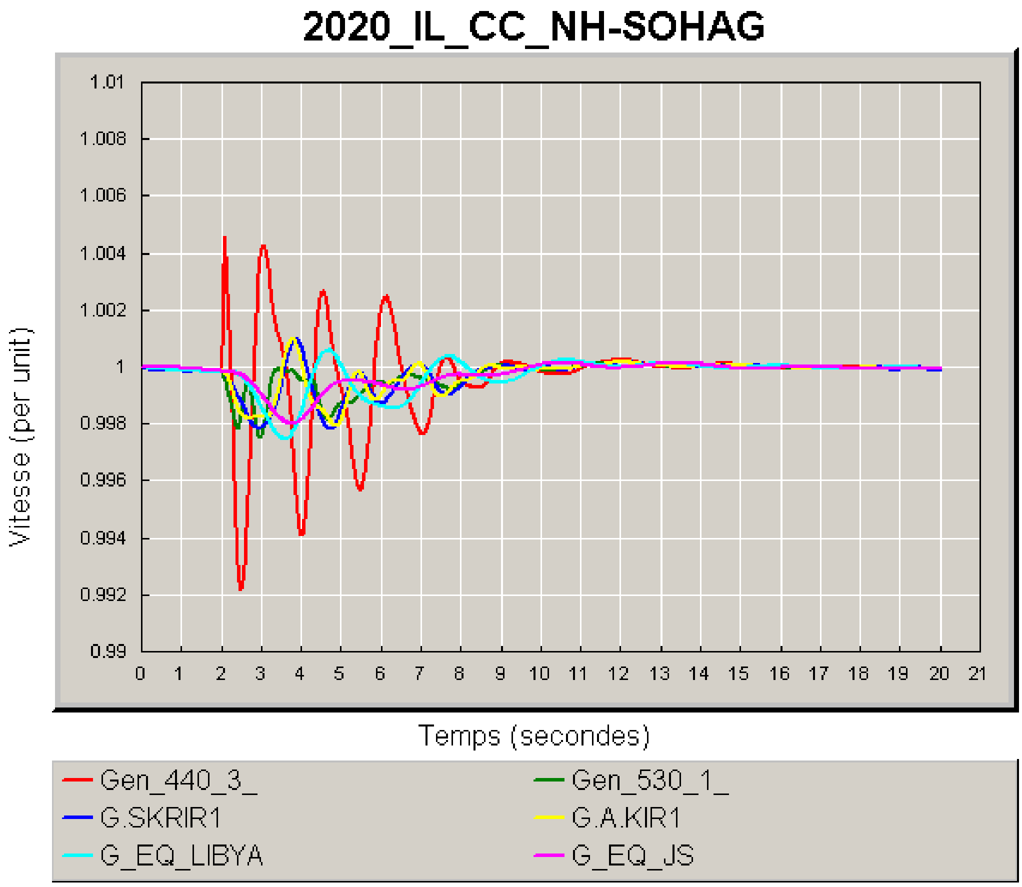
3.8.3 IMPLEMENTATION OF AN ADDITIONAL CIRCUIT NAG HAMMADI – ASSIUT

The behaviour of the Ethiopian – Sudan system is the same as in case of SVC in Rabak (since the DC substation only faced one commutation failure in both cases)

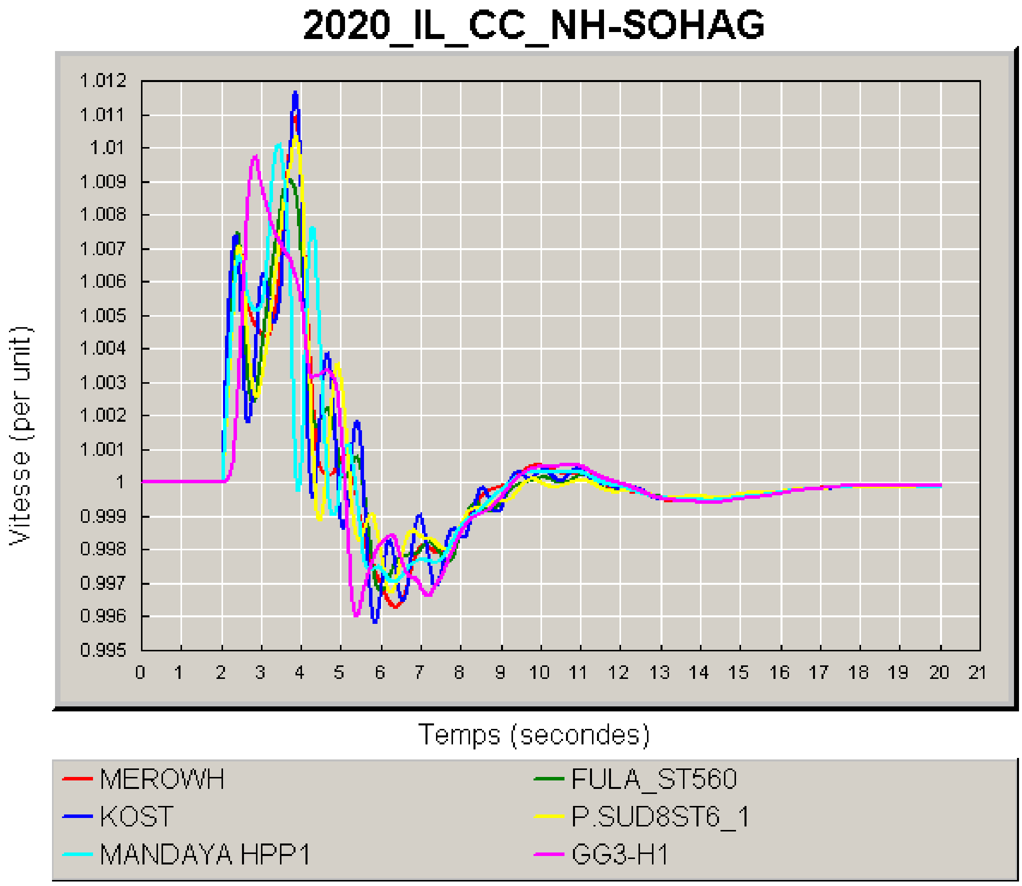
3.8.3.1 Voltage variation on the 500 kV



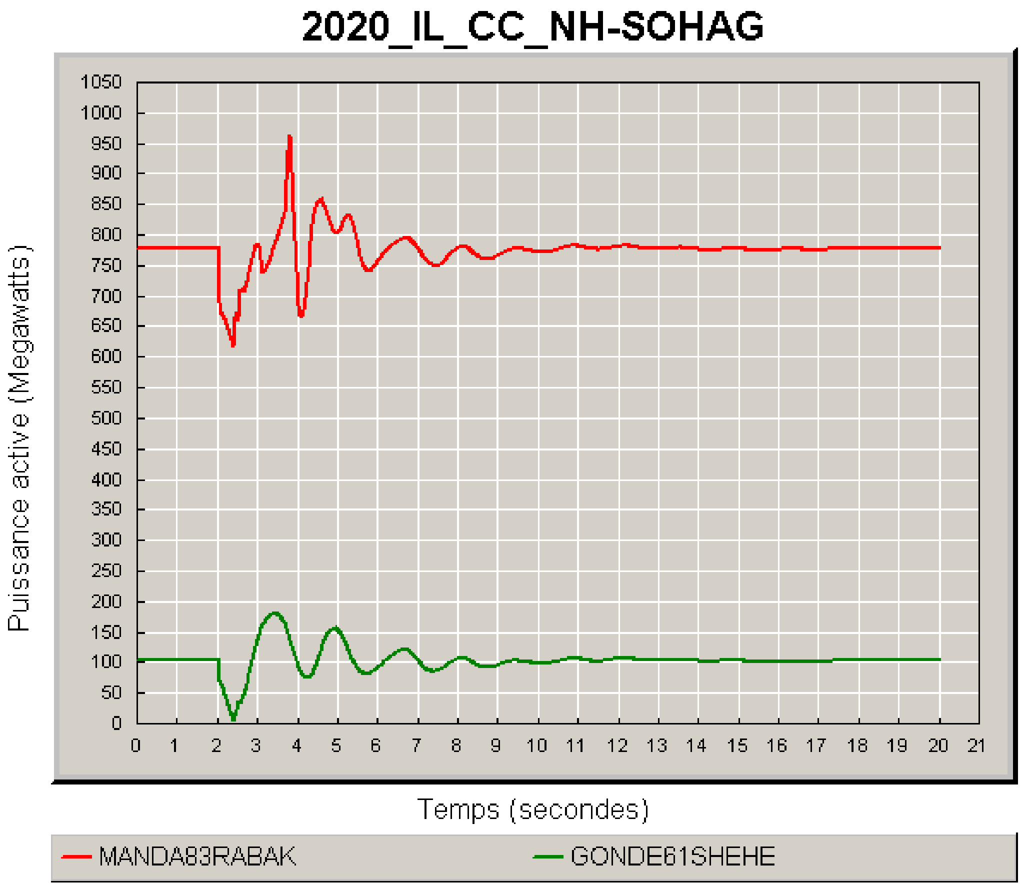
3.8.3.2 Frequency variation



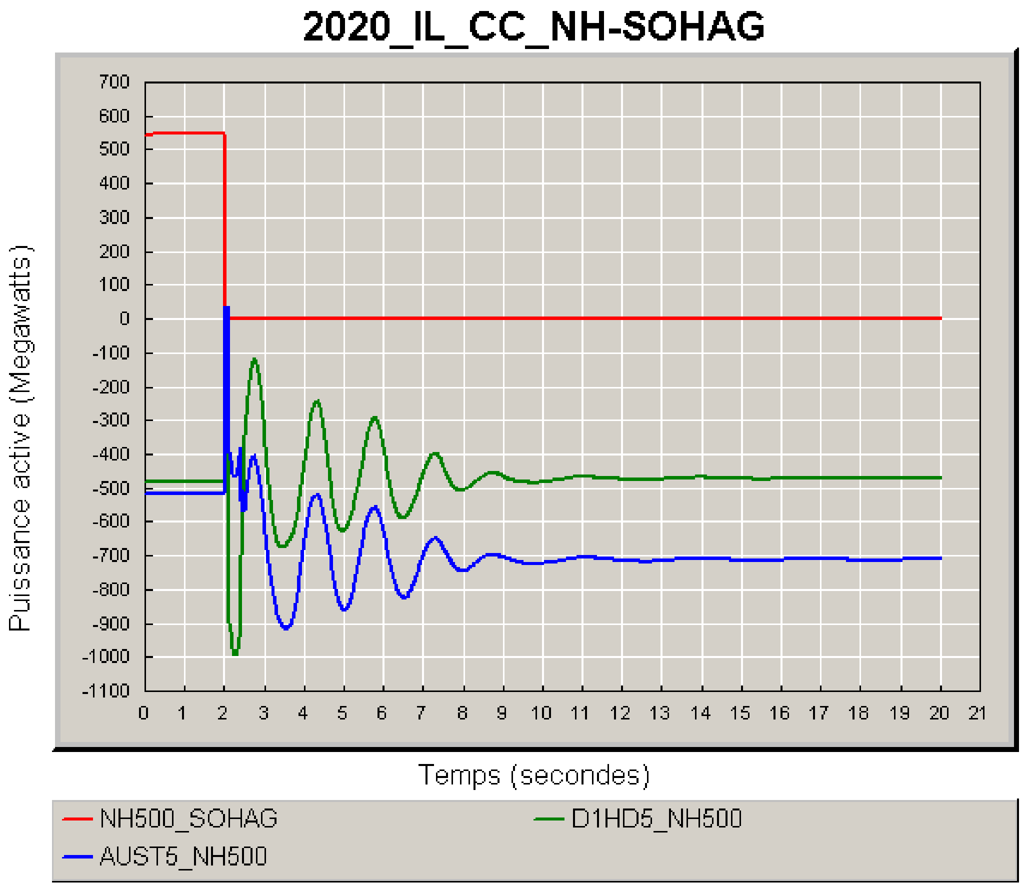
Gen_441_1 is a group of High Dam
Gen_530_1 is group 1 of Kurimat existing steam


2020_IL_CC_NH-SOHAG
1.012
1.011
1.01
1.009
1.008
1.007
1.006
1.005
1.004
1.003
1.002
1.001
1
0.999
0.998
0.997
0.996
0.995
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21
Vitesse (per unit)
Temps (secondes)
MEROWH
KOST
MANDAYA HPP1
FULA_ST560
P.SUD8ST6_1
GG3-H1

3.8.3.3 Power flow variation on ENTRO interconnection



3.8.3.4 Power flow variation on the circuit High Dam - Nag Hammadi - Assiut

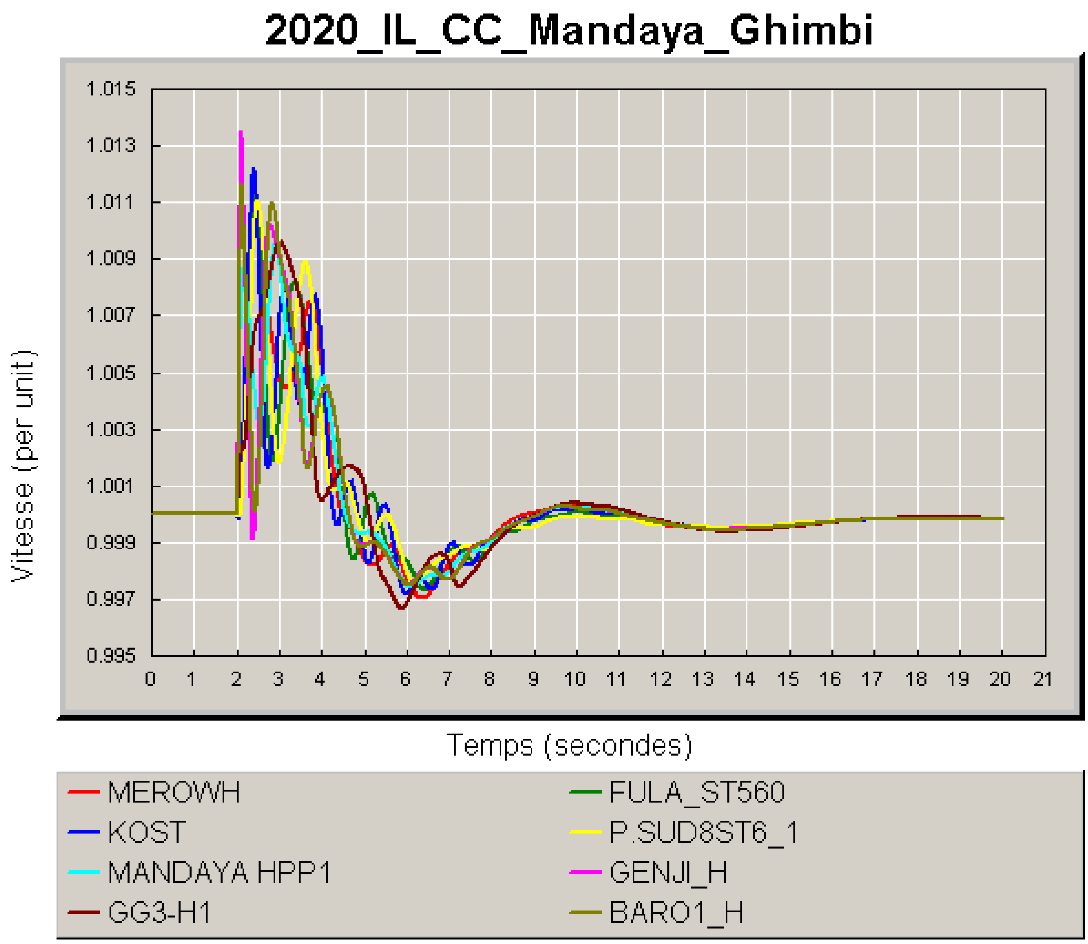


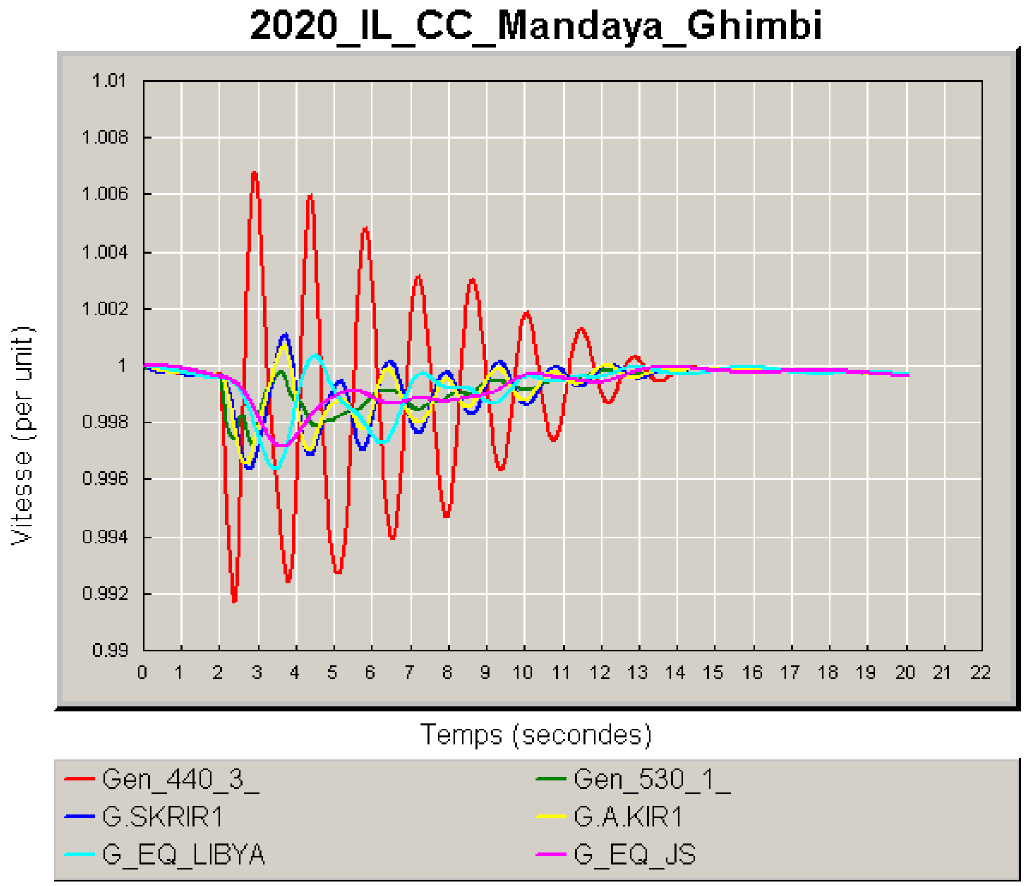
3.9 SHORT-CIRCUIT AT MANDAYA ON ONE OF THE 3 CIRCUITS MANDAYA - GHIMBI

Event : a 3 phase short-circuit at Mandaya end, on one of the 3 circuits Mandaya - Ghimbi, cleared in 100 ms by the opening of the circuit breakers.

The voltage drop in Rabak (to 0.5 pu) led to a transitory blocking of commutation of the rectifier station at Rabak. The flow on the DC interconnection is transitory reduced to 0, before recovering to its initial value. During the transitory blocking of the DC stations, the capacitors bank remained connected.

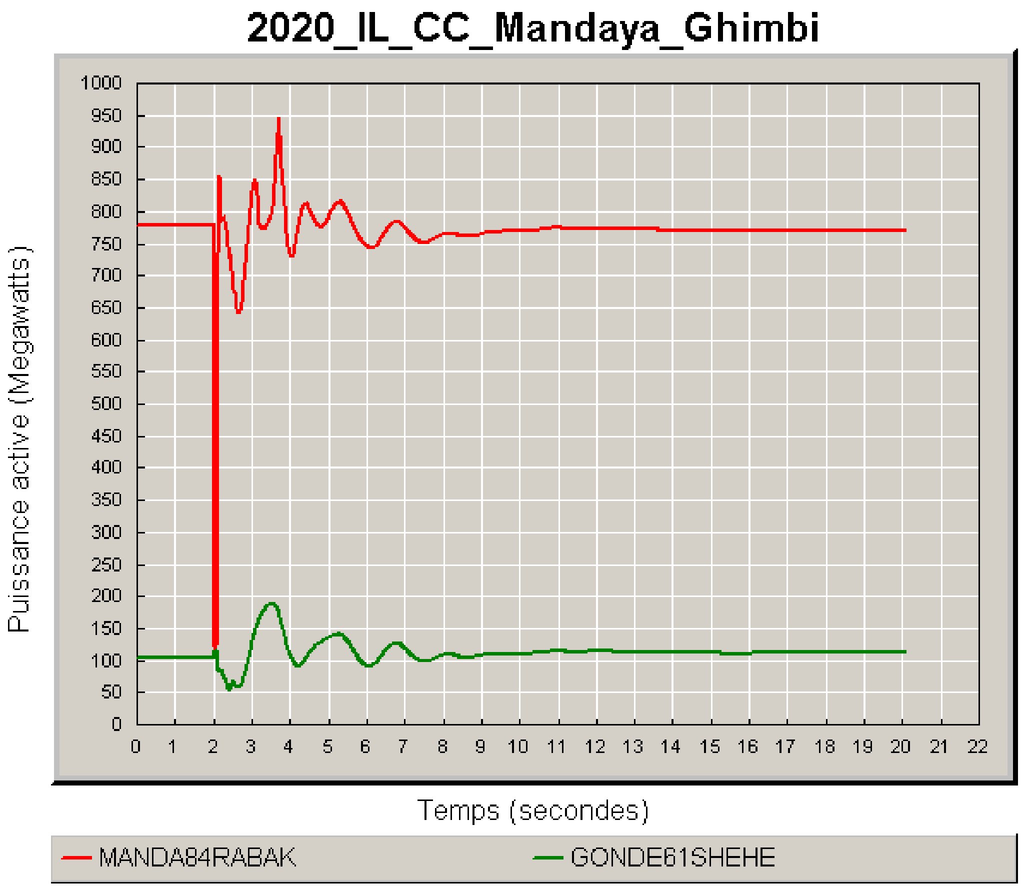
3.9.1 GENERATORS FREQUENCY VARIATION

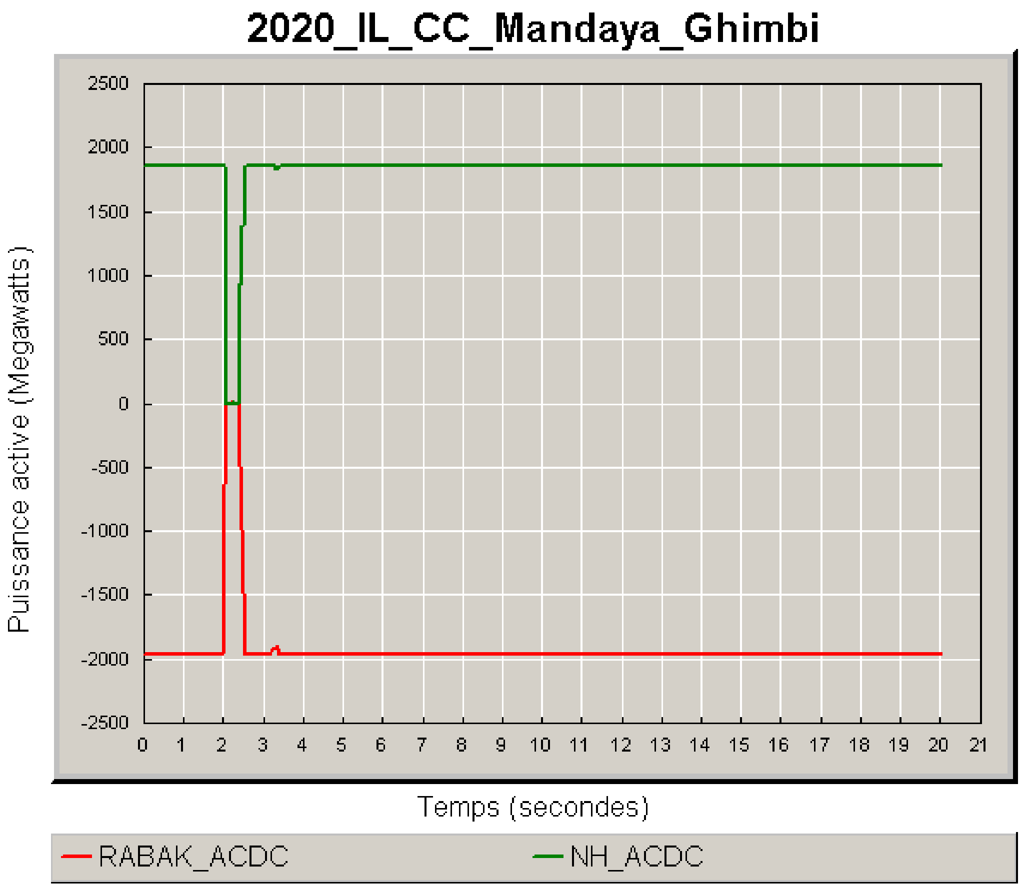




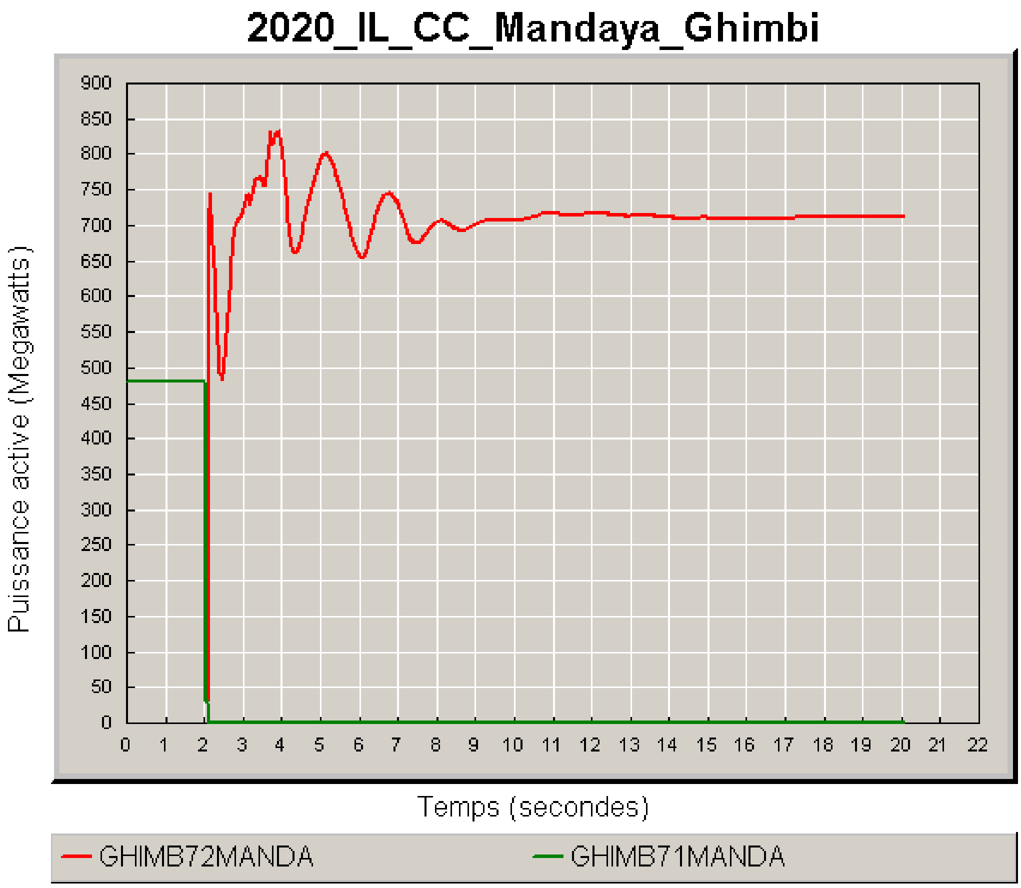
Gen_440_3 is a group of High Dam
Gen_530_1 is the existing steam turbine in Kurimat

3.9.2 POWER FLOW VARIATION ON ENTRO INTERCONNECTION

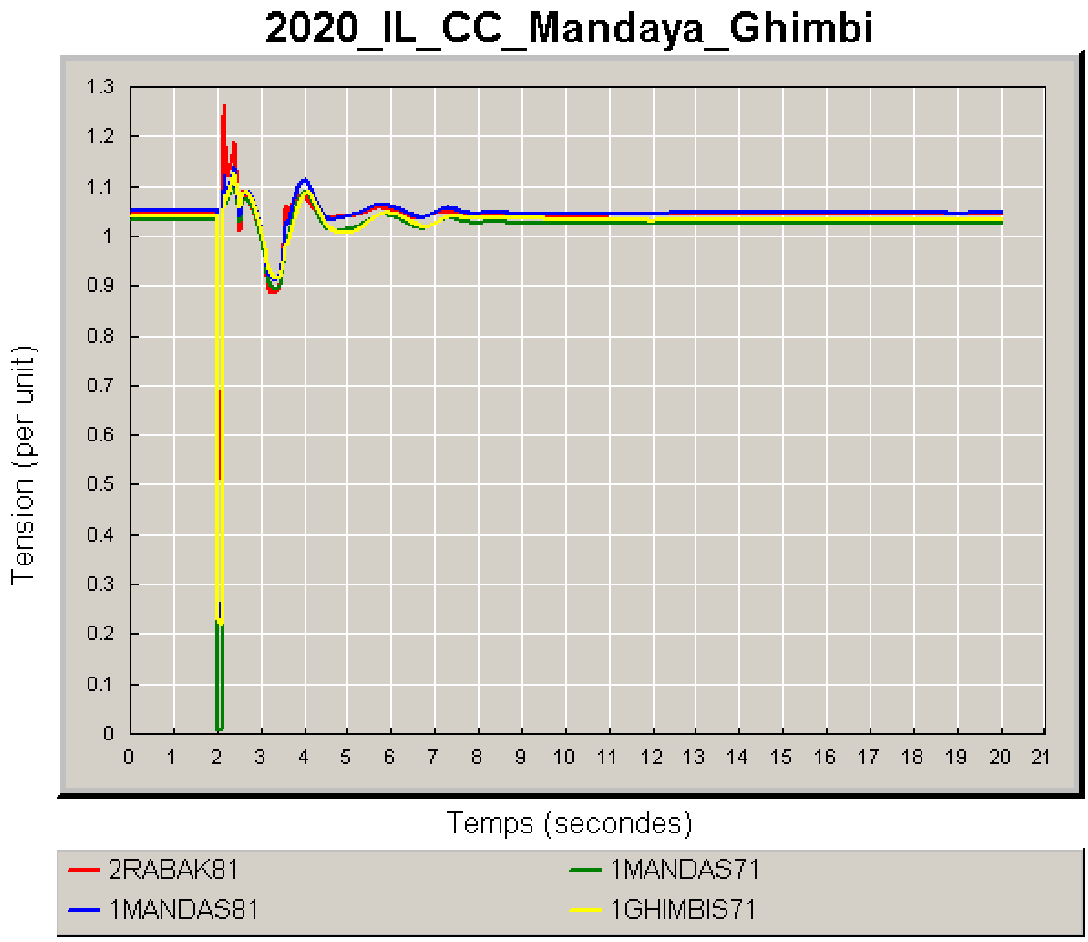


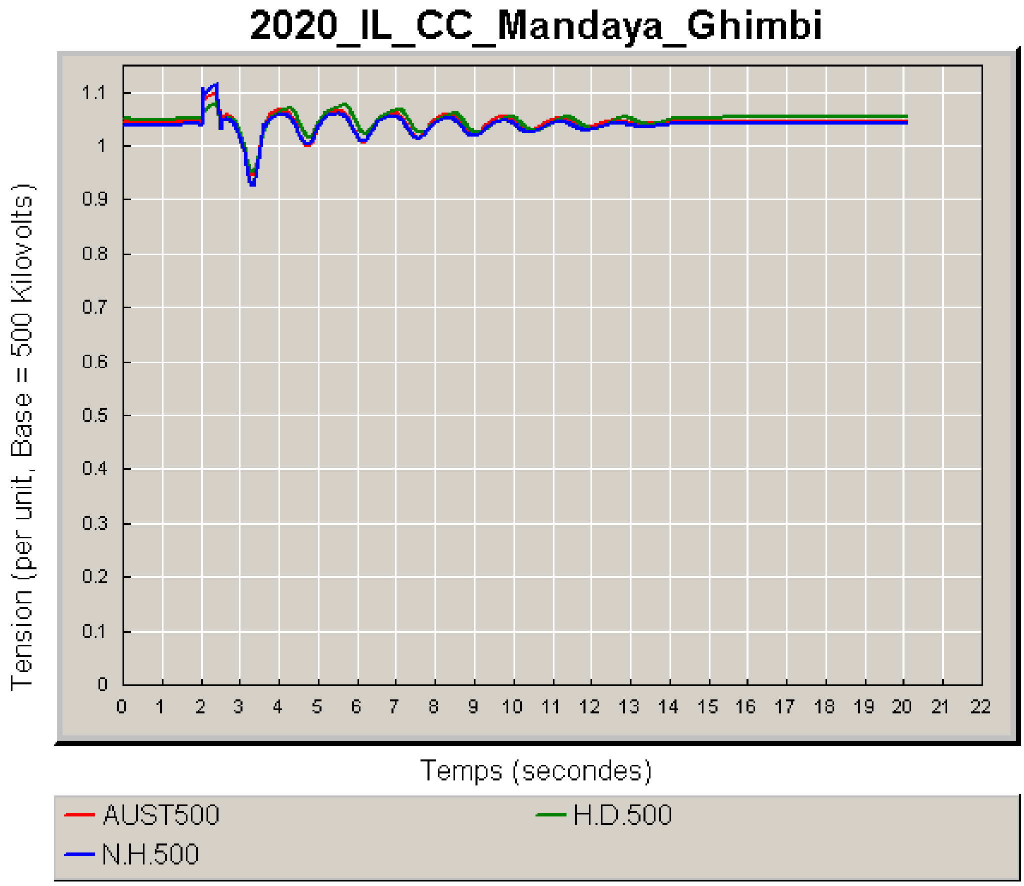

2020_IL_CC_Mandaya_Ghimbi
Puissance active (Megawatts)
2500
2000
1500
1000
500
0
-500
-1000
-1500
-2000
-2500
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21
Temps (secondes)
RABAK_ACDC
NH_ACDC

3.9.3 POWER FLOW VARIATION ON MANDAYA - GHIMBI



3.9.4 VOLTAGE VARIATION ON THE 500 KV



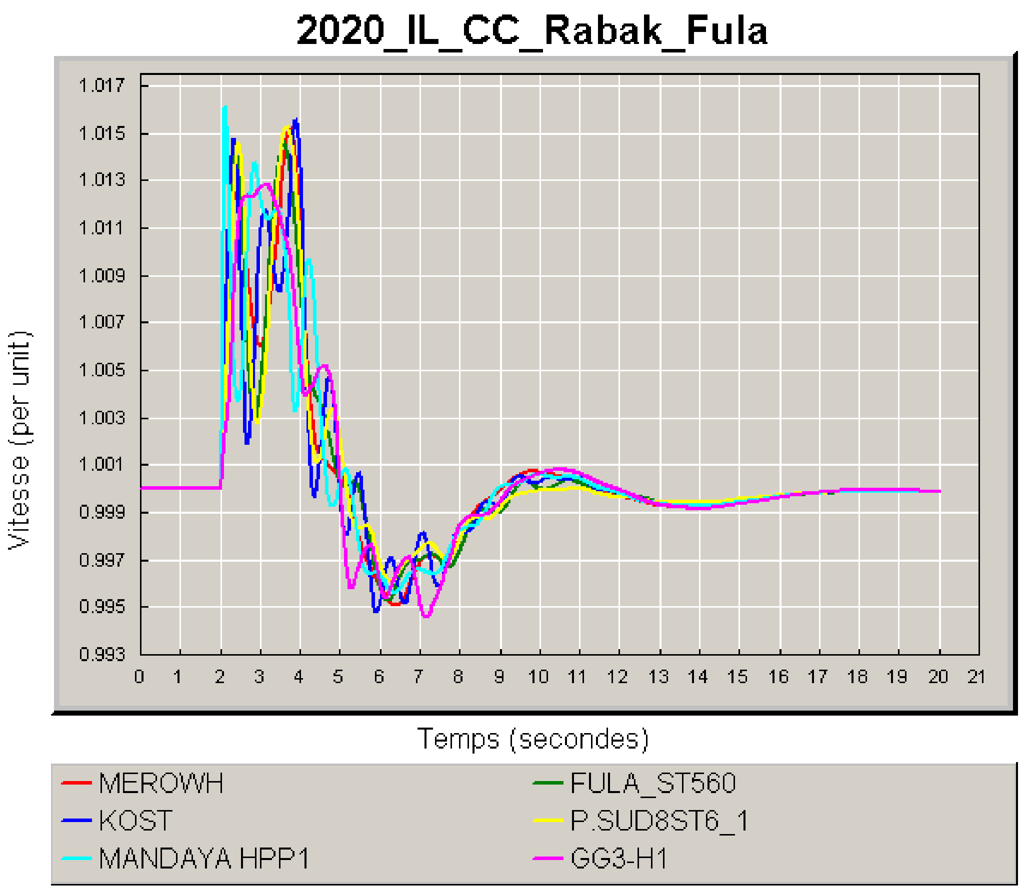

2020_IL_CC_Mandaya_Ghimbi
Tension (per unit, Base = 500 Kilovolts)
1.1
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22
Temps (secondes)
AUST500
H.D.500
N.H.500

3.10 SHORT-CIRCUIT AT RABAK ON RABAK - FULA

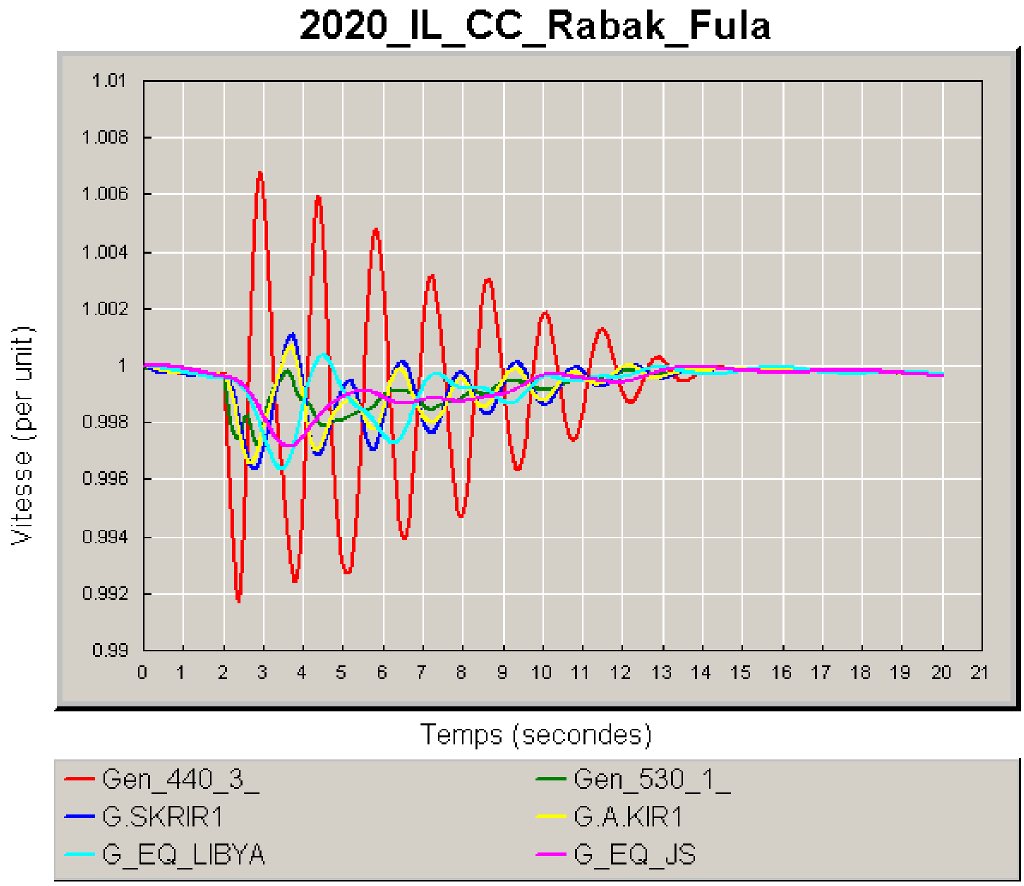
Event : a 3 phase short-circuit at Rabak end, on one of the 2 circuits Rabak - Fula, cleared in 120 ms by the opening of the circuit breakers.

The voltage drop in Rabak (to 0 pu) led to a transitory blocking of commutation of the rectifier station at Rabak. The flow on the DC interconnection is transitory reduced to 0, before recovering to its initial value. During the transitory blocking of the DC stations, the capacitors bank remained connected.

3.10.1 GENERATORS FREQUENCY VARIATION

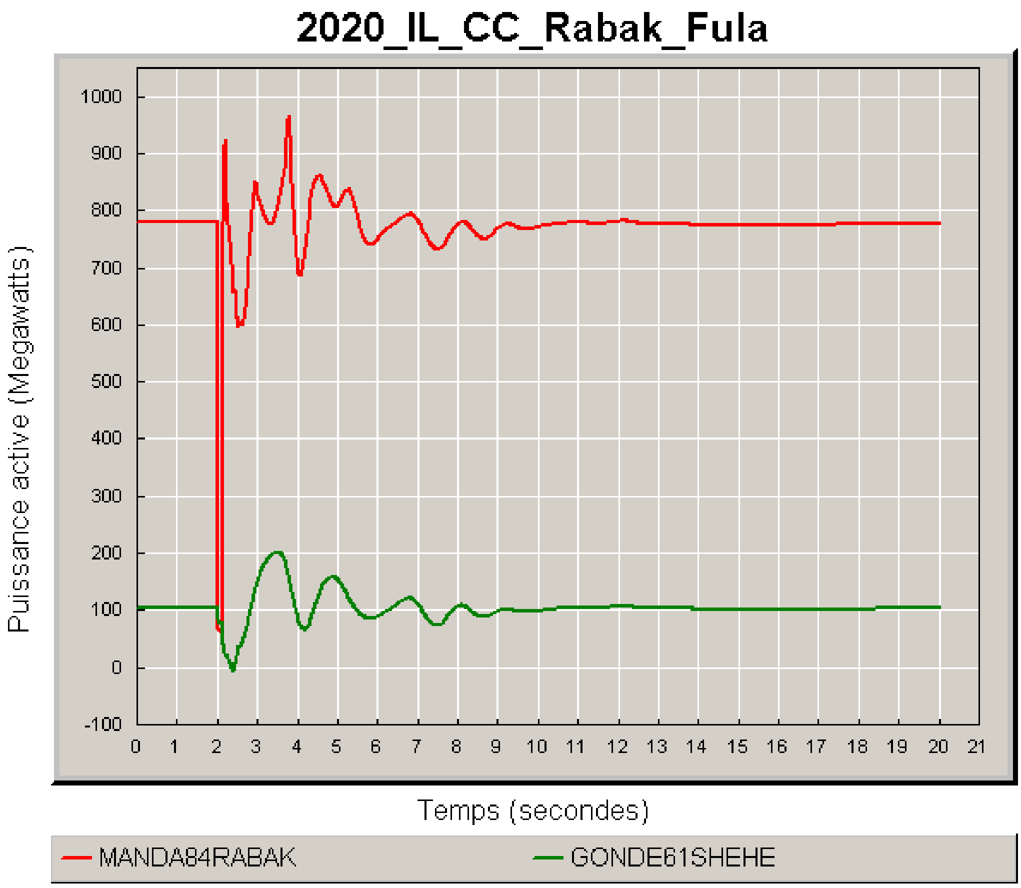


GG3 is Gibe 3

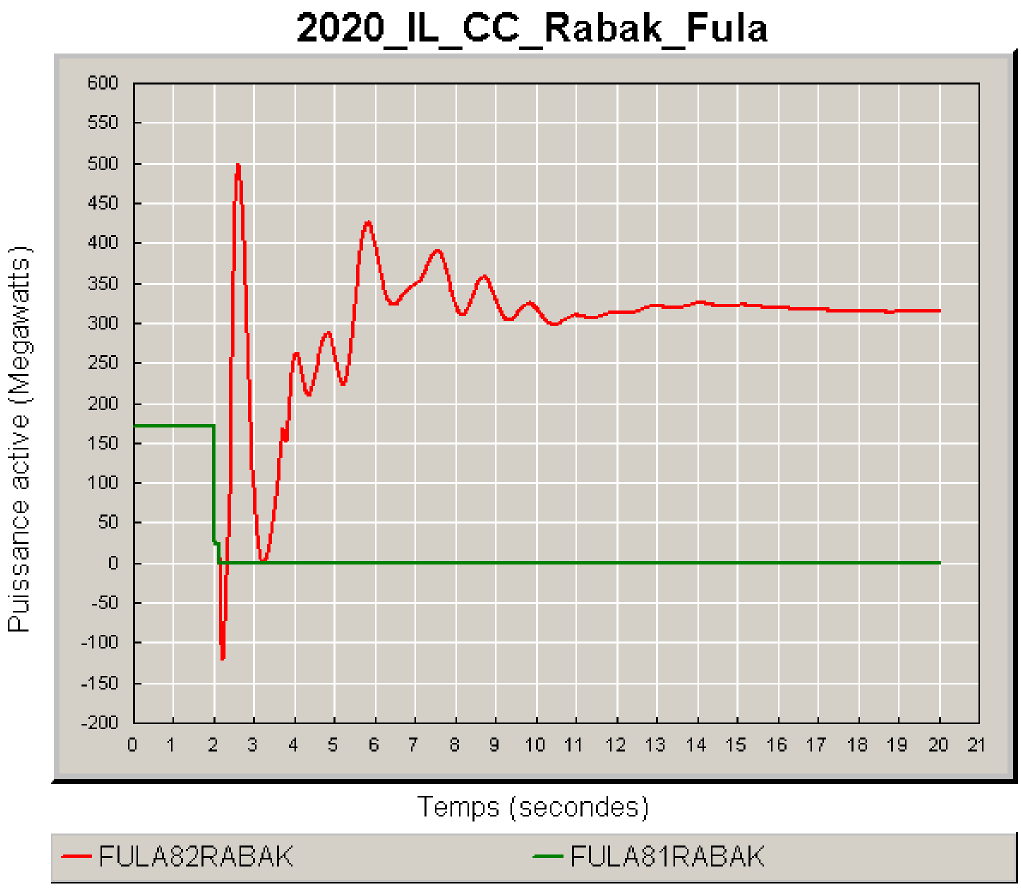


Gen_440_3 is a group of High Dam
Gen_530 is the existing steam turbine in Kurimat

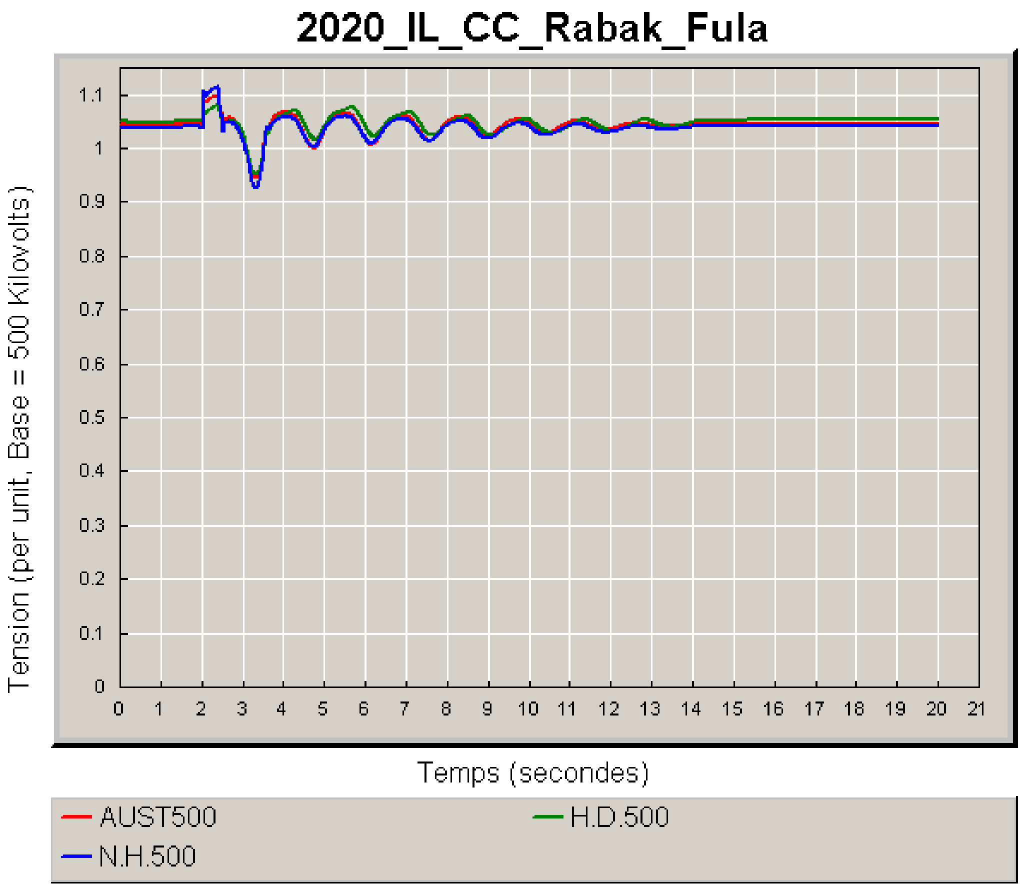
3.10.2 POWER FLOW VARIATION ON ENTRO INTERCONNECTION

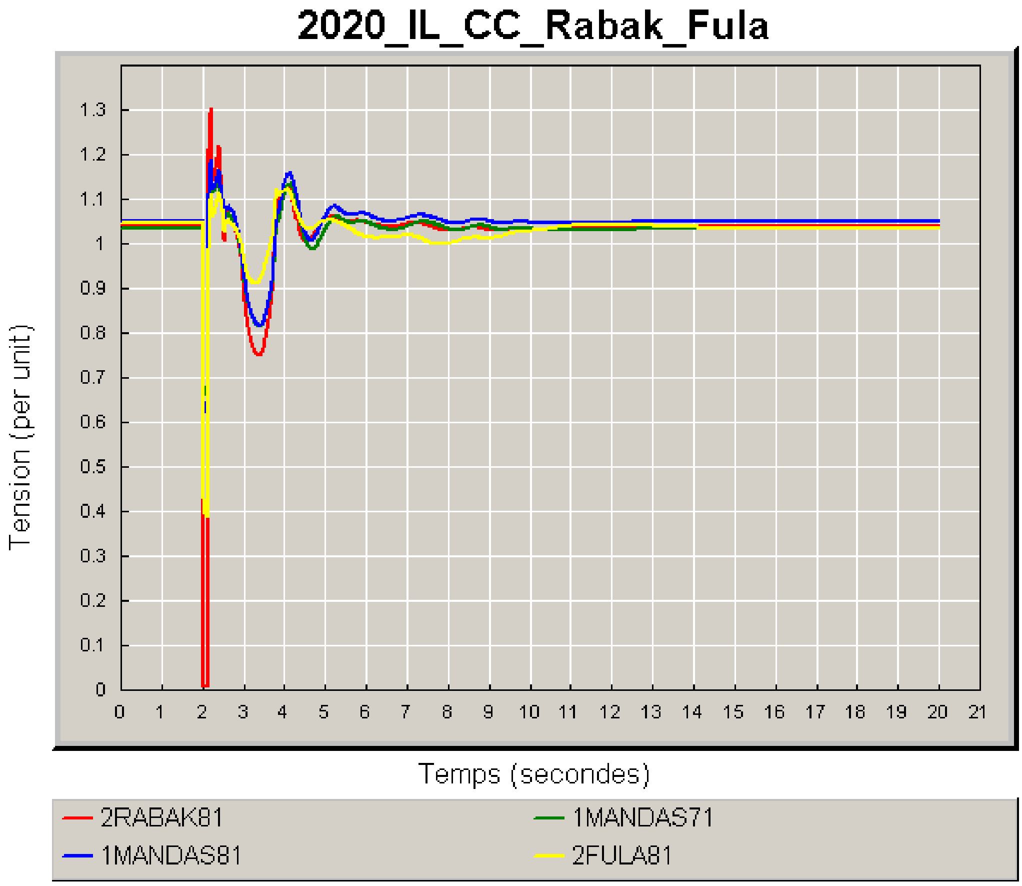


3.10.3 POWER FLOW VARIATION ON RABAK - FULA



3.10.4 VOLTAGE VARIATION ON THE 500 KV



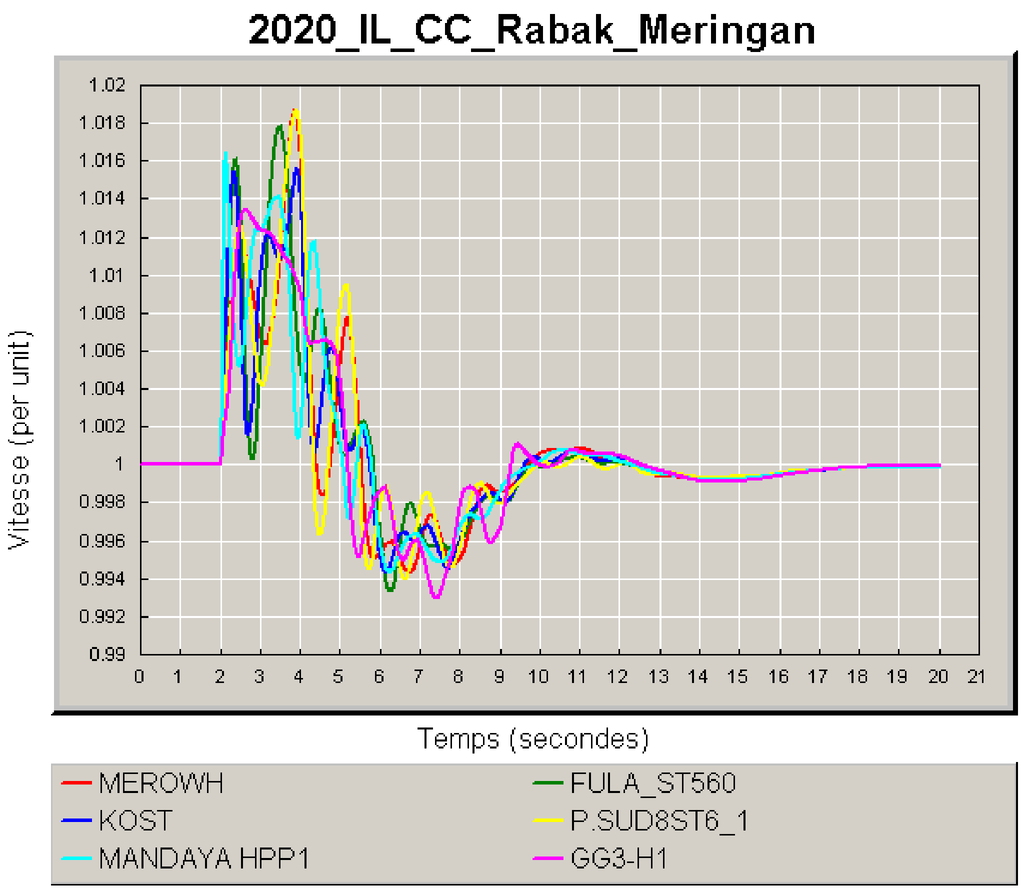

2020_IL_CC_Rabak_Fula
Tension (per unit)
1.3
1.2
1.1
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21
Temps (secondes)
2RABAK81
1MANDAS71
1MANDAS81
2FULA81

3.11 SHORT-CIRCUIT AT RABAK ON RABAK - MERINGAN

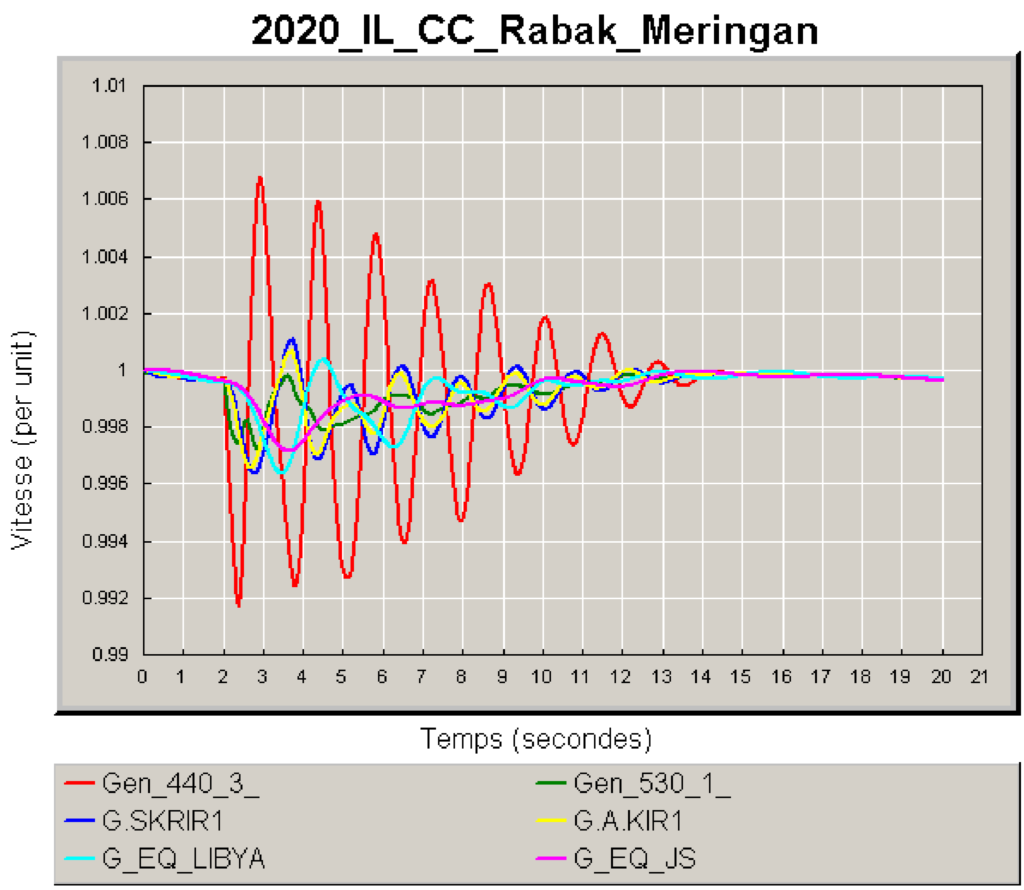
Event : a 3 phase short-circuit at Rabak end, on the circuit Rabak - Meringan, cleared in 120 ms by the opening of the circuit breakers.

The voltage drop in Rabak (to 0 pu) led to a transitory blocking of commutation of the rectifier station at Rabak. The flow on the DC interconnection is transitory reduced to 0, before recovering to its initial value. During the transitory blocking of the DC stations, the capacitors bank remained connected.

3.11.1 GENERATORS FREQUENCY VARIATION



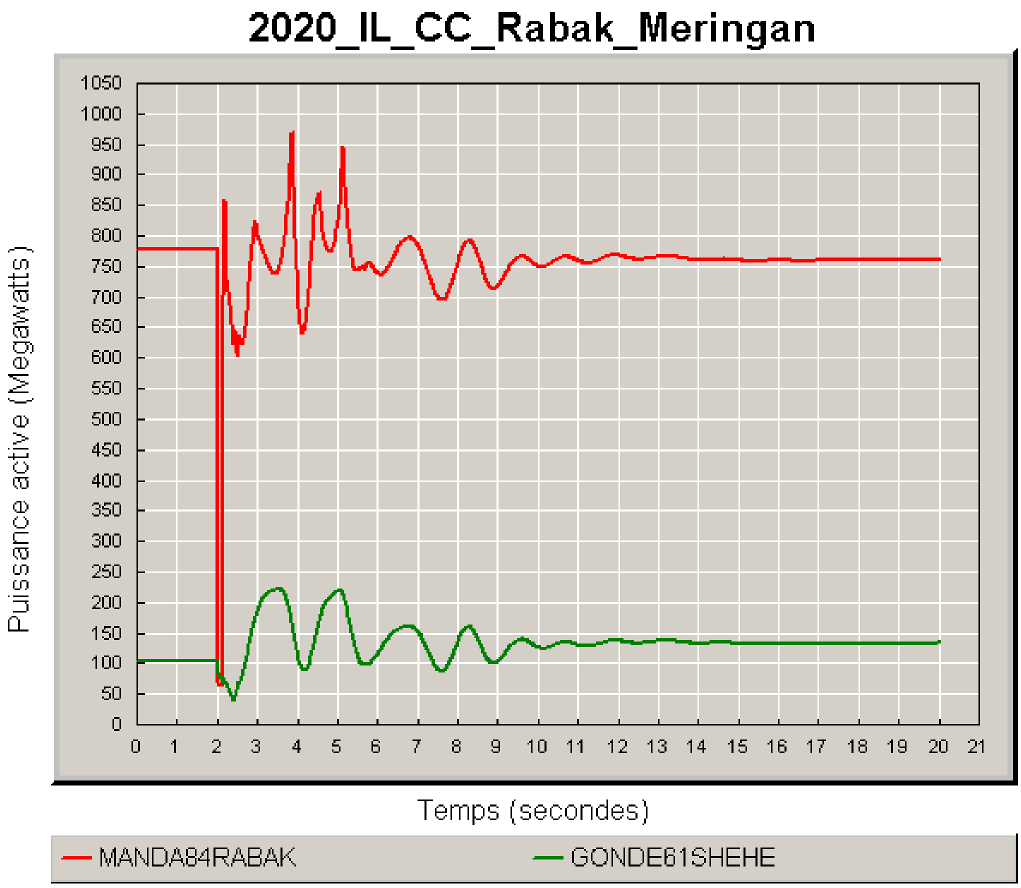
GG3 is Gibe III



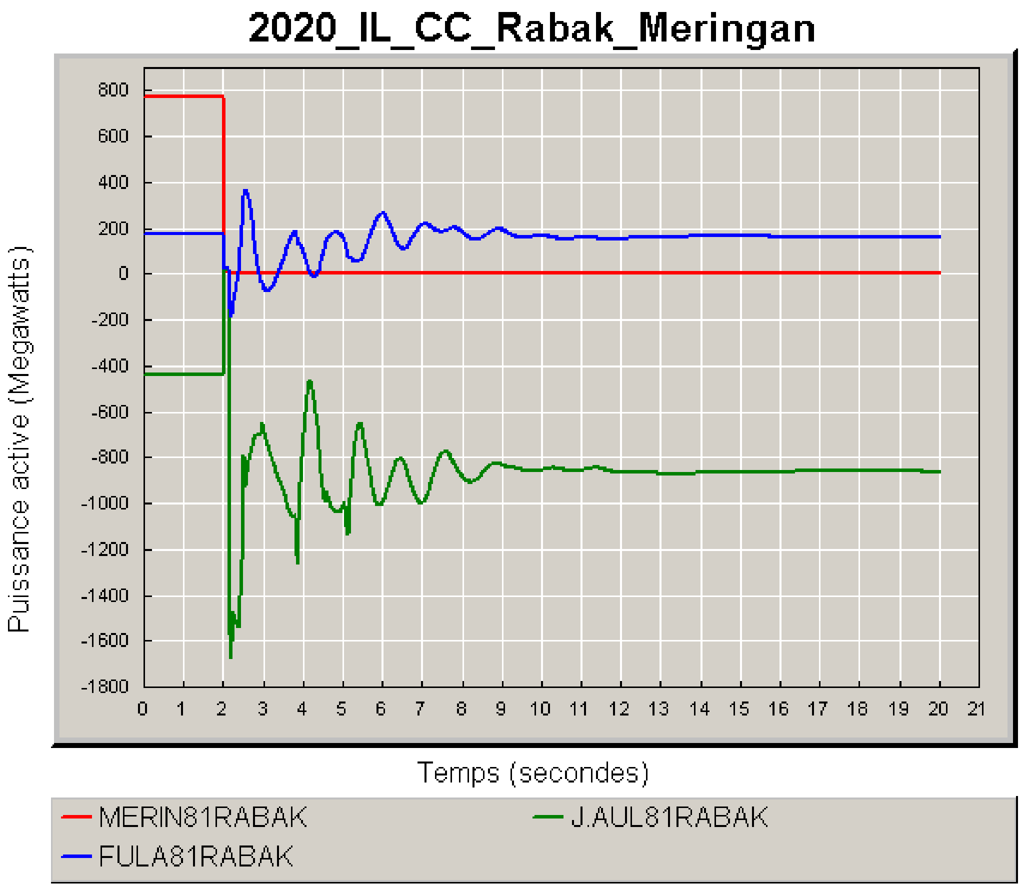
Gen_440_3 is a group of High Dam

Gen_530_1 is the existing steam turbine in Kurimat

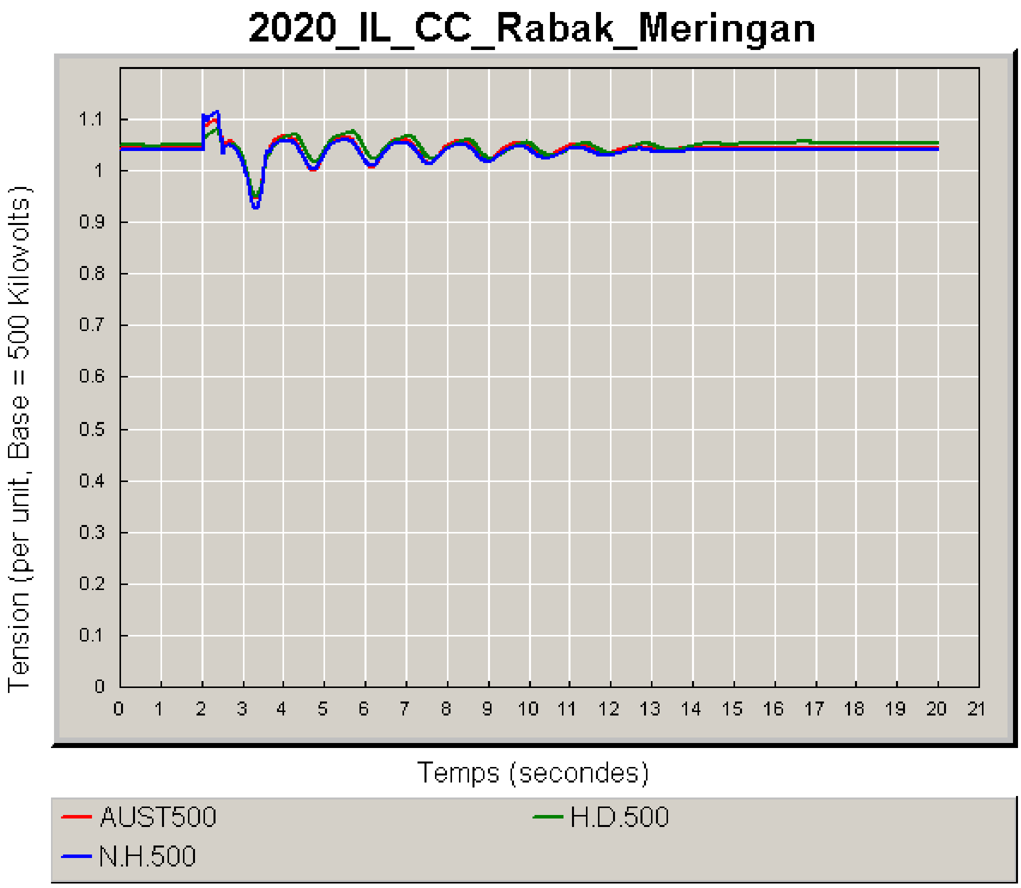
3.11.2 POWER FLOW VARIATION ON ENTRO AC INTERCONNECTION

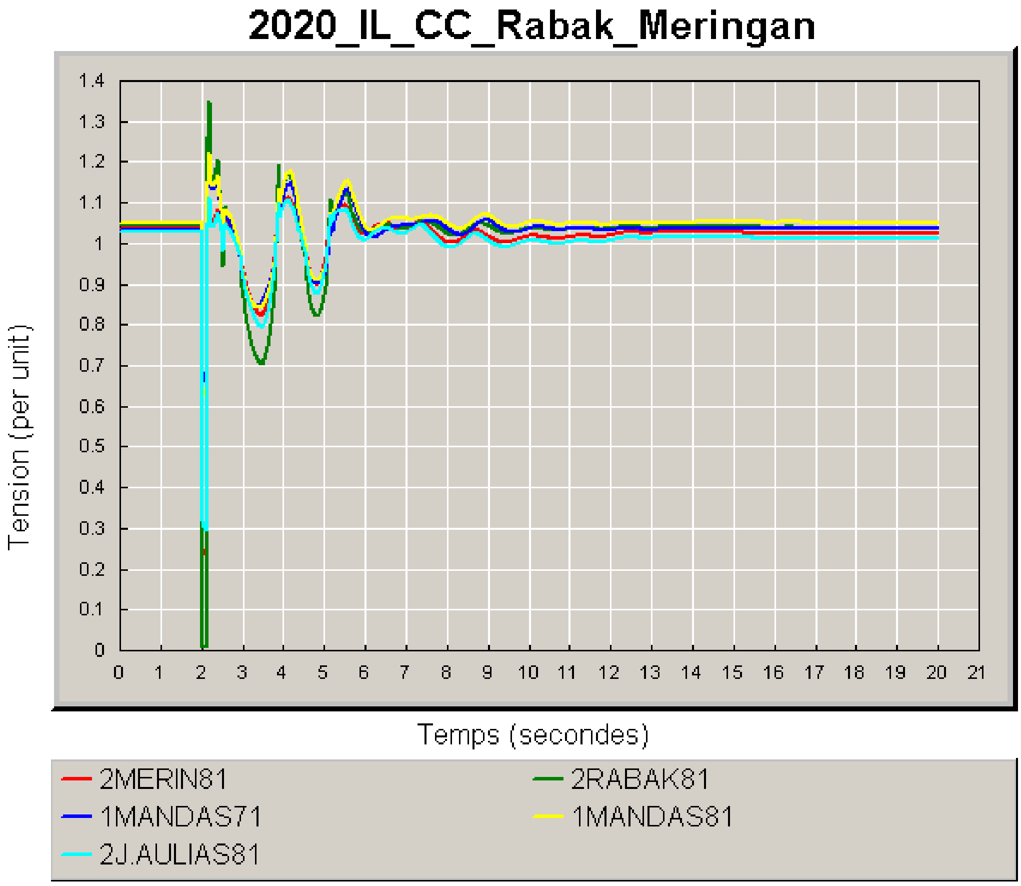


3.11.3 POWER FLOW VARIATION ON RABAK - FULA, RABAK - MERINGAN AND RABAK - J.AULIA

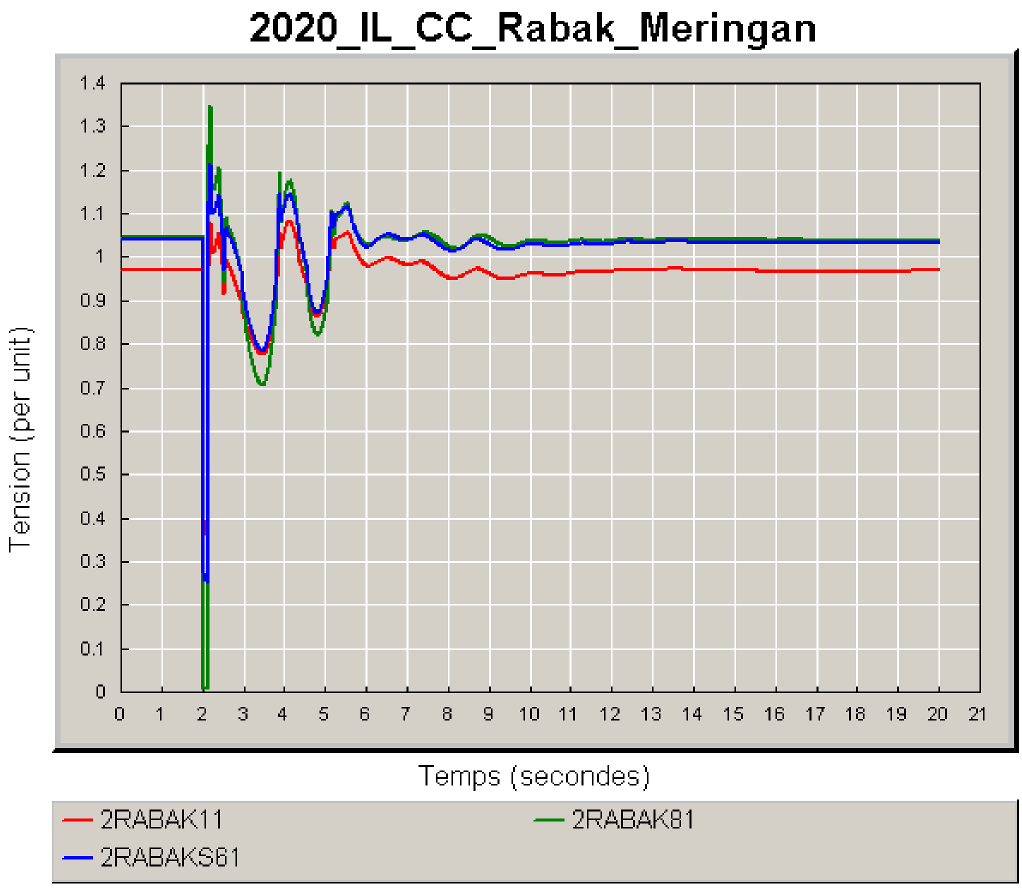


3.11.4 VOLTAGE VARIATION ON THE 500 KV




2020_IL_CC_Rabak_Meringan
Tension (per unit)
1.4
1.3
1.2
1.1
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21
Temps (secondes)
2MERIN81
2RABAK81
1MANDAS71
1MANDAS81
2J.AULIAS81

3.11.5 VOLTAGE VARIATION AT RABAK SUBSTATION



Rabak11 is Kosti unit lternator busbar, in 11 kV.

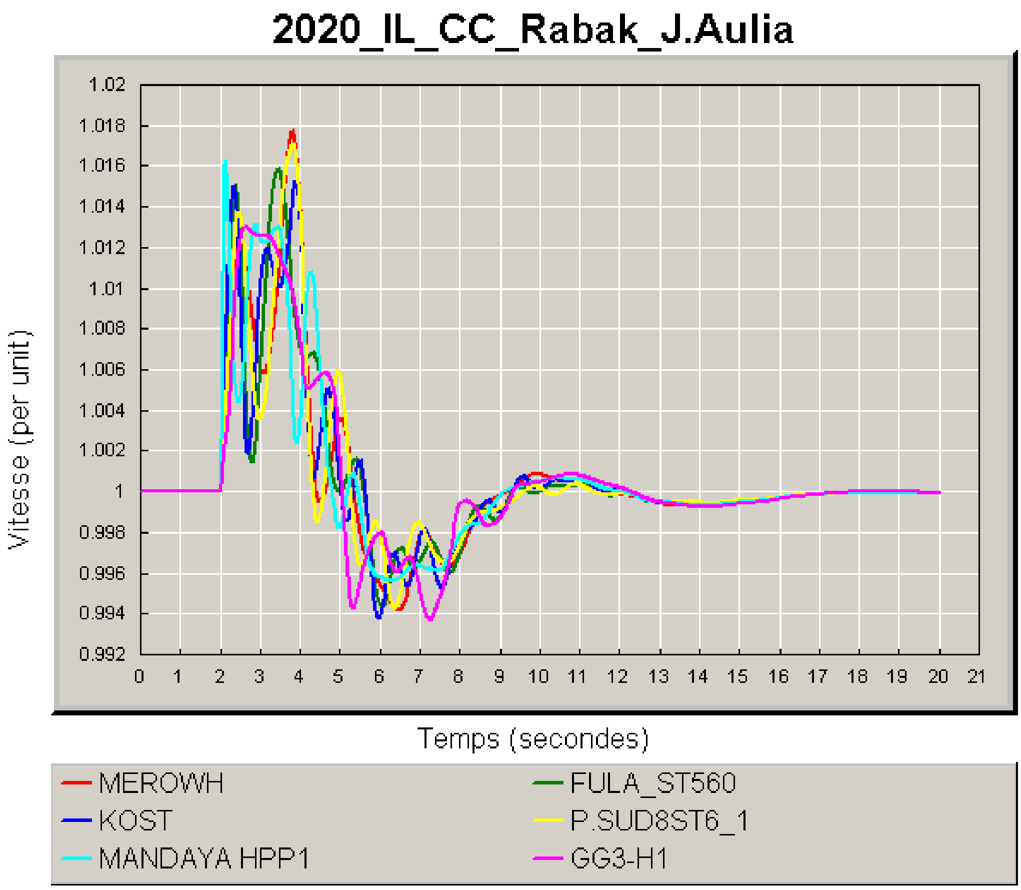
3.12 SHORT-CIRCUIT AT RABAK ON RABAK - JEBEL AULIA

Event : a 3 phase short-circuit at Rabak end, on the circuit Rabak - Jebel Aulia, cleared in 120 ms by the opening of the circuit breakers.

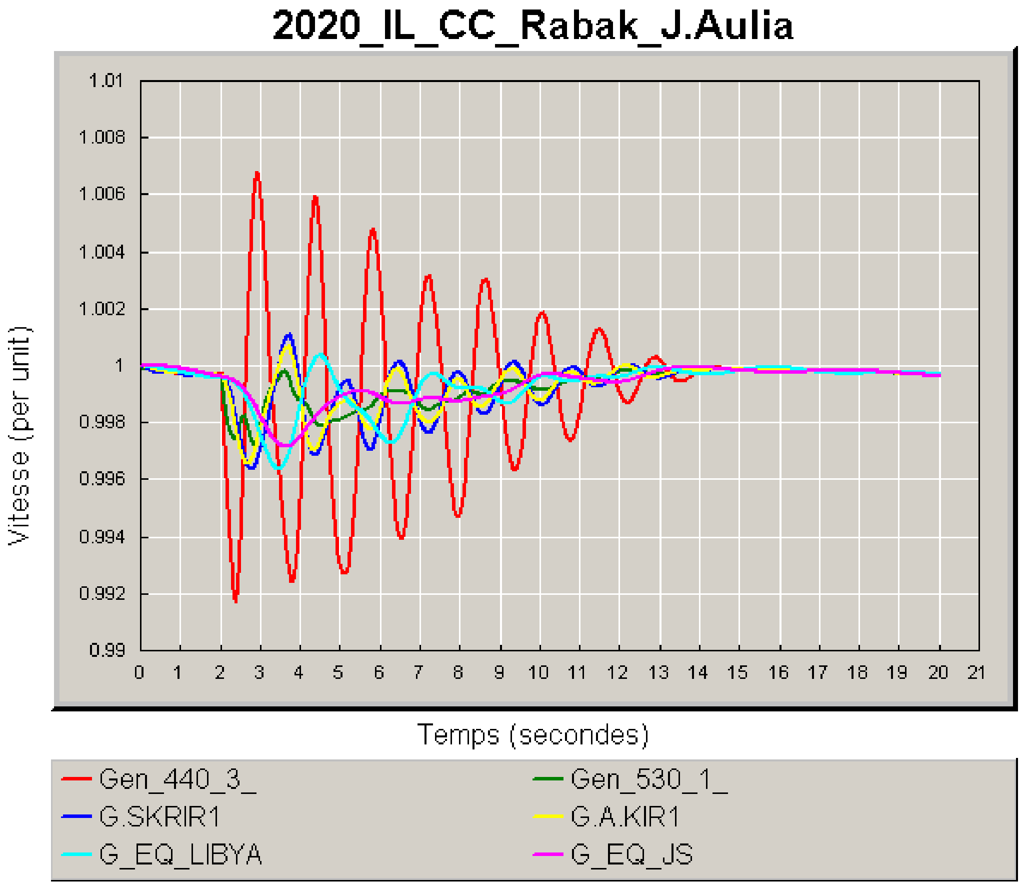
The voltage drop in Rabak (to 0 pu) led to a transitory blocking of commutation of the rectifier station at Rabak. The flow on the DC interconnection is transitory reduced to 0, before recovering to its initial value. During the transitory blocking of the DC stations, the capacitors bank remained connected.

For the Egyptian side, the impact on the system and its behaviour is very similar to the case of SC on Rabak - Fula

3.12.1 GENERATORS FREQUENCY VARIATION



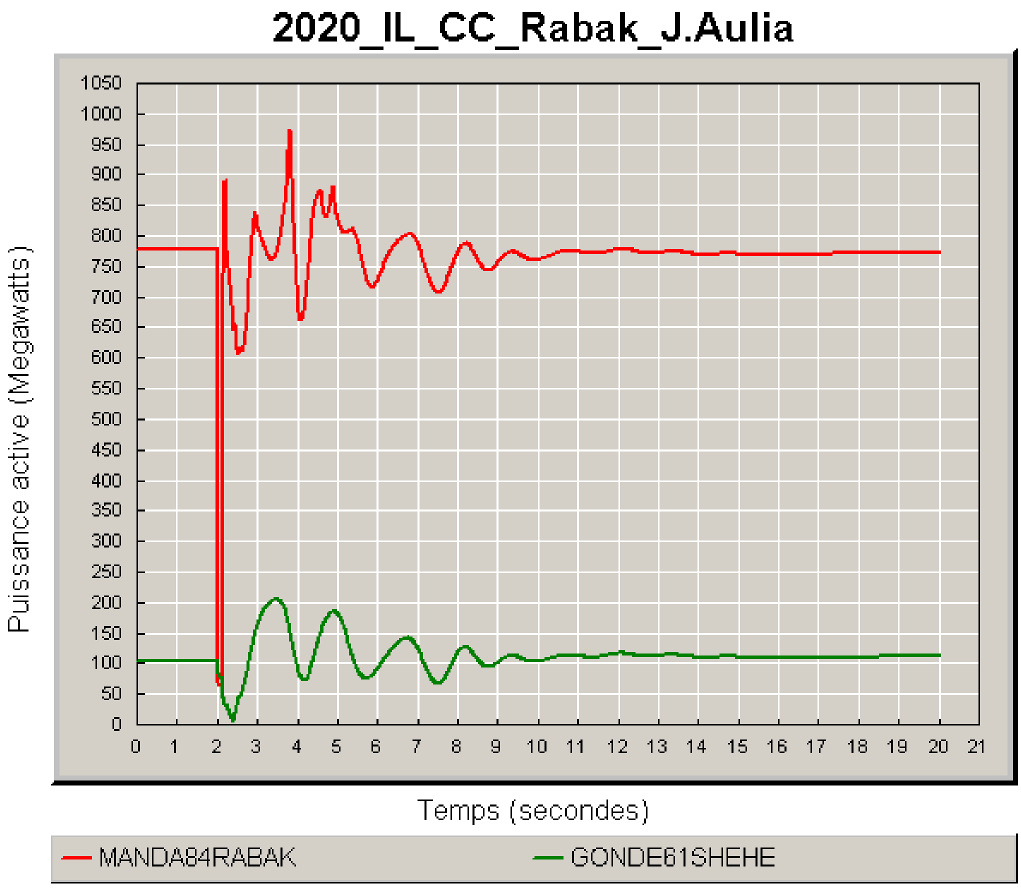
GG3 is Gibe III



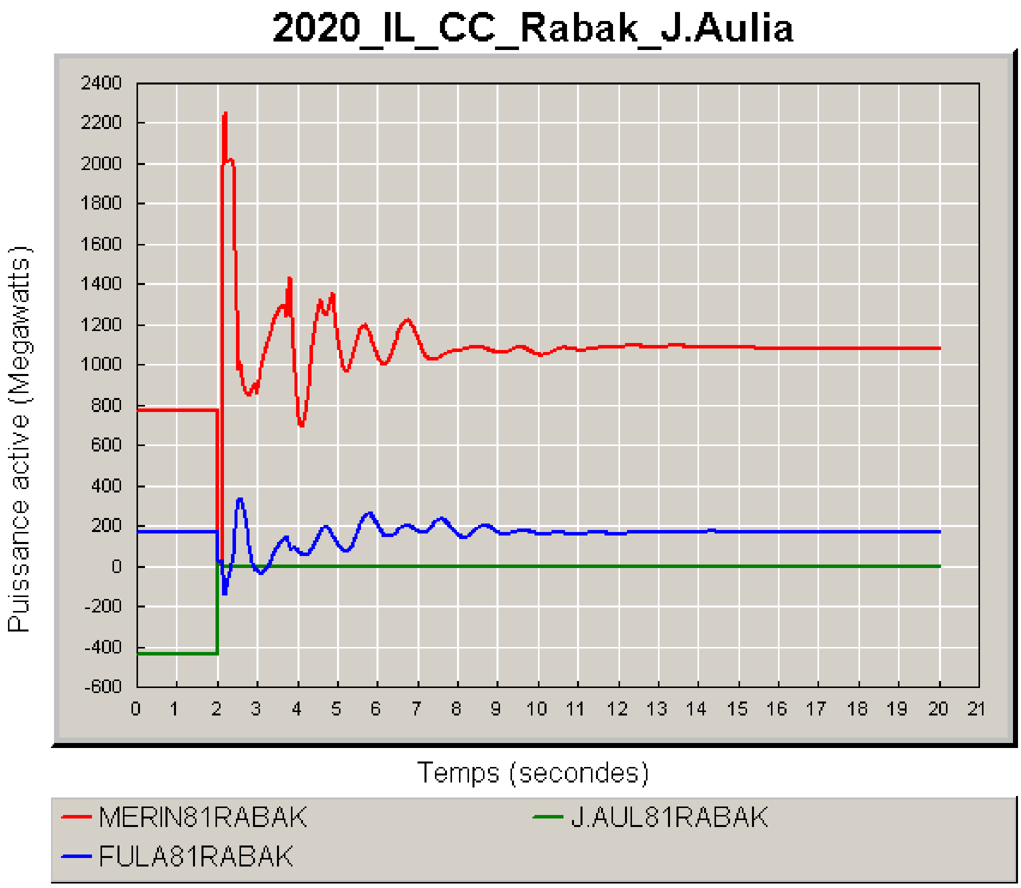
Gen_440_3 is a group of High Dam

Gen_530_1 is the existing steam turbine in Kurimat

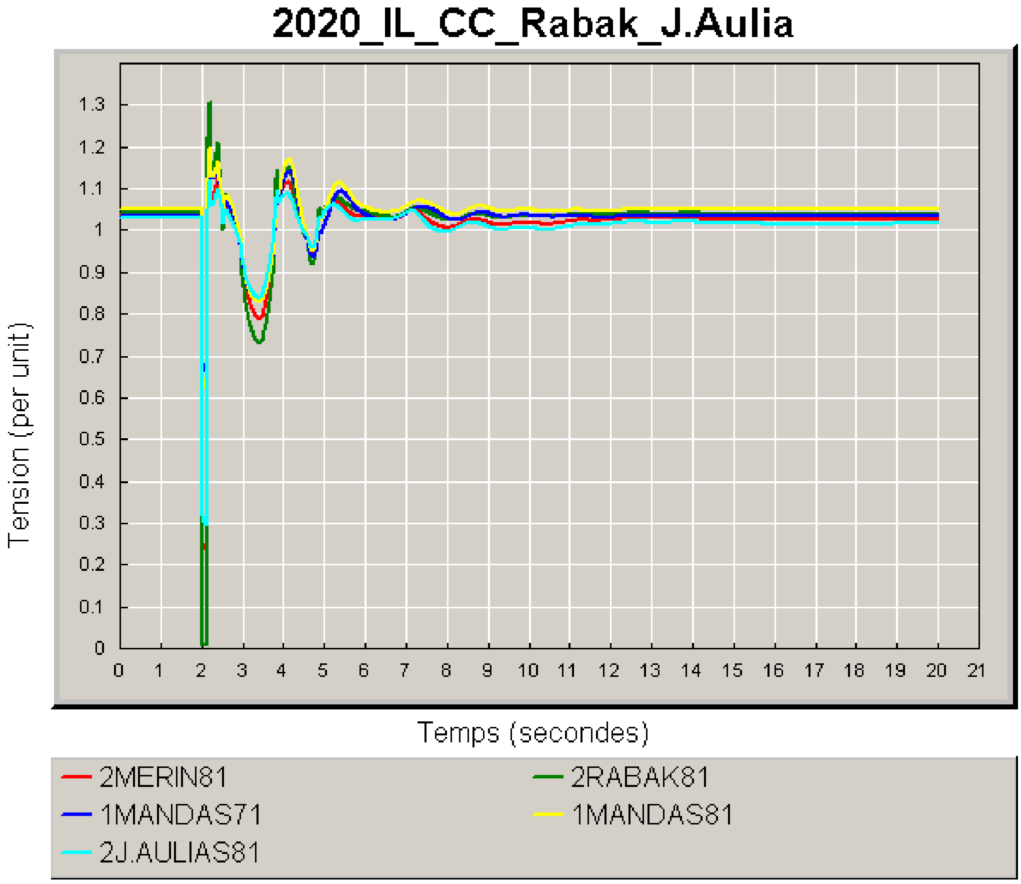
3.12.2 POWER FLOW VARIATION ON ENTRO INTERCONNECTION

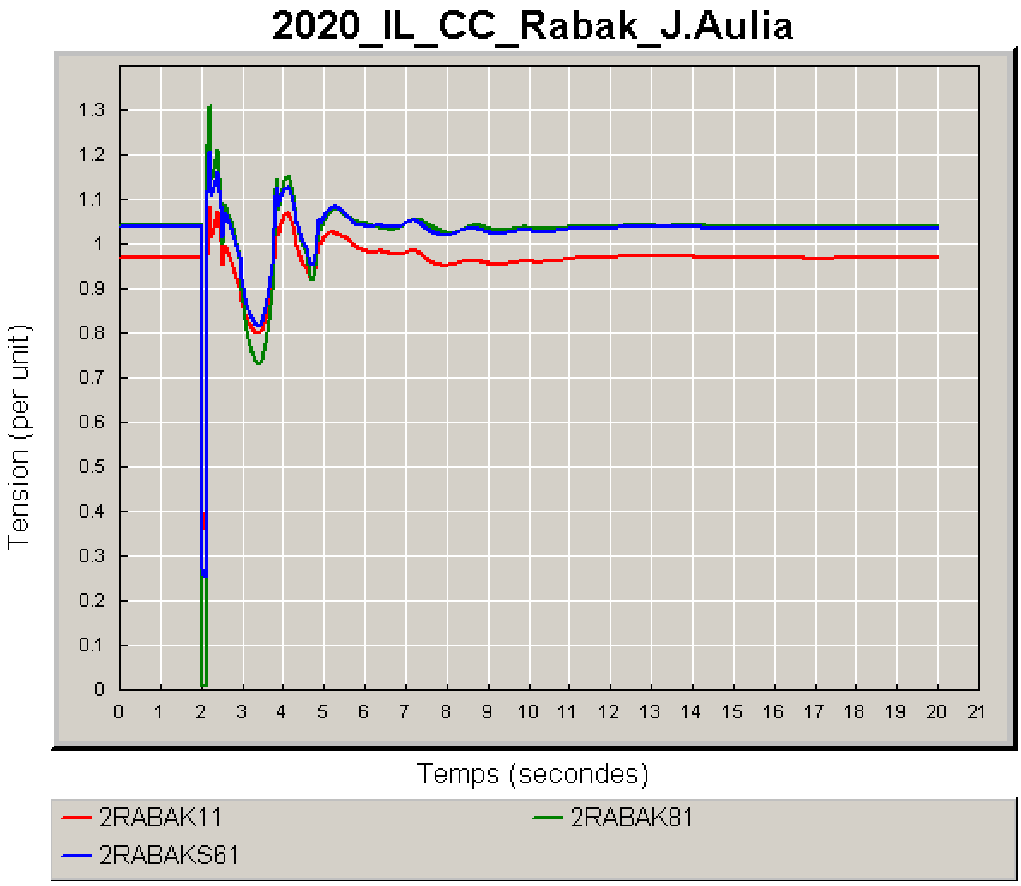


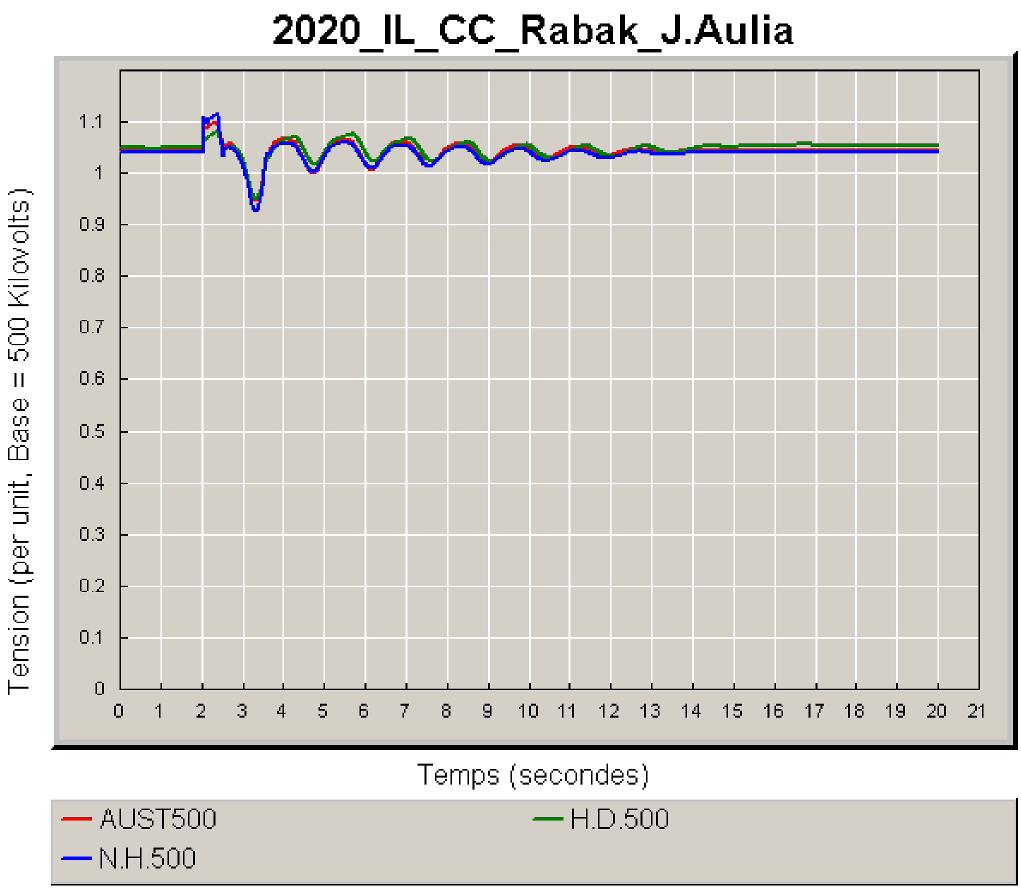
3.12.3 POWER FLOW VARIATION ON RABAK - JEBEL AULIA AND RABAK - MERINGAN



3.12.4 VOLTAGE VARIATION ON THE 500 KV



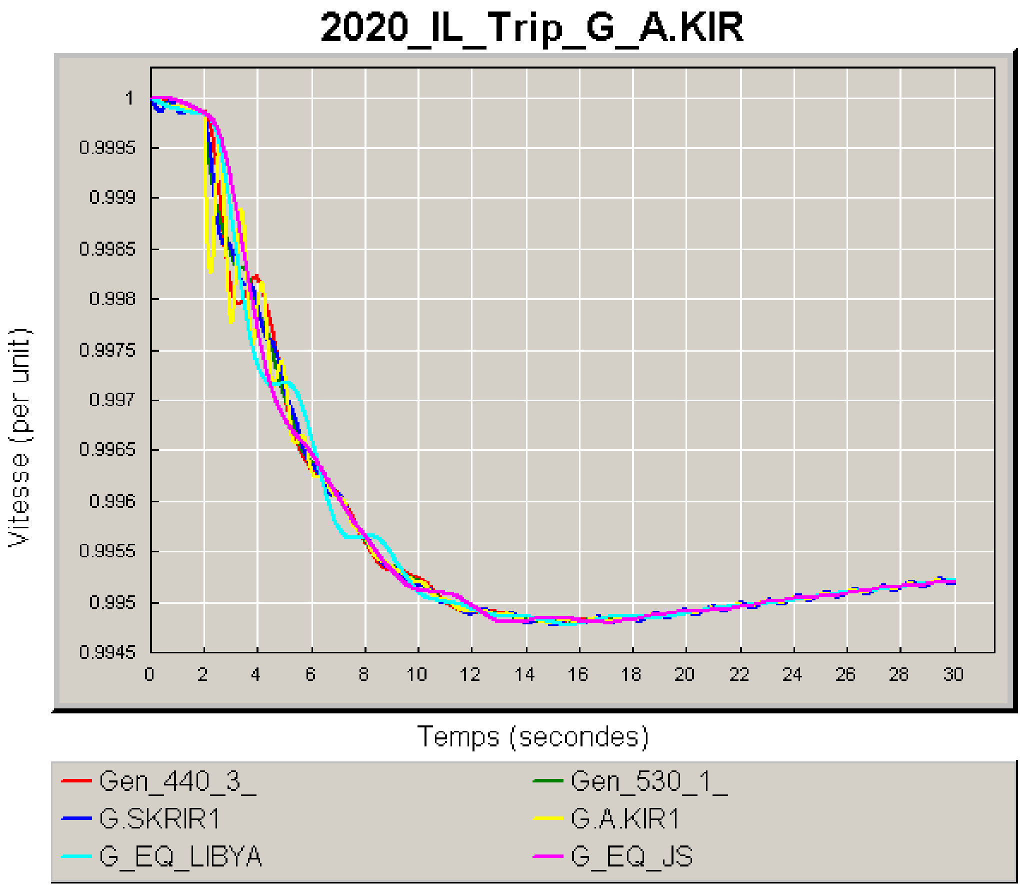

2020_IL_CC_Rabak_J.Aulia
Tension (per unit)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
1.2
1.3
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
Temps (secondes)
2RABAK11
2RABAK81
2RABAKS61


2020_IL_CC_Rabak_J.Aulia
Tension (per unit, Base = 500 Kilovolts)
1.1
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21
Temps (secondes)
AUST500
H.D.500
N.H.500

3.13 TRIPPING OF THE MAIN UNIT IN EGYPT : ABU KIR 650 MW STEAM TURBINE

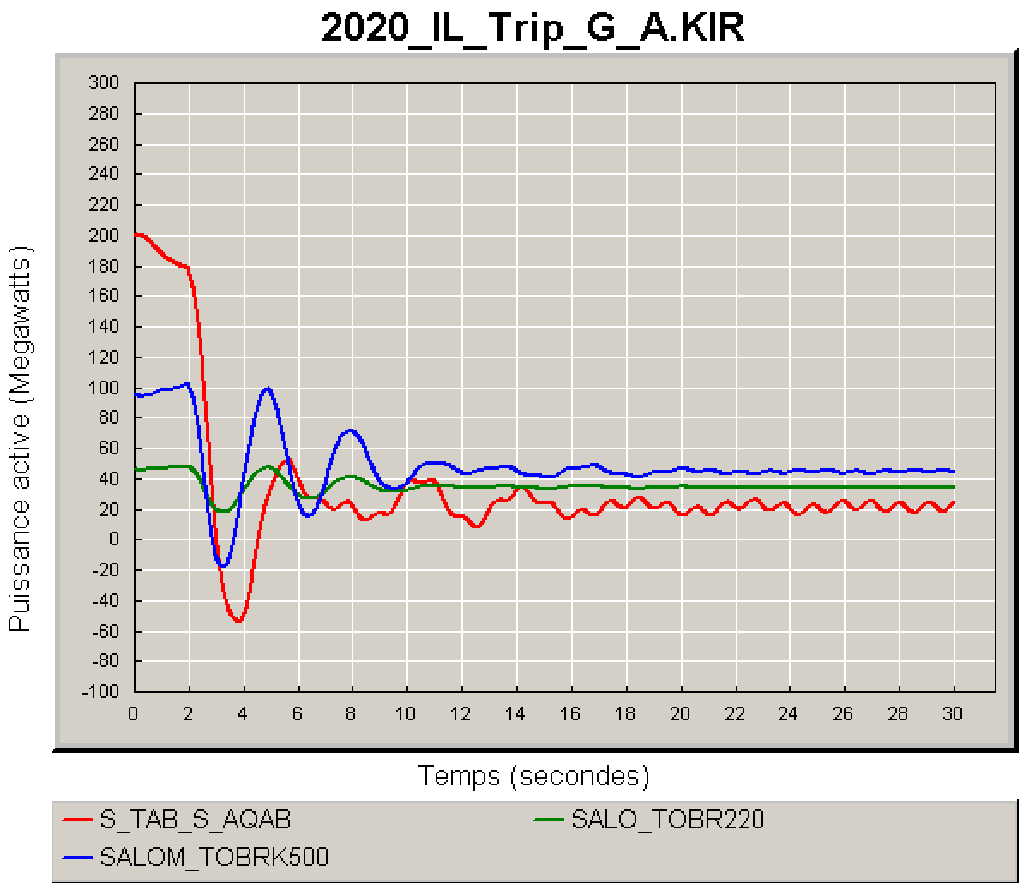
The Ethipian and Sudanese system are not affected.

3.13.1 GENERATORS FREQUENCY VARIATION

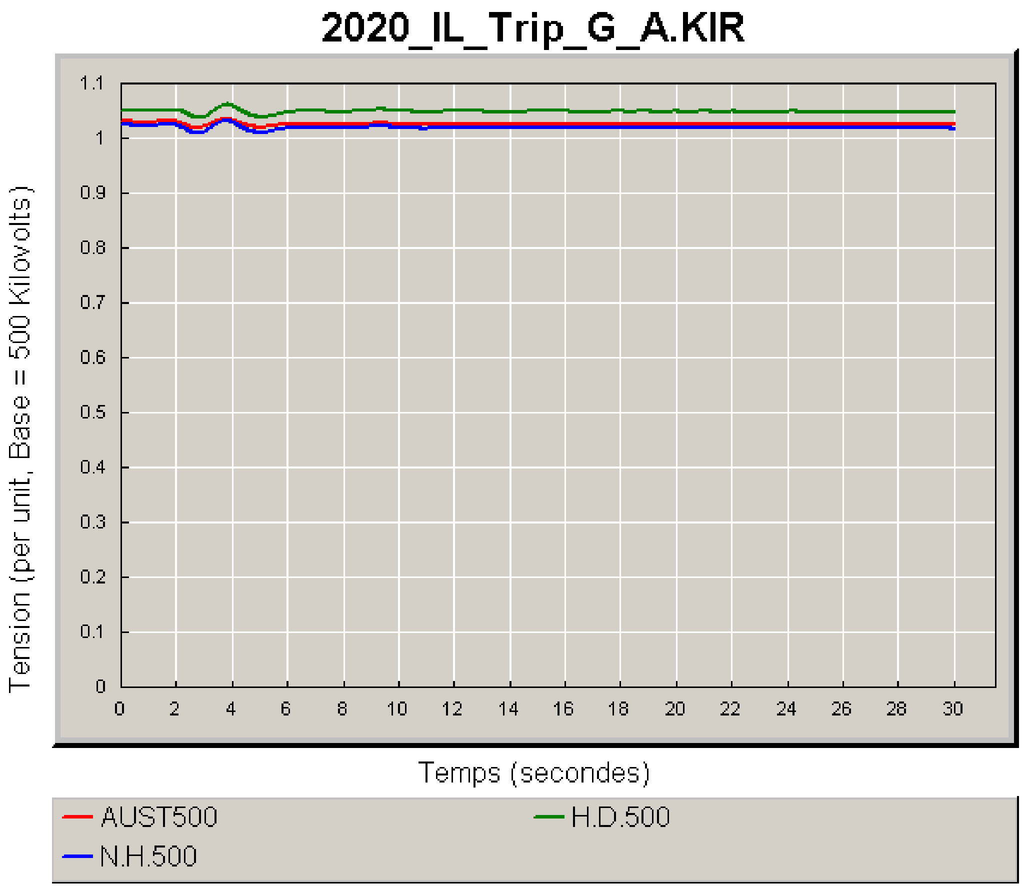


Gen_441_1 is a group of High Dam
Gen_530_1 is group 1 of Kurimat existing steam

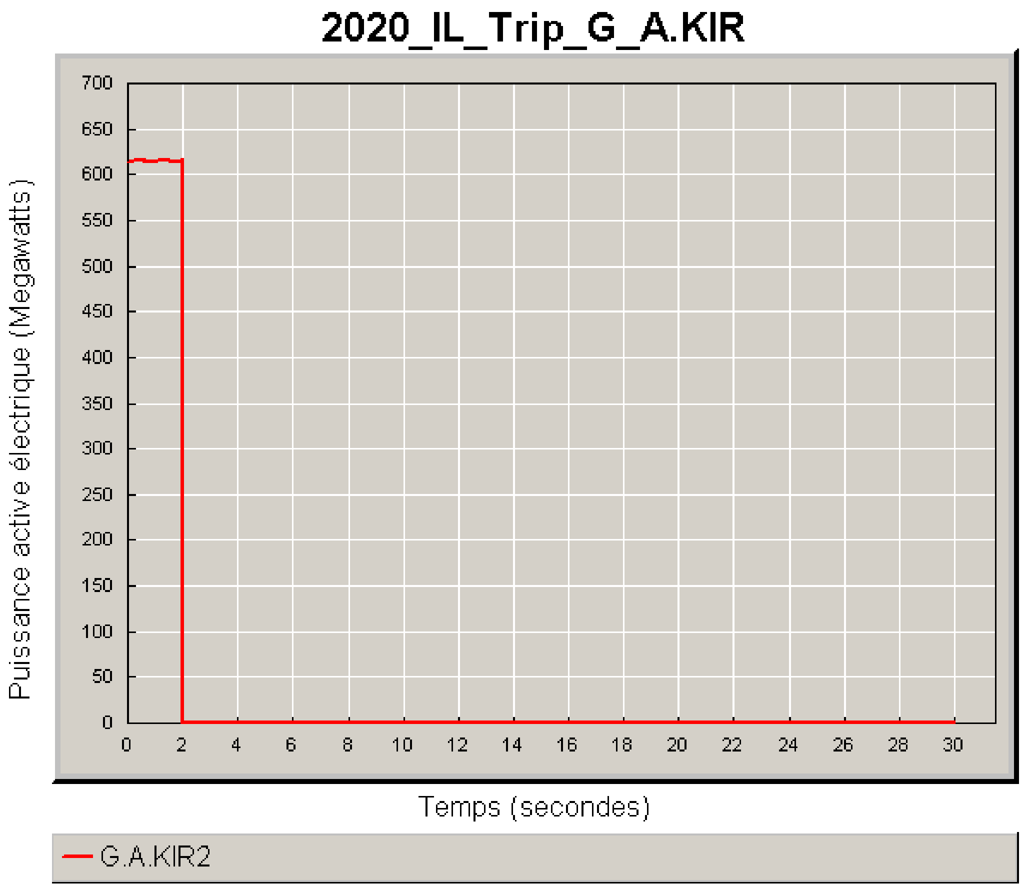
3.13.2 POWER FLOW VARIATION ON EGYPT - LIBYA AND EGYPT - JORDAN INTERCONNECTION



3.13.3 VOLTAGE VARIATION



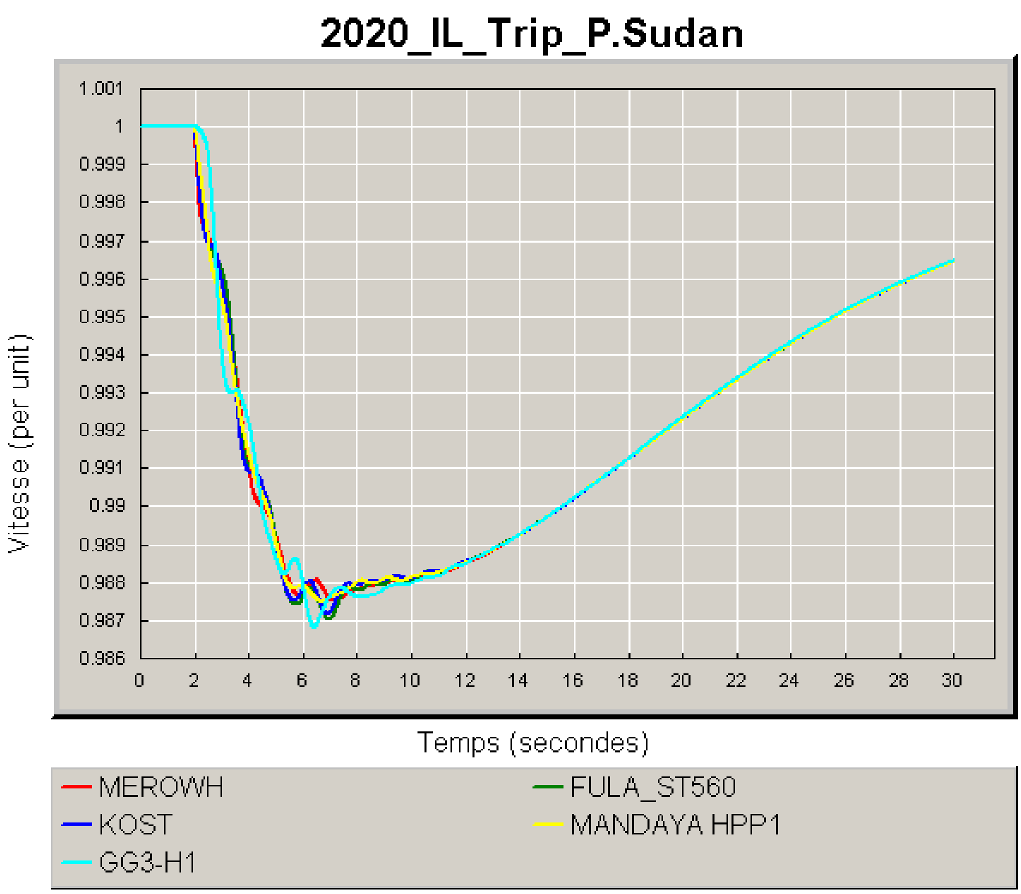
3.13.4 OUTPUT VARIATION OF ABU KIR ST



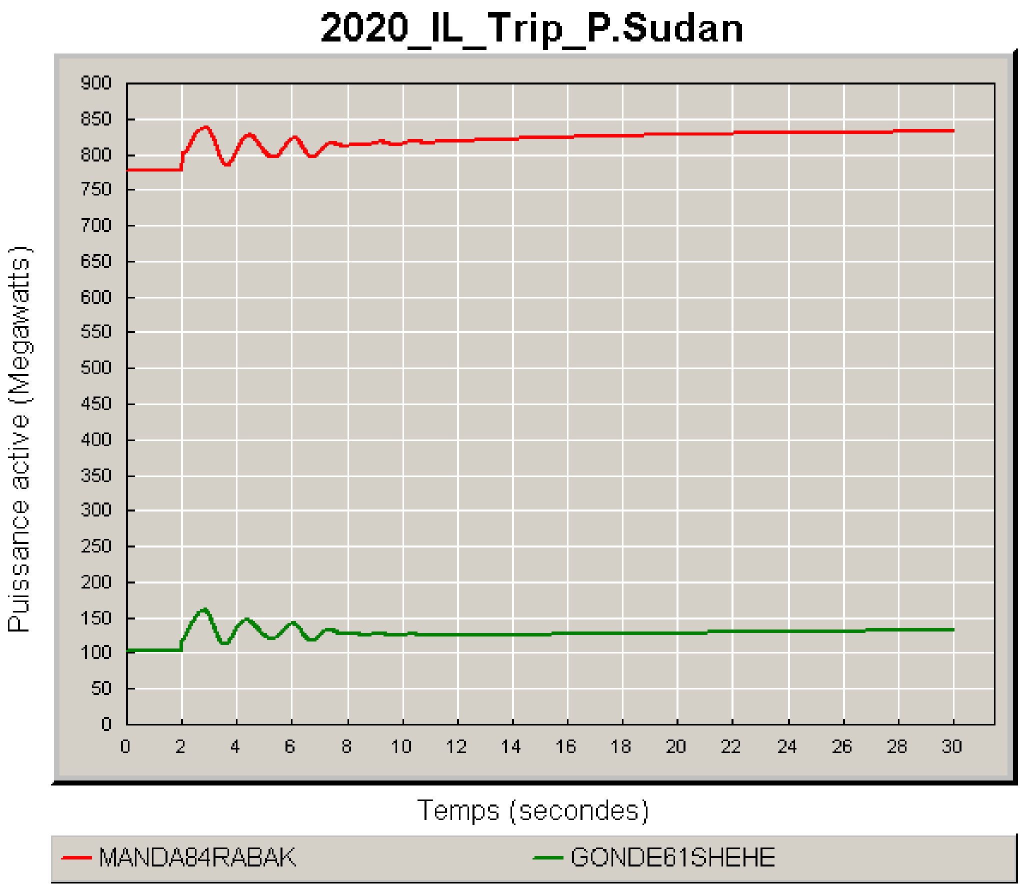
3.14 TRIPPING OF THE MAIN UNIT IN SUDAN : PORT SUDAN 530 MW STEAM TURBINE

Event : the 670 MVA steam unit of Port-Sudan (the main unit in Sudan) is tripped.

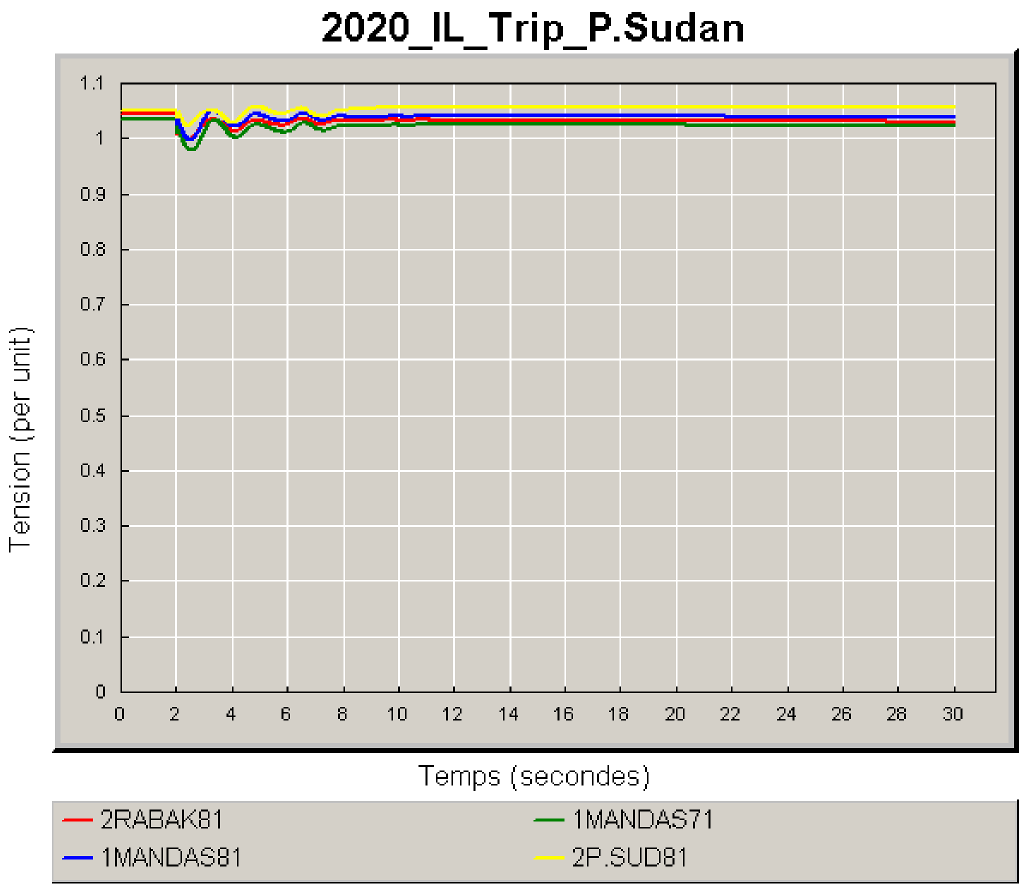
3.14.1 GENERATORS FREQUENCY VARIATION



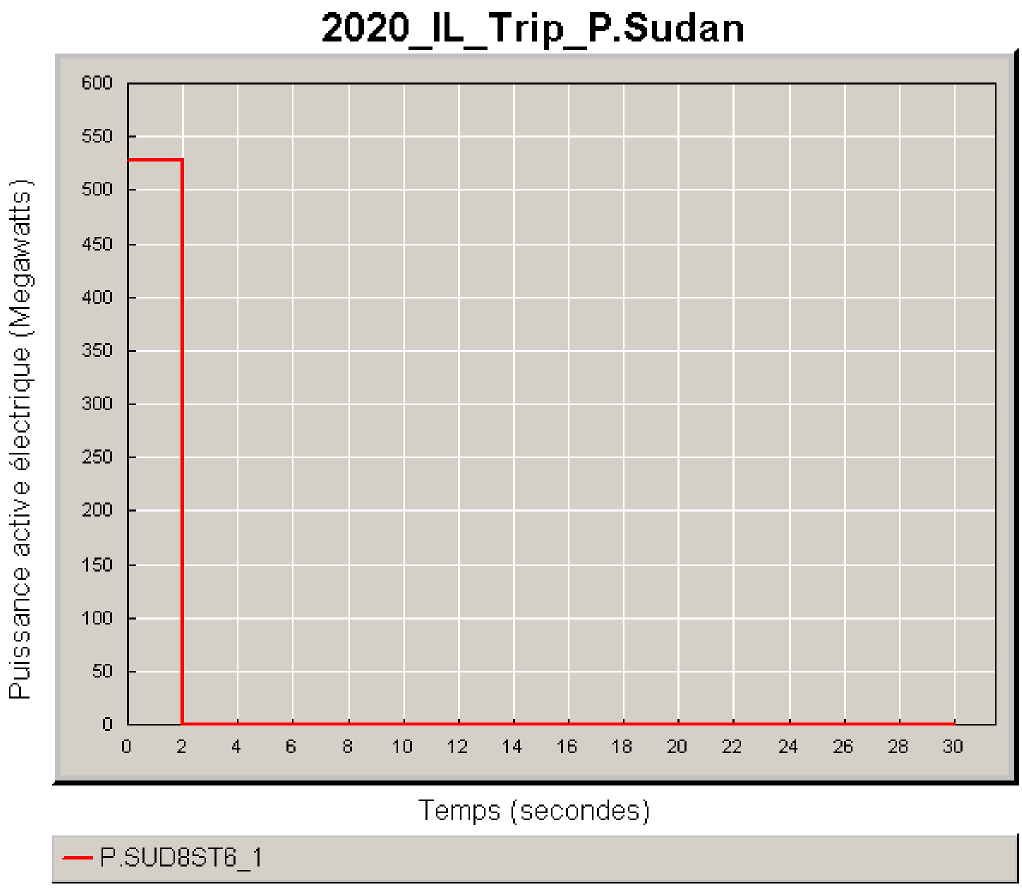
3.14.2 POWER FLOW VARIATION ON ENTRO INTERCONNECTION



3.14.3 VOLTAGE VARIATION

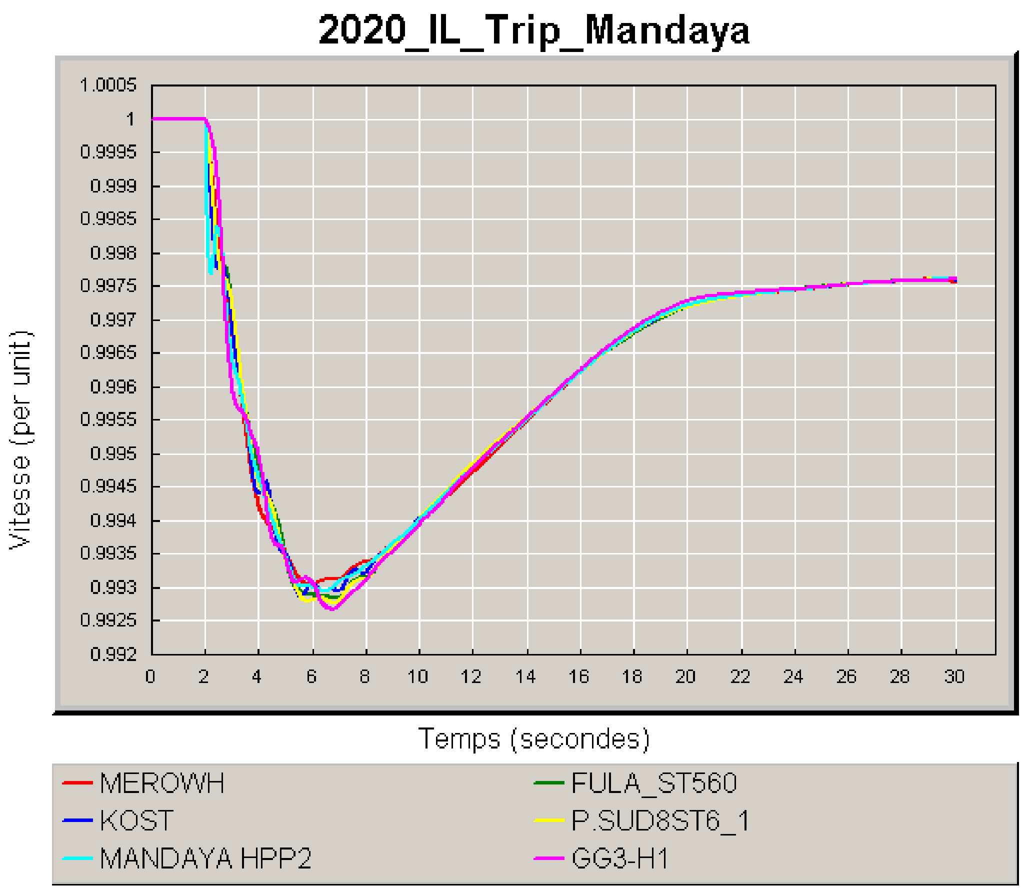


3.14.4 OUTPUT VARIATION FOR SOME GENERATION UNITS



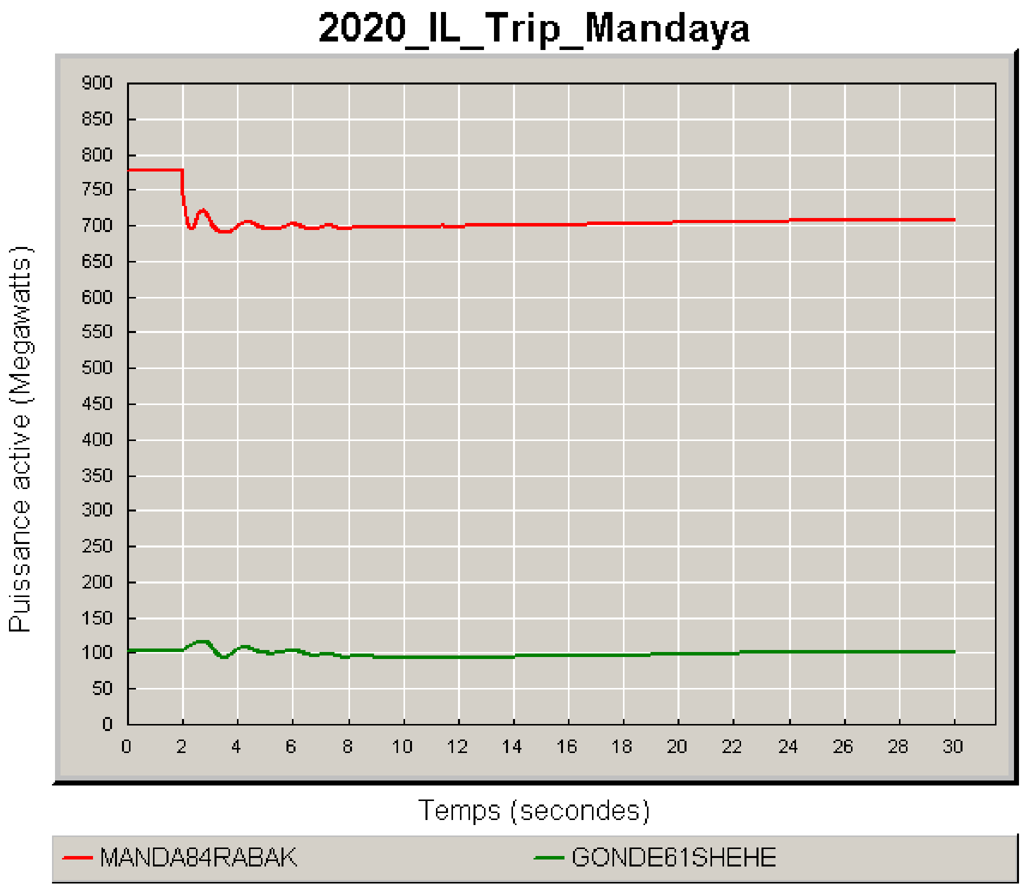
3.15 TRIPPING OF THE MAIN 2 UNITS IN ETHIOPIA : 2 UNITS OF 212.5 MW IN MANDAYA

3.15.1 GENERATORS FREQUENCY VARIATION

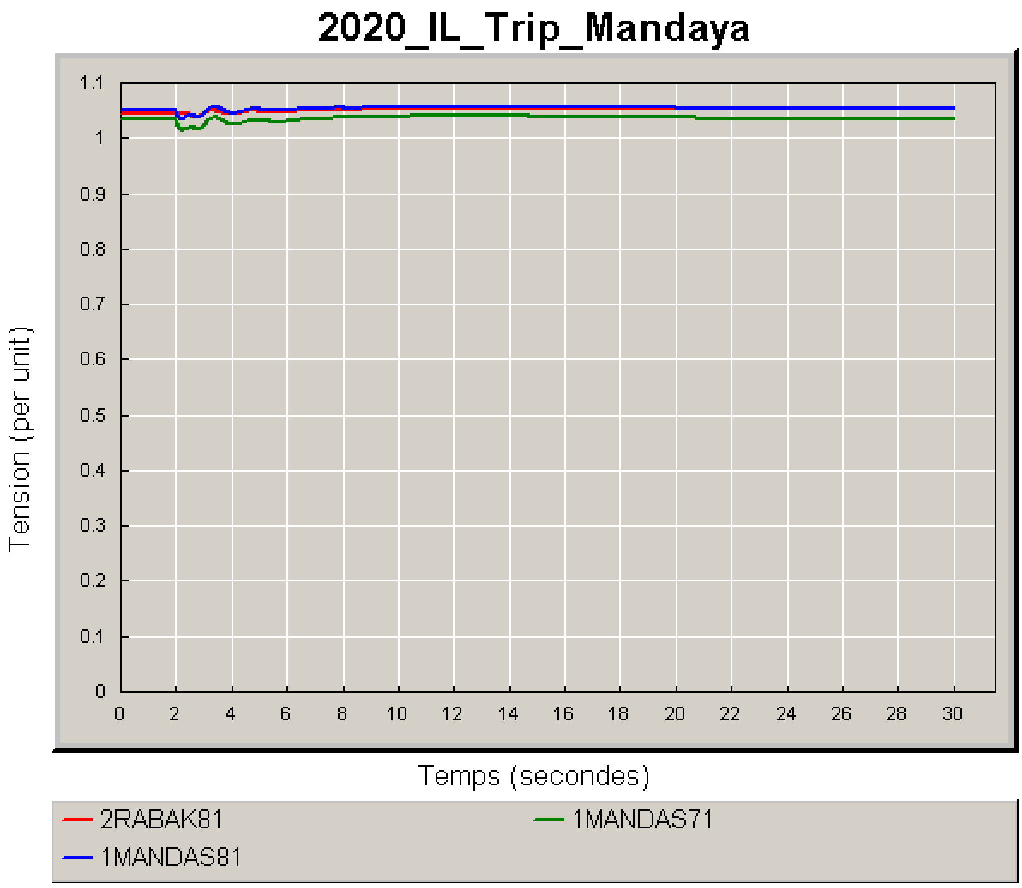


GG3 is Gibe III

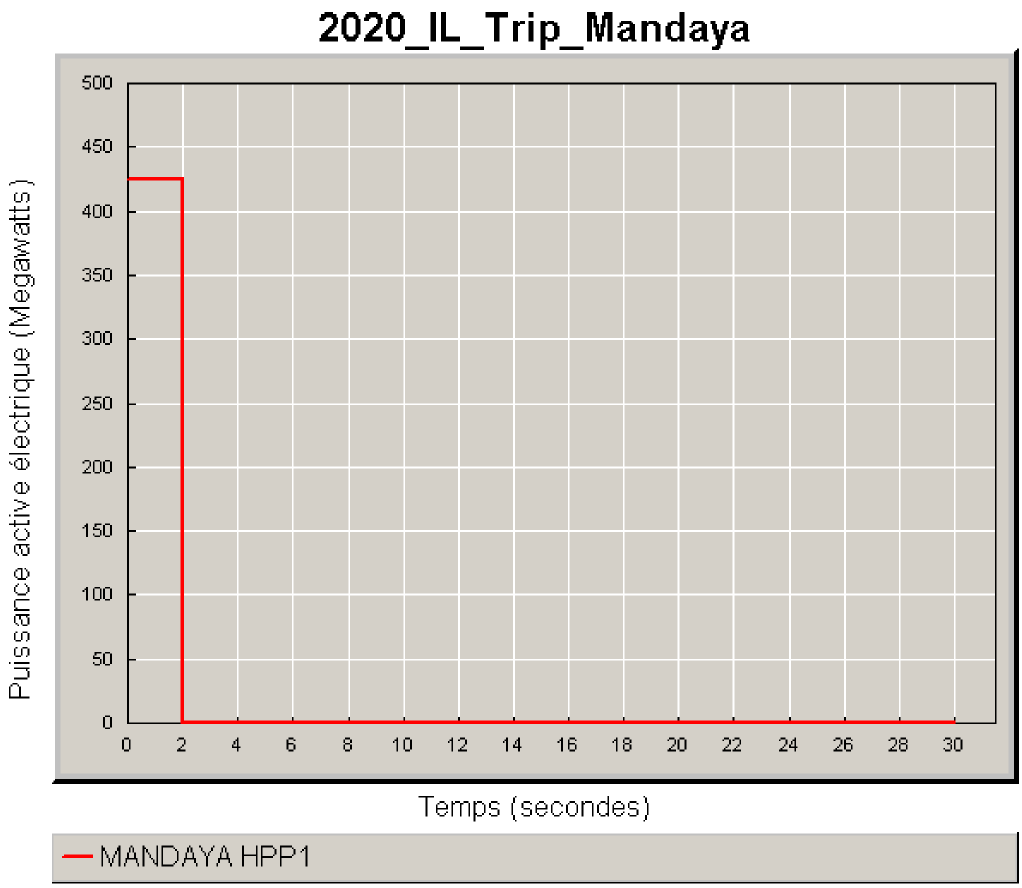
3.15.2 POWER FLOW VARIATION ON ENTRO INTERCONNECTION



3.15.3 VOLTAGE VARIATION

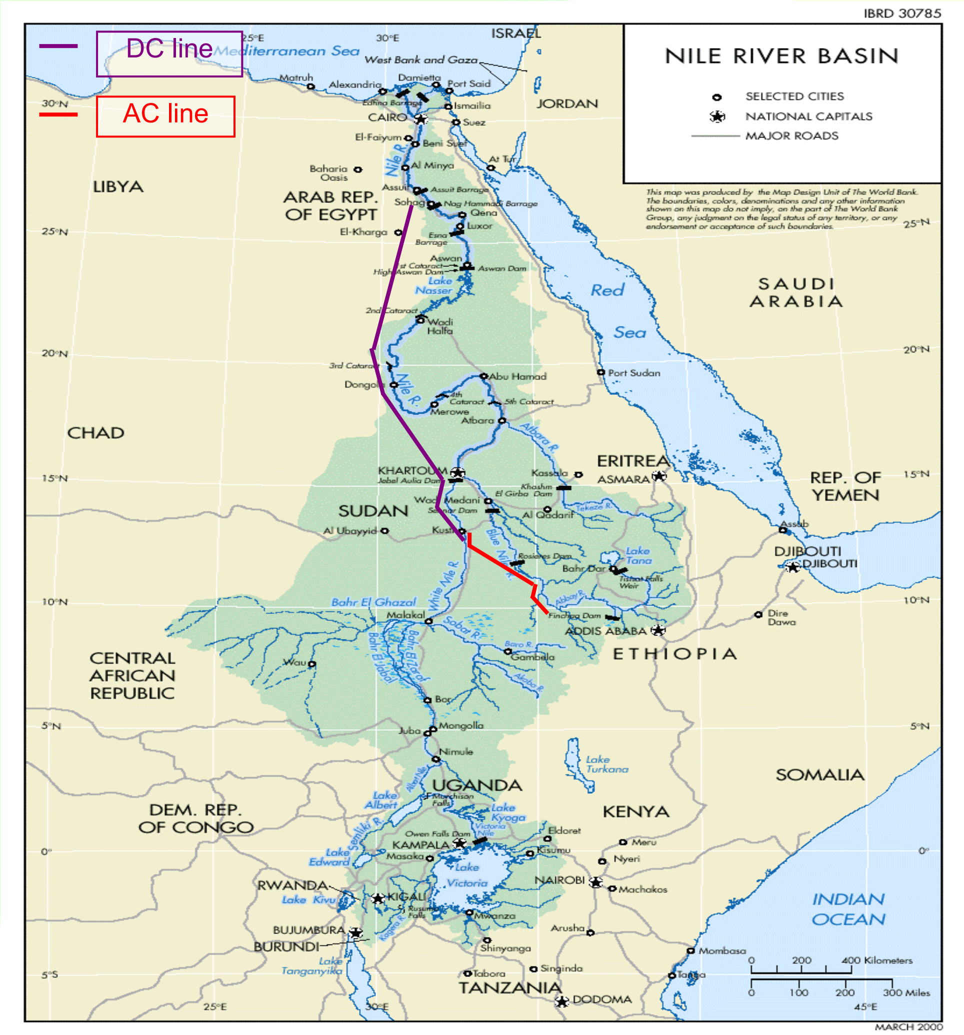


3.15.4 OUTPUT VARIATION FOR SOME GENERATION UNITS



Nile Basin Initiative
Eastern Nile Subsidiary Action Program
Eastern Nile Technical Regional Office

EASTERN NILE POWER TRADE PROGRAM STUDY



M1 - 2025 APPENDIX - STABILITY STUDY

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ABBREVIATIONS AND ACRONYMS

AC	Alternative Current
CCG	Combined Cycle Gas turbine
DC	Direct Current
ENPTPS	Eastern Nile Power Trade Program Study
EDF	Electricité de France
EN	Eastern Nile
ENTRO	Eastern Nile Technical Regional Office
GEP	Generation Expansion Plan
HPP	Hydro Power Plant
HD	High Dam
HV	High Voltage
HVDC	High Voltage Direct Current
NBI	Nile Basin Initiative
NH	Nag Hammadi
OHL	Over Head Line
p.u	Per Unit
SC	Short Circuit
ST	Steam Turbine
SVC	Static Voltage Compensator
SW	Scott Wilson
TPP	Thermal Power Plant

Note : Kosti / Rabak

The location of the HVDC converter station Sudan was modified during the Line Routing study.

Initially located at Rabak (East side of the Nile) in Phase I, the line routing study during Phase II located the interconnection substation in Sudan on the West side of the Nile river at Kosti.

The name used in the simulation was Rabak.

1 TRANSIENT STABILITY ANALYSIS HYPOTHESIS

The volume of spinning reserve was set as followed :

- Libya : 50 MW
- Jordan and Syria : 100 MW
- Egypt : 380 MW (104 MW on hydropower plants + 275 MW on thermal plants)
- Sudan : 350 MW
- Ethiopia : 390 MW (hydropower plant only)

In Egypt, the spinning reserve was sized to avoid the activation of the first step of the automatic under frequency load shedding scheme and to recover an acceptable frequency (49.8Hz) following the tripping of one pole of the DC link.

Load voltage and frequency dependency coefficients

	dP/dV	dP/df	dQ/dV	dQ/df
Egypt	0.83	1.46	4.01	-0.88
Ethiopia	0.94	1.26	3.67	-1.29
Sudan	0.79	1.53	4.14	-0.72

Table 1. Load voltage and frequency dependency coefficients

Load demand of Libya, Jordan and Syria

The 2025 peak load demand for Libya reached 9 480 MW.

The 2025 peak load demand for Jordan and Syria reached 21 080 MW.

Calculation of the damping magnitude of the power oscillations

The power oscillations evolve according to the formula :

$$A.e^{-\alpha t}.\cos(\omega t+\varphi) \quad \text{with } \omega=2\pi f_x$$

From the curves it is possible to measure the frequency, f_x of the oscillations. (generally a low value close to 0.3Hz or 0.5Hz)

The apparent damping coefficient D of the oscillation mode is equal to :

$$D=\frac{\alpha}{\sqrt{(\alpha^2+\beta^2)}} \quad \text{with } \beta = 2\pi f$$

and α is like that $e^{-\alpha t}=0.05$ with t is the damping duration.

The international literature concerning the inter-area oscillations, indicates that an inter-area oscillation mode is acceptably damped if the damping coefficient is close to 5% and it is well damped if the damping coefficient is higher than 5%.

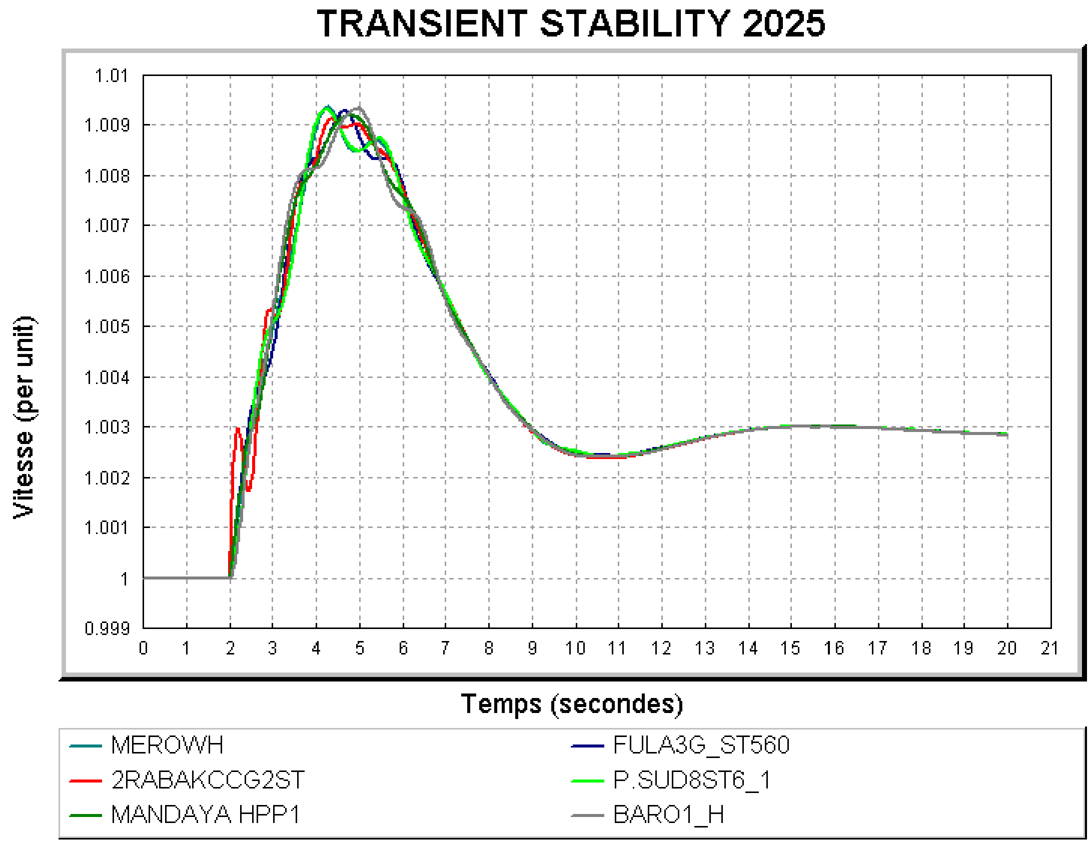
According to the above formula, the apparent damping coefficient for the average frequency was estimated from the curves and the results.

2 RESULTS OF SIMULATIONS FOR 2025 PEAK LOAD PERIOD

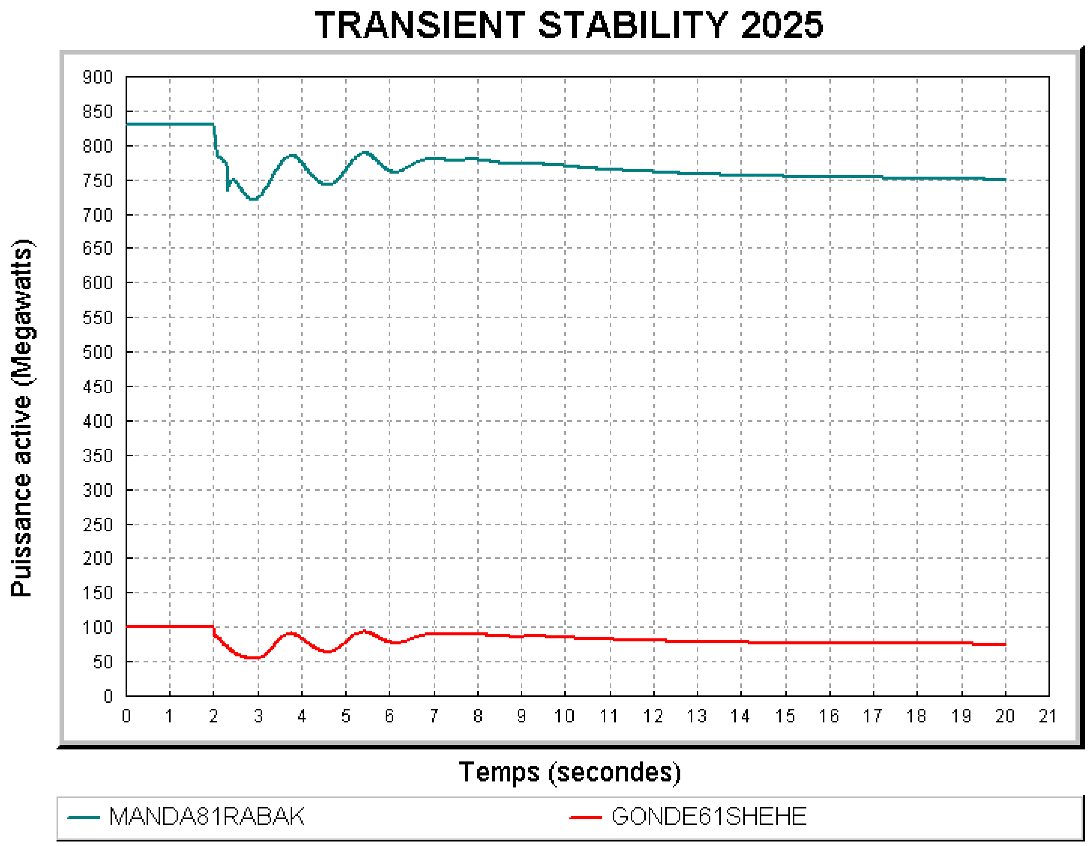
2.1 TRIPPING OF ONE OF THE 2 POLES OF THE DC INTERCONECTION AT KOSTI

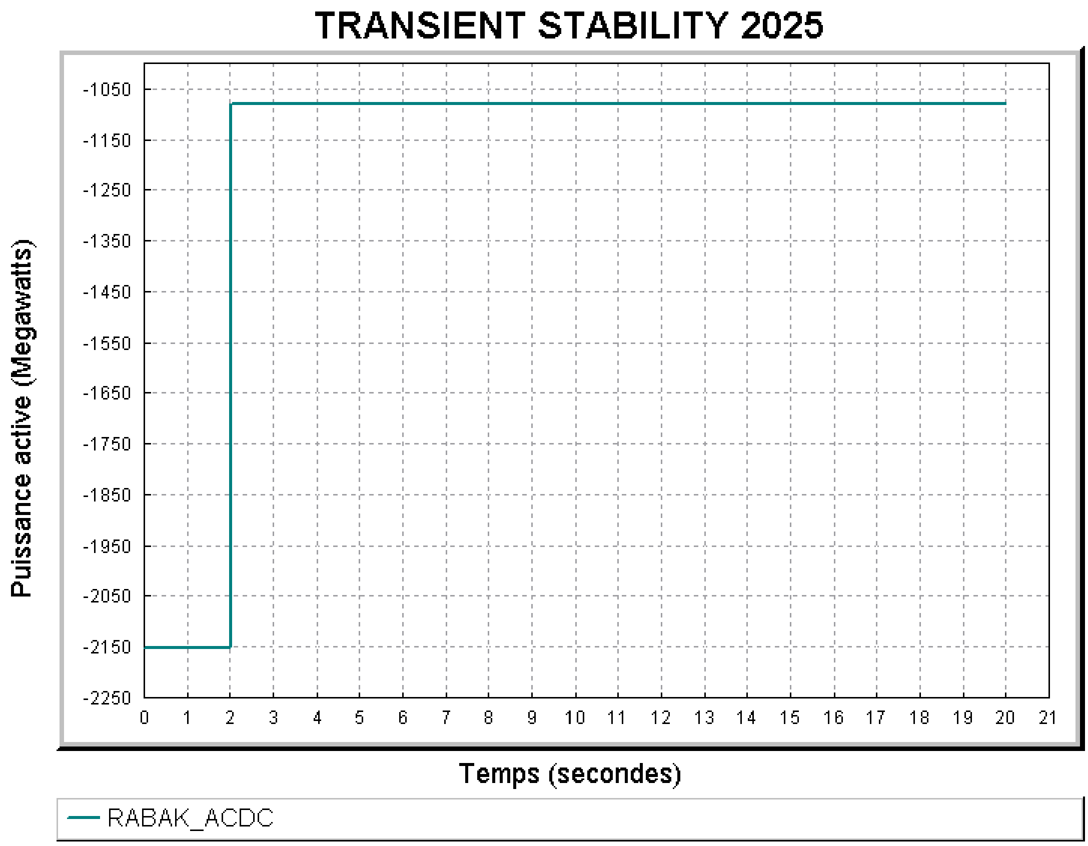
Event : one of the 2 poles was tripped following an internal fault. 300 ms after, half of the capacitor banks of the filters was disconnected at Kosti terminal.

2.1.1 GENERATOR FREQUENCY VARIATION

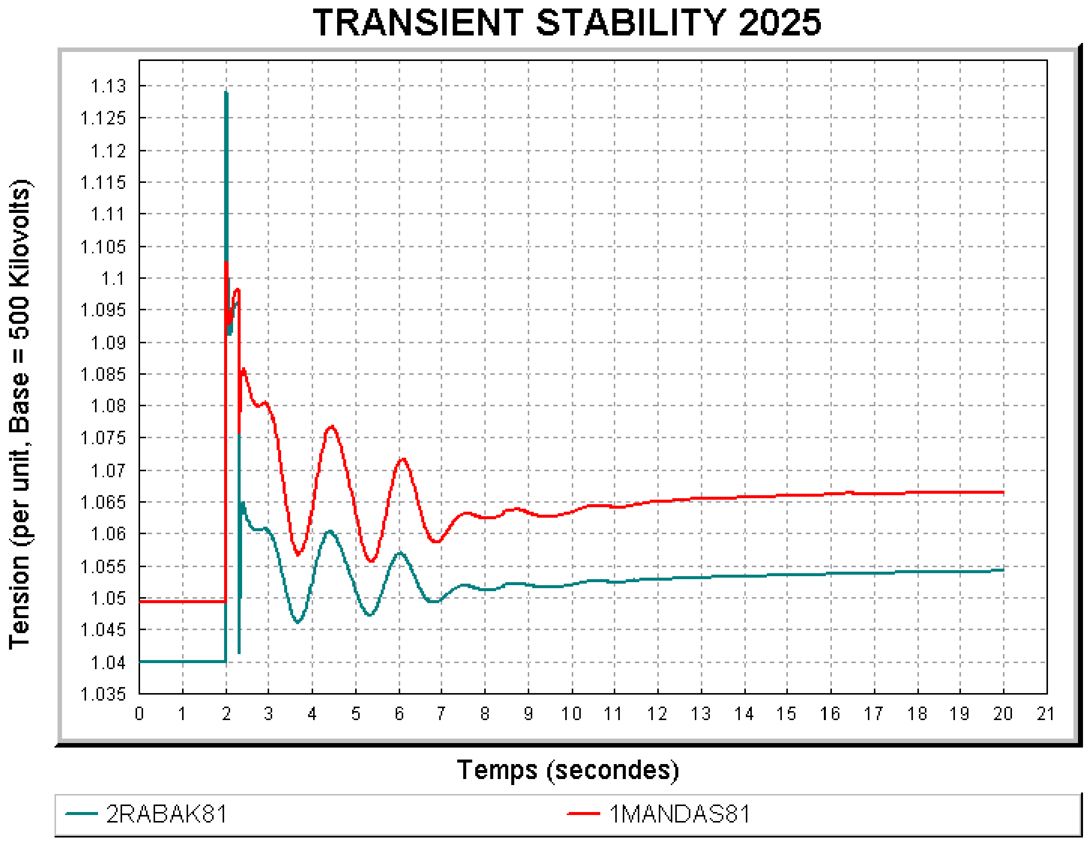


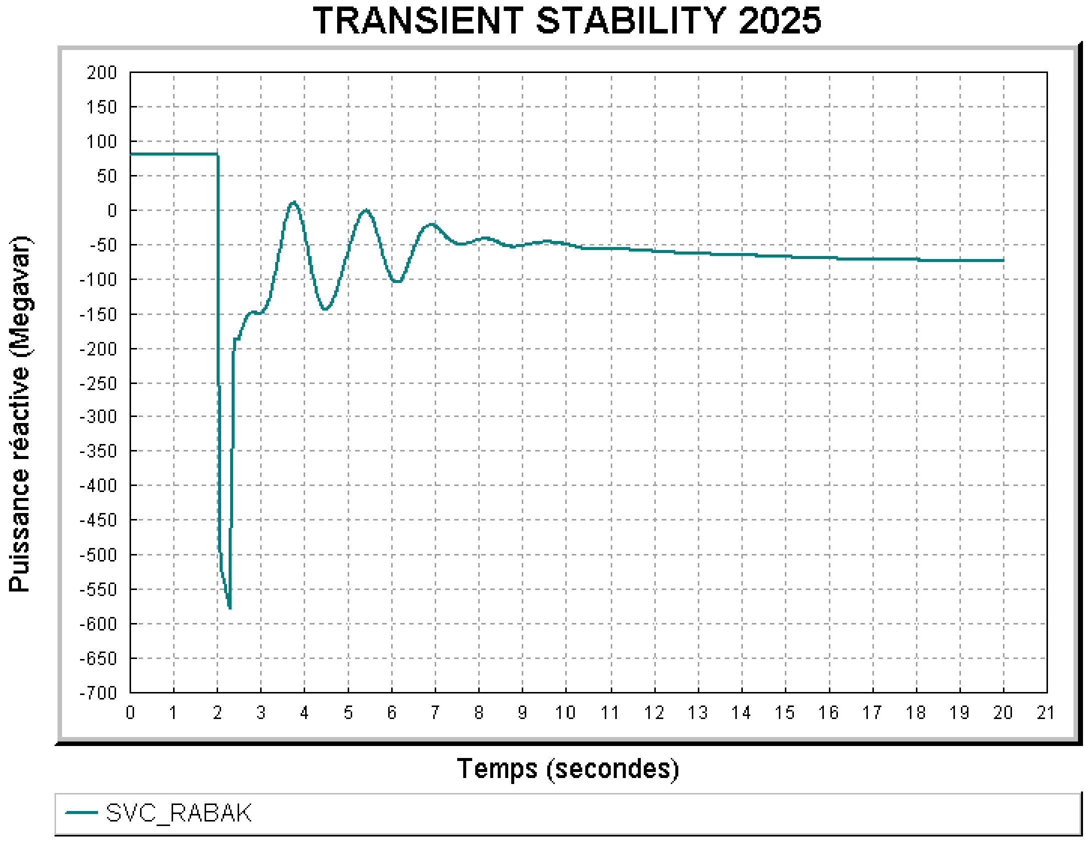
2.1.2 POWER FLOW VARIATION ON ENTRO INTERCONNECTION




TRANSIENT STABILITY 2025
Puissance active (Megawatts)
-1050
-1150
-1250
-1350
-1450
-1550
-1650
-1750
-1850
-1950
-2050
-2150
-2250
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21
Temps (secondes)
RABAK_ACDC

2.1.3 VOLTAGE VARIATION ON THE 500 KV

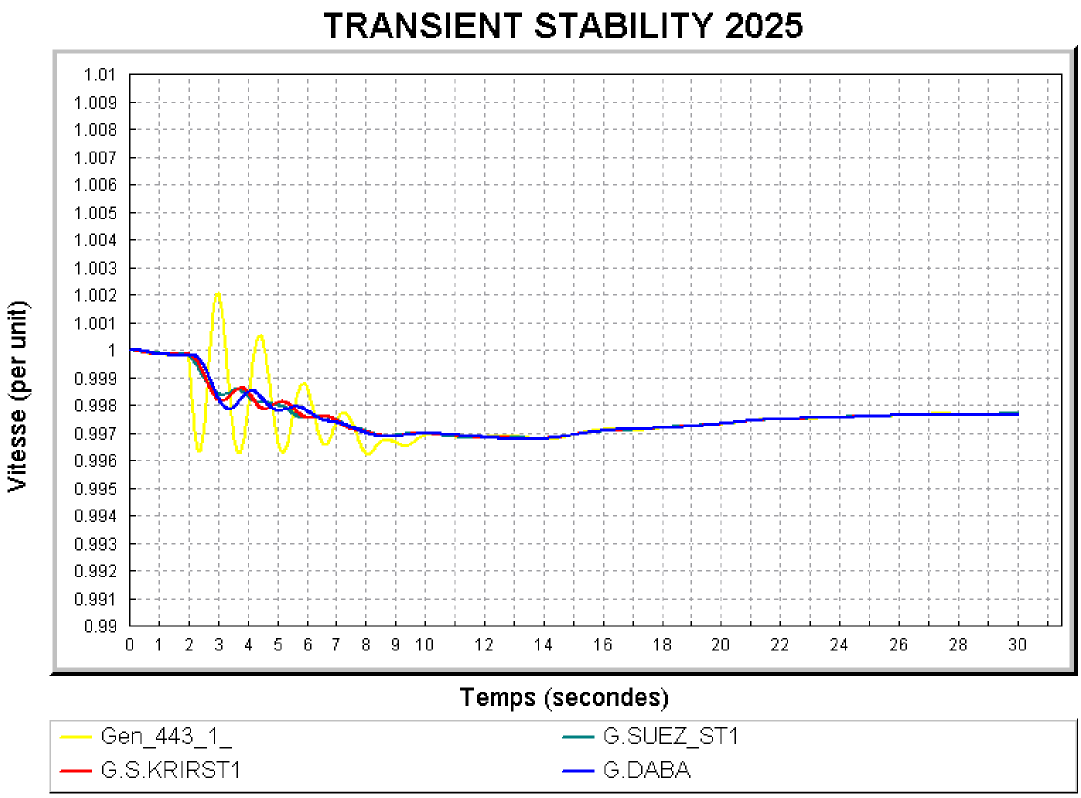



TRANSIENT STABILITY 2025
200
150
100
50
0
-50
-100
-150
-200
-250
-300
-350
-400
-450
-500
-550
-600
-650
-700
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21
Puissance réactive (Megavar)
Temps (secondes)
SVC_RABAK

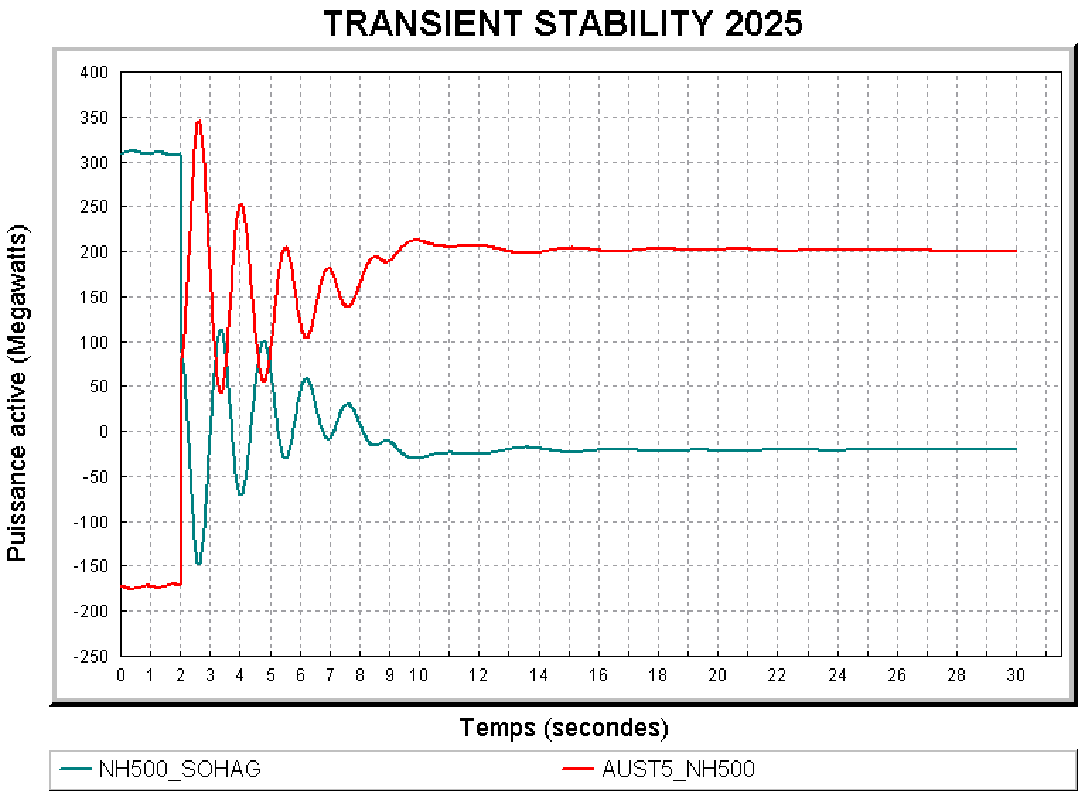
2.2 TRIPPING OF ONE OF THE 2 POLES OF THE DC INTERCONECTION AT NAG HAMMADI

Event : one of the 2 poles was tripped following an internal fault. 300 ms after, half of the capacitor banks of the filters was disconnected at Nag Hammadi terminal.

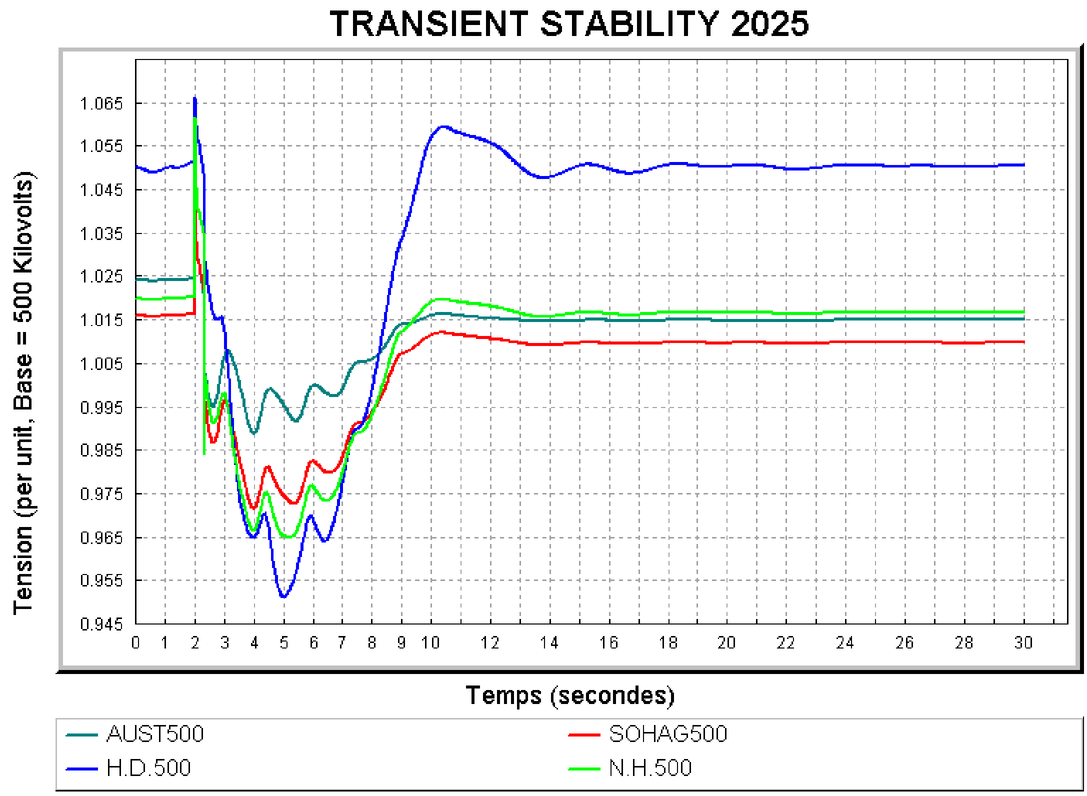
2.2.1 GENERATOR FREQUENCY VARIATION

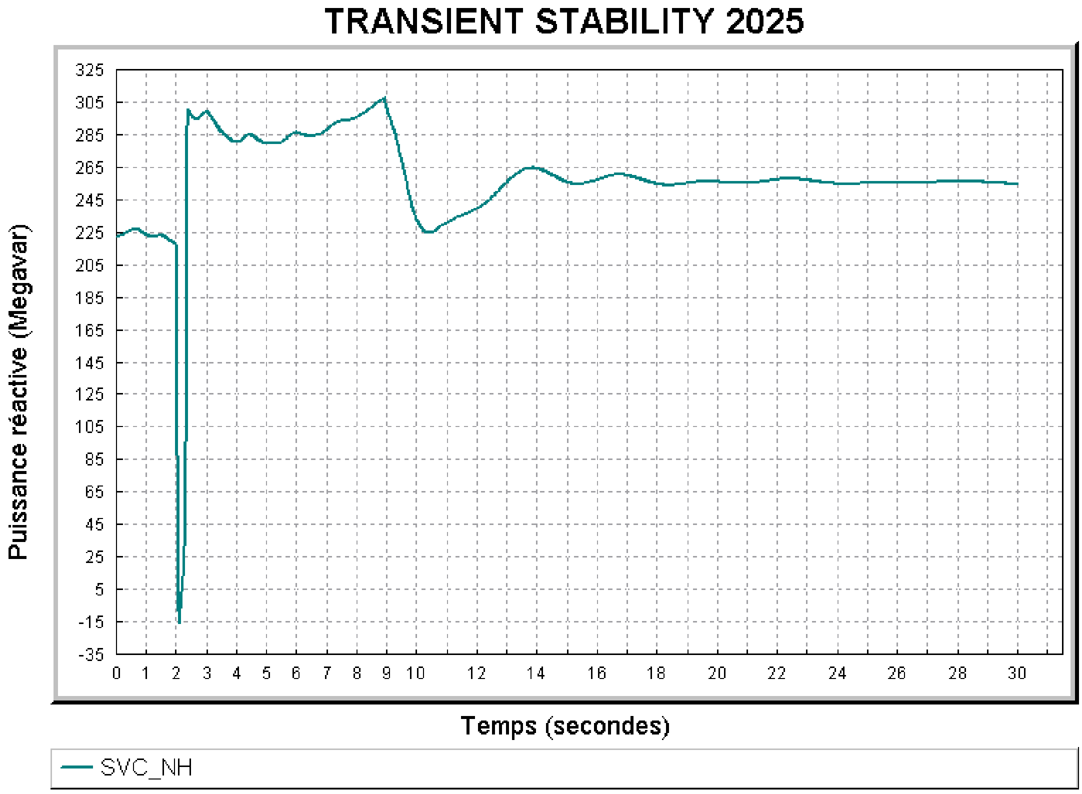


2.2.2 POWER FLOW VARIATION



2.2.3 VOLTAGE VARIATION ON THE 500 KV




TRANSIENT STABILITY 2025
Puissance réactive (Megavar)
325
305
285
265
245
225
205
185
165
145
125
105
85
65
45
25
5
-15
-35
0 1 2 3 4 5 6 7 8 9 10 12 14 16 18 20 22 24 26 28 30
Temps (secondes)
SVC_NH

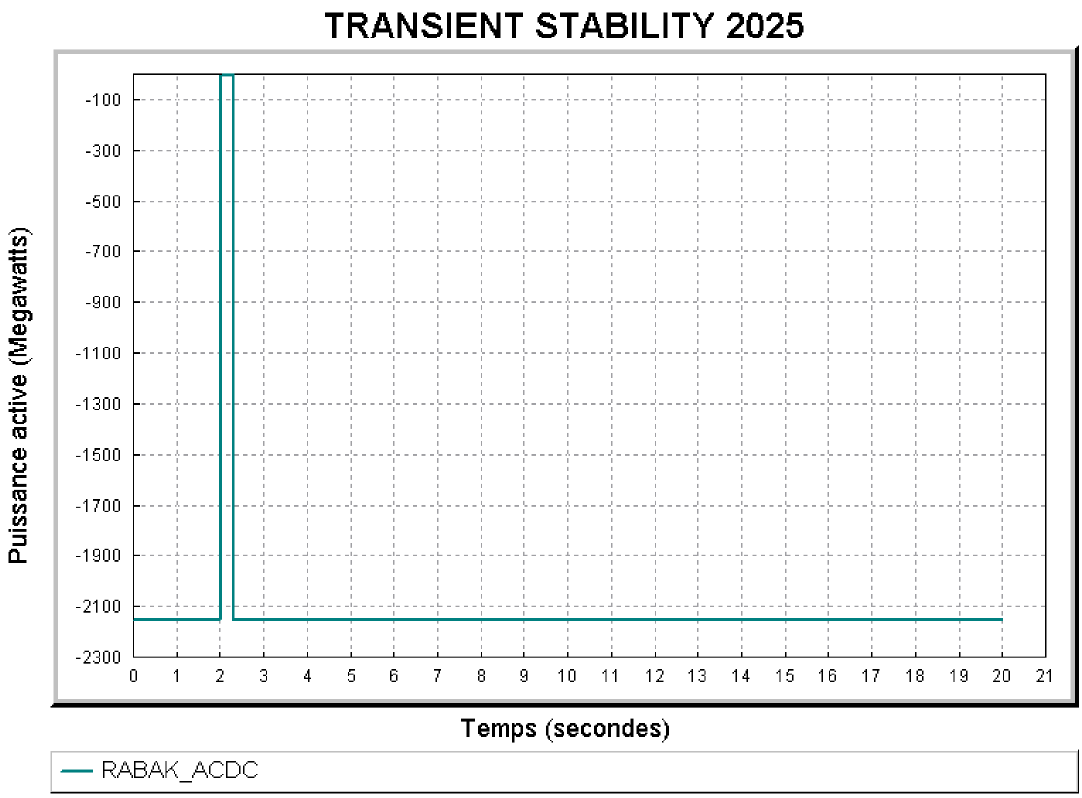
2.3 TRANSITORY BLOCKING OF THE CONVERTER STATION

Event: A fault on the commutation of the converter at Kosti station or Nag Hammadi station induced a temporary blocking of the converter station.

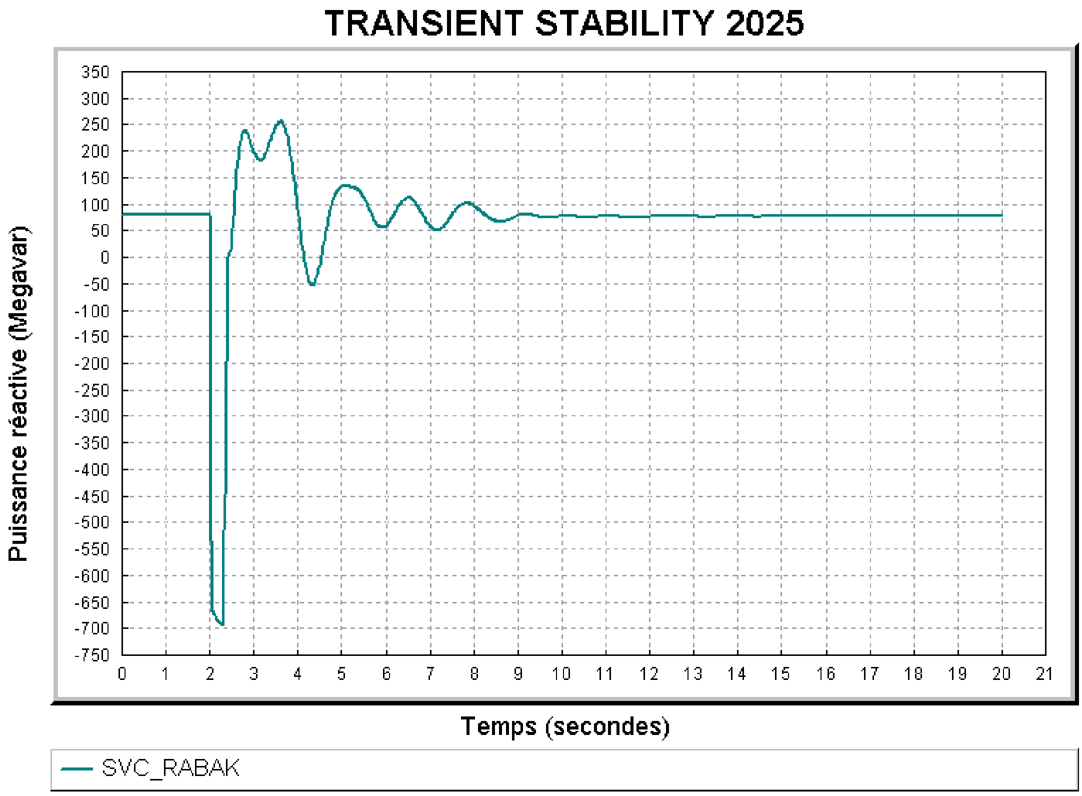
The power exchange was reduced to zero during 300 ms. After this period, the converter stations operated normally and the power exchange recovered its initial value.

During the blocking, the capacitor banks of the filters remained connected on the system.

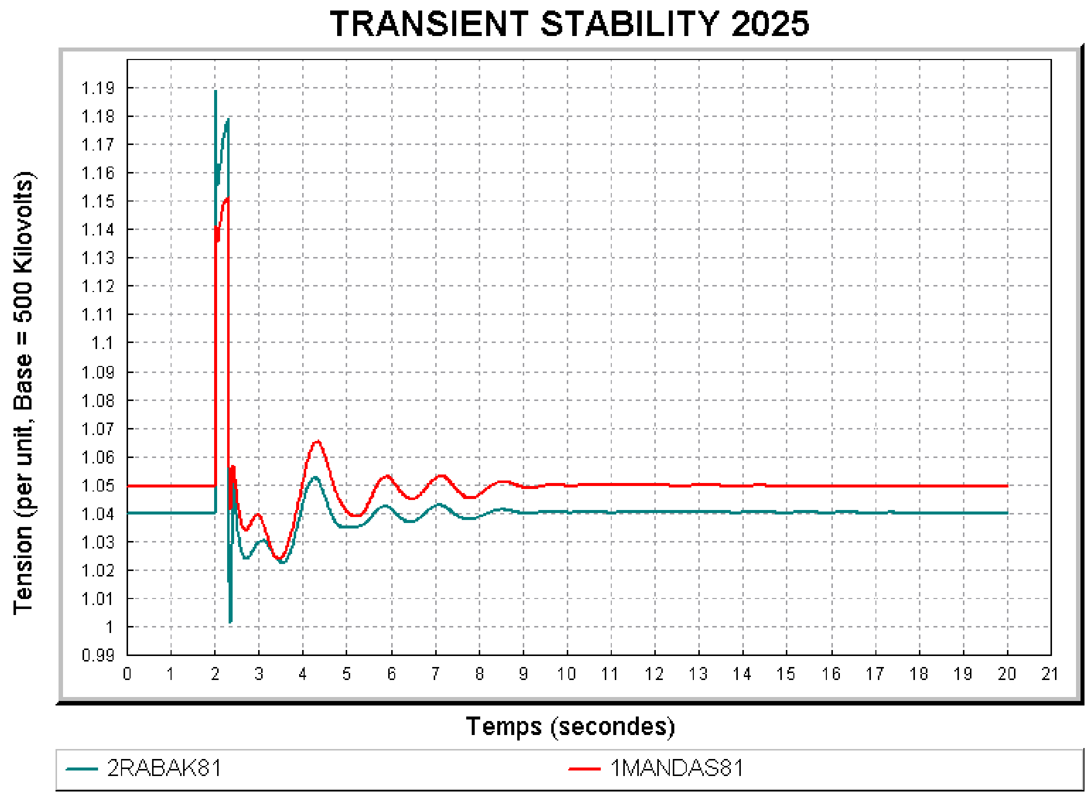
2.3.1 BLOCKING OF THE KOSTI ACDC CONVERTER STATION



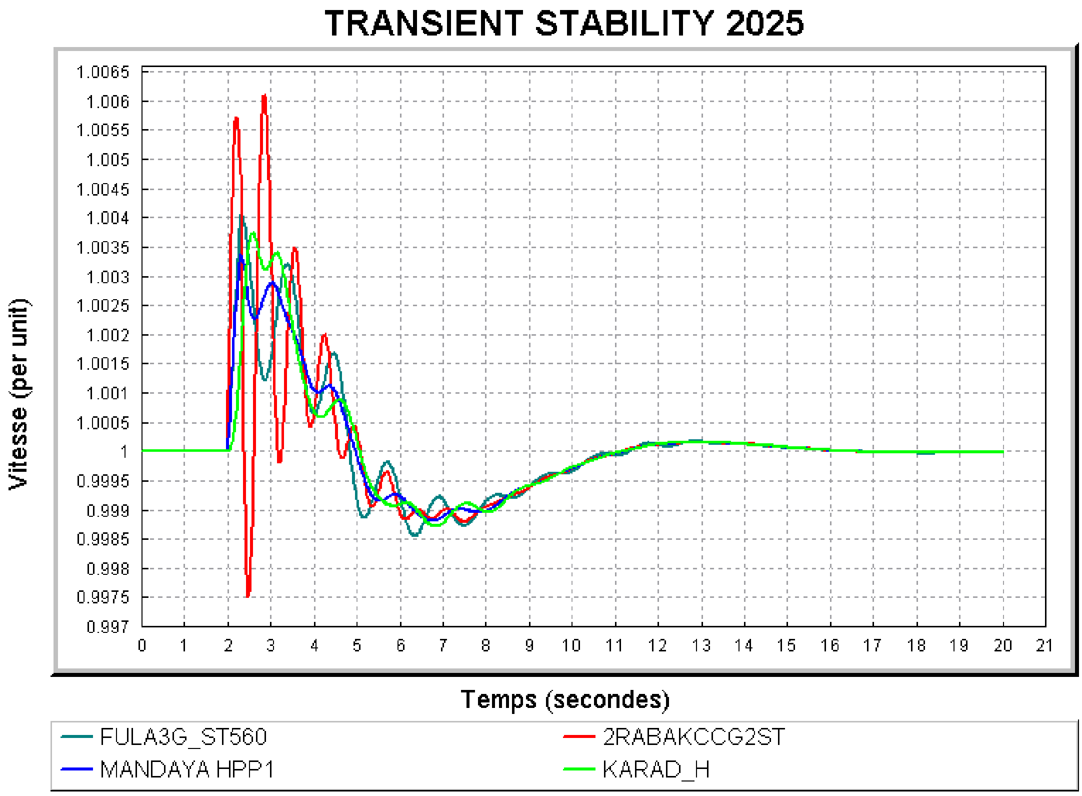
2.3.2 KOSTI SVC REACTIVE GENERATION



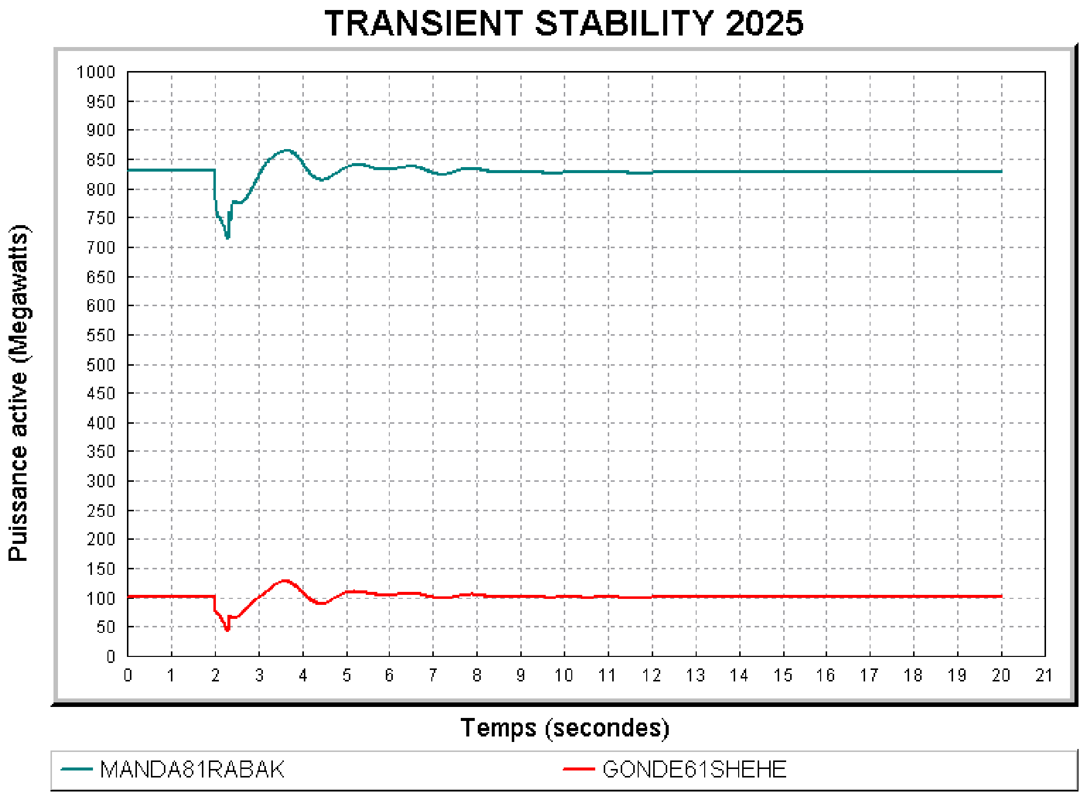
2.3.3 VOLTAGE VARIATION ON THE 500 KV



2.3.4 GENERATOR FREQUENCY VARIATION



2.3.5 POWER FLOW VARIATION ON ENTRO INTERCONNECTION



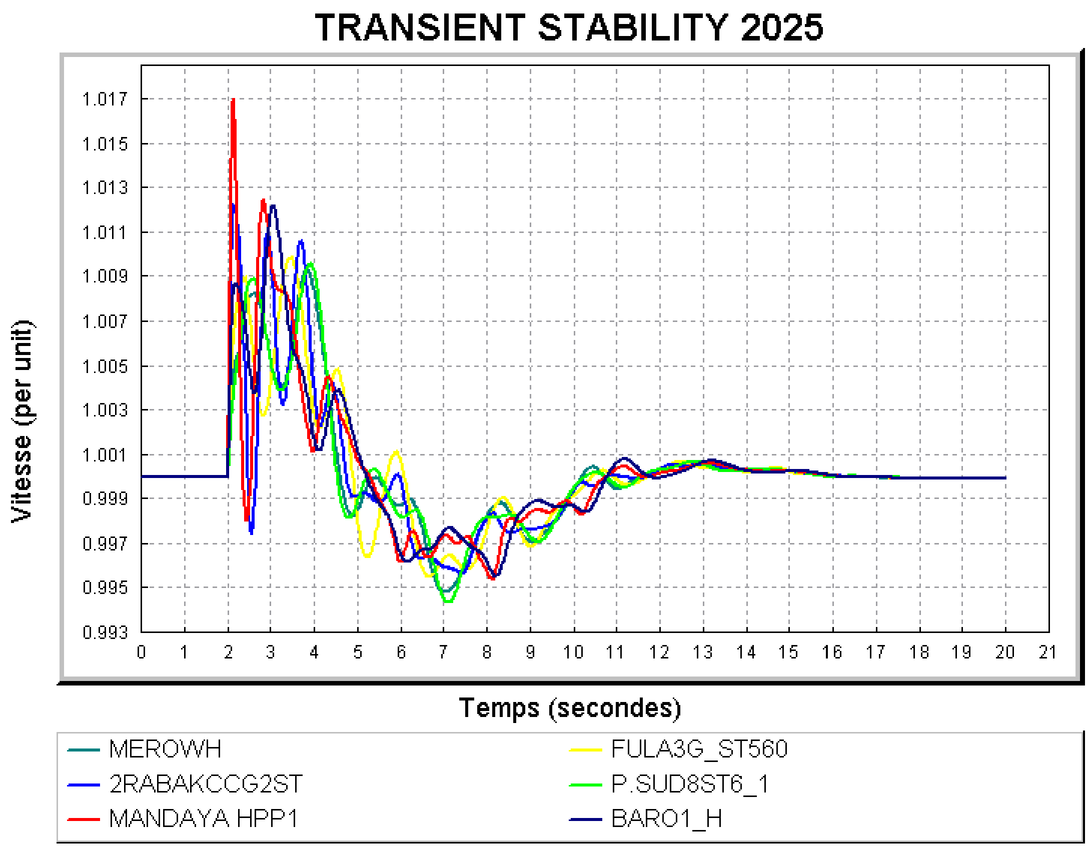
2.4 SHORT-CIRCUIT AT KOSTI ON ONE OF THE FOUR KOSTI - MANDAYA CIRCUITS

Event : a 3 phase short-circuit at Kosti end, on one of the 4 circuits Mandaya - Kosti, cleared in 120 ms by the opening of the circuit breakers.

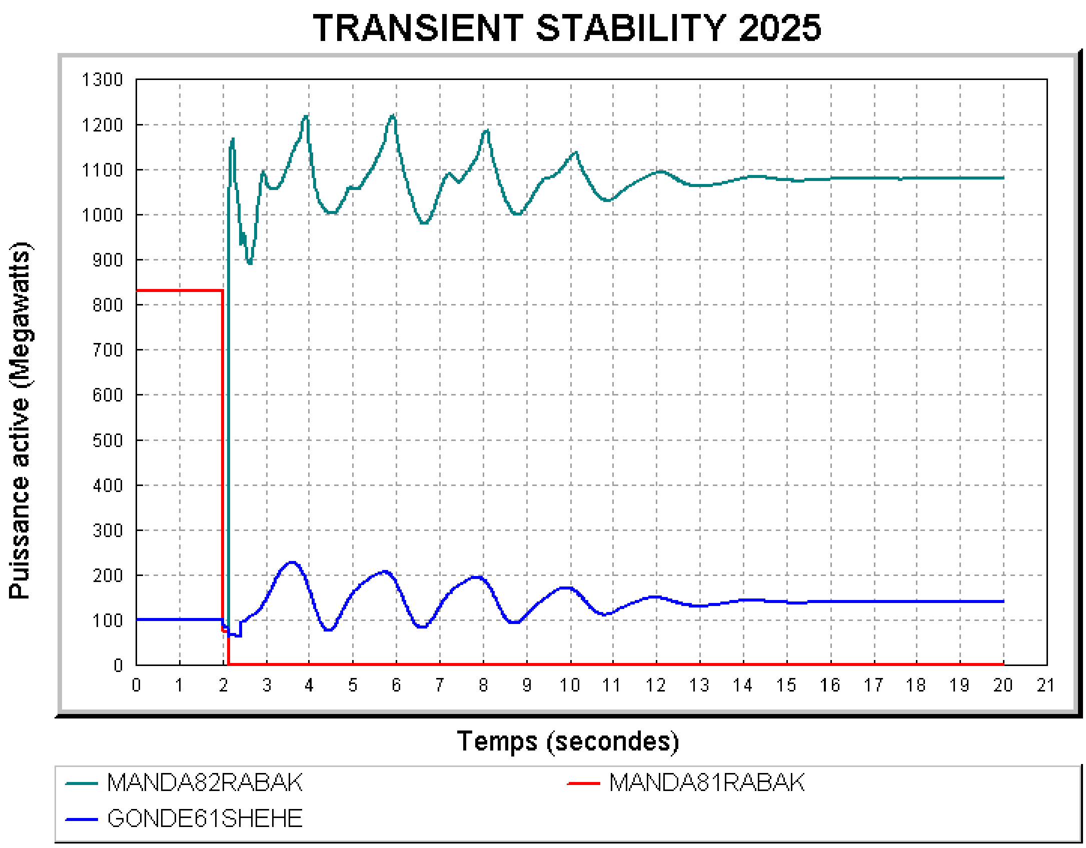
The voltage drop in Kosti led to a transitory blocking of commutation of the inverter station at Kosti. The flow on the DC interconnection is transitory reduced to 0, before recovering to its initial value 300 ms after the clearing of the fault.

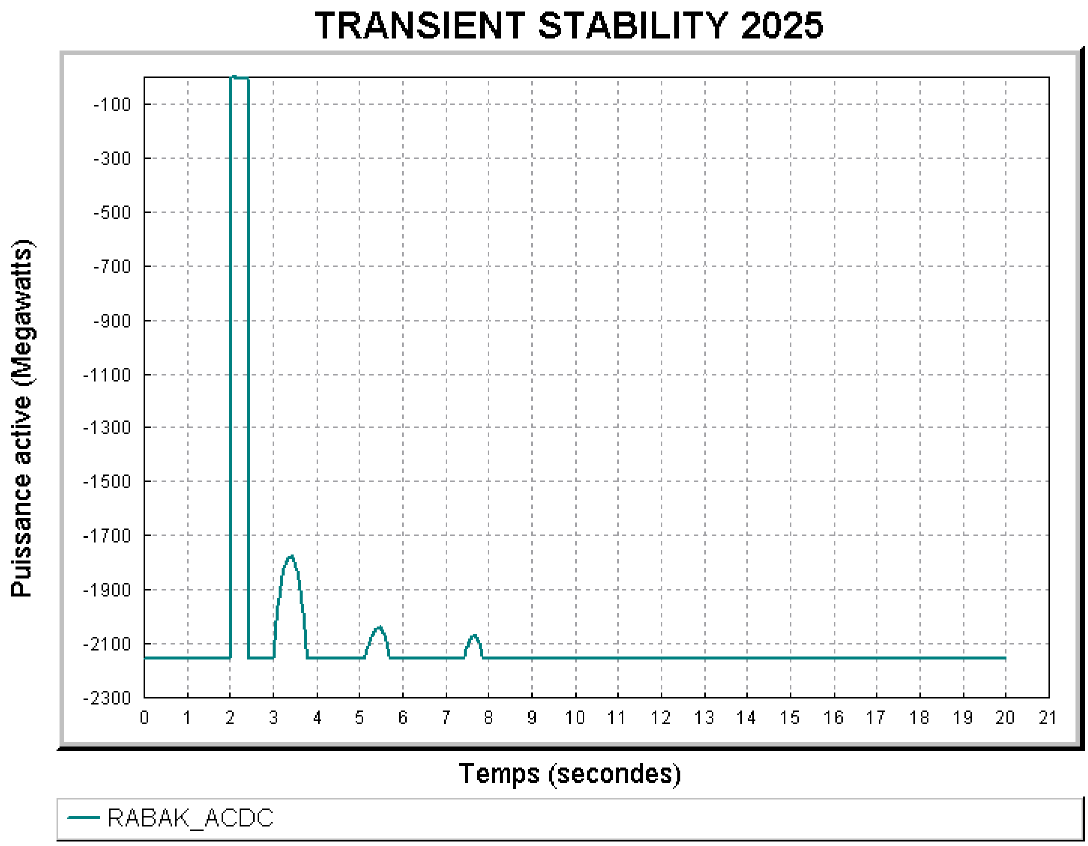
During the transitory blocking of the DC stations, the capacitors bank remained connected.

2.4.1 GENERATOR FREQUENCY VARIATION

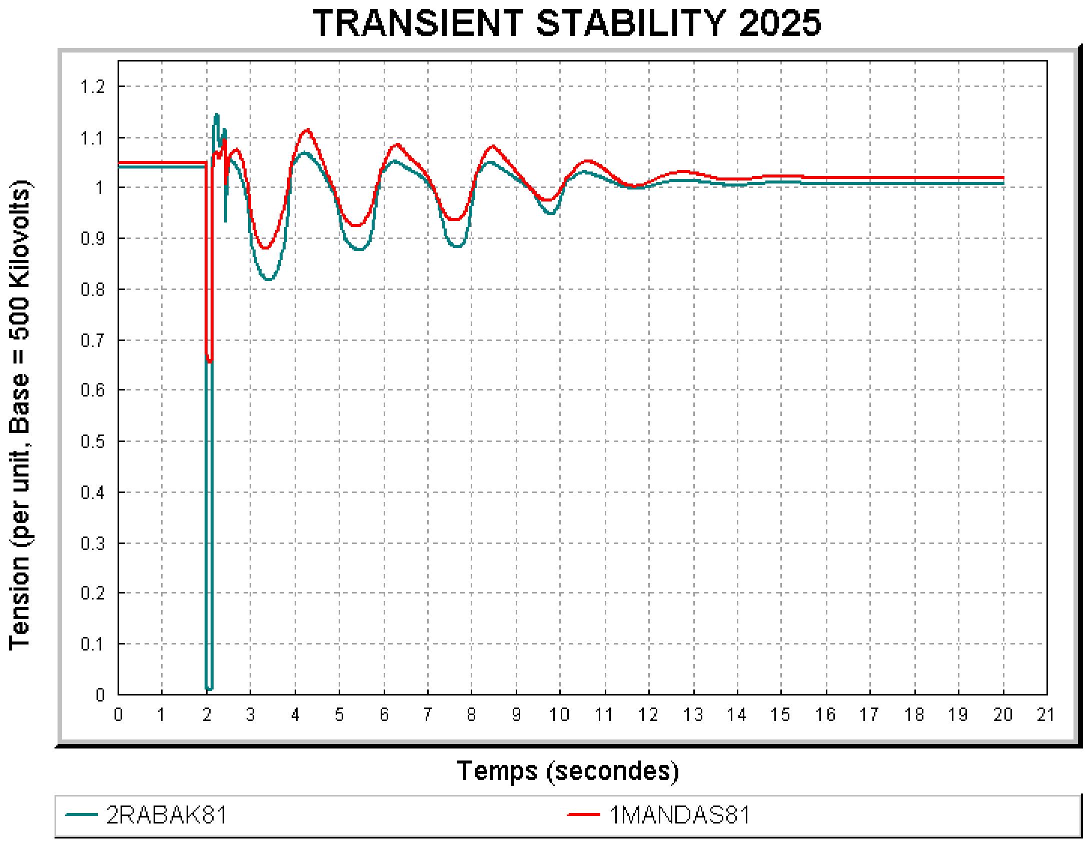


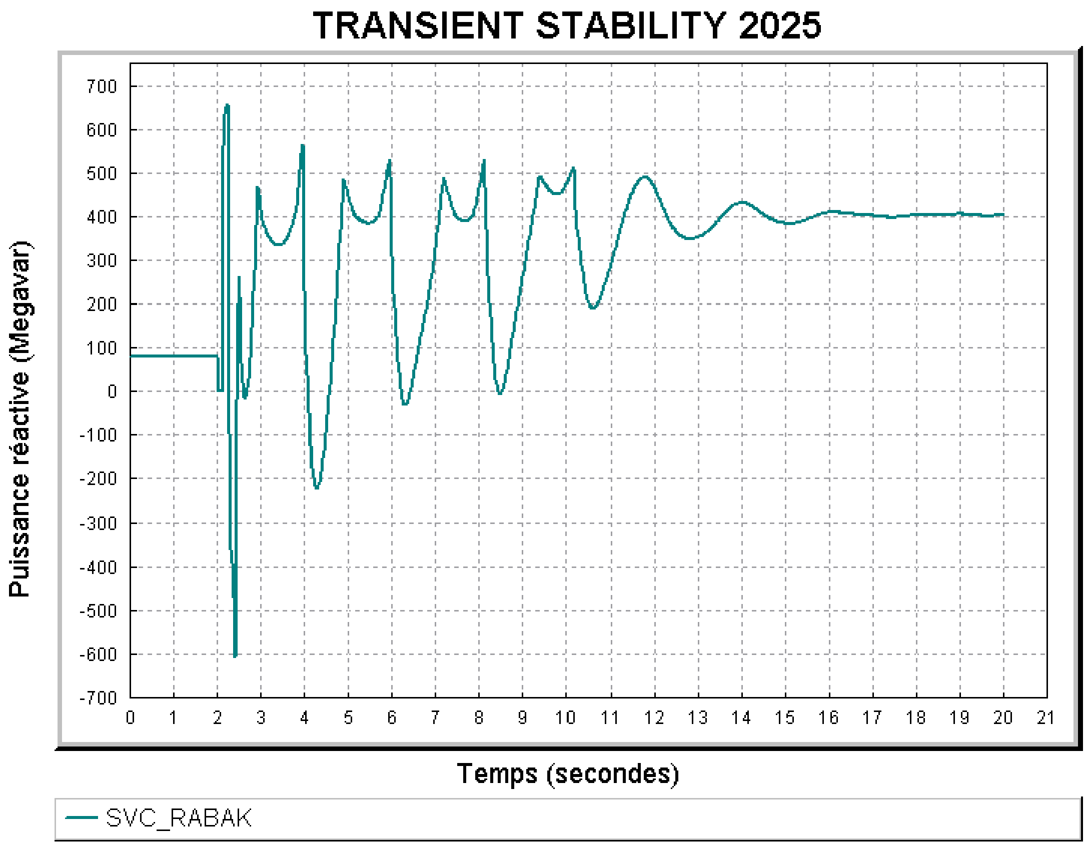
2.4.2 POWER FLOW VARIATION ON ENTRO INTERCONNECTION




TRANSIENT STABILITY 2025
Puissance active (Megawatts)
-100
-300
-500
-700
-900
-1100
-1300
-1500
-1700
-1900
-2100
-2300
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
Temps (secondes)
RABAK_ACDC

2.4.3 VOLTAGE VARIATION ON THE 500 KV




TRANSIENT STABILITY 2025
Puissance réactive (Megavar)
700
600
500
400
300
200
100
0
-100
-200
-300
-400
-500
-600
-700
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
Temps (secondes)
SVC_RABAK

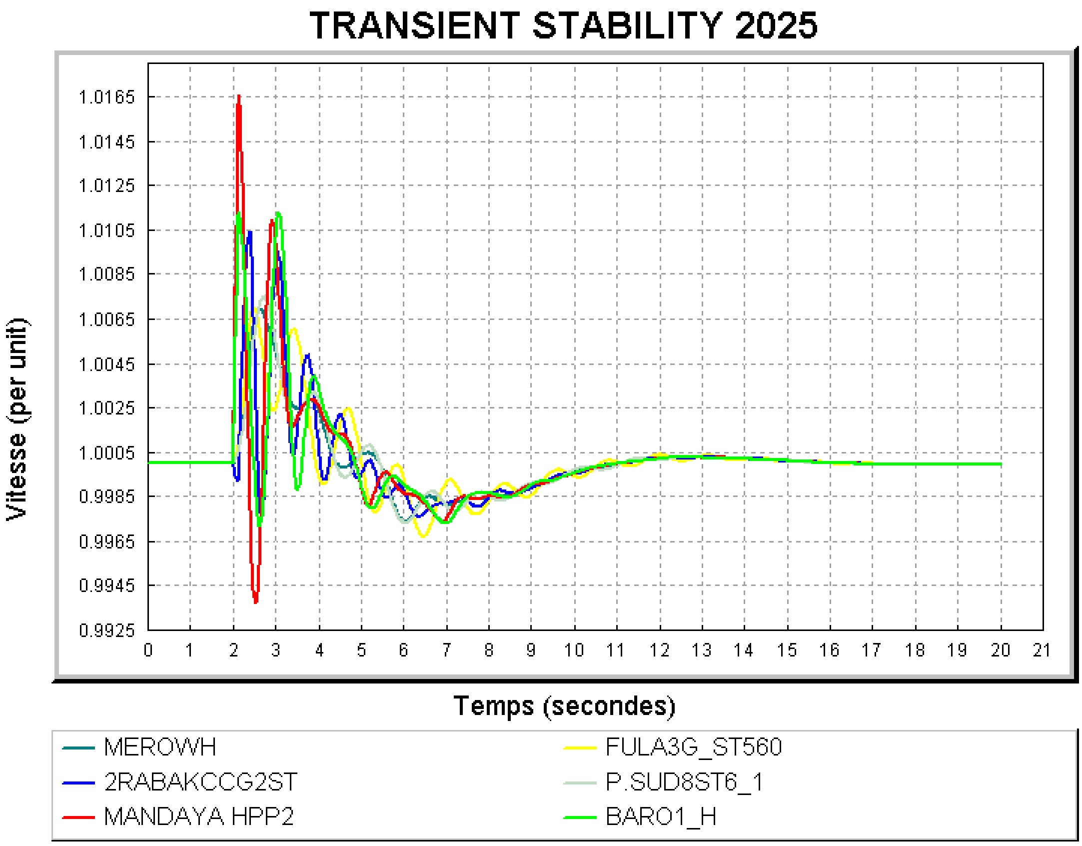
2.5 SHORT-CIRCUIT AT MANDAYA ON ONE OF THE FOUR MANDAYA – KOSTI CIRCUITS

Event : a 3 phase short-circuit at Mandaya end, on one of the 4 circuits Mandaya - Kosti, cleared in 120 ms by the opening of the circuit breakers.

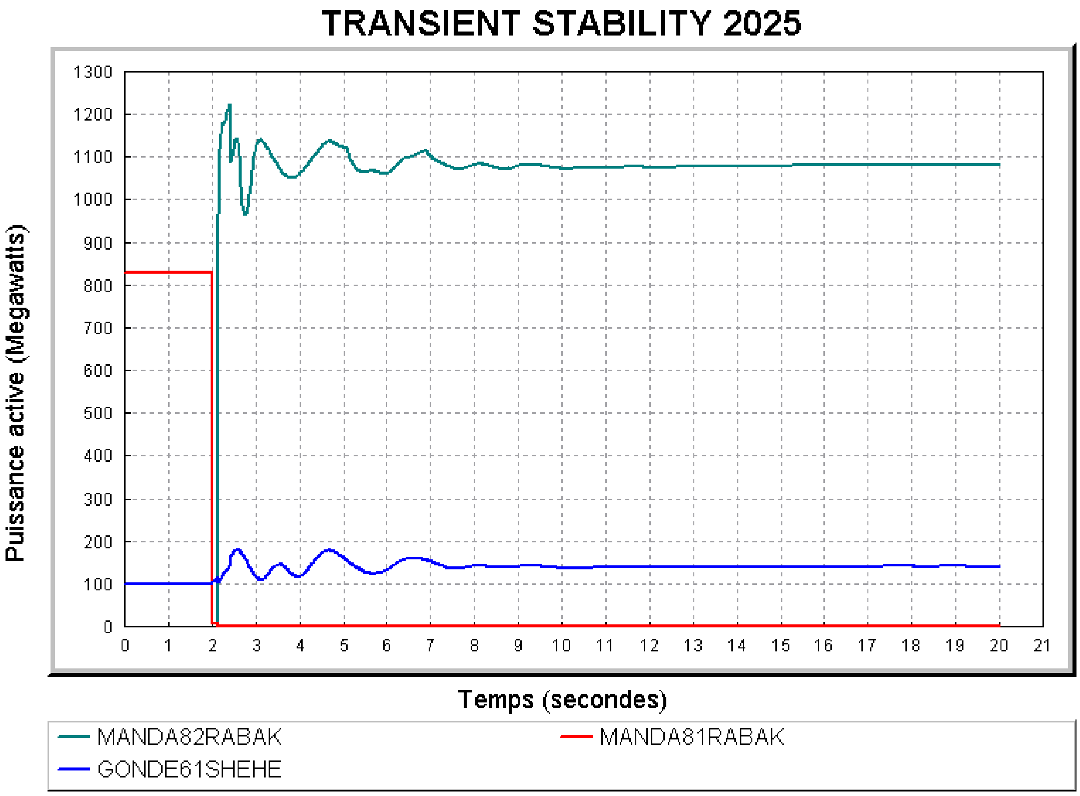
The voltage drop in Kosti led to a transitory blocking of commutation of the inverter station at Kosti. The flow on the DC interconnection is transitory reduced to 0, before recovering to its initial value 300 ms after the clearing of the fault.

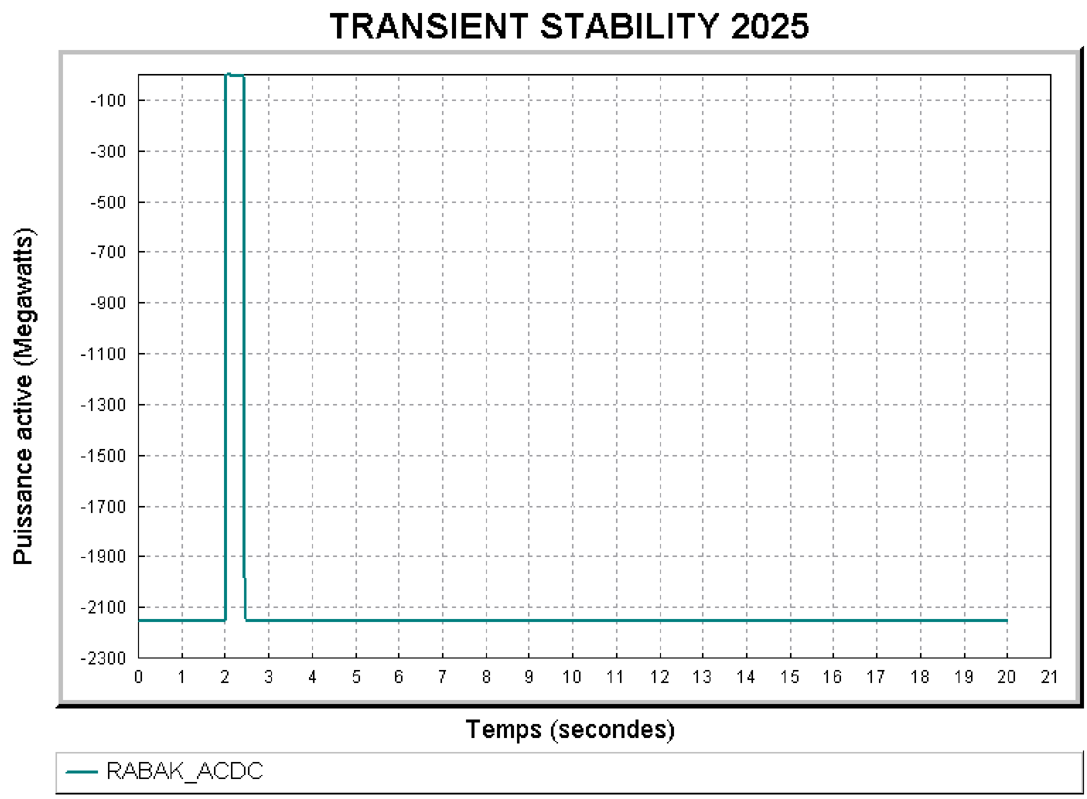
During the transitory blocking of the DC stations, the capacitors bank remained connected.

2.5.1 GENERATOR FREQUENCY VARIATION

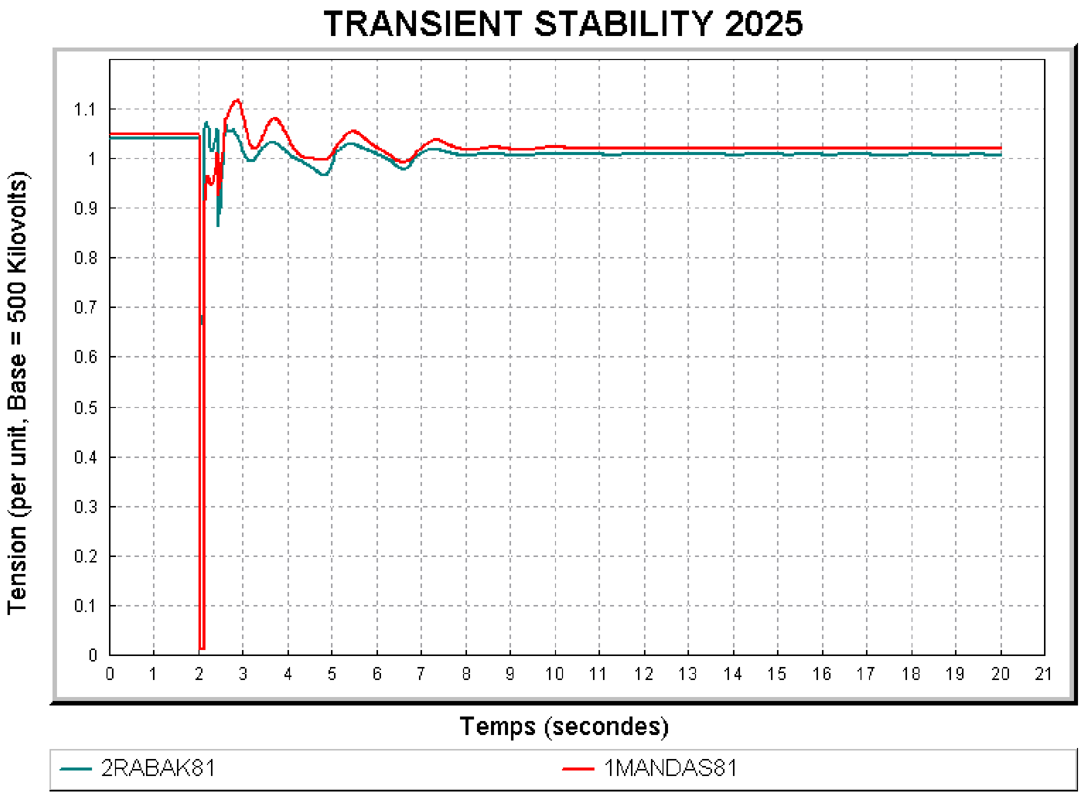


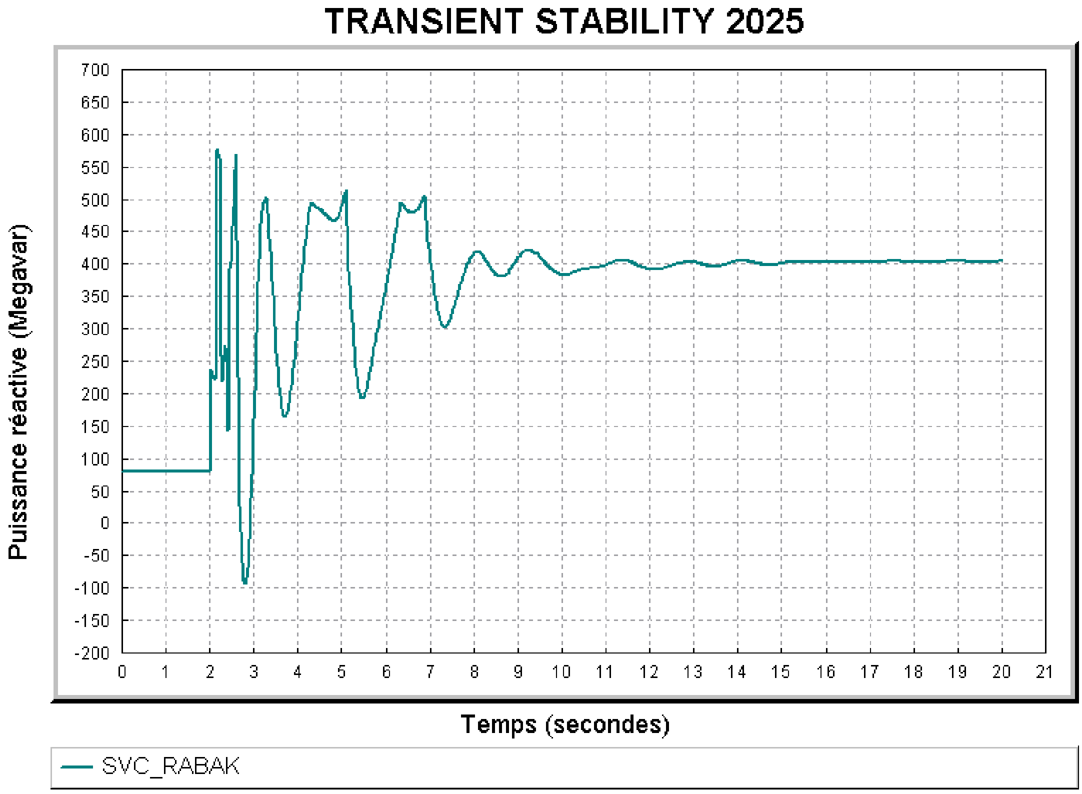
2.5.2 POWER FLOW VARIATION ON ENTRO INTERCONNECTION




TRANSIENT STABILITY 2025
Puissance active (Megawatts)
-100
-300
-500
-700
-900
-1100
-1300
-1500
-1700
-1900
-2100
-2300
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21
Temps (secondes)
RABAK_ACDC

2.5.3 VOLTAGE VARIATION ON THE 500 KV



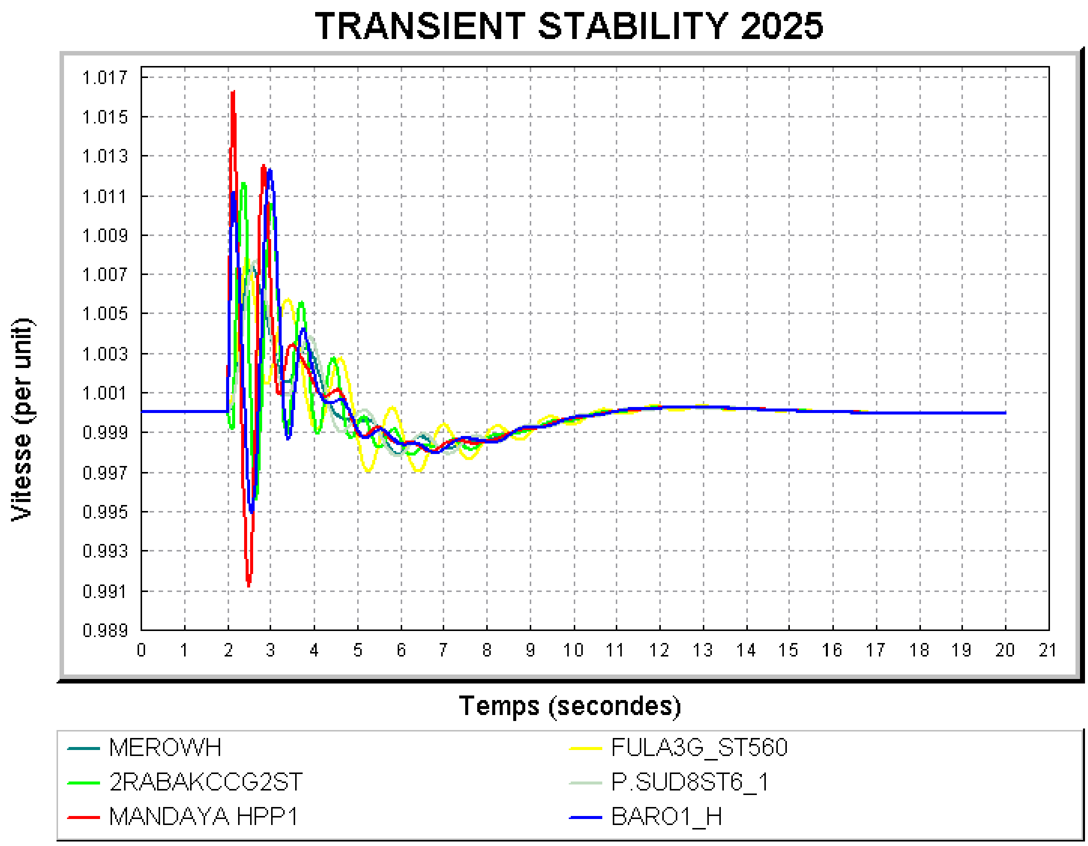

TRANSIENT STABILITY 2025
Puissance réactive (Megavar)
700
650
600
550
500
450
400
350
300
250
200
150
100
50
0
-50
-100
-150
-200
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21
Temps (secondes)
SVC_RABAK

2.6 SHORT-CIRCUIT ON ONE OF THE FOUR 400/500 KV TRANSFORMERS AT MANDAYA

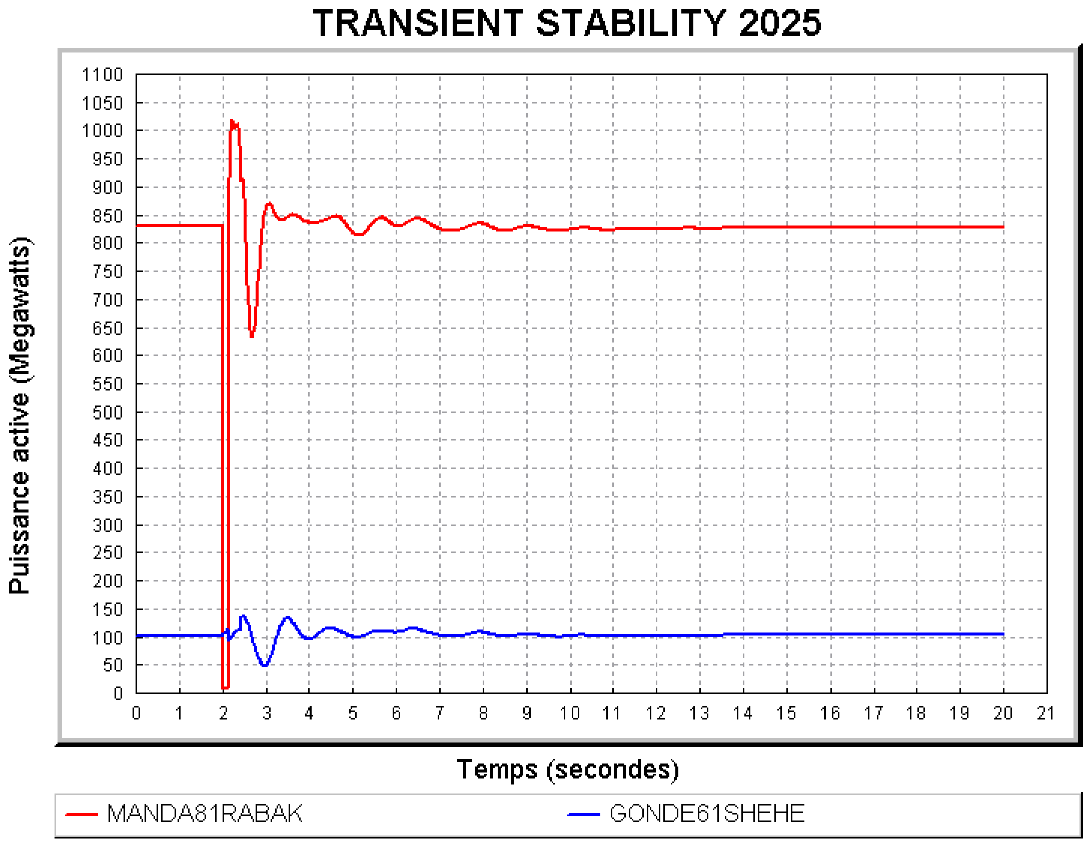
Event : a 3 phase short-circuit at the 500 kV side on one of the four 500/400 kV transformers at Mandaya, cleared in 120 ms by the opening of the circuit breakers.

The voltage drop in Kosti close to 0.6 p.u. led to a transitory blocking of commutation of the converter station at Kosti. The flow on the DC interconnection was transitory reduced to 0, before recovering its initial value 300 ms after the clearing of the fault. The capacitors banks of the filters remained connected.

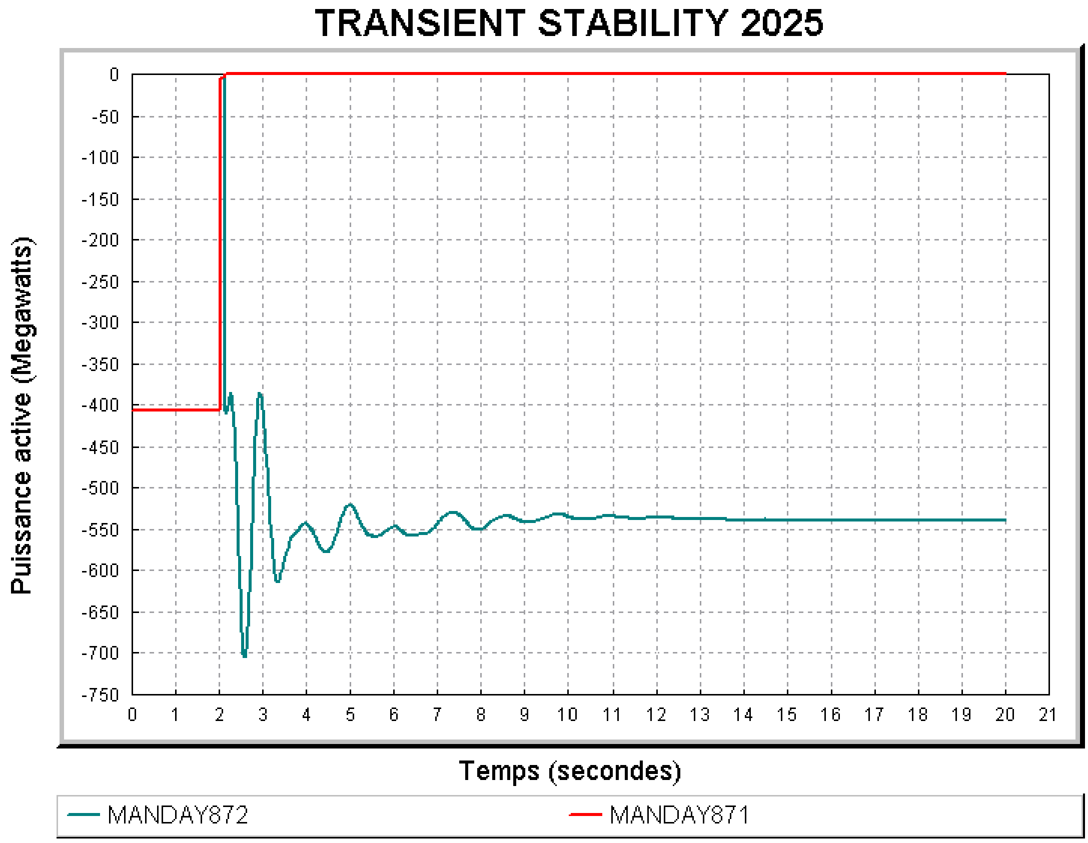
2.6.1 GENERATOR FREQUENCY VARIATION



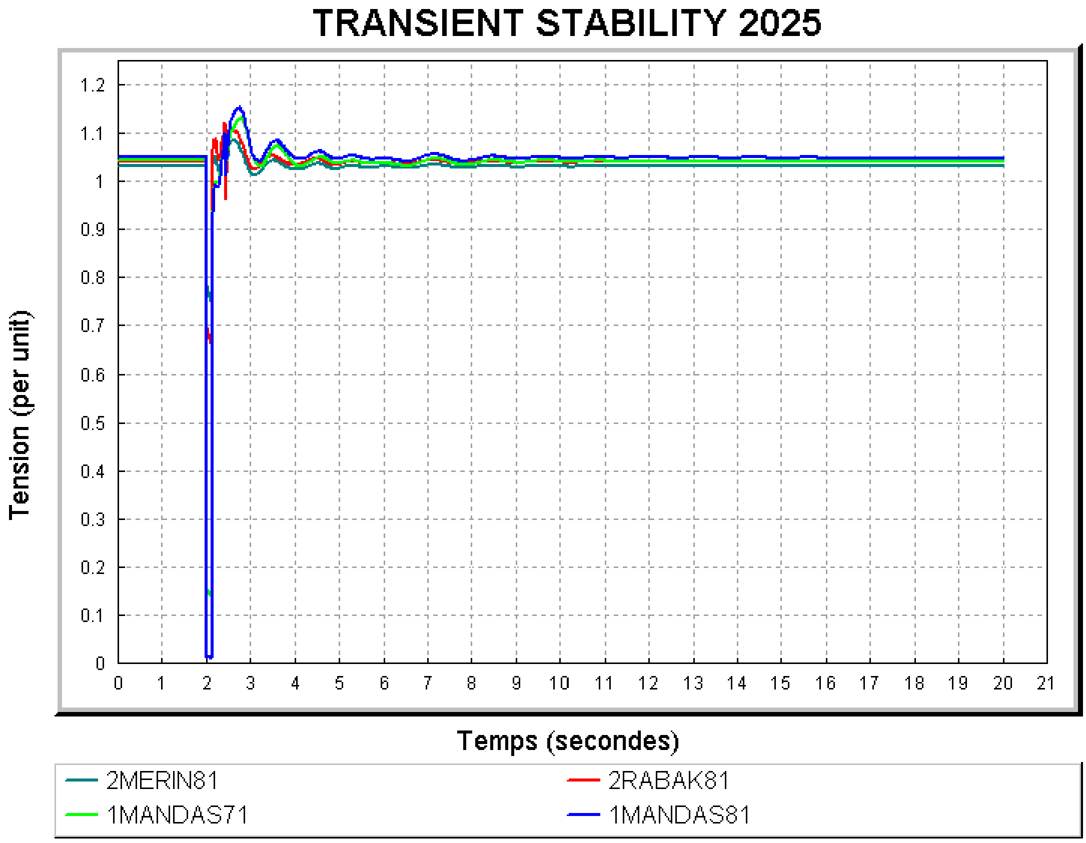
2.6.2 POWER FLOW VARIATION ON ENTRO INTERCONNECTION

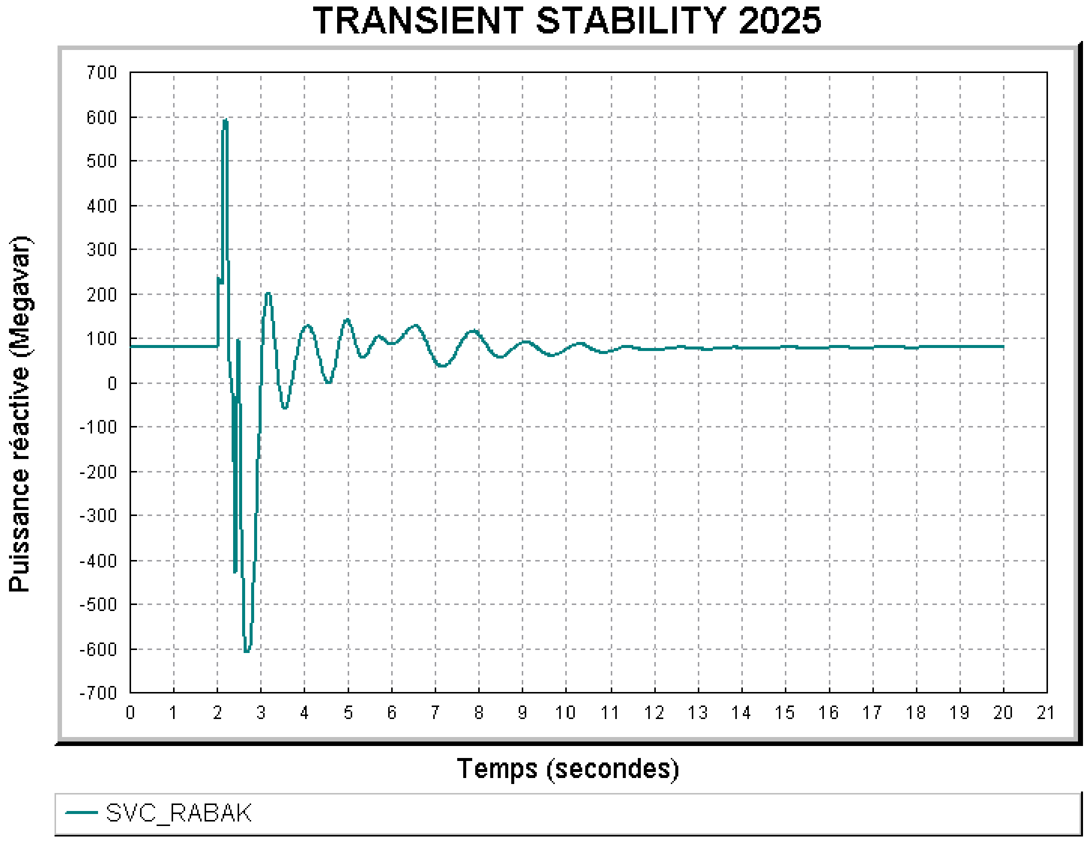


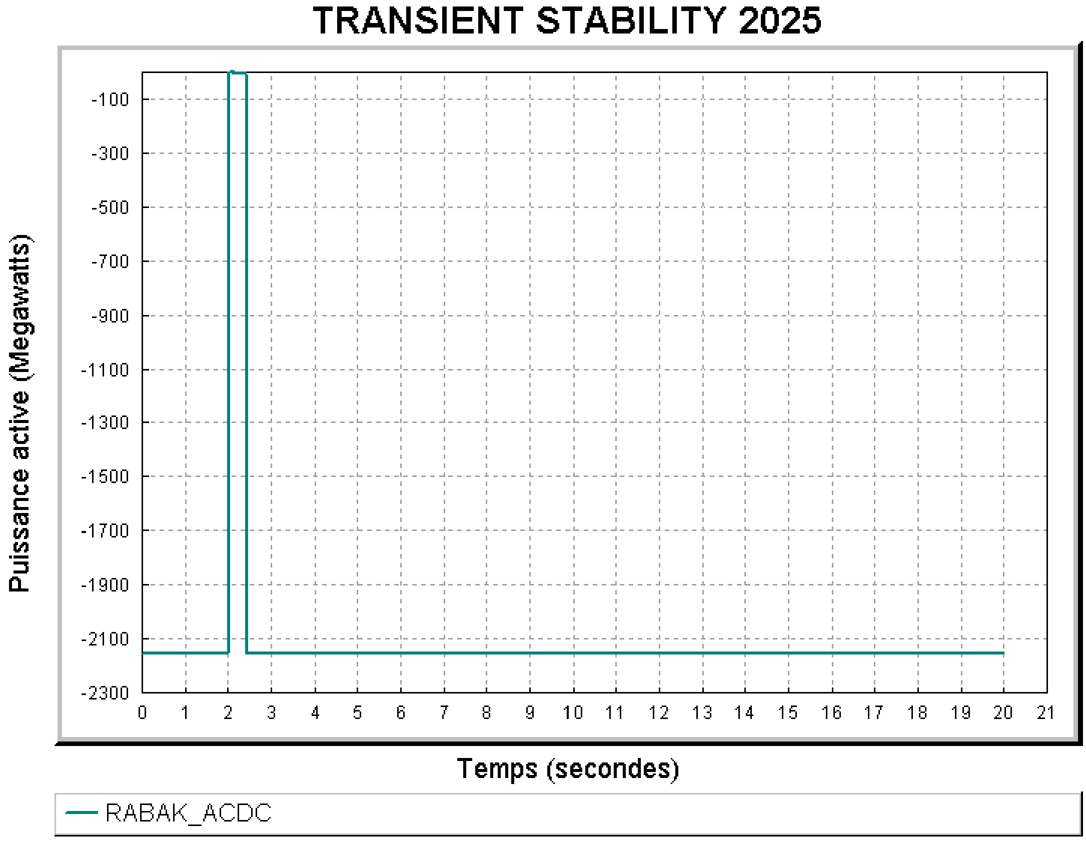
2.6.3 POWER FLOW VARIATION MANDAYA 500/400 KV TRANSFORMERS



2.6.4 VOLTAGE VARIATION ON THE 500 KV



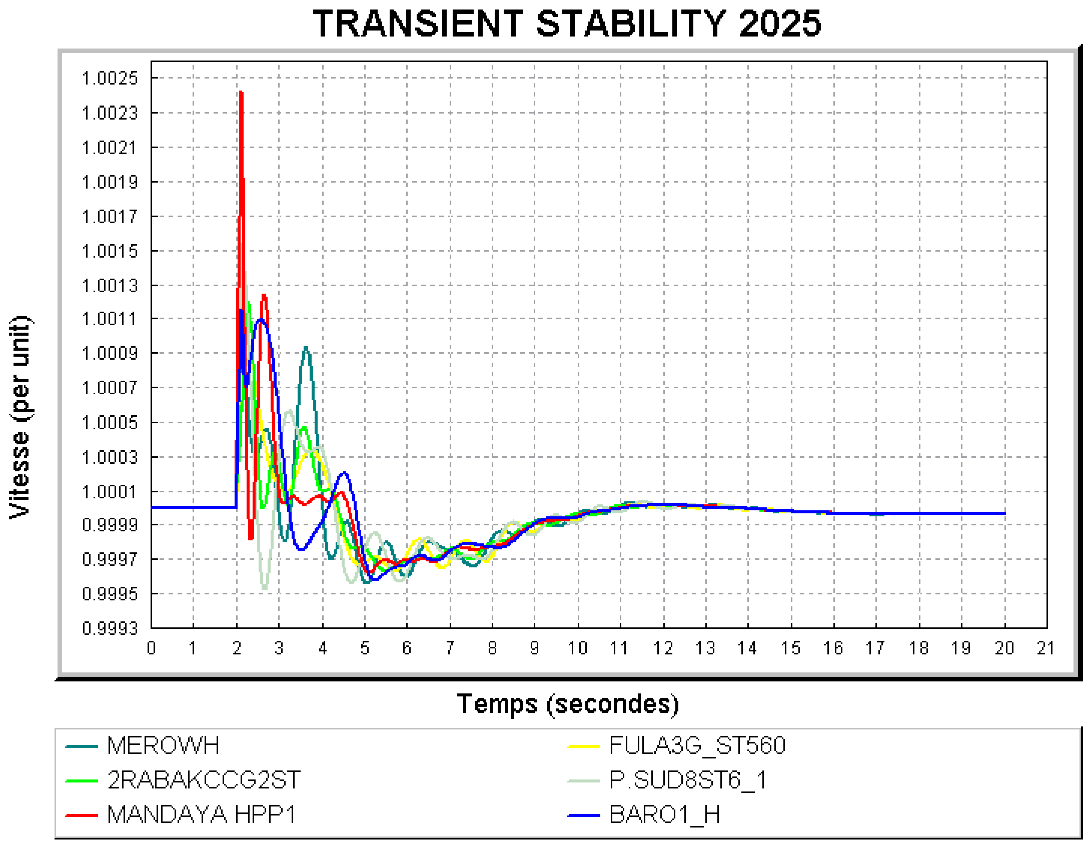

TRANSIENT STABILITY 2025
Puissance réactive (Megavar)
700
600
500
400
300
200
100
0
-100
-200
-300
-400
-500
-600
-700
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21
Temps (secondes)
SVC_RABAK


TRANSIENT STABILITY 2025
Puissance active (Megawatts)
-100
-300
-500
-700
-900
-1100
-1300
-1500
-1700
-1900
-2100
-2300
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
Temps (secondes)
RABAK_ACDC

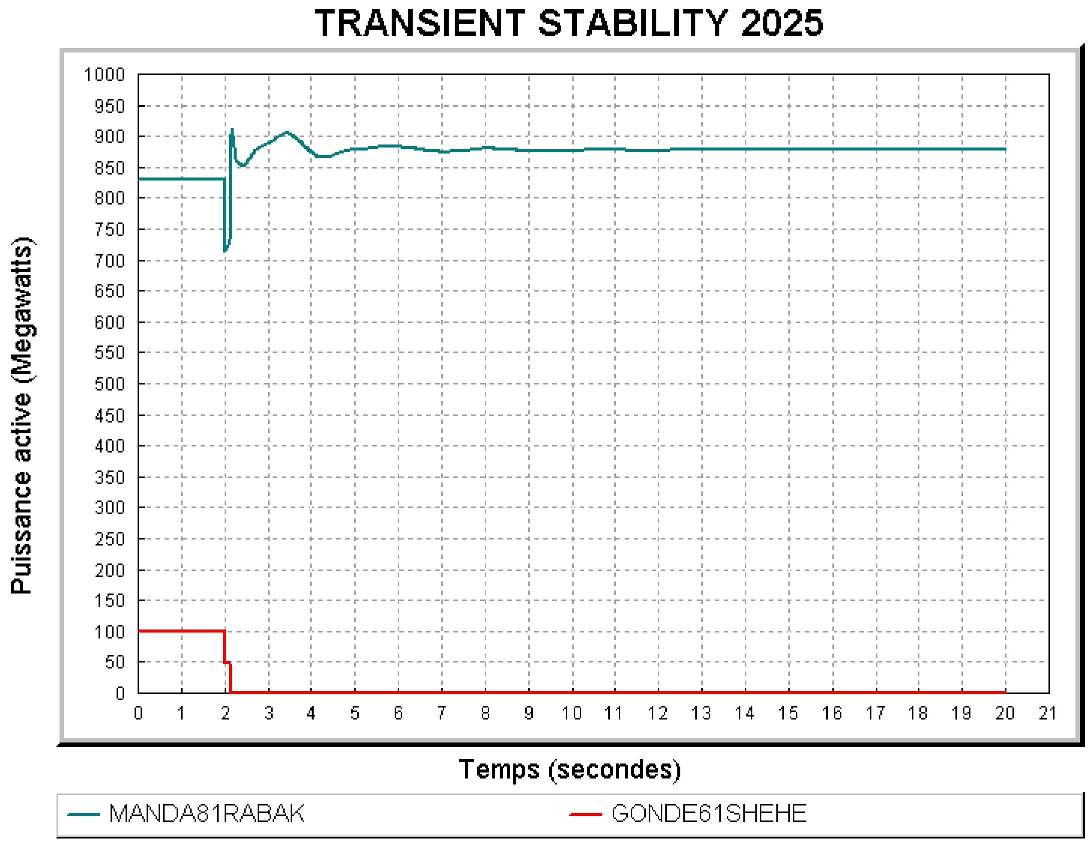
2.7 SHORT-CIRCUIT AT GEDAREF, ON THE 220 KV PHASE-SHIFT TRANSFORMER

Event : a 3 phase short-circuit at Gedaref 220 kV end, on the 220 kV phase shift transformer, cleared in 120 ms by the opening of the circuit breakers.

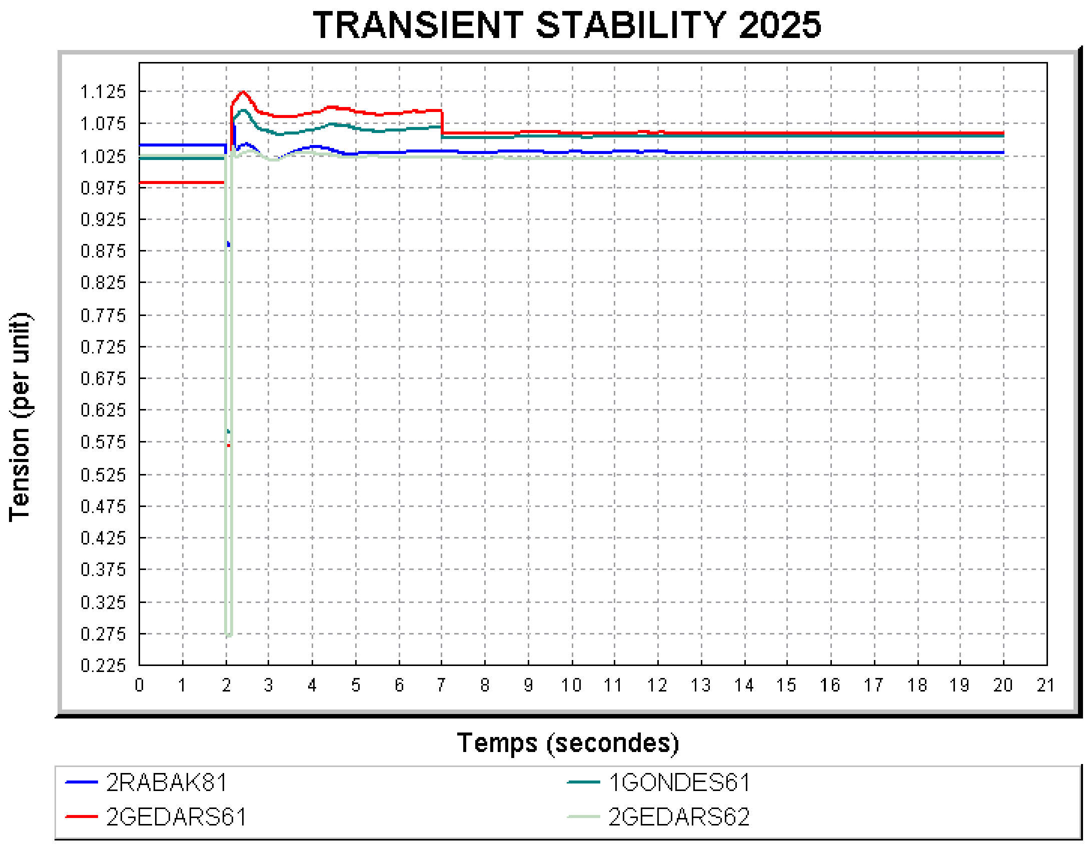
2.7.1 GENERATOR FREQUENCY VARIATION

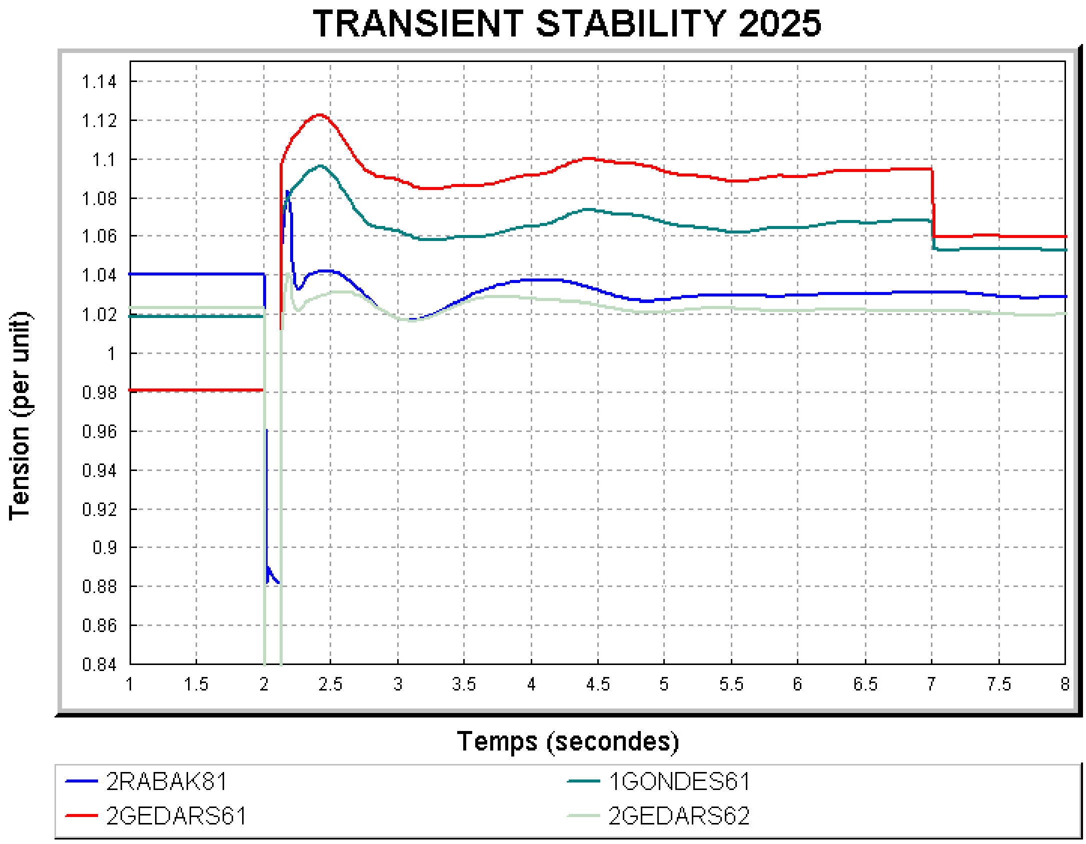


2.7.2 POWER FLOW VARIATION ON ENTRO INTERCONNECTION



2.7.3 VOLTAGE VARIATION ON THE 500 KV




TRANSIENT STABILITY 2025
Tension (per unit)
1.14
1.12
1.1
1.08
1.06
1.04
1.02
1
0.98
0.96
0.94
0.92
0.9
0.88
0.86
0.84
1
1.5
2
2.5
3
3.5
4
4.5
5
5.5
6
6.5
7
7.5
8
Temps (secondes)
2RABAK81
1GONDES61
2GEDARS61
2GEDARS62

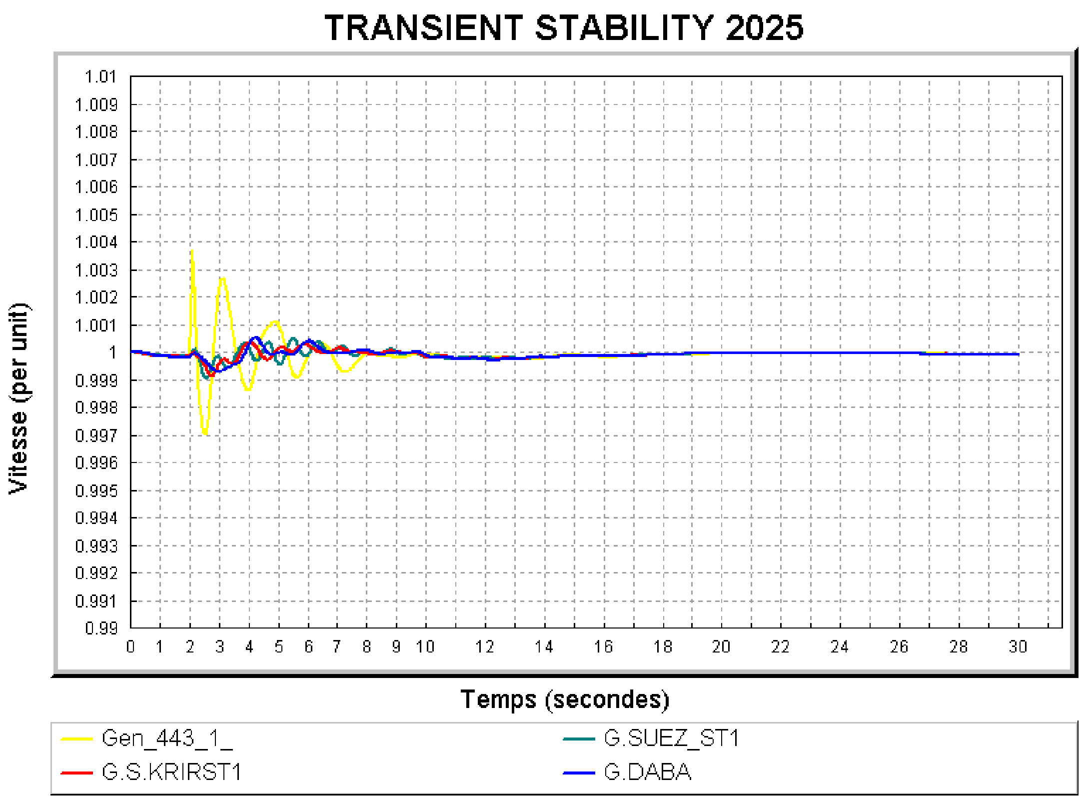
2.8 SHORT-CIRCUIT AT NAG HAMMADI SIDE, ON ONE OF THE TWO CIRCUITS HIGH DAM - NAG HAMMADI

Event : a 3 phase short-circuit at Nag Hammadi end, on one of the 2 circuits High Dam - Nag Hammadi, cleared in 100 ms by the opening of the circuit breakers.

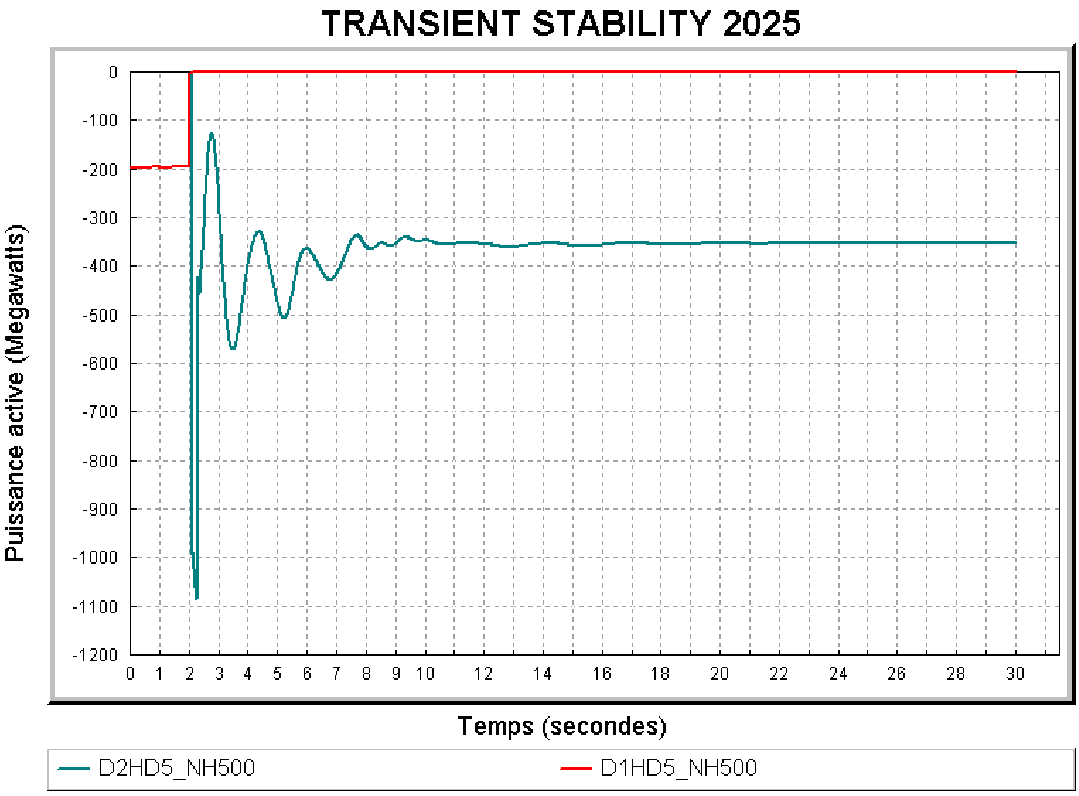
Following the tripping, a transitory blocking of commutation of the inverter station at Nag Hammadi. The flow on the DC interconnection is transitory reduced to 0, before starting, 300 ms after the voltage return, its recovery to its initial value.

During the transitory blocking of the DC stations, the capacitors bank remained connected.

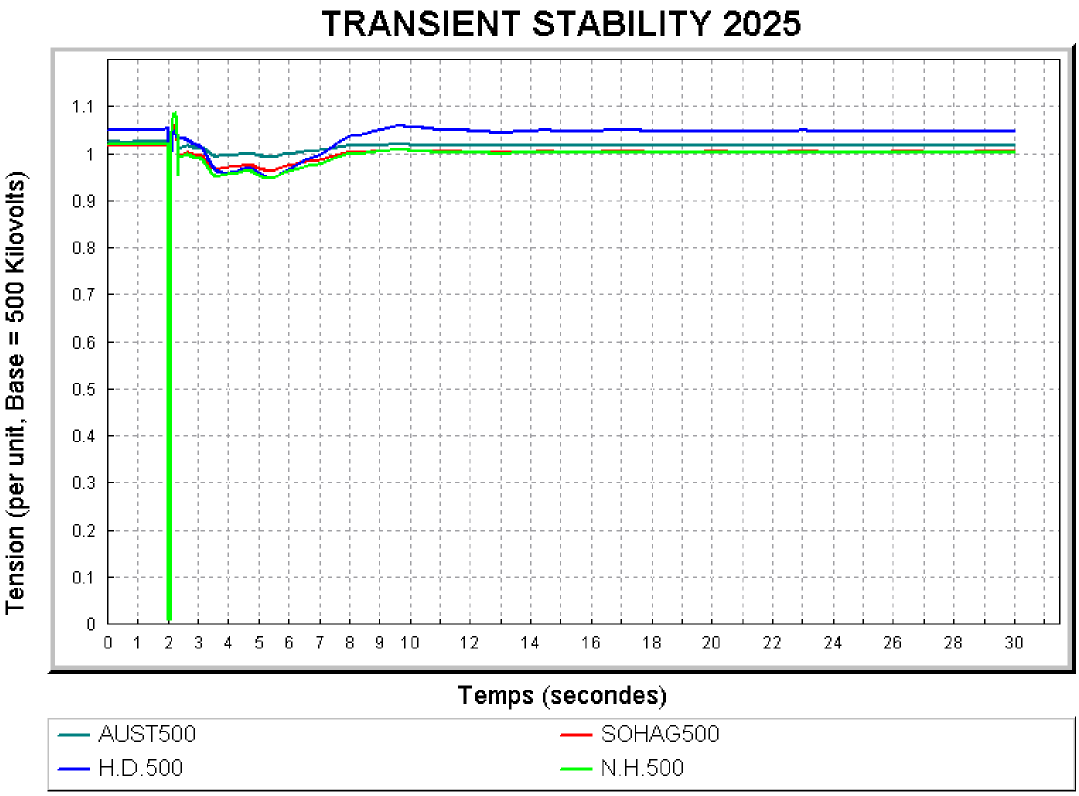
2.8.1 GENERATOR FREQUENCY VARIATION

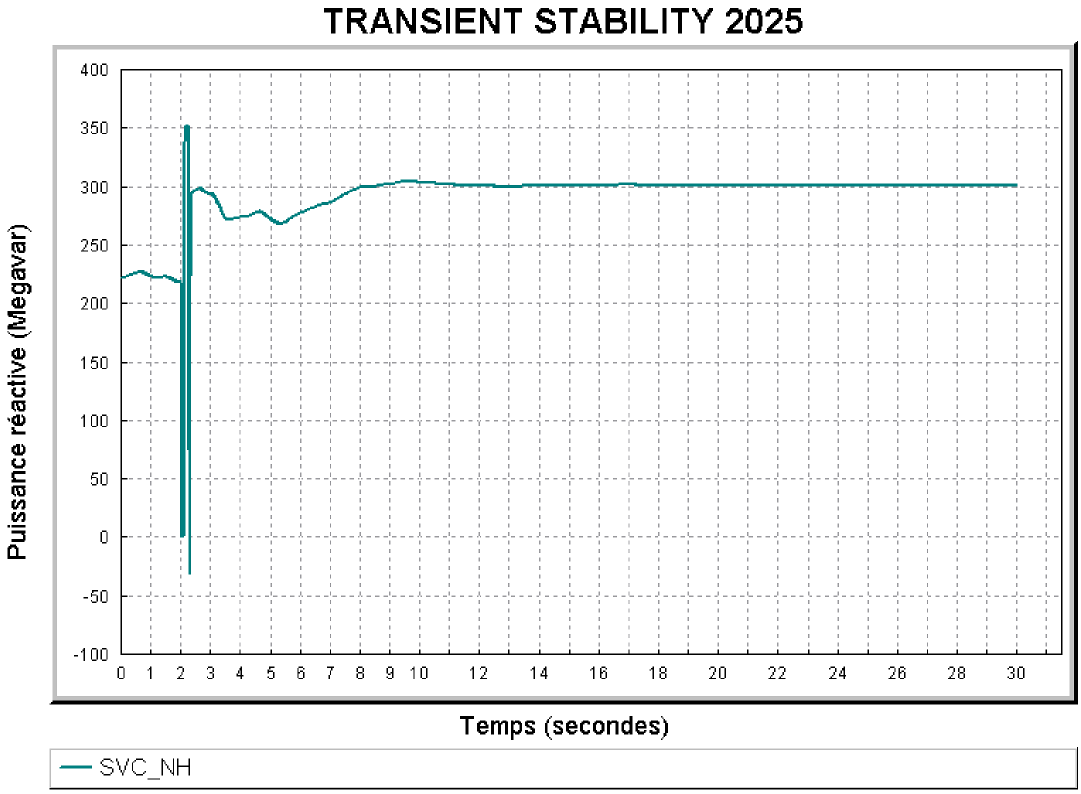


2.8.2 POWER FLOW VARIATION ON THE 2 CIRCUITS NAG HAMMADI – HIGH DAM



2.8.3 VOLTAGE VARIATION ON THE 500 KV




TRANSIENT STABILITY 2025
Puissance réactive (Megavar)
400
350
300
250
200
150
100
50
0
-50
-100
0 1 2 3 4 5 6 7 8 9 10 12 14 16 18 20 22 24 26 28 30
Temps (secondes)
SVC_NH

2.9 SHORT-CIRCUIT AT NAG HAMMADI ON NH500 - SOHAG CIRCUIT

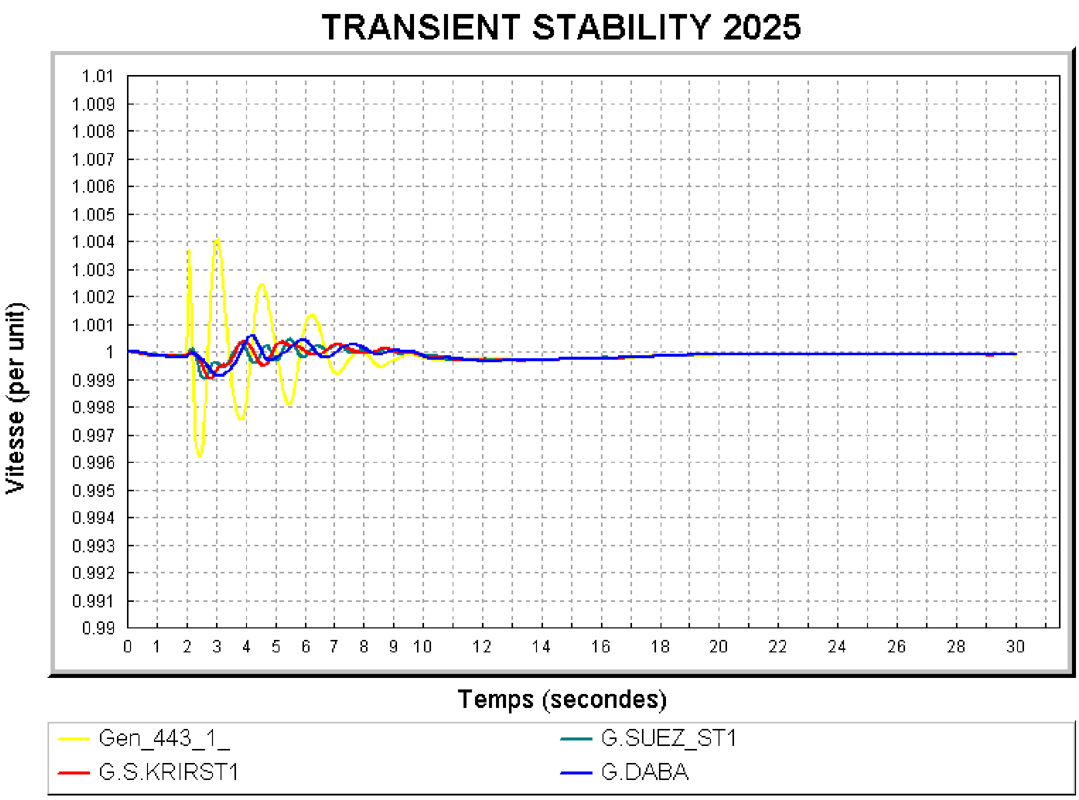
Event : a 3 phase short-circuit at Nag Hammadi end, on the circuit Nag Hammadi - Sohag, cleared in 100 ms by the opening of the circuit breakers.

The voltage drop in Nag Hammadi (to 0 pu) led to a transitory blocking of commutation of the inverter station at Nag Hammadi. The flow on the DC interconnection is transitory reduced to 0, before starting, 300 ms after the voltage return, its recovery to its initial value.

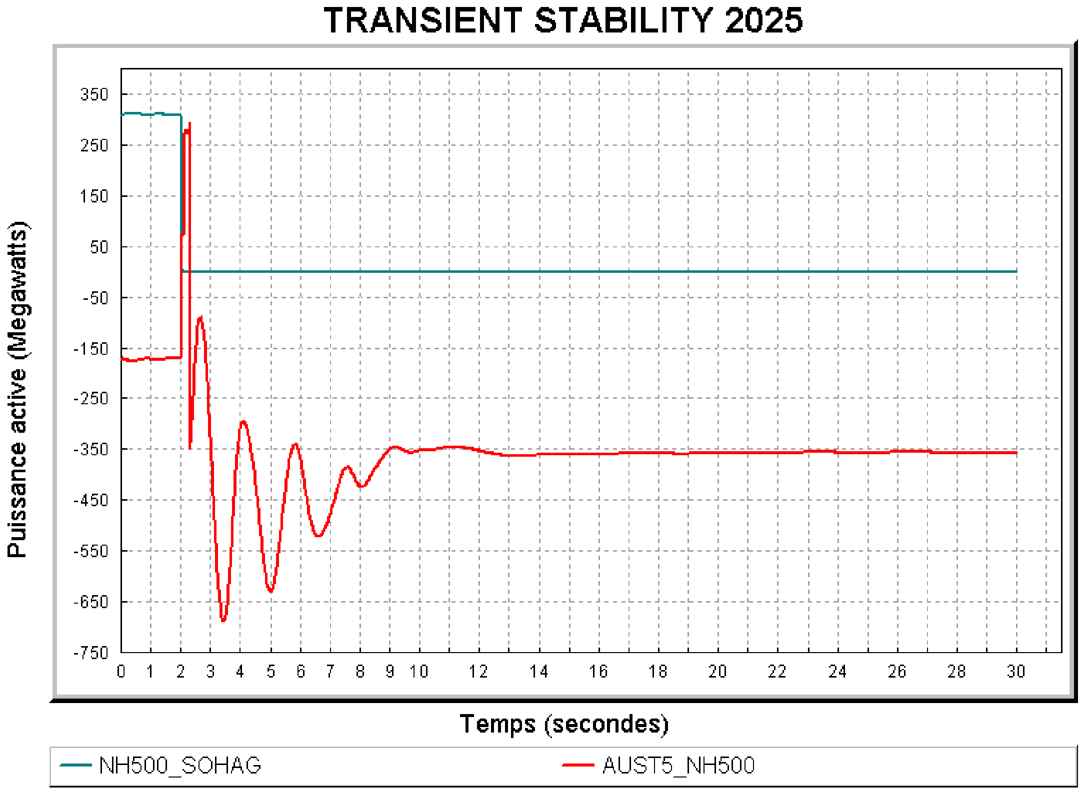
During the transitory blocking of the DC stations, the capacitors bank remained connected.

For the Ethiopian and Sudanese side, the impact on the system and its behaviour is very similar to the case of SC on High Dam - Nag Hammadi

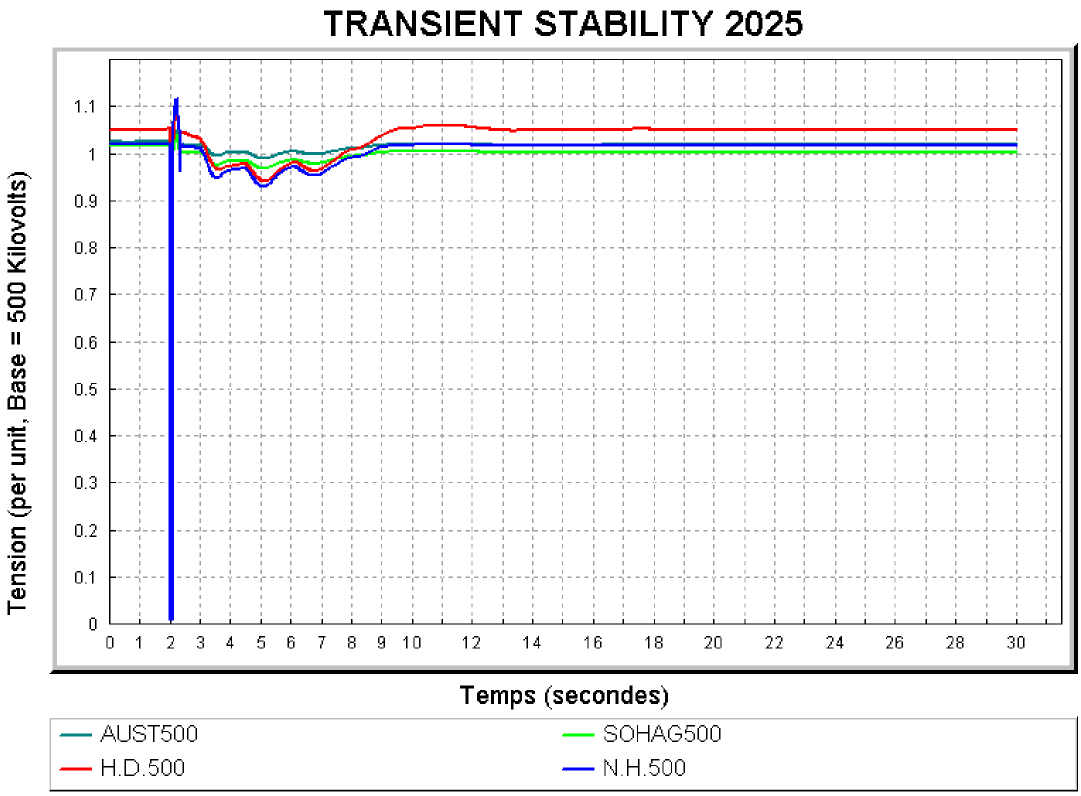
2.9.1 GENERATOR FREQUENCY VARIATION

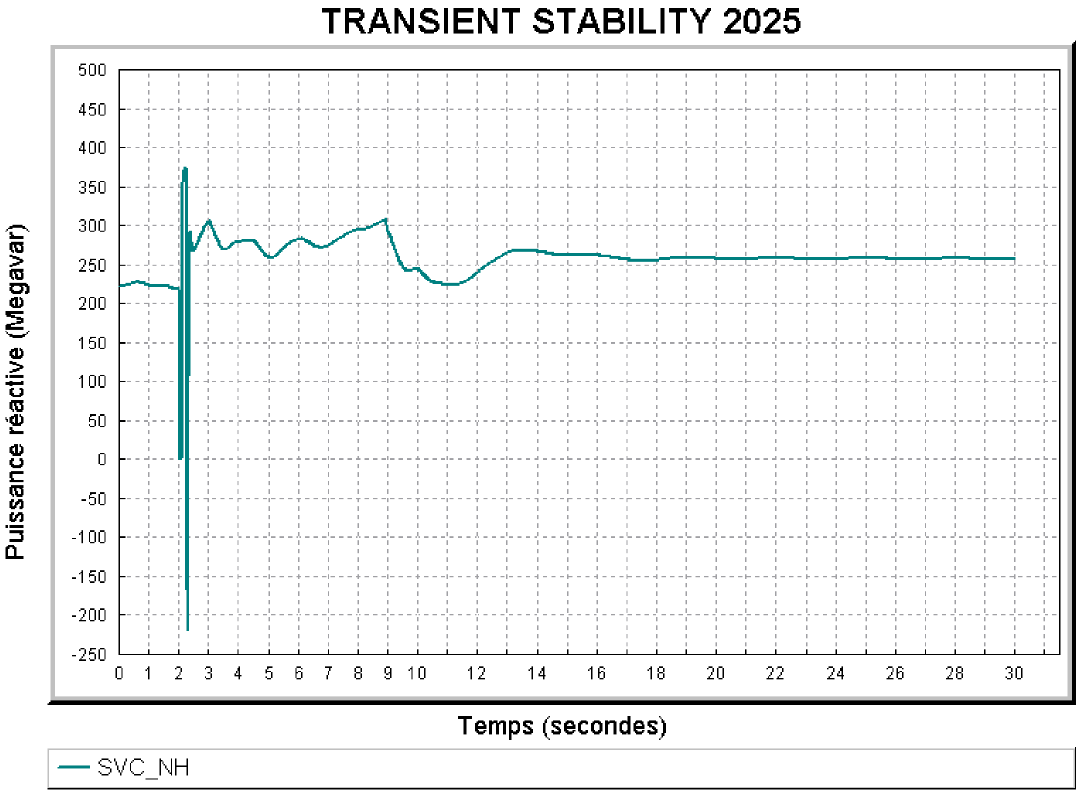


2.9.2 POWER FLOW VARIATION ON THE CIRCUIT HIGH DAM - NAG HAMMADI - ASSIUT



2.9.3 VOLTAGE VARIATION ON THE 500 KV




TRANSIENT STABILITY 2025
Puissance réactive (Megavar)
500
450
400
350
300
250
200
150
100
50
0
-50
-100
-150
-200
-250
0 1 2 3 4 5 6 7 8 9 10 12 14 16 18 20 22 24 26 28 30
Temps (secondes)
SVC_NH

2.10 SHORT-CIRCUIT AT NAG HAMMADI ON NH500 - ASSIUT CIRCUIT

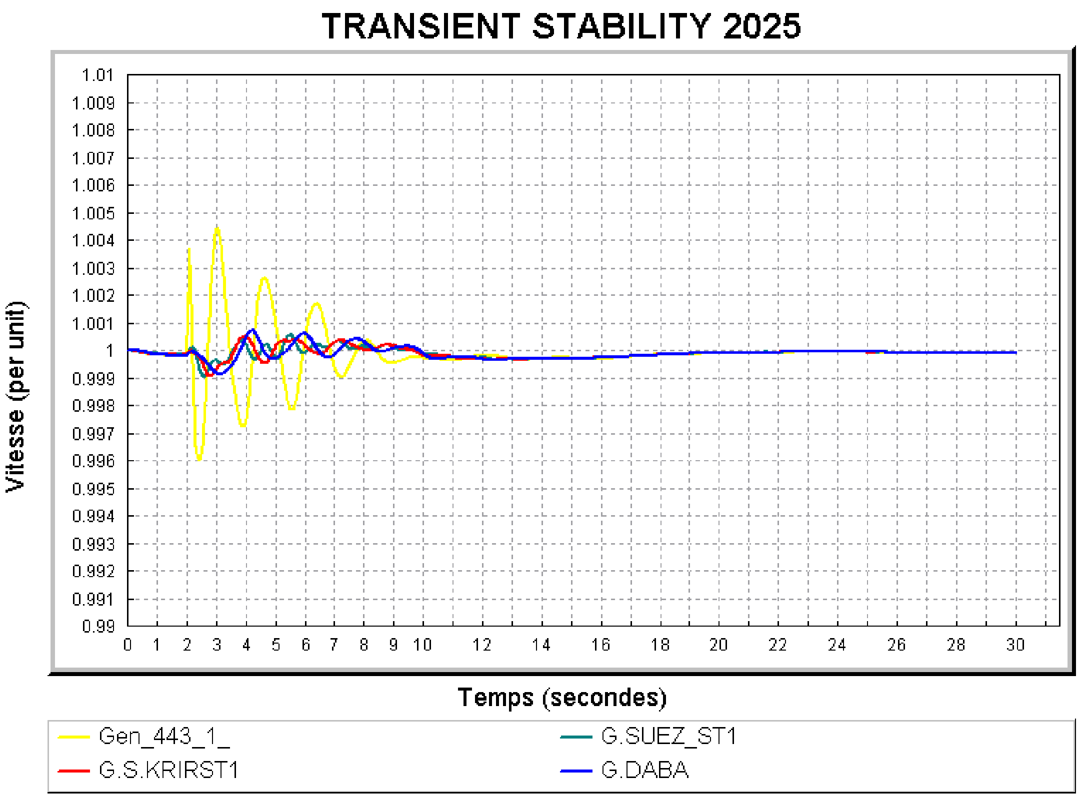
Event : a 3 phase short-circuit at Nag Hammadi end, on the circuit Nag Hammadi - Assiut, cleared in 100 ms by the opening of the circuit breakers.

The voltage drop in Nag Hammadi (to 0 pu) led to a transitory blocking of commutation of the inverter station at Nag Hammadi. The flow on the DC interconnection is transitory reduced to 0, before starting, 300 ms after the voltage return, its recovery to its initial value.

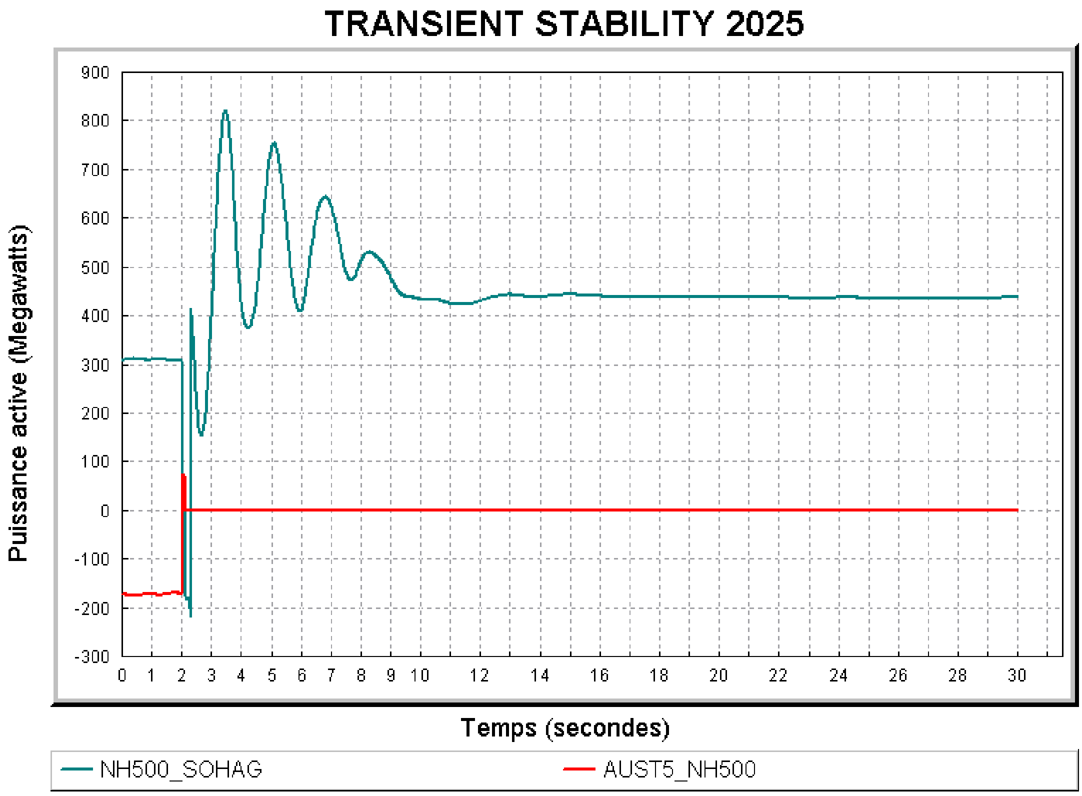
During the transitory blocking of the DC stations, the capacitors bank remained connected.

For the Ethiopian and Sudanese side, the impact on the system and its behaviour is very similar to the case of SC on High Dam - Nag Hammadi

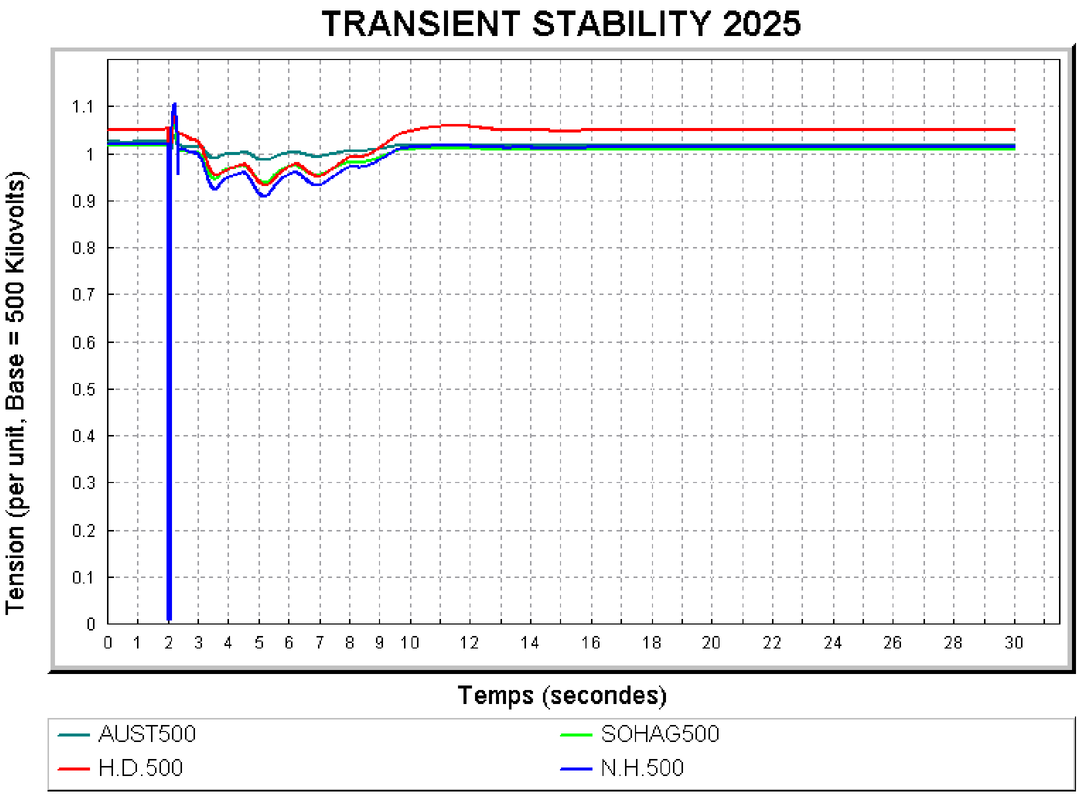
2.10.1 GENERATOR FREQUENCY VARIATION

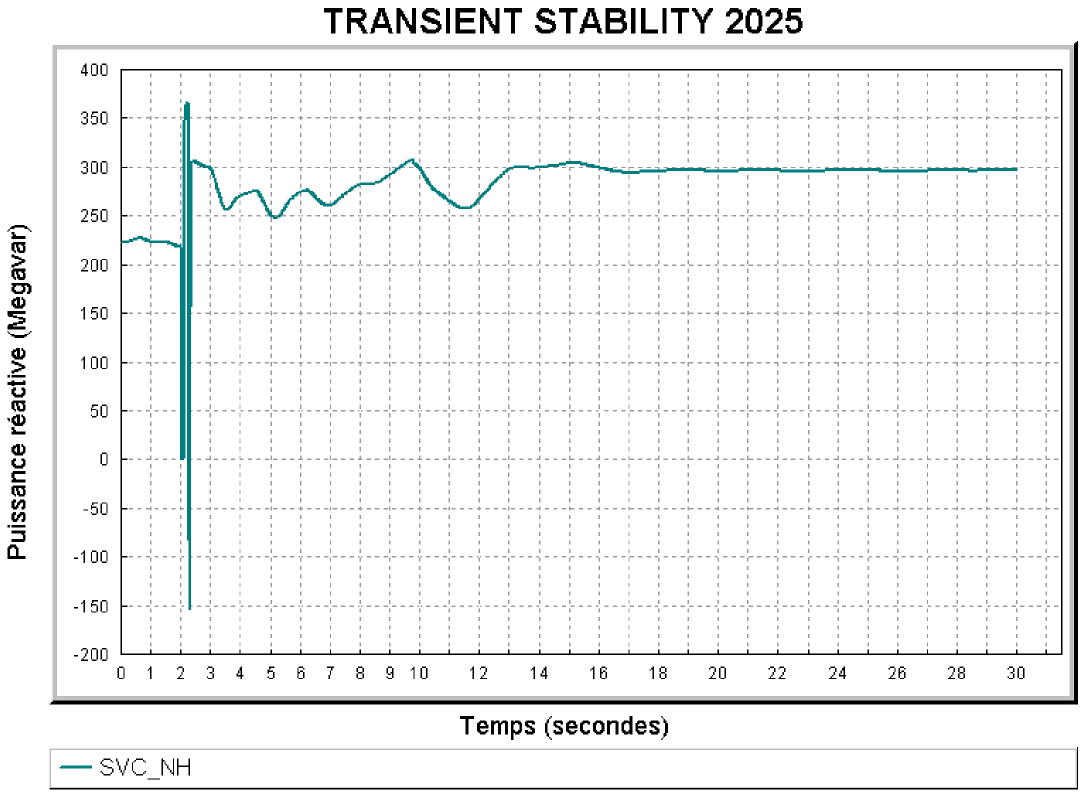


2.10.2 POWER FLOW VARIATION ON THE CIRCUIT HIGH DAM - NAG HAMMADI - SOHAG



2.10.3 VOLTAGE VARIATION ON THE 500 KV

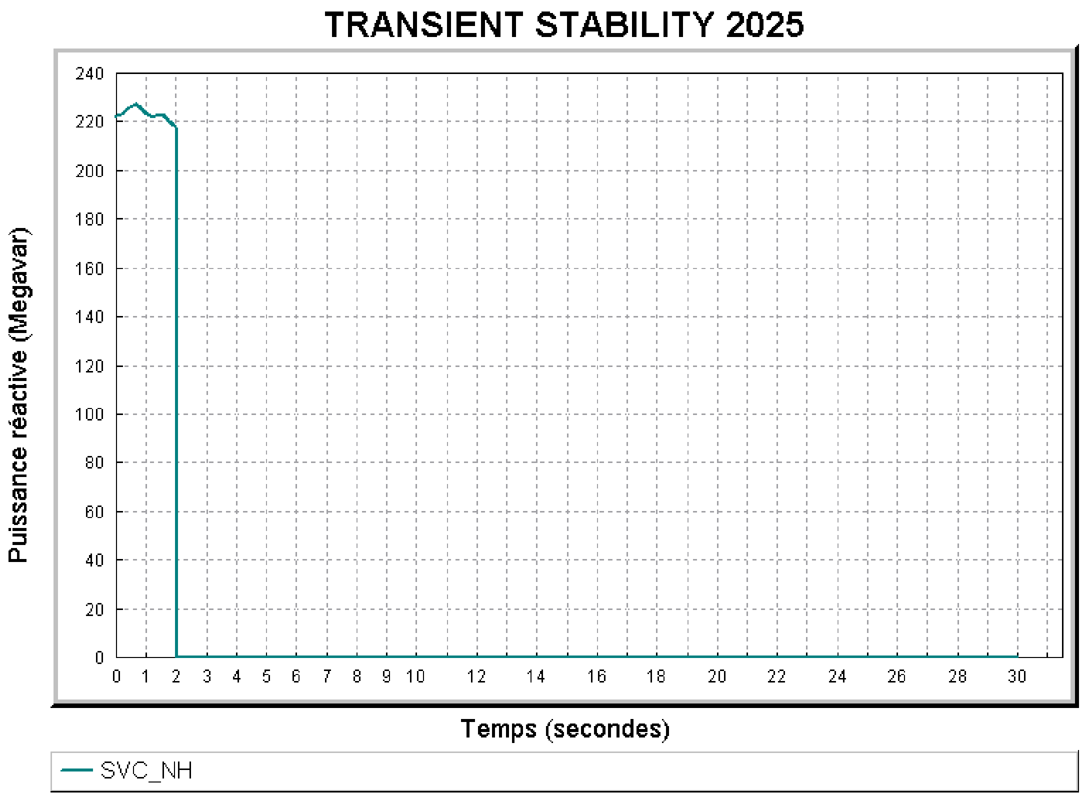



TRANSIENT STABILITY 2025
Puissance réactive (Megavar)
400
350
300
250
200
150
100
50
0
-50
-100
-150
-200
0
1
2
3
4
5
6
7
8
9
10
12
14
16
18
20
22
24
26
28
30
Temps (secondes)
SVC_NH

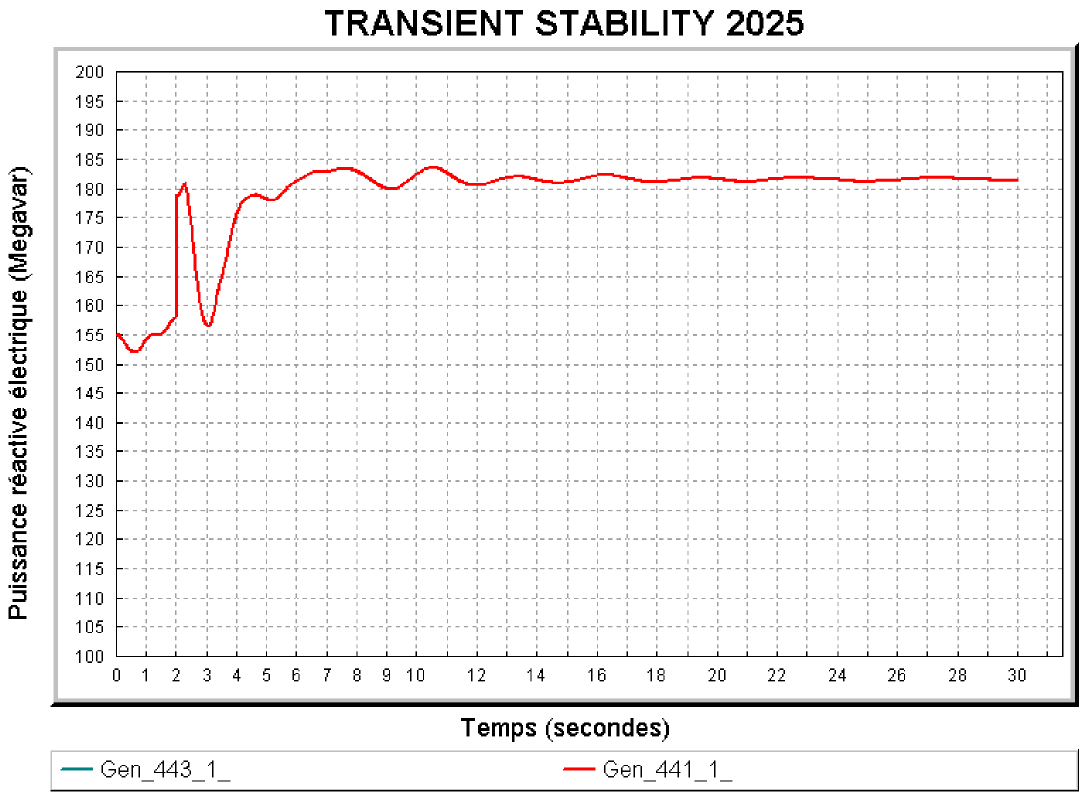
2.11 TRIPPING OF THE 300MVAR SVC AT NAG HAMMADI

Event: The 300MVAr SVC at Nag Hammadi was tripped, it generated 220MVAr.

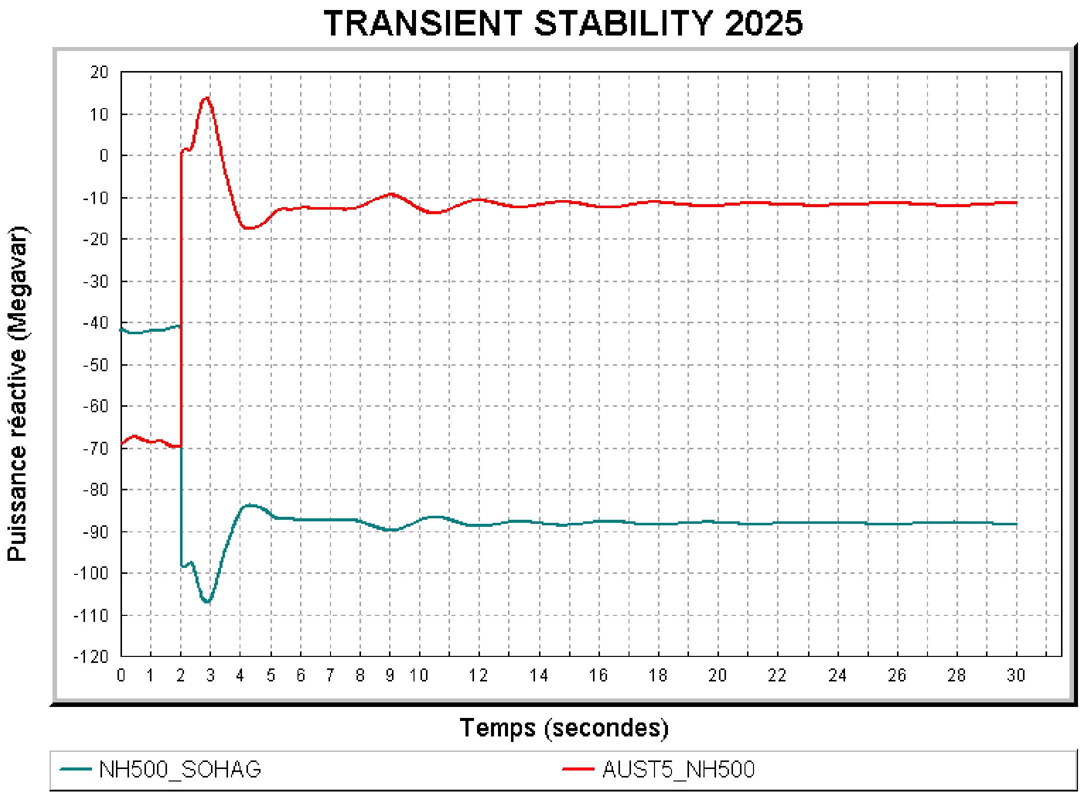
2.11.1 REACTIVE GENERATION OF THE SVC



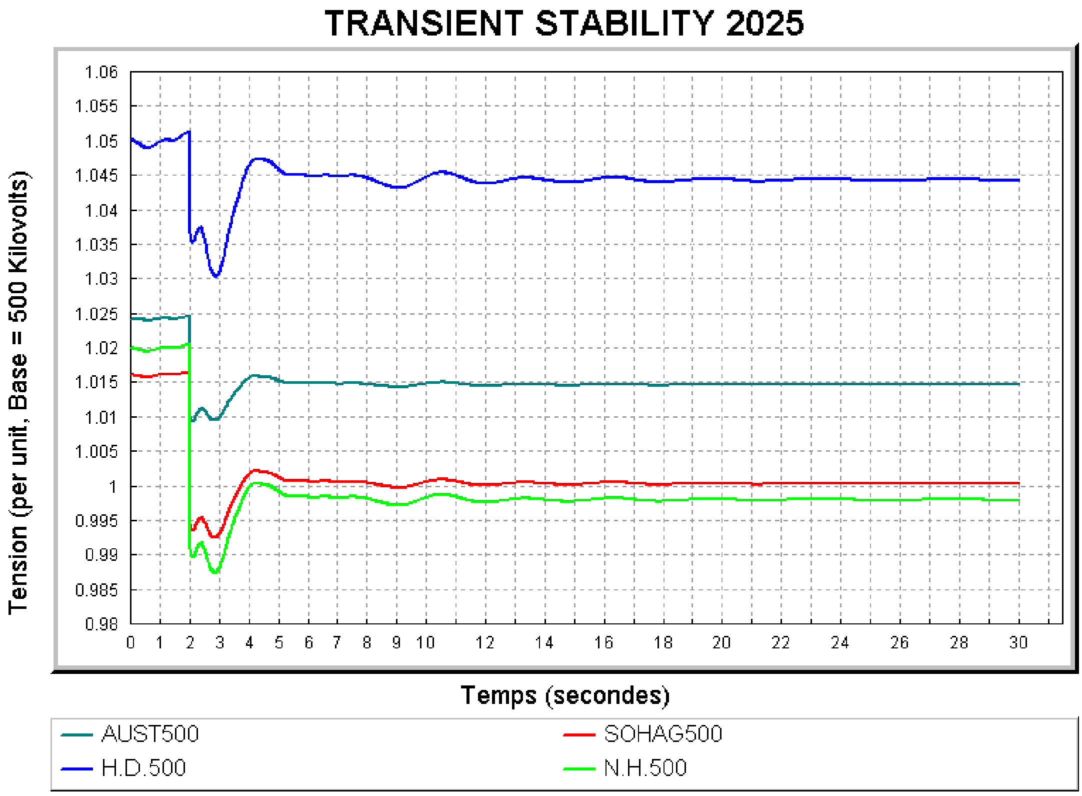
2.11.2 REACTIVE GENERATION OF THE HIGH DAM GENERATORS



2.11.3 REACTIVE FLOW OVER NAG HAMMADI ASSIUT AND NAG HAMMADI SOHAG CIRCUITS



2.11.4 VOLATGE PROFILE AT NAG HAMMADI, SOHAG, ASSIUT AND HIGH DAM



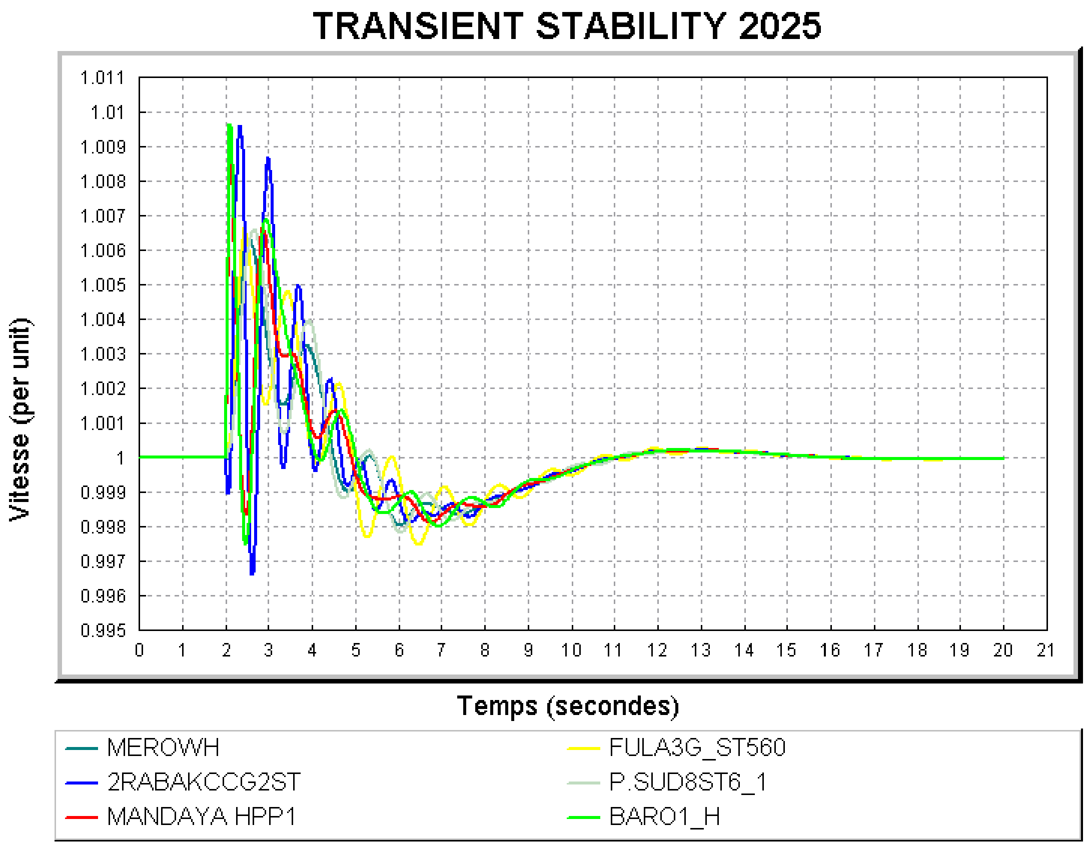
2.12 SHORT-CIRCUIT AT MANDAYA ON ONE OF THE 3 CIRCUITS MANDAYA - GHIMBI

Event : a 3 phase short-circuit at Mandaya end, on one of the 3 circuits Mandaya - Ghimbi, cleared in 100 ms by the opening of the circuit breakers.

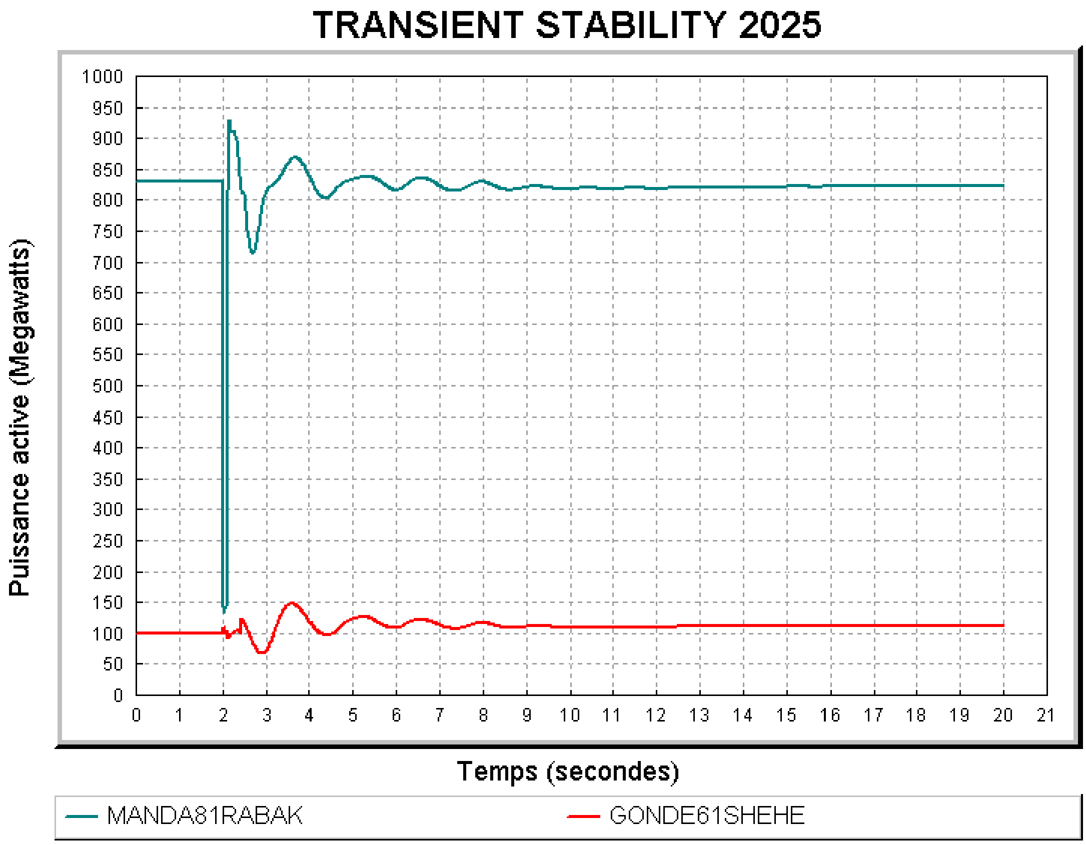
The voltage drop in Kosti led to a transitory blocking of commutation of the rectifier station at Kosti. The flow on the DC interconnection is transitory reduced to 0, before starting, 300 ms after the voltage return, its recovery to its initial value.

During the transitory blocking of the DC stations, the capacitors bank remained connected.

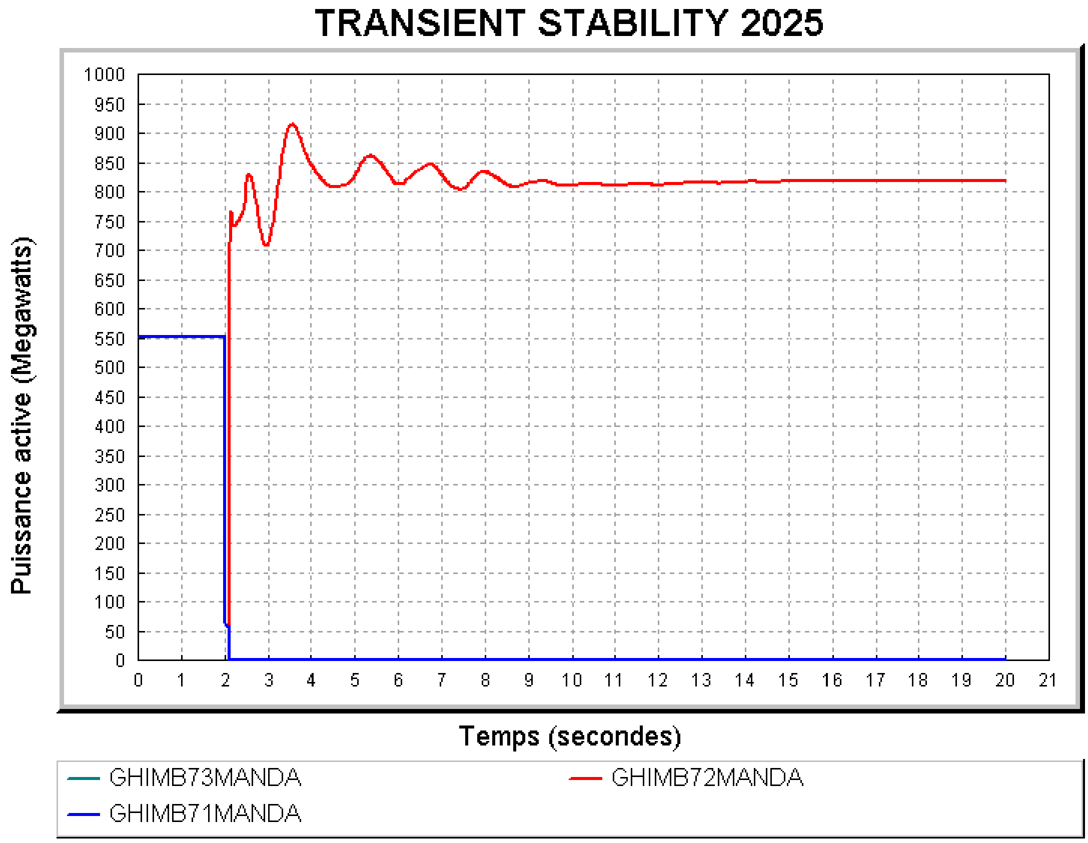
2.12.1 GENERATOR FREQUENCY VARIATION



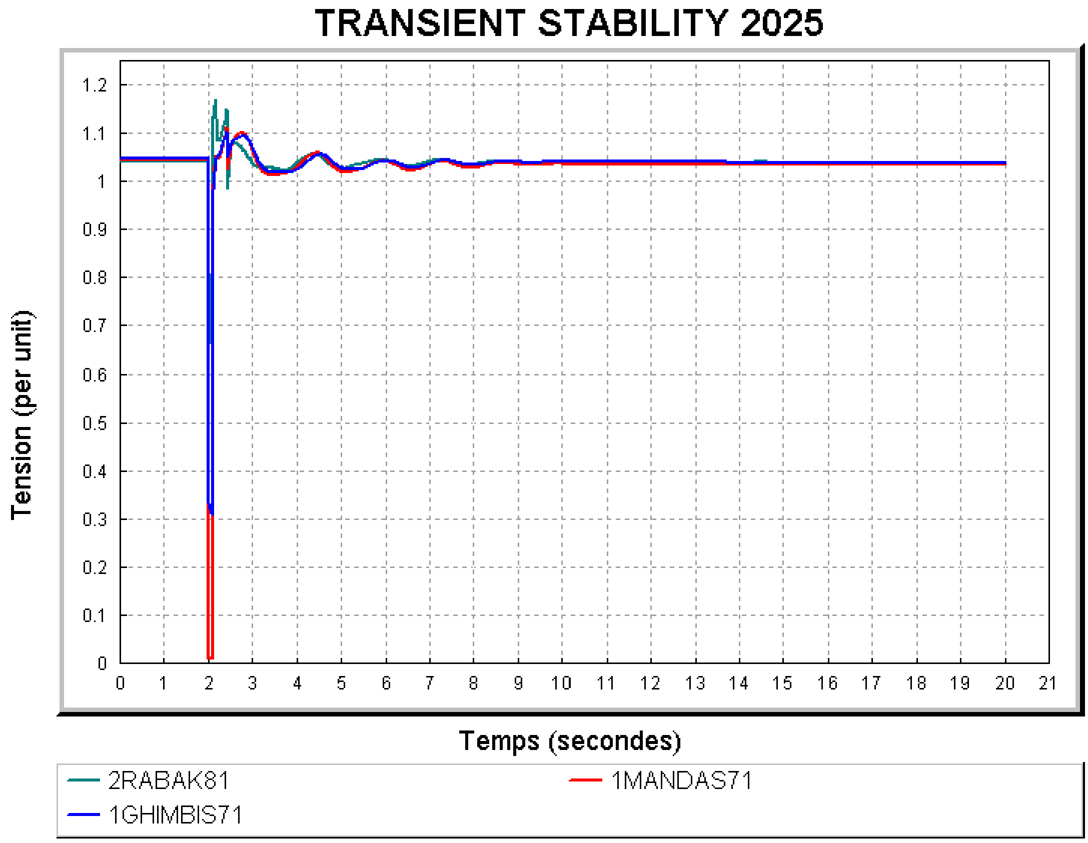
2.12.2 POWER FLOW VARIATION ON ENTRO INTERCONNECTION



2.12.3 POWER FLOW VARIATION ON MANDAYA - GHIMBI



2.12.4 VOLTAGE VARIATION ON THE 500 KV AND 400KV SUBSTATIONS



2.13 SHORT-CIRCUIT AT KARADOBI ON ONE OF THE 2 CIRCUITS KARADOBI - GHEDO

Event : a 3 phase short-circuit at Karadobi end, on one of the 2 circuits Karadobi - Ghedo, cleared in 100 ms by the opening of the circuit breakers.

Following the fault, the behaviour of the interconnected system was satisfactory, Sudan and Ethiopia operated in synchronism.

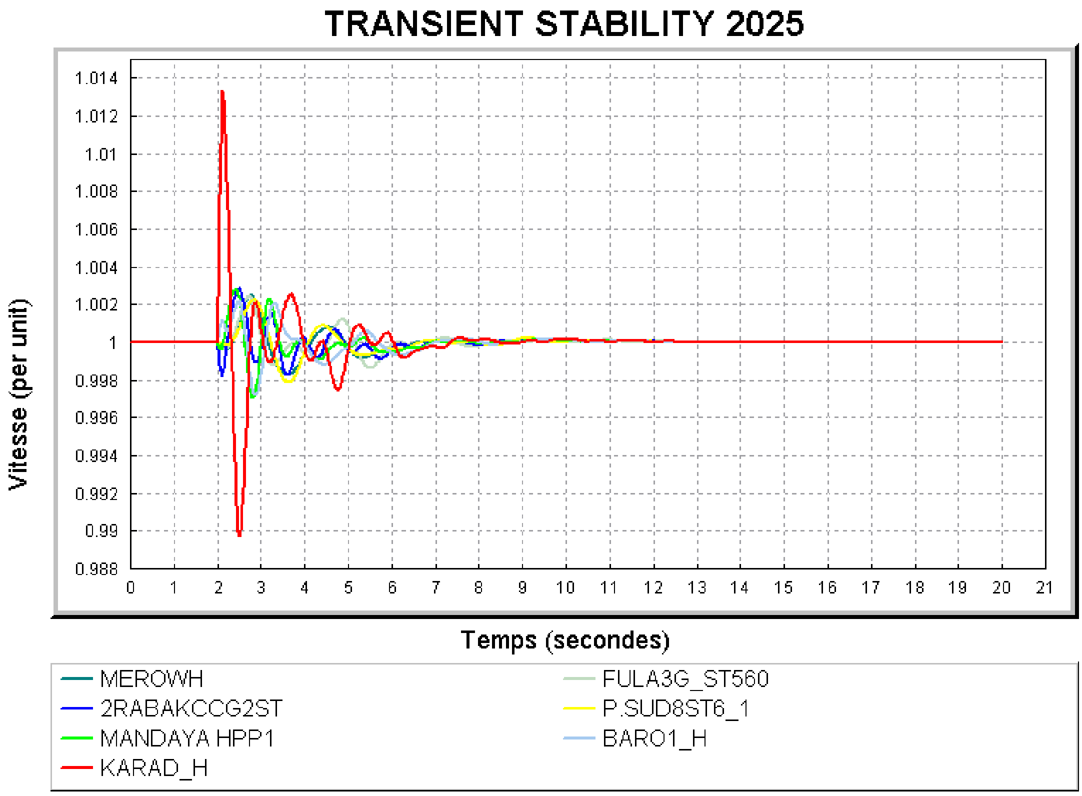
The voltage at Kosti remained above 0.9 p.u. therefore the operation of the converter station was satisfactory, there was no blocking of the station. The power exchange on the DC interconnection was kept constant.

The power oscillations on the remaining Karadobi Ghedo circuit were totally damped in 6 seconds. The transient power surge reached 1 400MW. The power flow stabilized at 900MW, below the thermal limit of a circuit equipped with 3 bundle conductors.

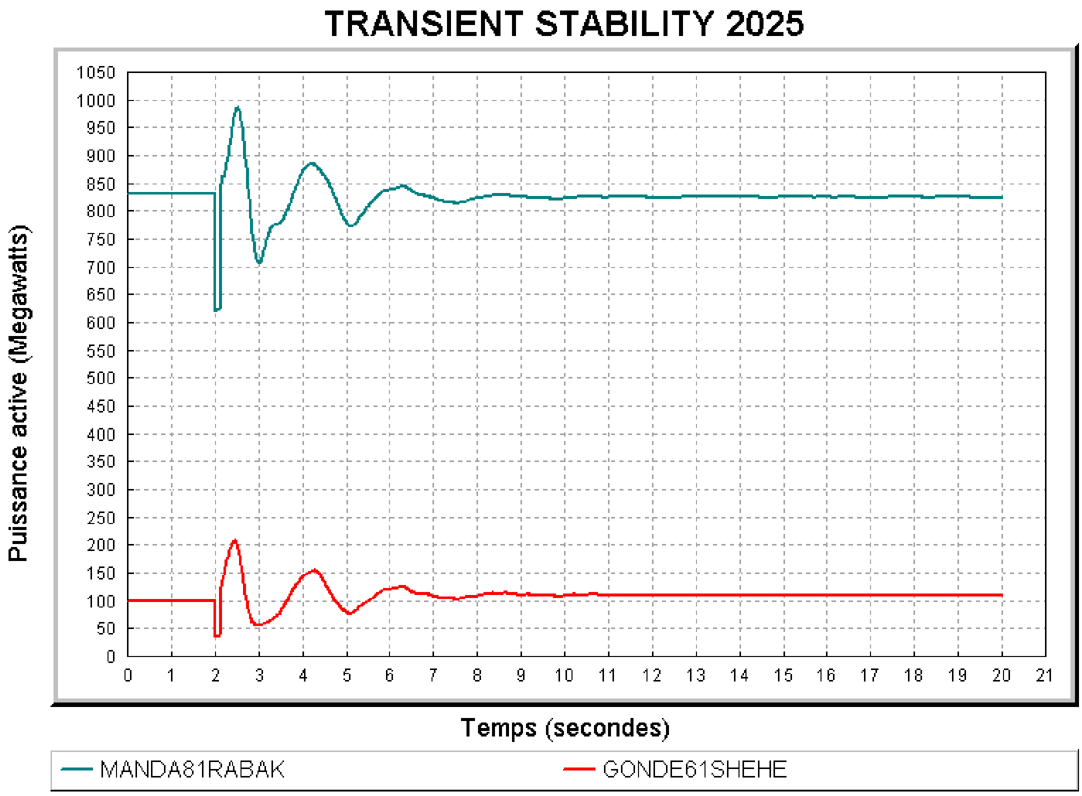
The power flows over the 500kV and 200kV AC interconnections were very slightly affected. The power exchange increased up to 20MW over the 220kV interconnection.

The frequency surge of Karadobi unit reached 1.3% (50.67Hz). The system frequency recovered its initial value in 7 seconds.

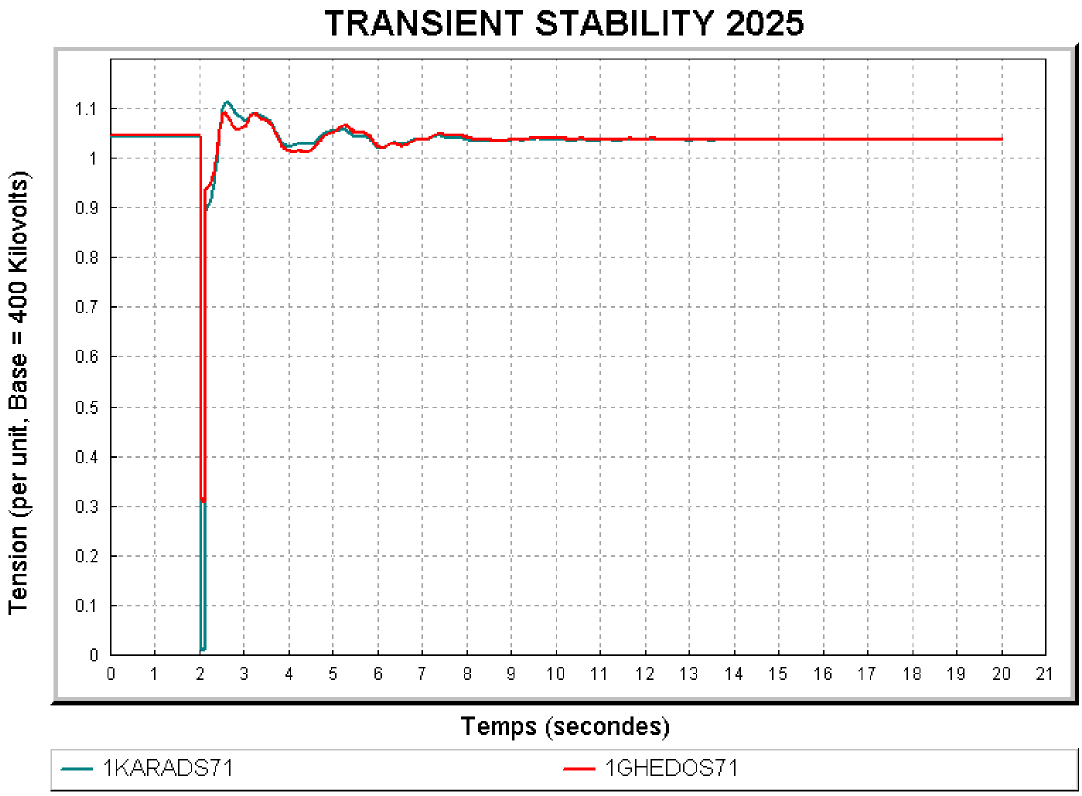
2.13.1 GENERATOR FREQUENCY VARIATION



2.13.2 POWER FLOW VARIATION ON ENTRO INTERCONNECTION



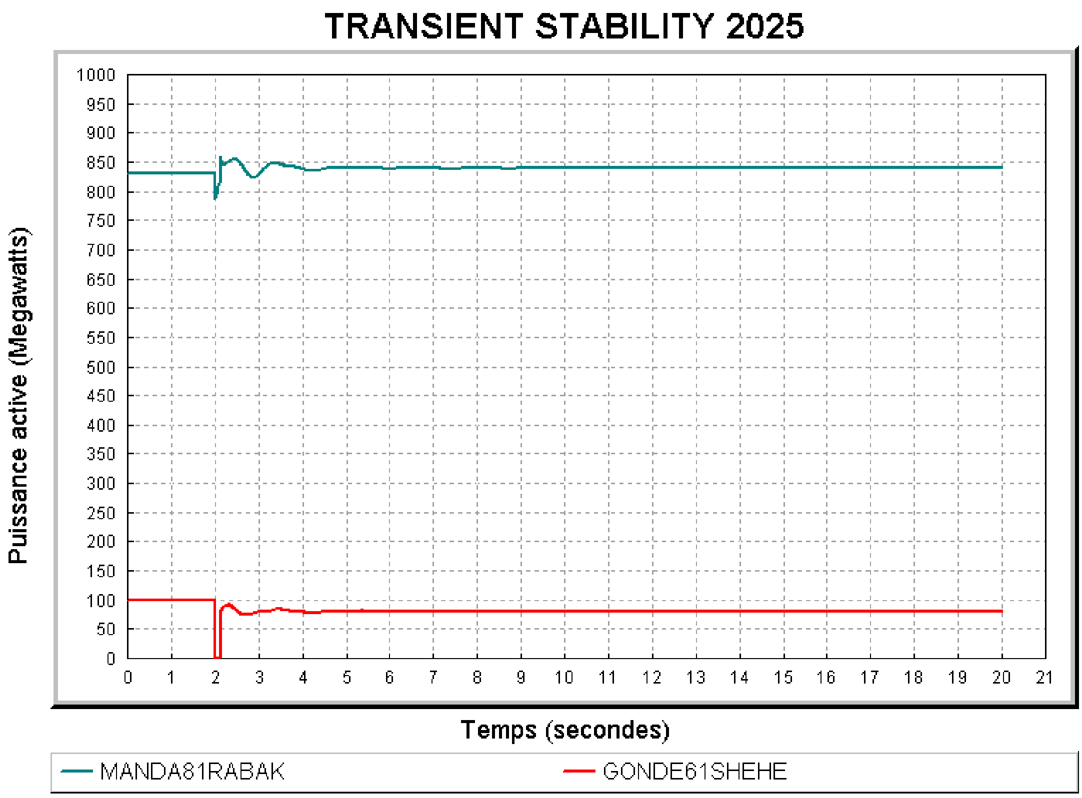
2.13.3 VOLTAGE VARIATION ON THE 400 KV



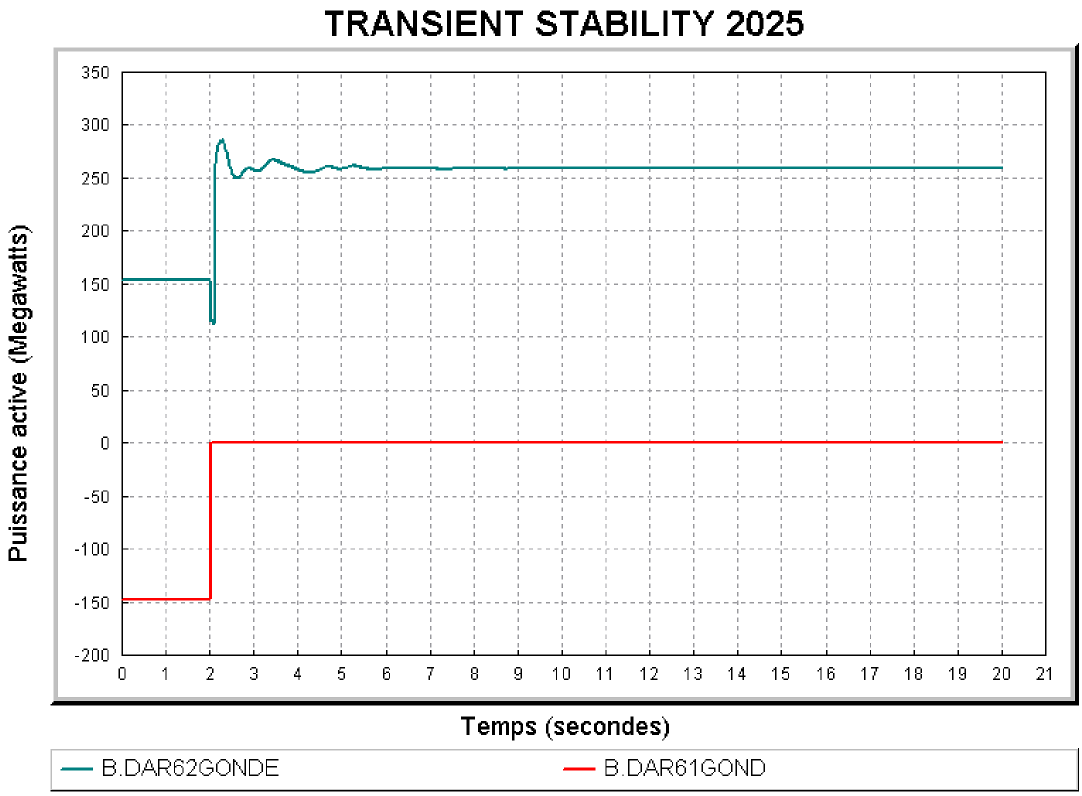
2.14 SHORT-CIRCUIT AT GONDER 230 KV BUSBAR, ON ONE OF THE TWO 230 KV CIRCUITS GONDER – BAHIR DAR

Event : a 3 phase short-circuit at Gonder end, on one of the two circuits Gonder – Bahir Dar. It was cleared in 100 ms by opening of the two circuit breakers.

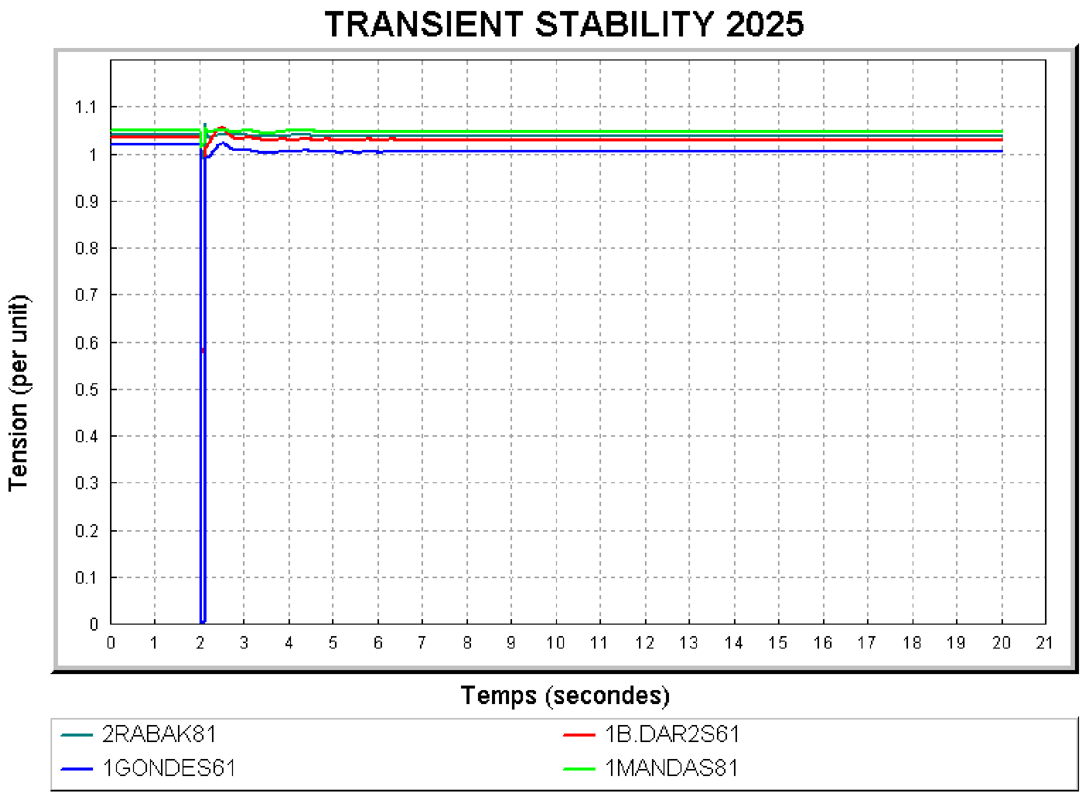
2.14.1 POWER FLOW VARIATION ON ENTRO INTERCONNECTION



2.14.2 POWER FLOW VARIATION ON GONDER – BAHIR DAR 230KV



2.14.3 VOLTAGE VARIATION ON THE 500 KV AND 230KV SUBSTATIONS



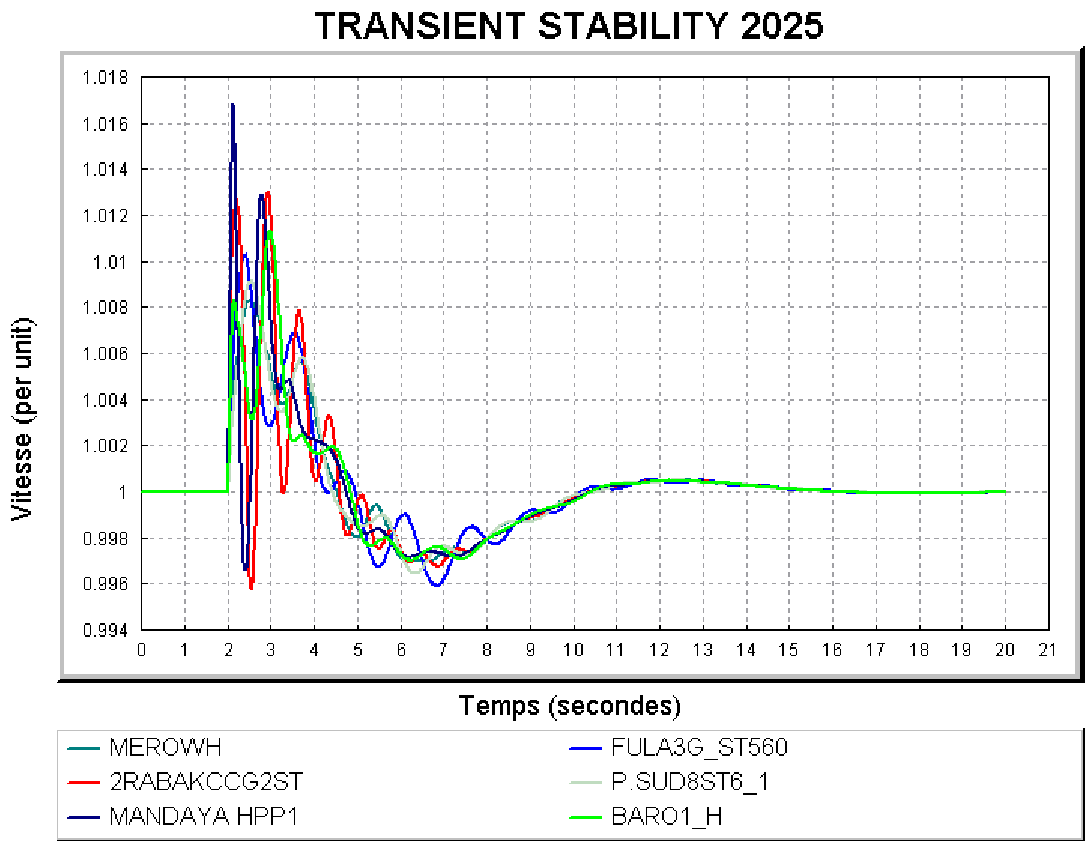
2.15 SHORT-CIRCUIT AT KOSTI ON KOSTI - FULA

Event : a 3 phase short-circuit at Kosti end, on one of the 2 circuits Kosti - Fula, cleared in 120 ms by the opening of the circuit breakers.

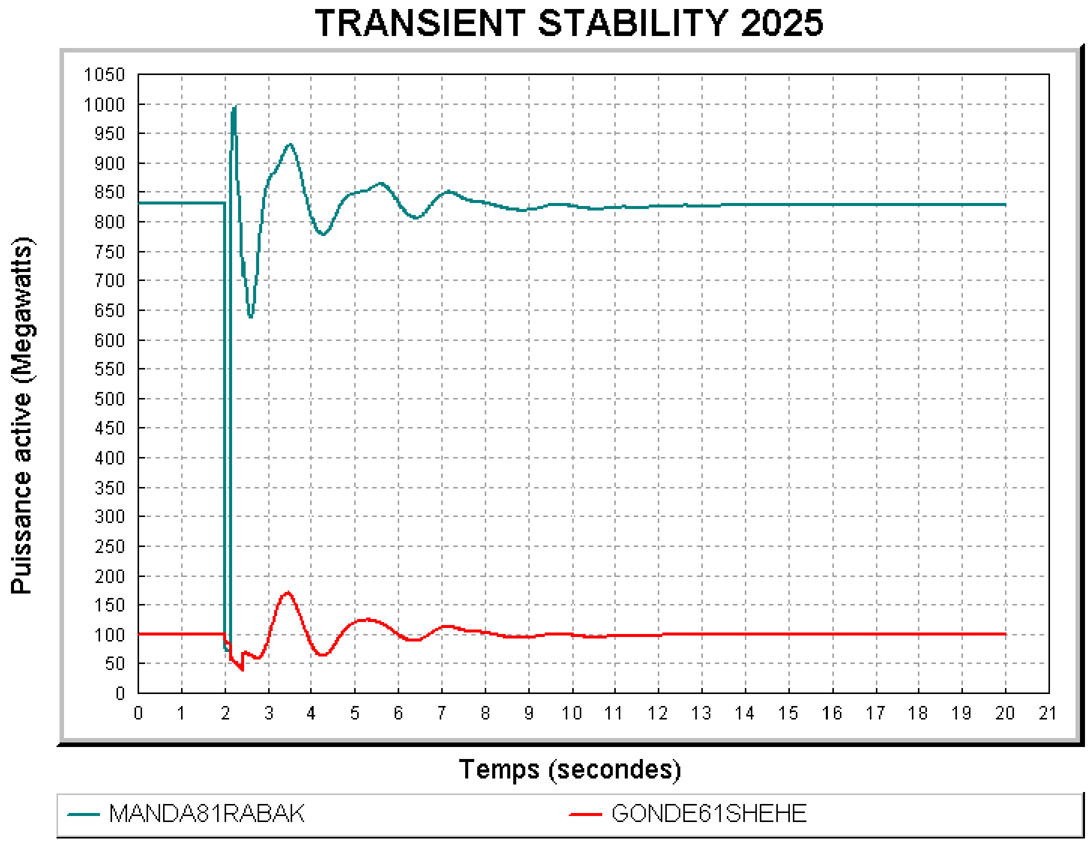
The voltage drop in Kosti led to a transitory blocking of commutation of the rectifier station at Kosti. The flow on the DC interconnection was transitory reduced to 0, before starting, 300 ms after the voltage return, its recovery to its initial value.

During the transitory blocking of the DC stations, the capacitors bank remained connected.

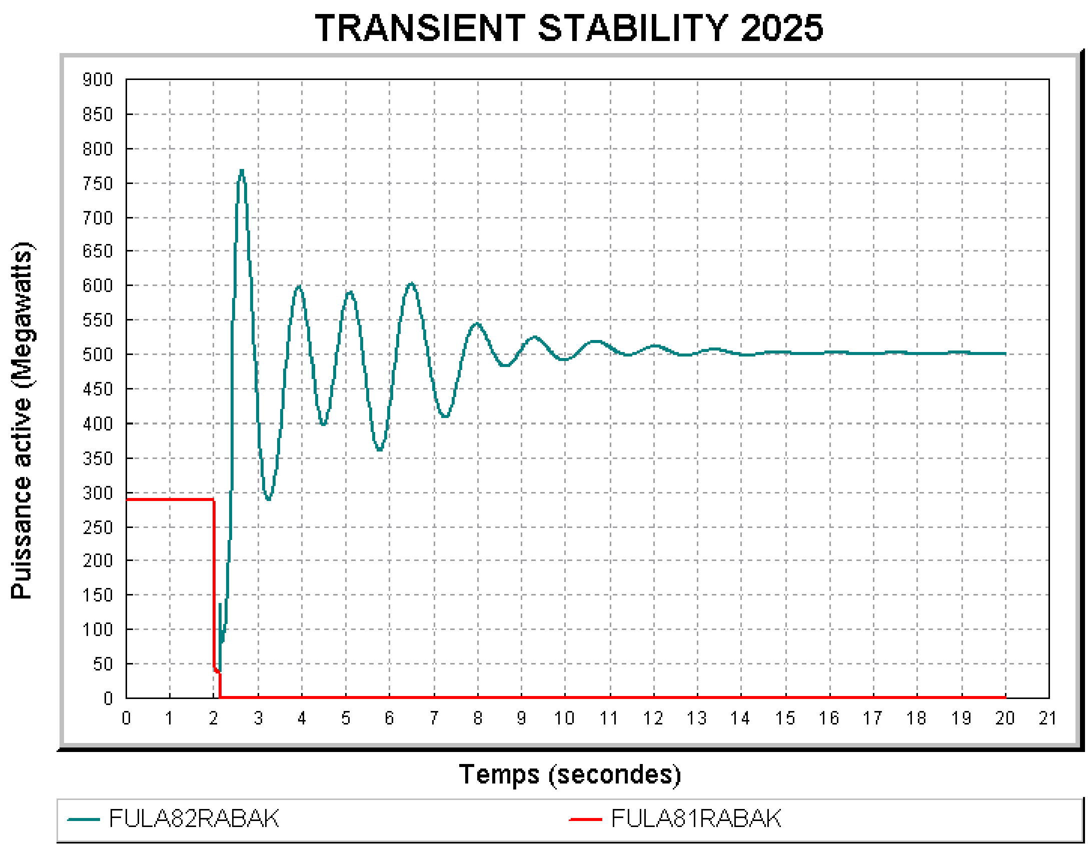
2.15.1 GENERATOR FREQUENCY VARIATION



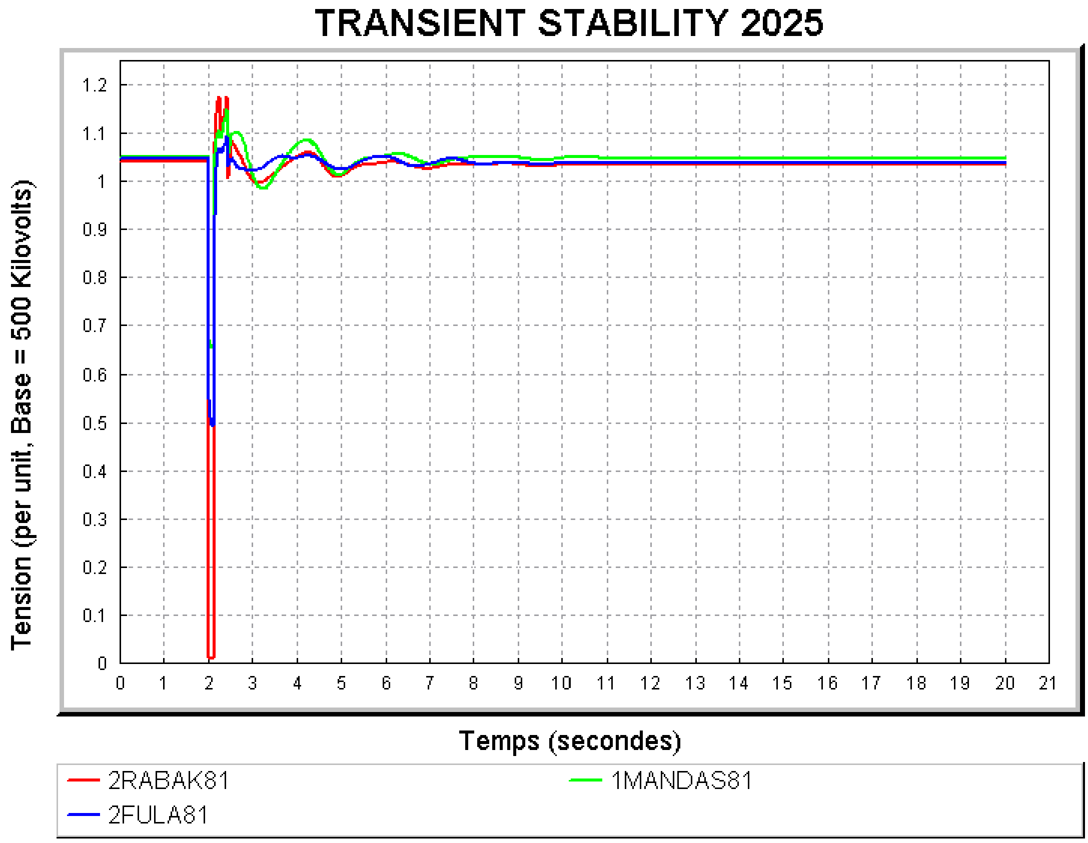
2.15.2 POWER FLOW VARIATION ON ENTRO INTERCONNECTION

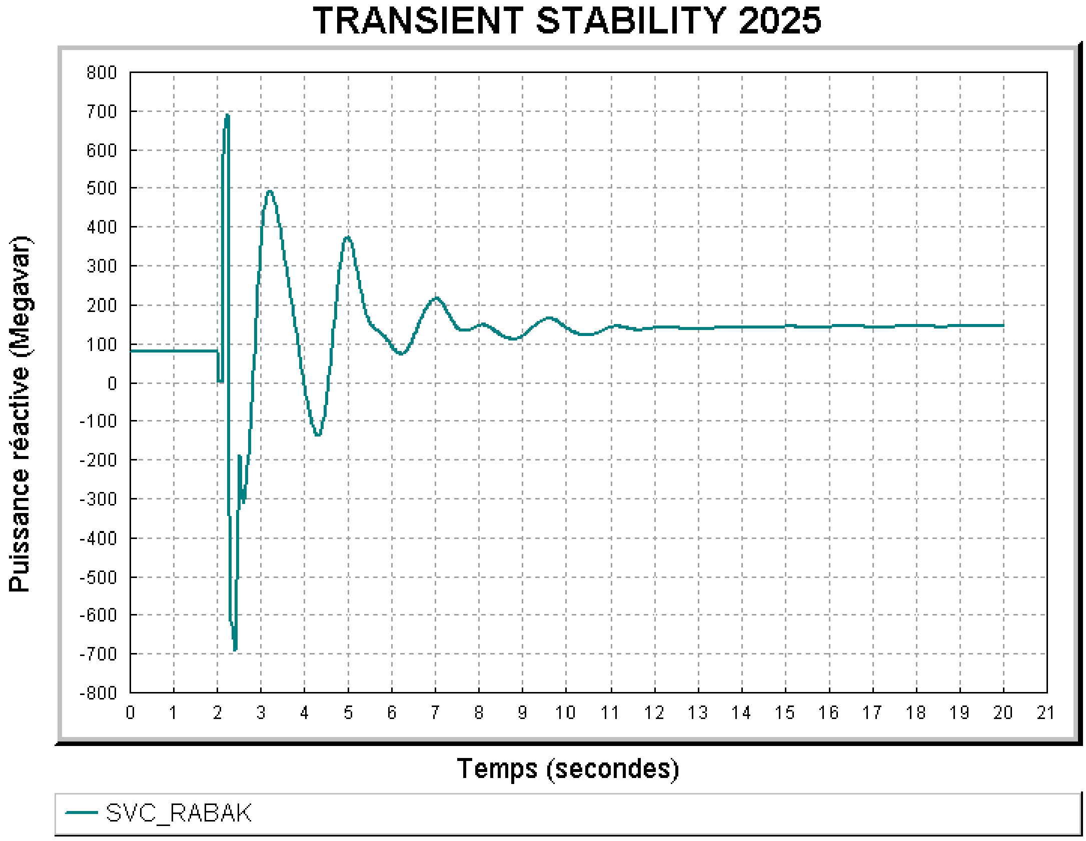


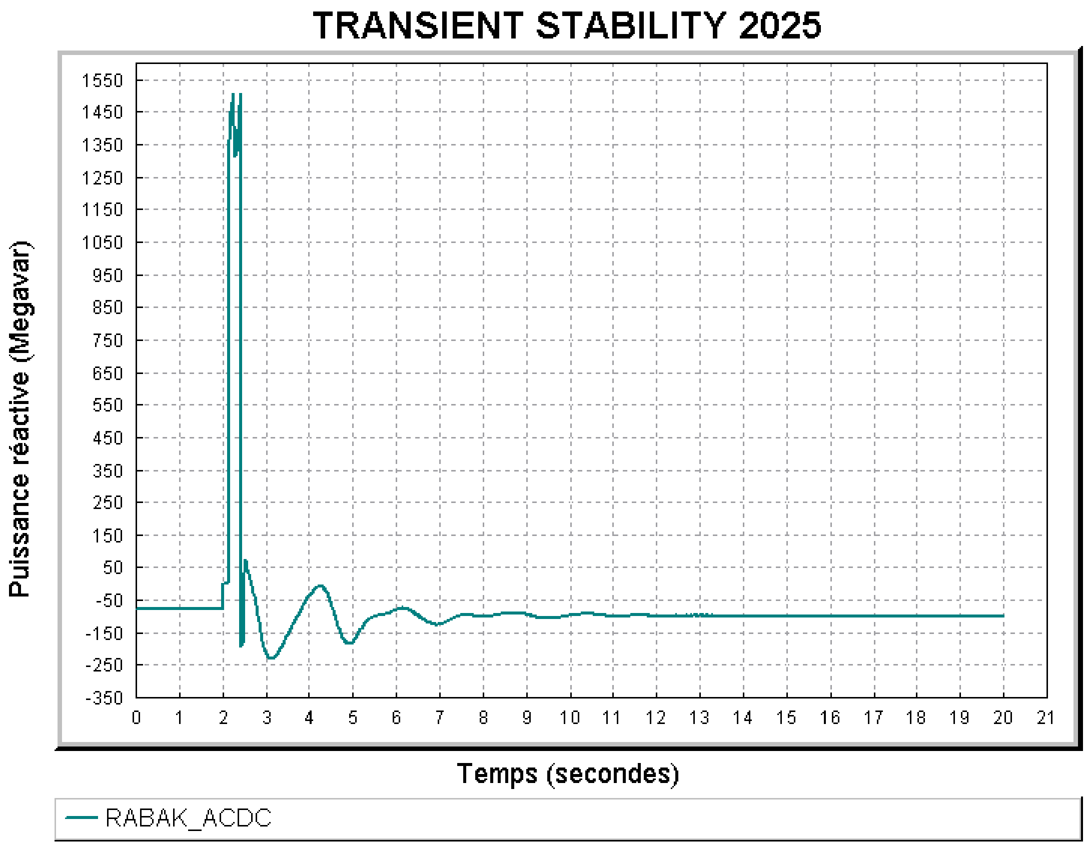
2.15.3 POWER FLOW VARIATION ON KOSTI - FULA



2.15.4 VOLTAGE VARIATION ON THE 500 KV




TRANSIENT STABILITY 2025
Puissance réactive (Megavar)
800
700
600
500
400
300
200
100
0
-100
-200
-300
-400
-500
-600
-700
-800
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21
Temps (secondes)
SVC_RABAK


TRANSIENT STABILITY 2025
Puissance réactive (Megavar)
1550
1450
1350
1250
1150
1050
950
850
750
650
550
450
350
250
150
50
-50
-150
-250
-350
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
Temps (secondes)
RABAK_ACDC

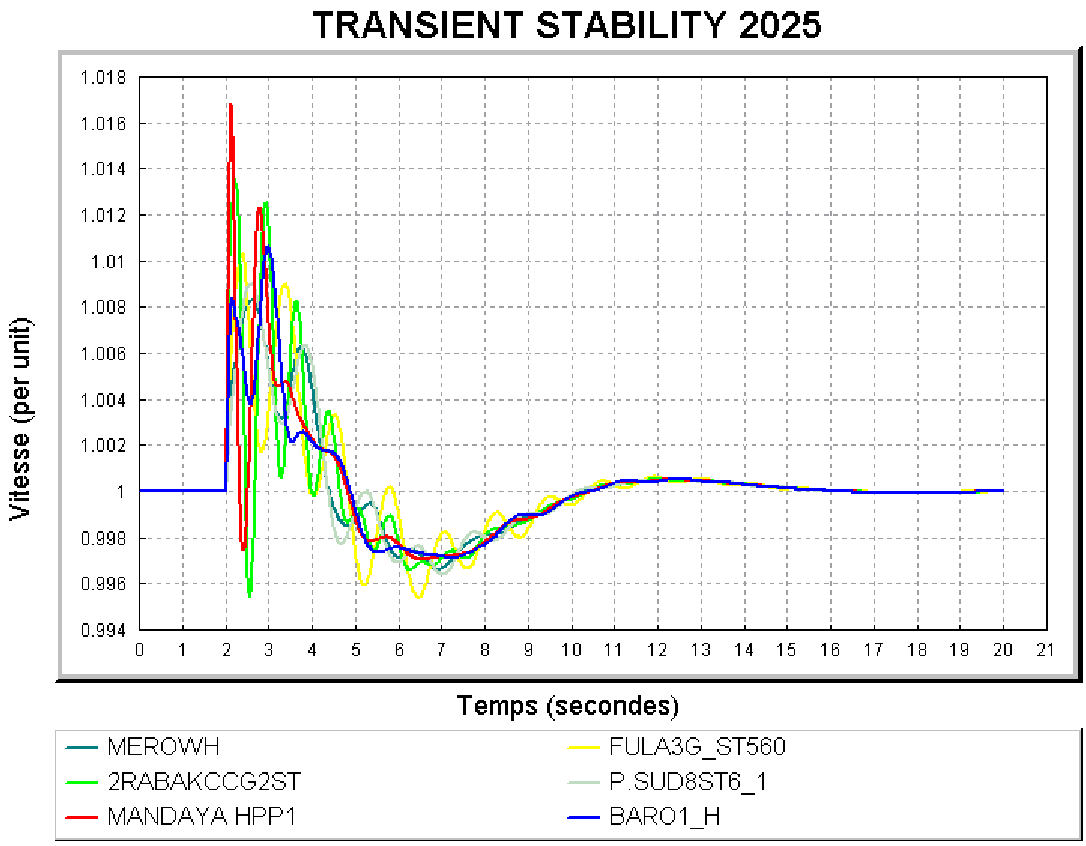
2.16 SHORT-CIRCUIT AT KOSTI ON ONE OF THE TWO 500KV KOSTI - MERINGAN

Event : a 3 phase short-circuit at Kosti end, on one of the two circuits Kosti - Meringan, cleared in 120 ms by the opening of the circuit breakers.

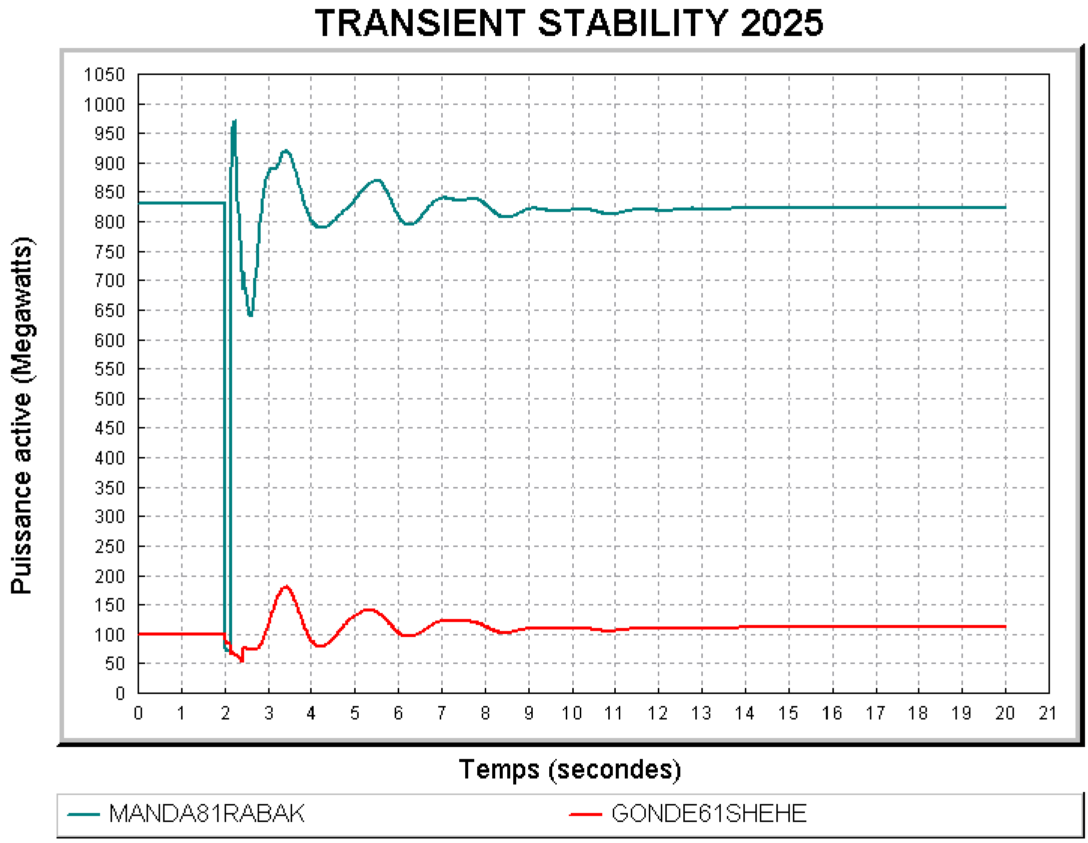
The voltage drop in Kosti led to a transitory blocking of commutation of the rectifier station at Kosti. The flow on the DC interconnection is transitory reduced to 0, before starting, 300 ms after the voltage return, its recovery to its initial value.

During the transitory blocking of the DC stations, the capacitors bank remained connected.

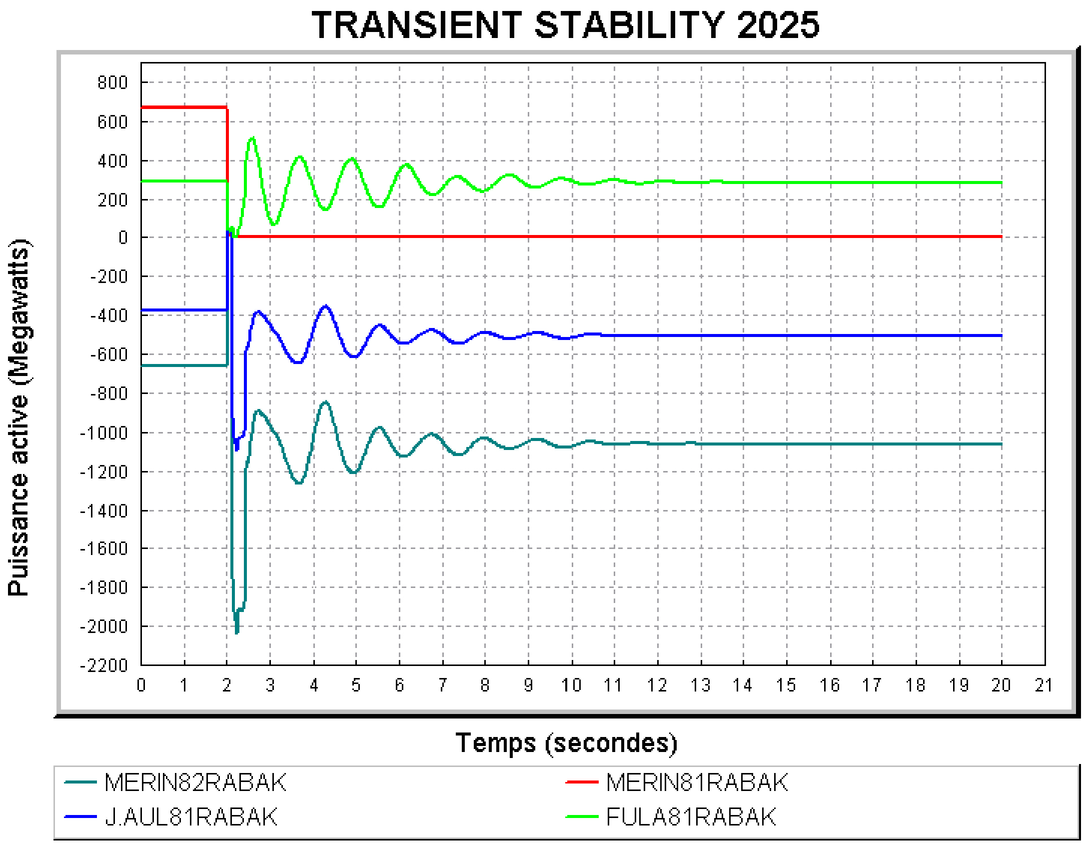
2.16.1 GENERATOR FREQUENCY VARIATION



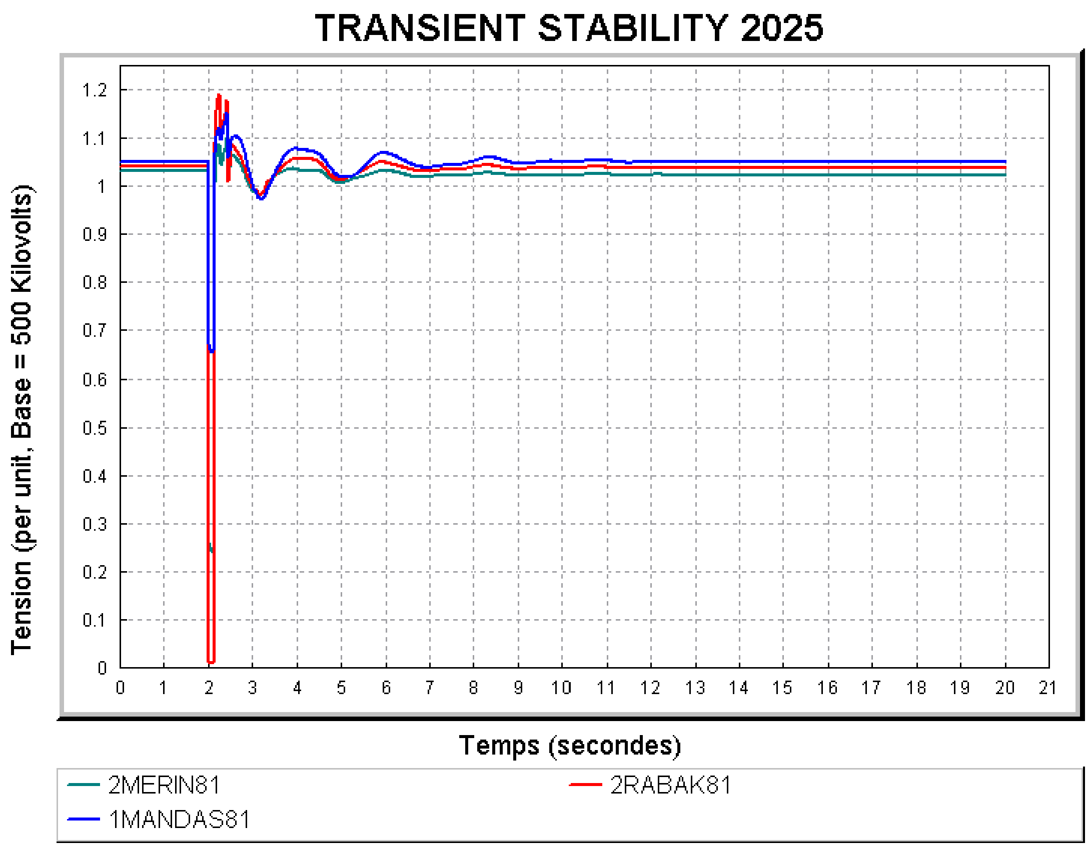
2.16.2 POWER FLOW VARIATION ON ENTRO INTERCONNECTION

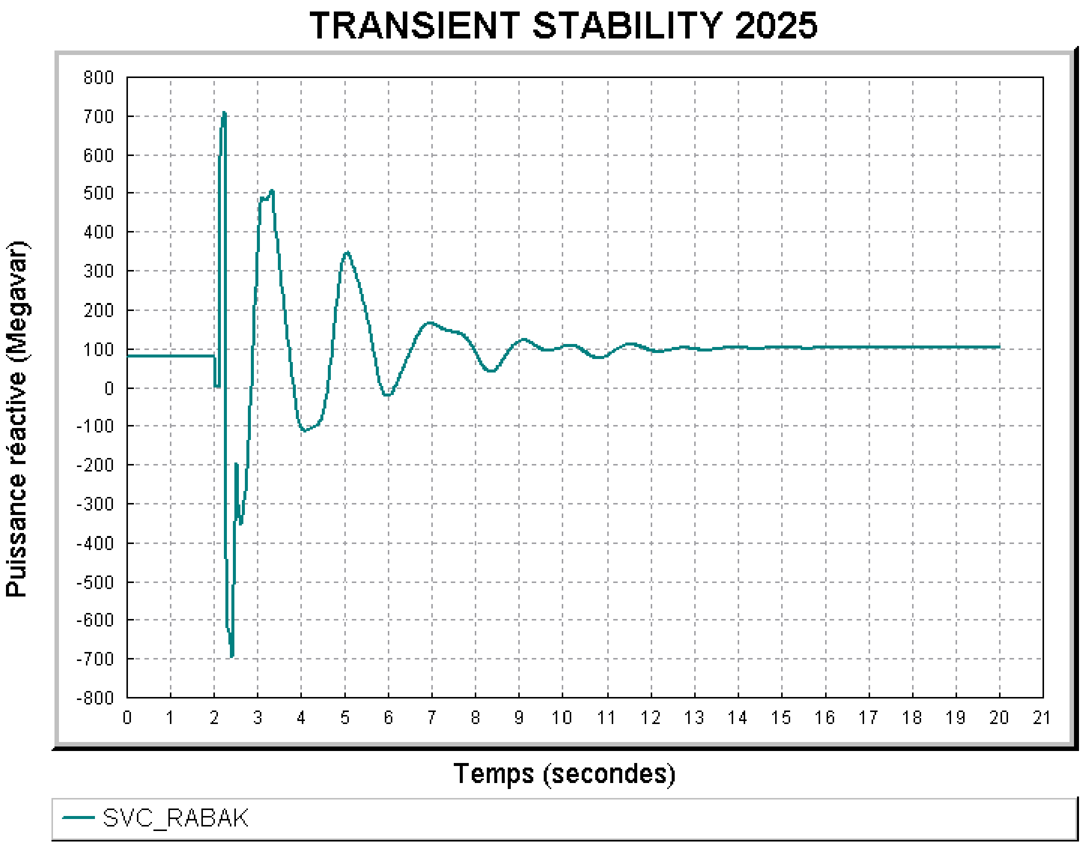


2.16.3 POWER FLOW VARIATION ON KOSTI - MERINGAN, KOSTI - FULA AND KOSTI - J. AULIA



2.16.4 VOLTAGE VARIATION ON THE 500 KV




TRANSIENT STABILITY 2025
Puissance réactive (Megavar)
800
700
600
500
400
300
200
100
0
-100
-200
-300
-400
-500
-600
-700
-800
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21
Temps (secondes)
SVC_RABAK

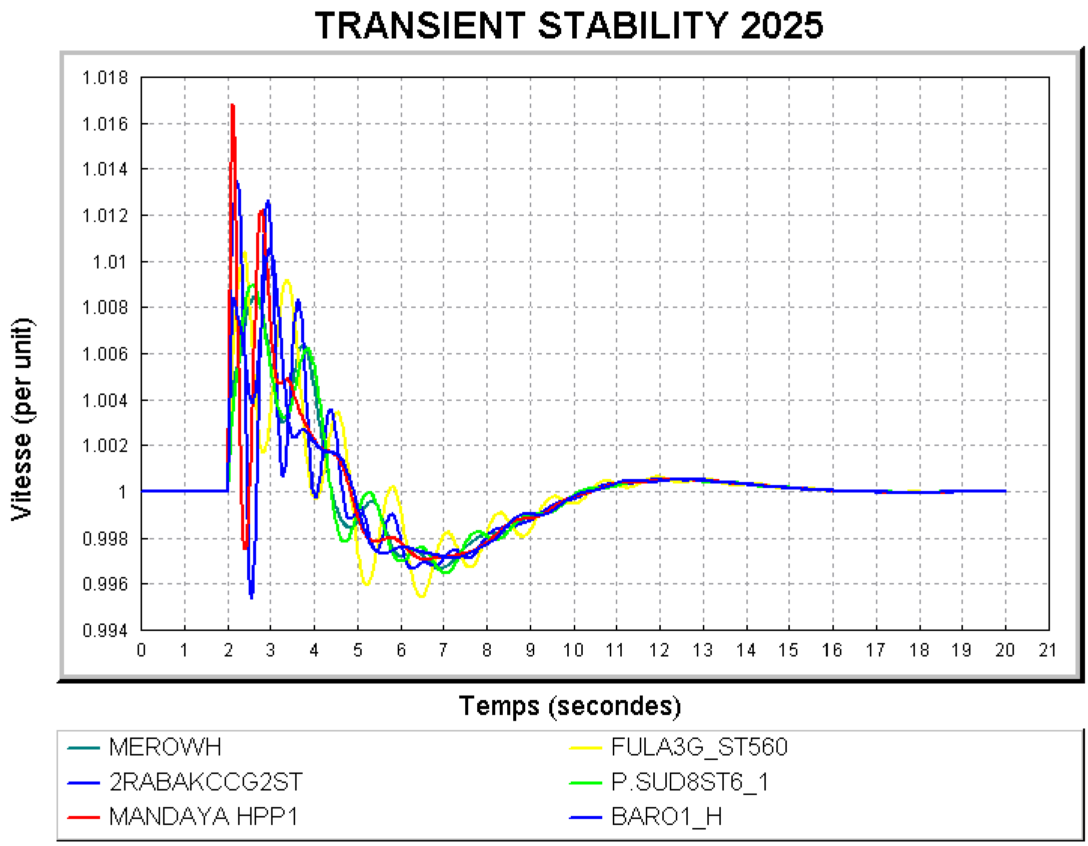
2.17 SHORT-CIRCUIT AT KOSTI ON KOSTI - JEBEL AULIA

Event : a 3 phase short-circuit at Kosti end, on the circuit Kosti – Jebel Aulia, cleared in 120 ms by the opening of the circuit breakers.

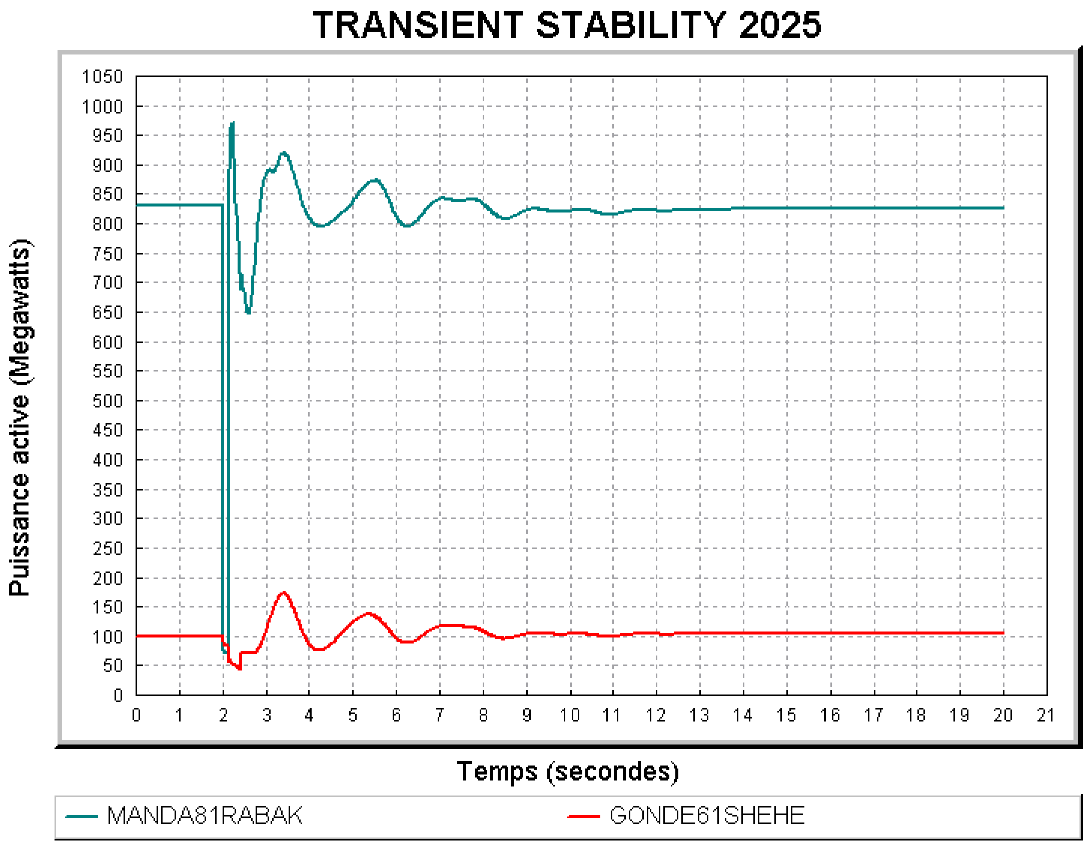
The voltage drop in Kosti led to a transitory blocking of commutation of the rectifier station at Kosti. The flow on the DC interconnection is transitory reduced to 0, before starting, 300 ms after the voltage return, its recovery to its initial value.

During the transitory blocking of the DC stations, the capacitors bank remained connected.

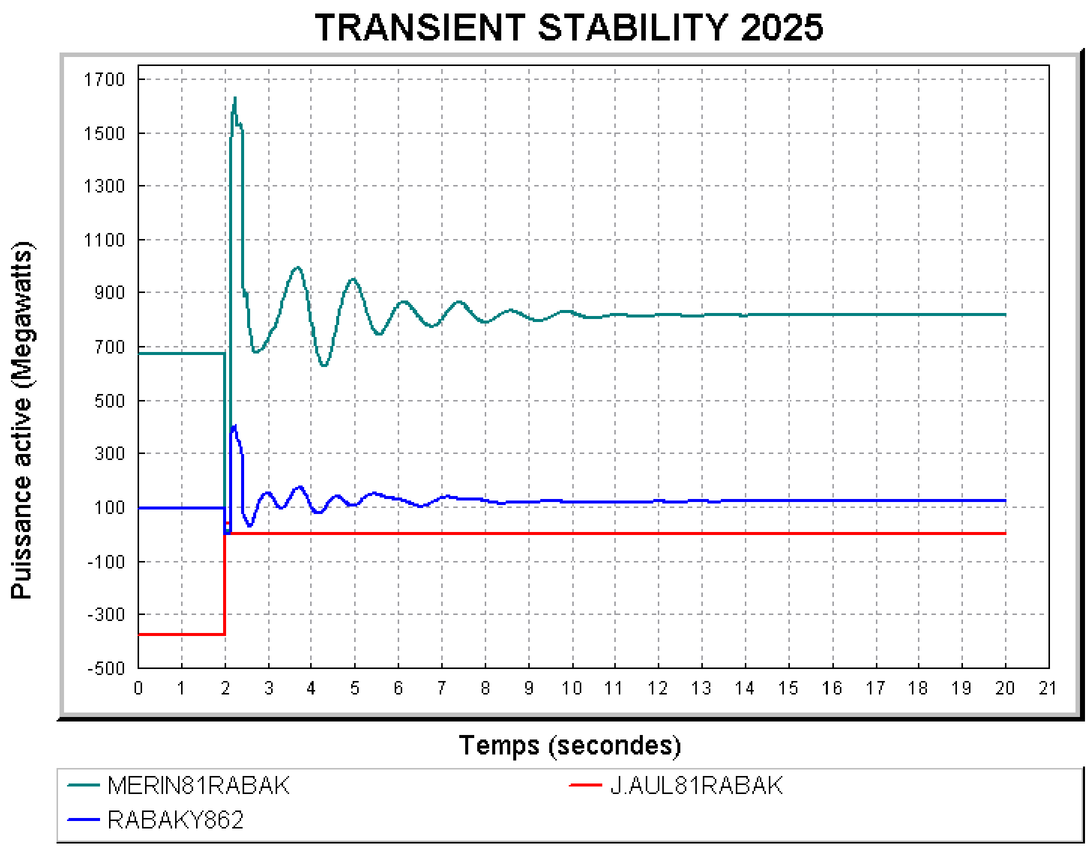
2.17.1 GENERATOR FREQUENCY VARIATION



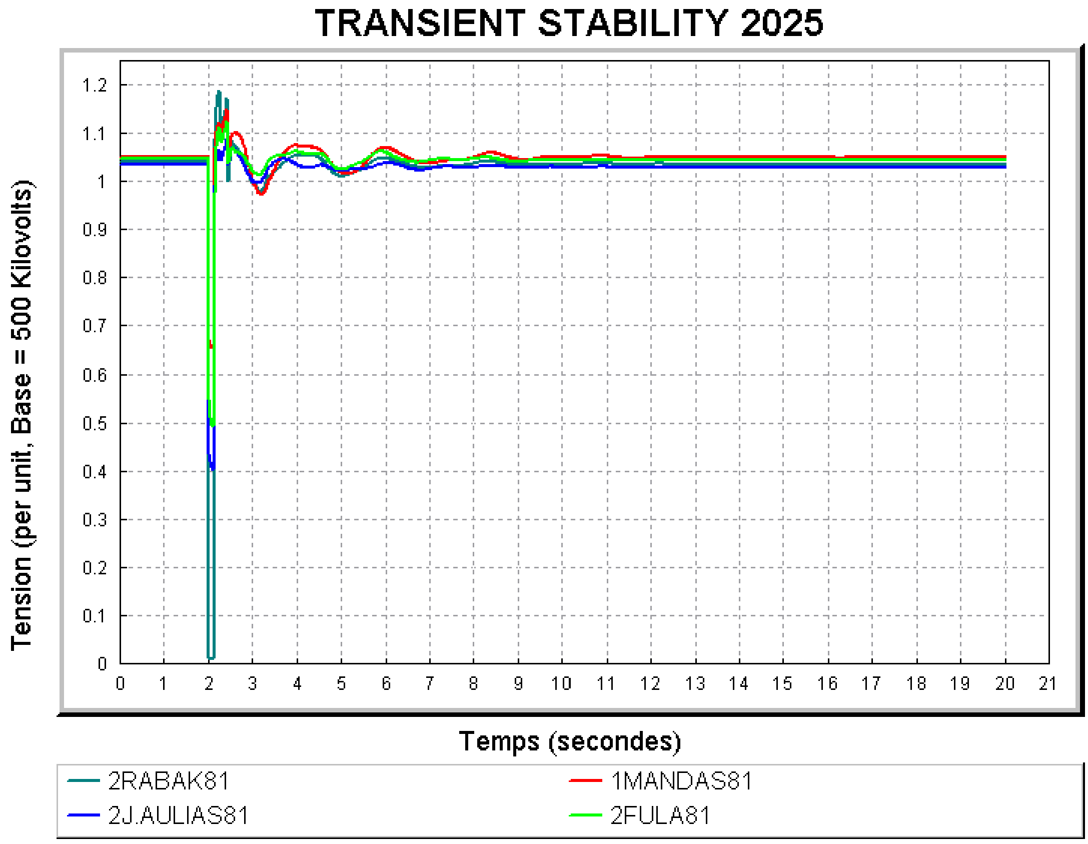
2.17.2 POWER FLOW VARIATION ON ENTRO INTERCONNECTION

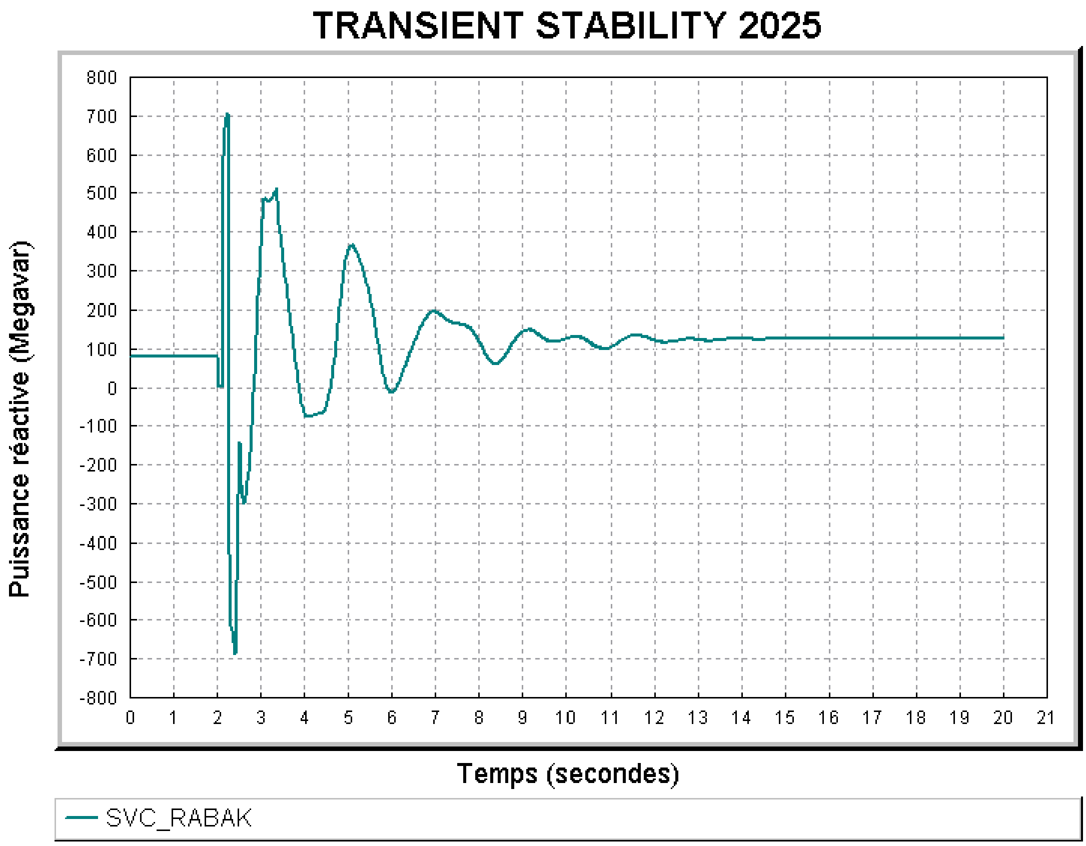


2.17.3 POWER FLOW VARIATION ON KOSTI - JEBEL AULIA, KOSTI – MERINGAN AND KOSTI TRANSFORMER



2.17.4 VOLTAGE VARIATION ON THE 500 KV

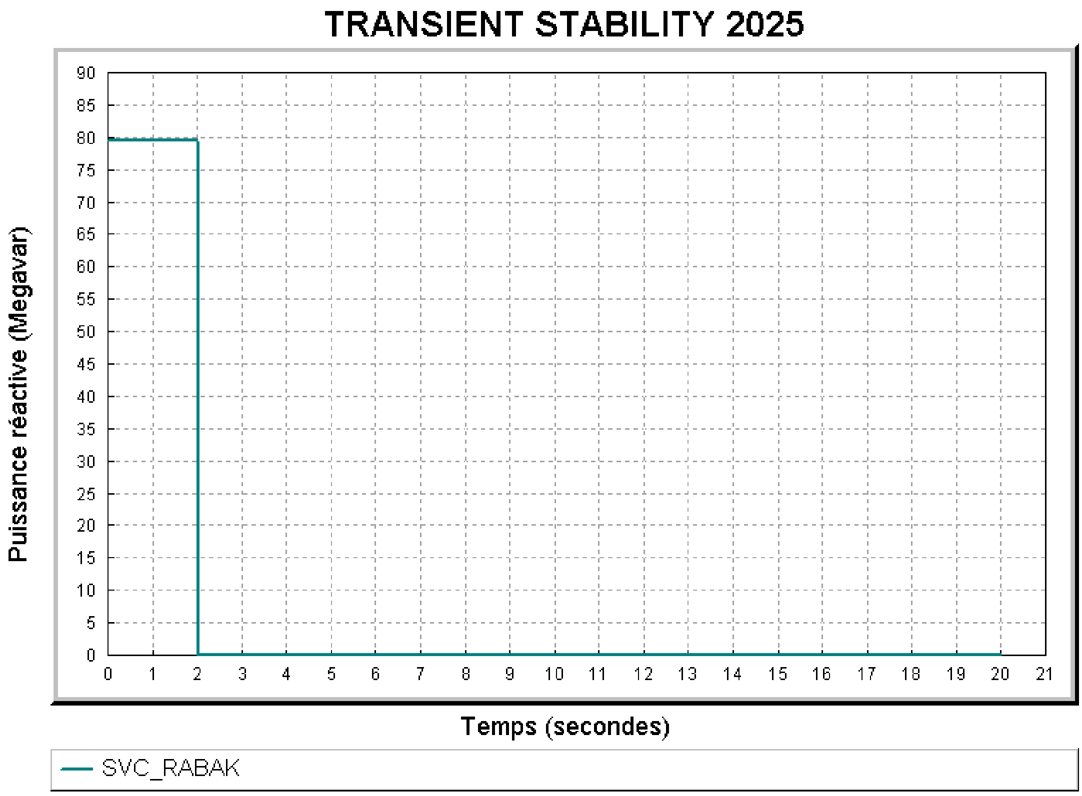



TRANSIENT STABILITY 2025
Puissance réactive (Megavar)
800
700
600
500
400
300
200
100
0
-100
-200
-300
-400
-500
-600
-700
-800
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21
Temps (secondes)
SVC_RABAK

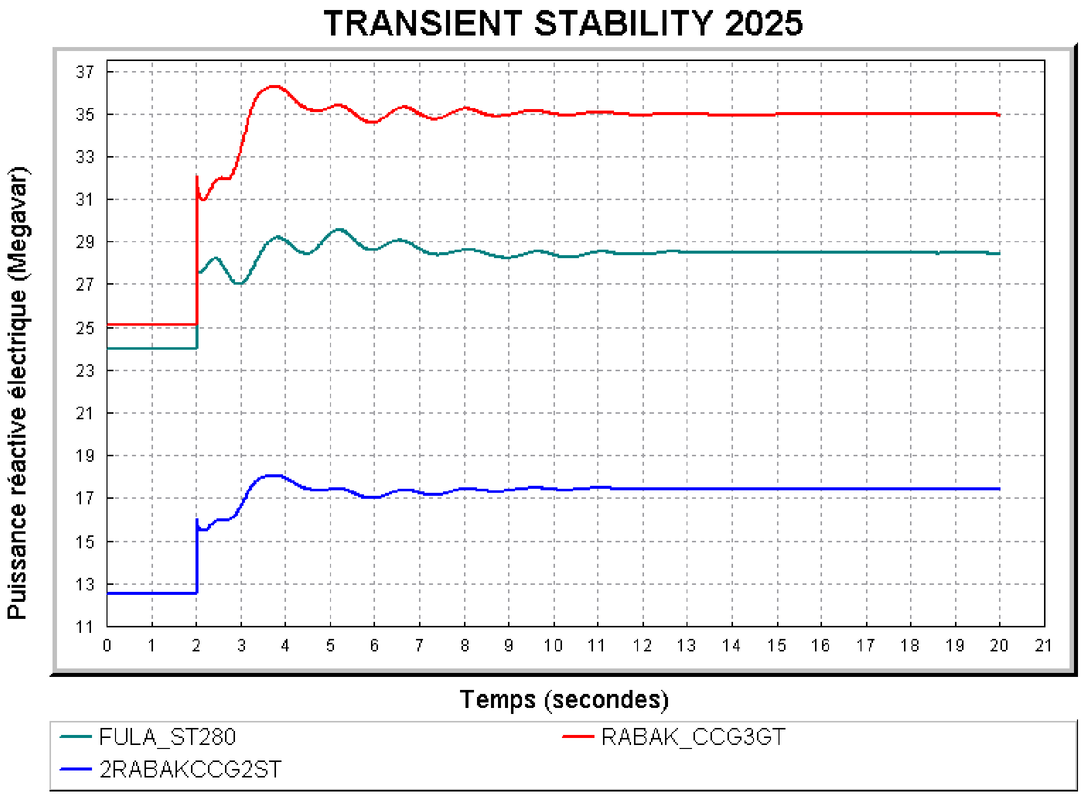
2.18 TRIPPING OF THE 500MVAR SVC AT KOSTI

Event: The 500MVAr SVC at Kosti was tripped, it generated 80MVAr.

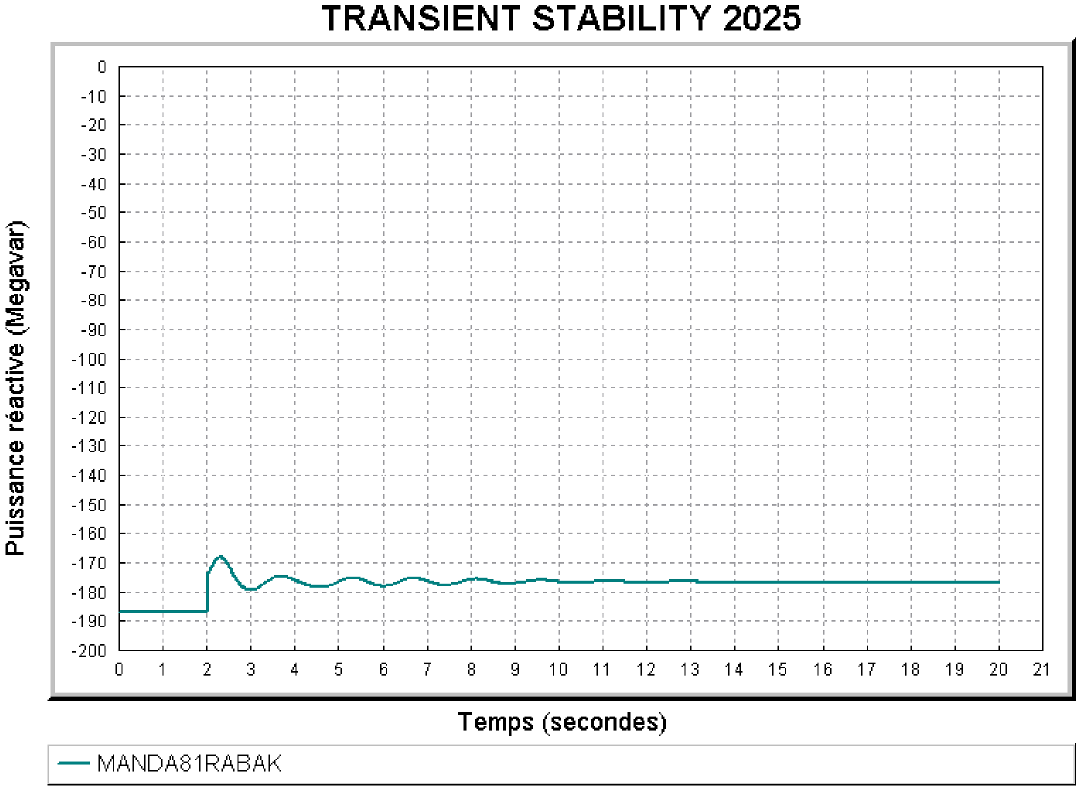
2.18.1 REACTIVE GENERATION OF THE SVC



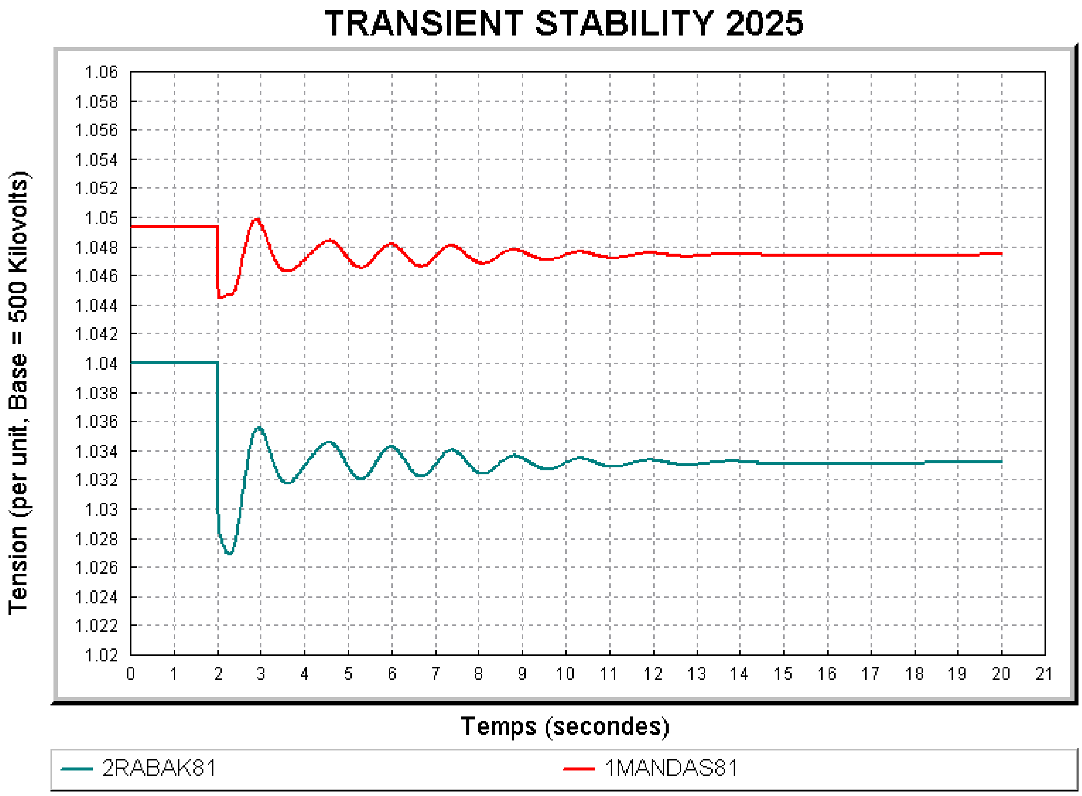
2.18.2 REACTIVE GENERATION OF THE GENERATORS CLOSE TO KOSTI



2.18.3 REACTIVE FLOW OVER ONE CIRCUIT MANDAYA KOSTI



2.18.4 VOLATGE PROFILE AT KOSTI AND MANDAYA 500KV SUBSTATIONS



2.19 TRIPPING OF THE LARGEST UNIT IN EGYPT : ABU KIR 650 MW STEAM TURBINE

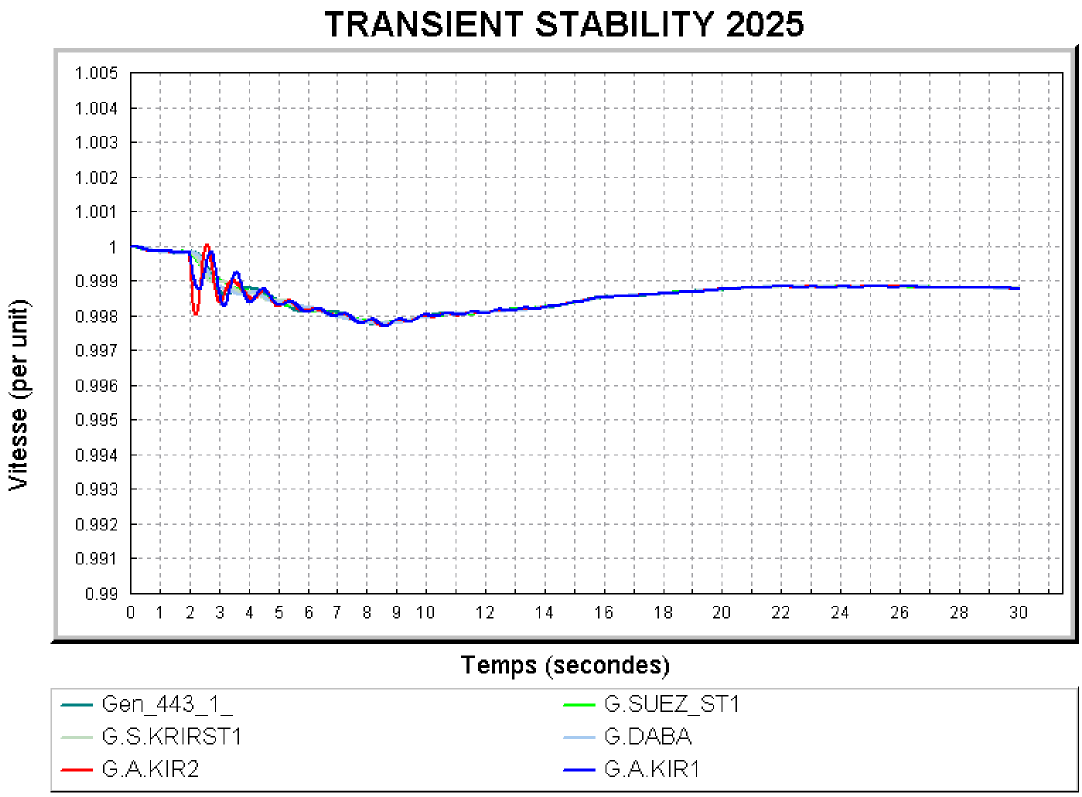
Event : the 765 MVA steam unit of Abu Kir was tripped, it generated 615 MW

Following the tripping of the largest steam unit in operation, the behaviour of the system was satisfactory.

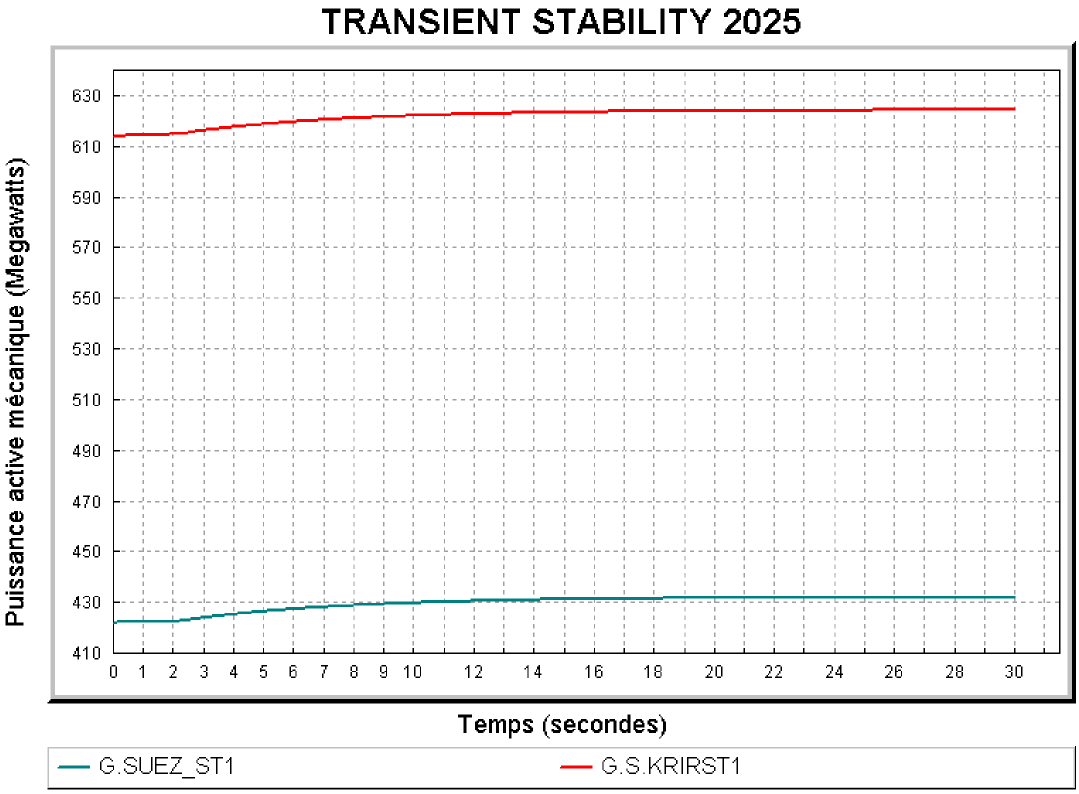
The Egyptian frequency decreased to 49.88 Hz, before recovering to 49.94 Hz. The self regulation of the load was estimated to 143 MW in Egypt interconnected to Libya and Jordan.

The voltage was not significantly affected.

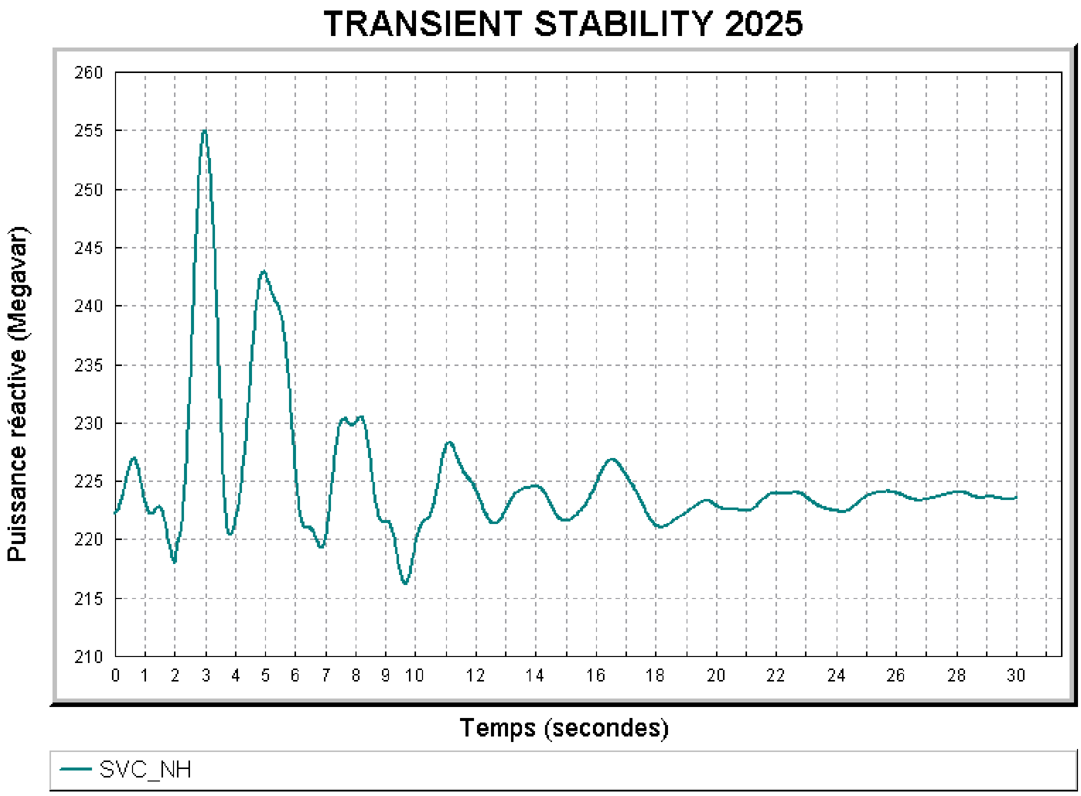
2.19.1 GENERATOR FREQUENCY VARIATION



2.19.2 MECHANICAL POWER VARIATION



2.19.3 NAG HAMMADI SVC VARIATION



2.20 TRIPPING OF TWO 280MVA UNITS IN MANDAYA

Event : 2 units of Mandaya, the largest units in operation in the Ethiopian system were tripped. Their initial generation amounted 242.85MW.

The final frequency reached 49.94Hz, the reduction of demand amounted to:

- 20MW in Sudan
- 6MW in Ethiopia

The amount of primary reserve delivered in Sudan is equal to the decrease of imported power (294MW minus the reduction of load demand of 20MW):

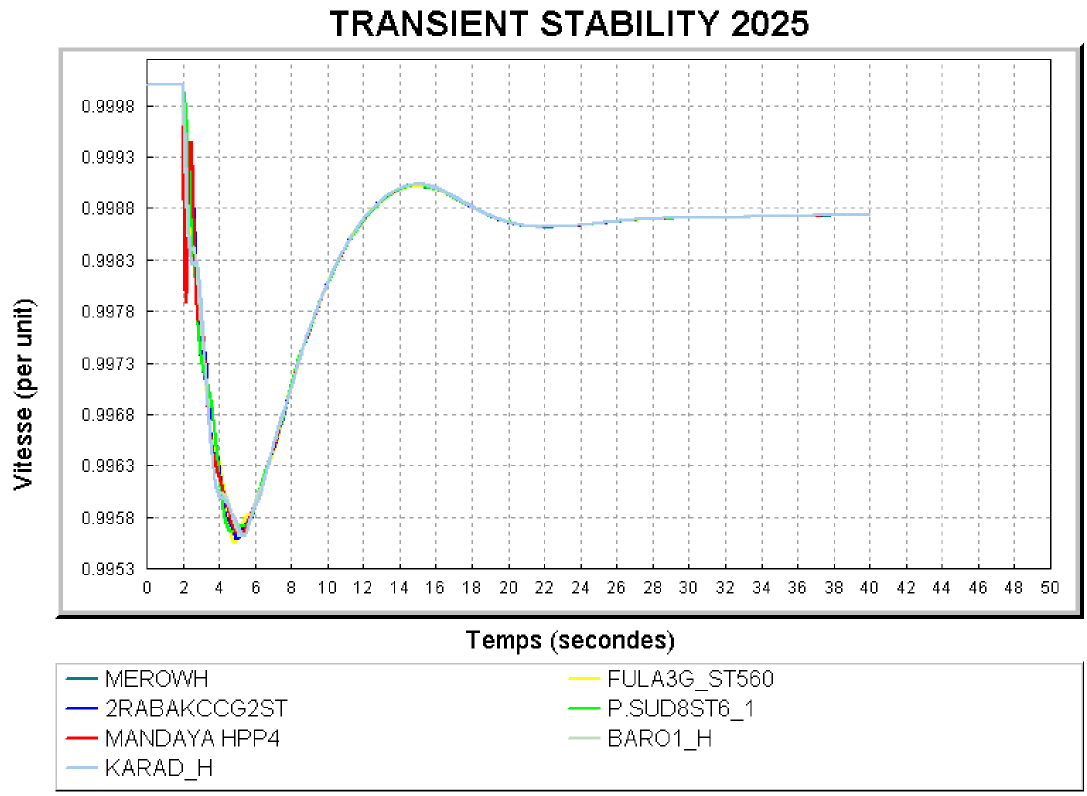
- Amount of delivered primary reserve 274MW

The amount of primary reserve delivered in Ethiopia is equal to the decrease of generated power (486MW° minus the reduction of power exchange (294MW) and minus the reduction of load demand (6MW):

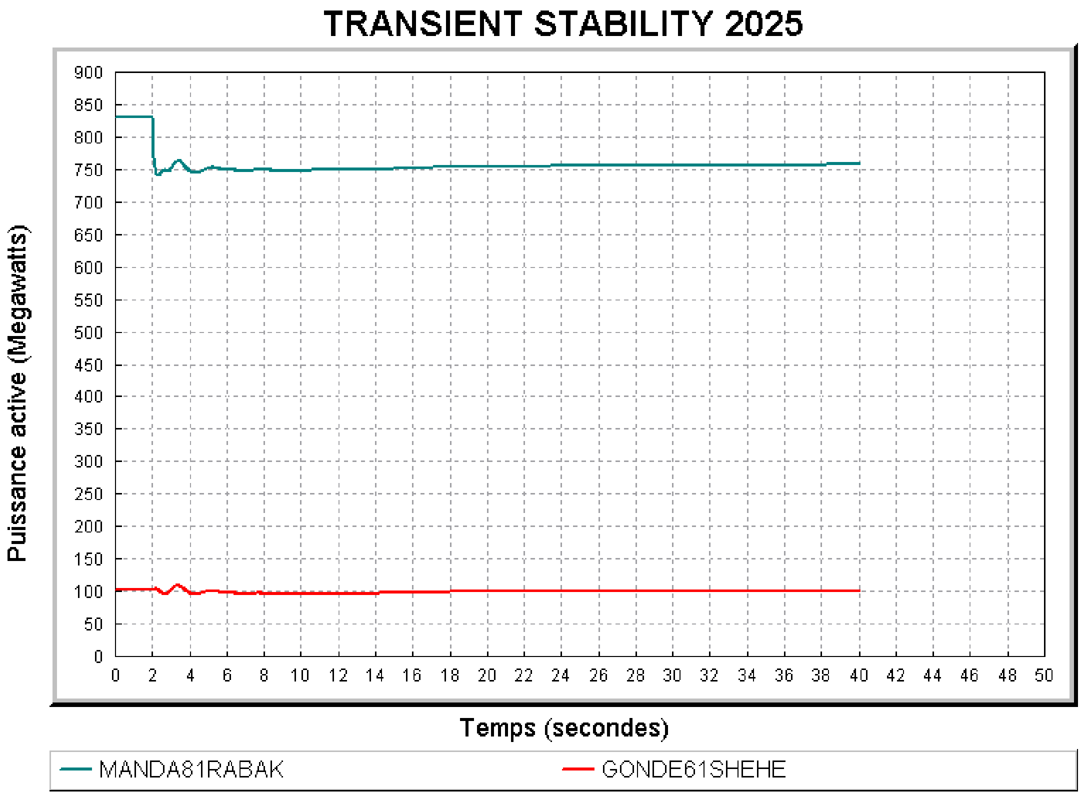
- Amount of delivered primary reserve 186MW

The variation of transmission losses due to the modification of the unit commitment and the delivery of the primary reserve was neglected to simplify the calculation.

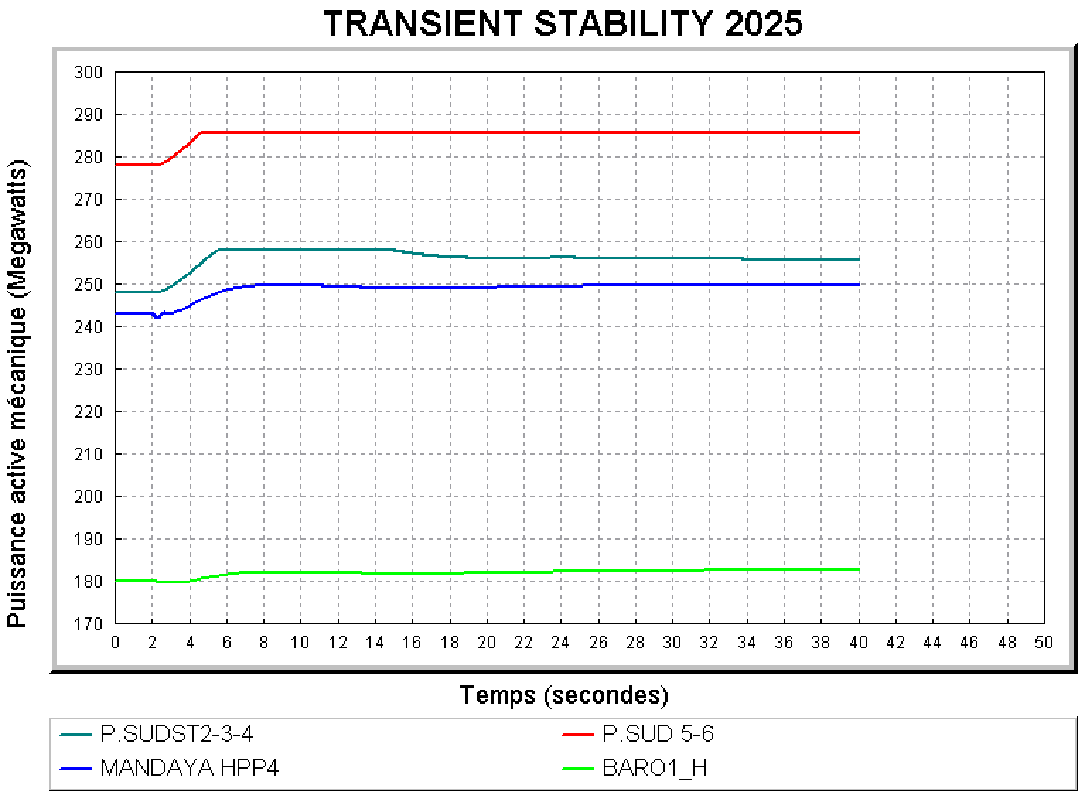
2.20.1 GENERATOR FREQUENCY VARIATION



2.20.2 POWER FLOW VARIATION ON ENTRO INTERCONNECTION



2.20.3 MECHANICAL POWER VARIATION



2.21 TRIPPING OF THE LARGEST UNIT IN SUDAN : PORT-SUDAN 670MVA STEAM UNIT

Event : The 670MVA Steam Unit of Port-Sudan, the largest units in operation in the Sudan system was tripped. Its initial generation amounted 579MW.

The final frequency reached 49.92Hz, the reduction of demand amounted to:

- 27MW in Sudan
- 7.5MW in Ethiopia

The amount of primary reserve delivered in Sudan is equal to the decrease of generated power (579MW° minus the increase of imported power (260MW)and minus reduction of load demand (27MW):

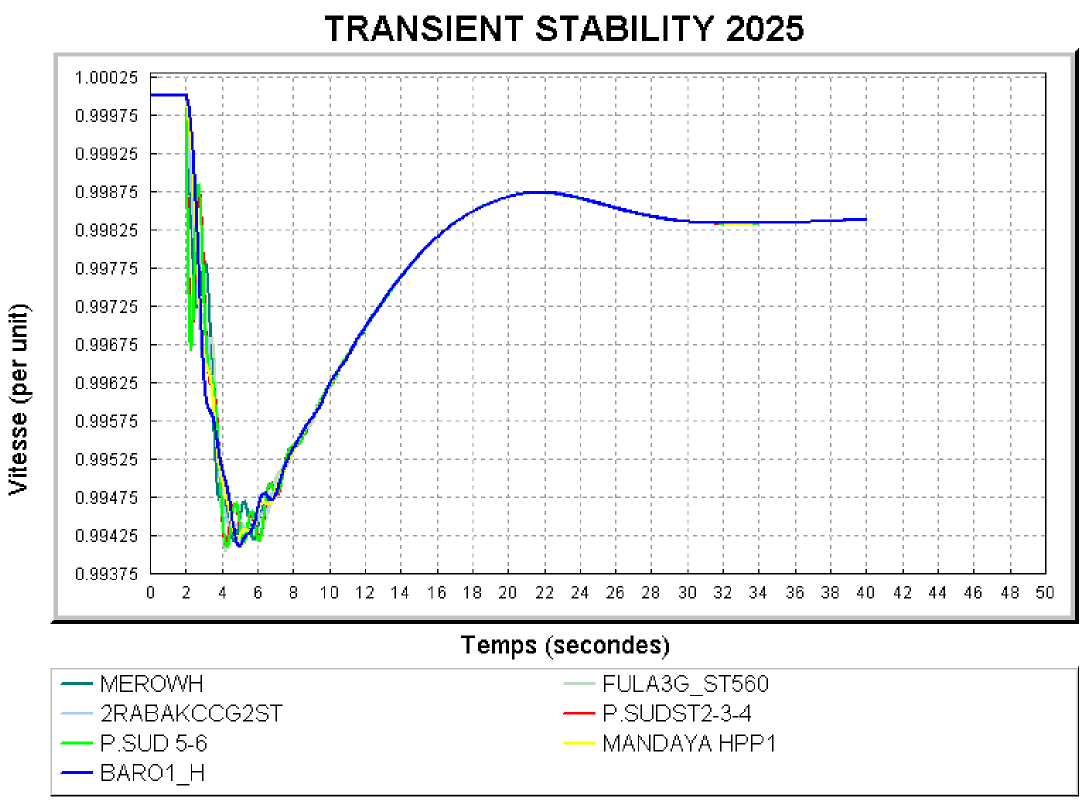
- Amount of delivered primary reserve 292MW

The amount of primary reserve delivered in Ethiopia is equal to the increase of the exported minus the reduction of load demand (7.5MW):

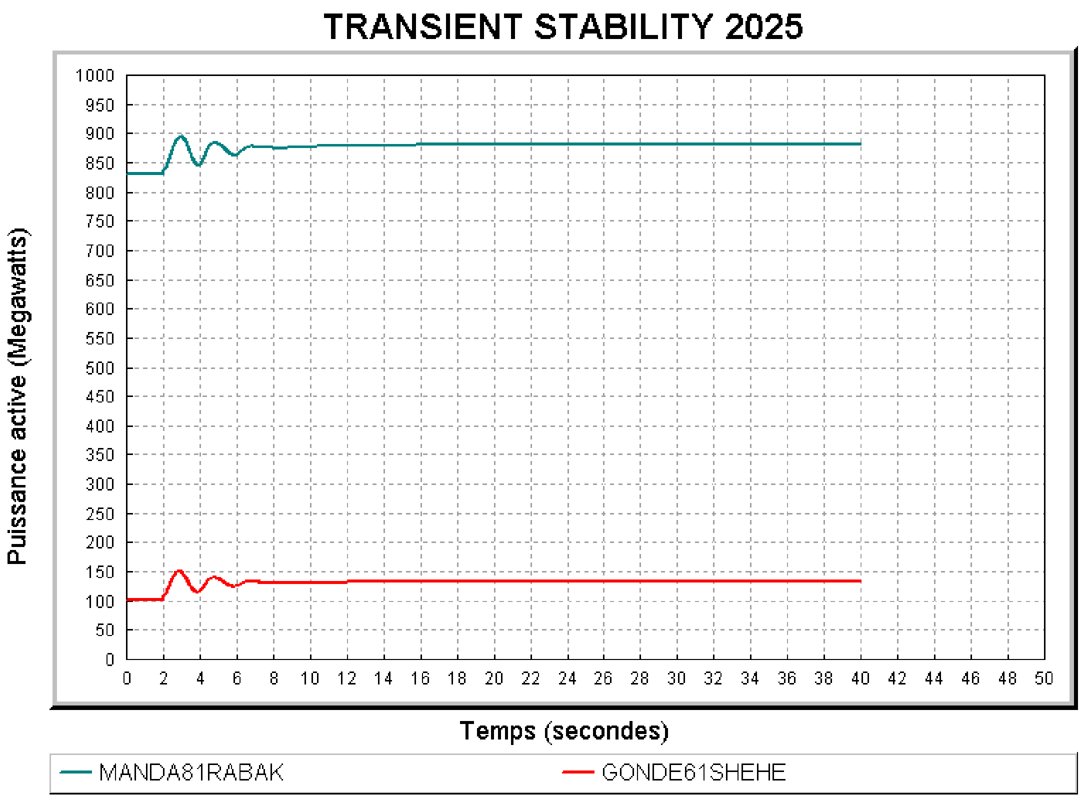
- Amount of delivered primary reserve 252.5MW

The variation of transmission losses due to the modification of the unit commitment and the delivery of the primary reserve was neglected to simplify the calculation.

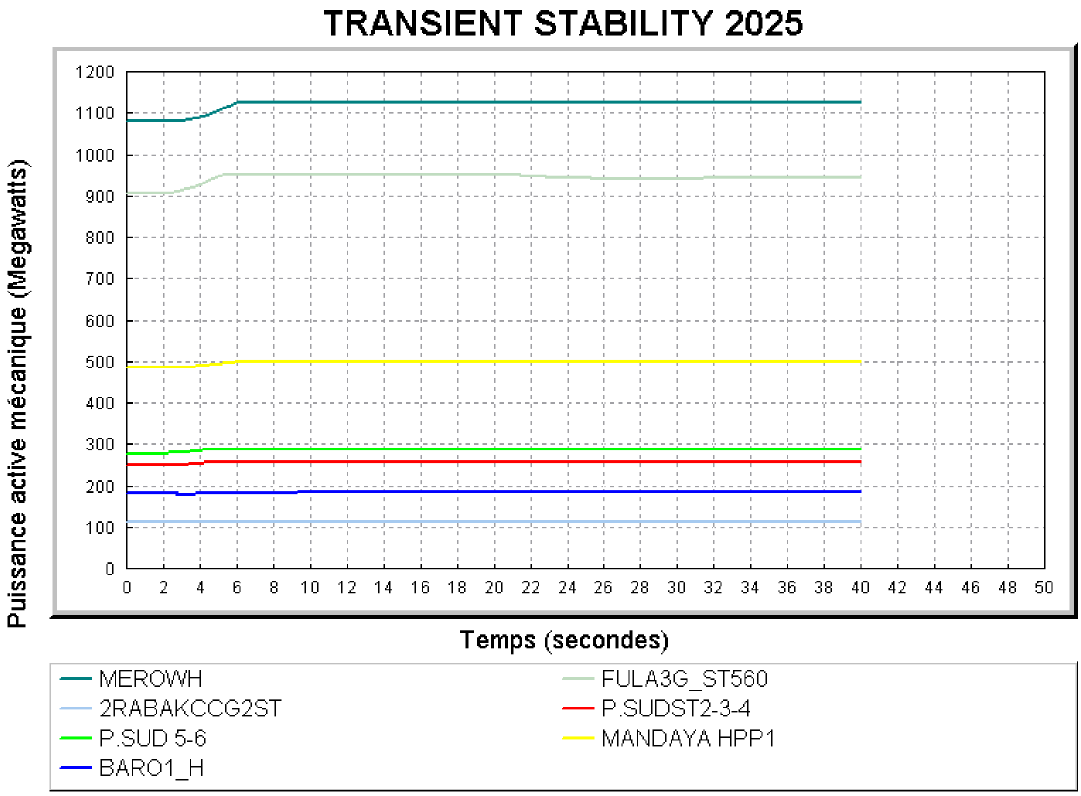
2.21.1 GENERATOR FREQUENCY VARIATION



2.21.2 *POWER FLOW VARIATION ON ENTRO INTERCONNECTION*

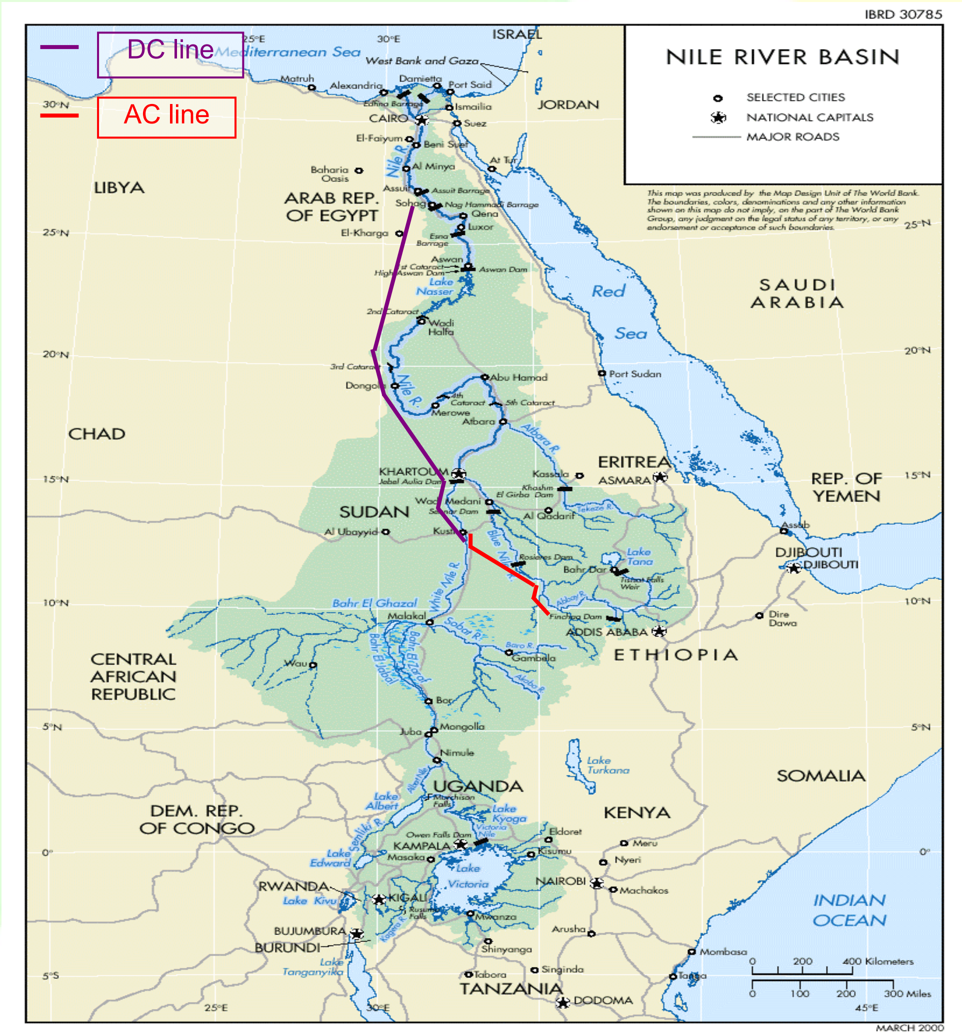


2.21.3 MECHANICAL POWER VARIATION



Nile Basin Initiative
Eastern Nile Subsidiary Action Program
Eastern Nile Technical Regional Office

EASTERN NILE POWER TRADE PROGRAM STUDY



M1 - 2030 APPENDIX - STABILITY STUDY

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ABBREVIATIONS AND ACRONYMS

AC	Alternative Current
CCG	Combined Cycle Gas turbine
DC	Direct Current
ENPTPS	Eastern Nile Power Trade Program Study
EDF	Electricité de France
EN	Eastern Nile
ENTRO	Eastern Nile Technical Regional Office
GEP	Generation Expansion Plan
HPP	Hydro Power Plant
HD	High Dam
HV	High Voltage
HVDC	High Voltage Direct Current
NBI	Nile Basin Initiative
NH	Nag Hammadi
OHL	Over Head Line
p.u	Per Unit
SC	Short Circuit
ST	Steam Turbine
SVC	Static Voltage Compensator
SW	Scott Wilson
TPP	Thermal Power Plant

Note : Kosti / Rabak

The location of the interconnection in Sudan was modified during the Line Routing study.

Initially located at Rabak (East side of the Nile) in Phase I, the line routing study (during Phase II) located the interconnection substation in Sudan on the West side of the Nile river at Kosti,

The name used in the simulation was Rabak.

1 TRANSIENT STABILITY ANALYSIS HYPOTHESIS

The volume of spinning reserve set as followed :

- Libya : 50 MW
- Jordan and Syria : 100 MW
- Egypt : 404 MW (104 MW on hydropower plants + 300 MW on thermal plants)
- Sudan : 349 MW
- Ethiopia : 304 MW (hydropower plant only)

	dP/dV	dP/df	dQ/dV	dQ/df
Egypt	0.83	1.46	4.01	-0.88
Ethiopia	0.94	1.26	3.67	-1.29
Sudan	0.79	1.53	4.14	-0.72

Table 1: Load voltage and frequency dependency coefficients

Load of Libya, Jordan and Syria

The 2030 peak load forecast for Libya reached 10 990 MW.

The 2030 peak load forecast for Jordan and Syria reached 23 550 MW.

Calculation of the damping magnitude of the power oscillations

The power oscillations evolve according to the formula :

$$\mathbf{A.e^{-\alpha t}.cos(\omega t+\varphi)} \quad \text{with } \omega=2\pi f_x$$

From the curves it is possible to measure the frequency, f_x of the oscillations. (generally a low value close to 0.3Hz or 0.5Hz)

The apparent damping coefficient D of the oscillation mode is equal to :

$$\mathbf{D}=\frac{\alpha}{\sqrt{(\alpha^2+\beta^2)}} \quad \text{with } \beta = 2\pi f$$

and α is like that $e^{-\alpha t}=0.05$ with ***t*** is the damping duration.

The international literature concerning the inter-area oscillations, indicates that an inter-area oscillation mode is acceptably damped if the damping coefficient is close to 5% and it is well damped if the damping coefficient is higher than 5%.

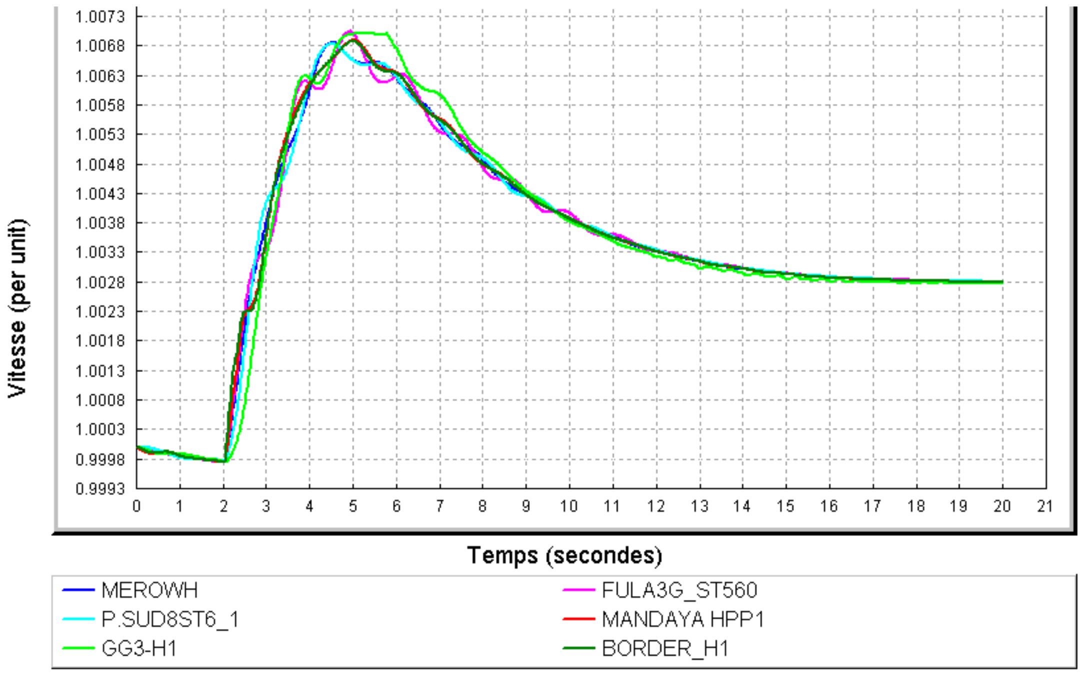
According to the above formula, the apparent damping coefficient for the average frequency was estimated from the curves and the results.

2 2030 PEAK LOAD SITUATION

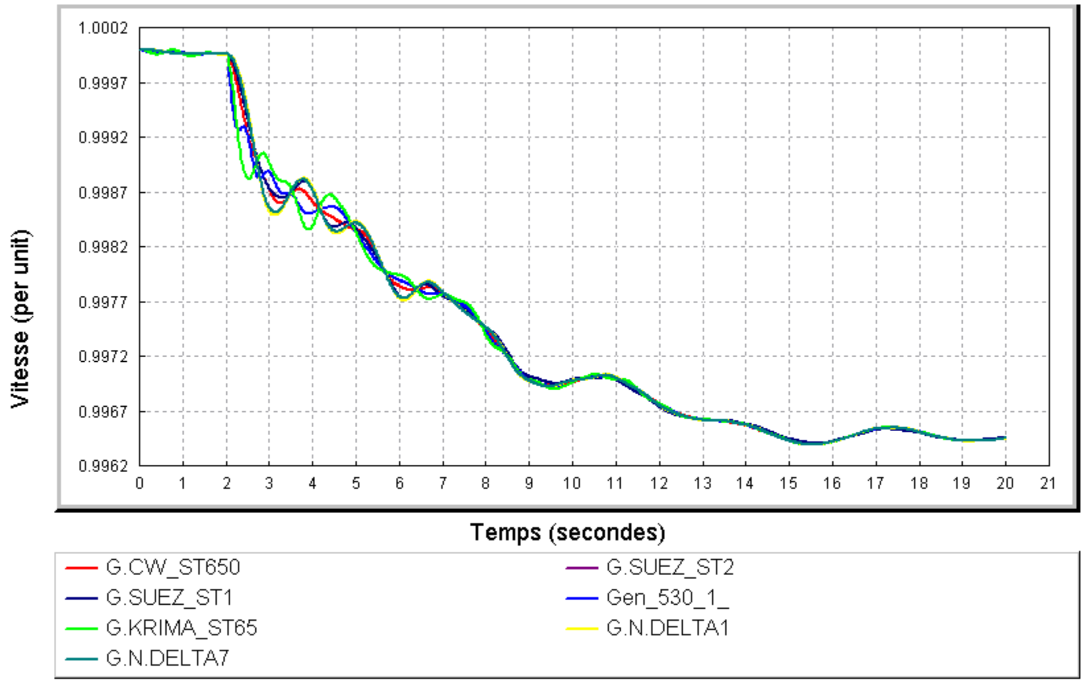
2.1 TRIPPING OF ONE OF THE 2 POLES OF THE DC INTERCONNECTION

Event : one of the 2 poles was tripped following an internal fault. 300 ms after, half of the capacitor banks of each HVDC substations (NH and Kosti) were disconnected.

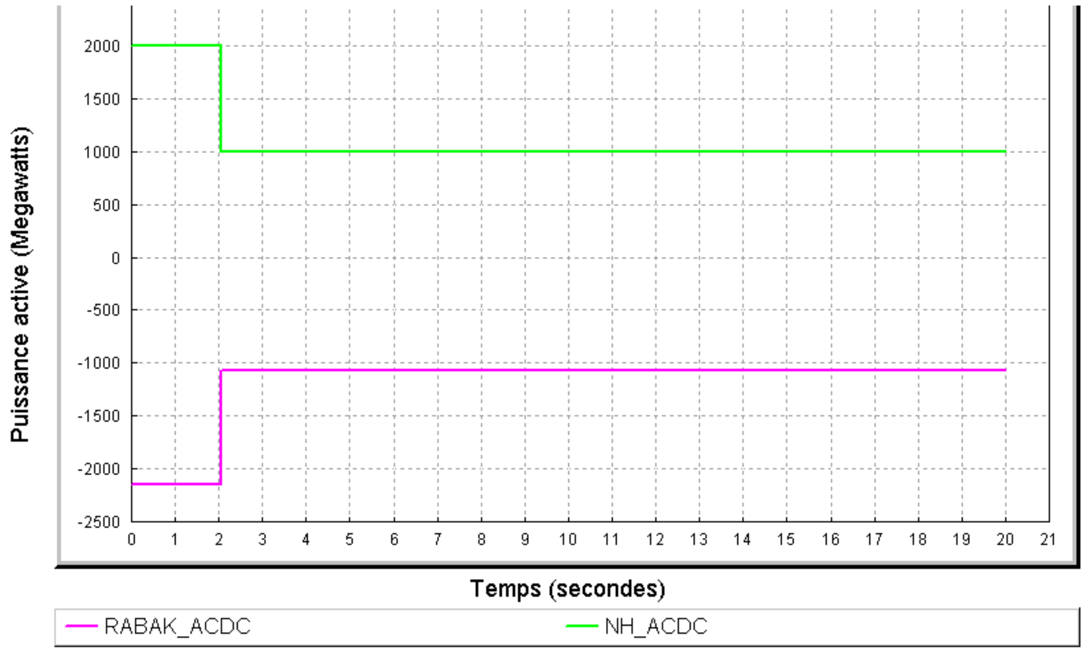
2.1.1 GENERATORS FREQUENCY VARIATION

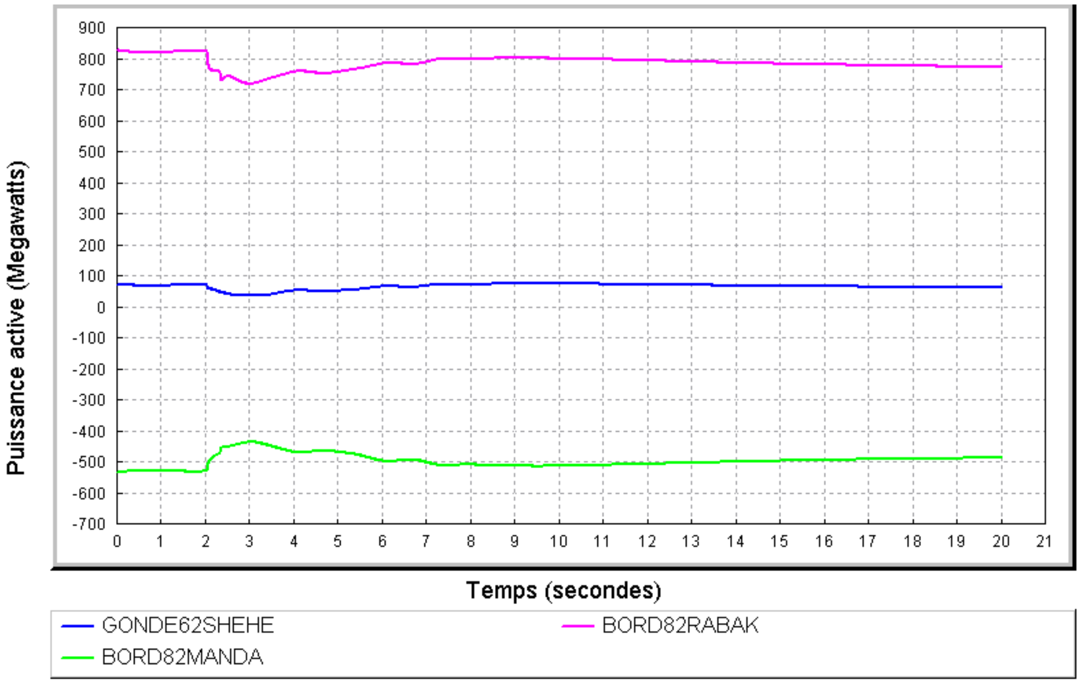


GG3 is Gibe 3

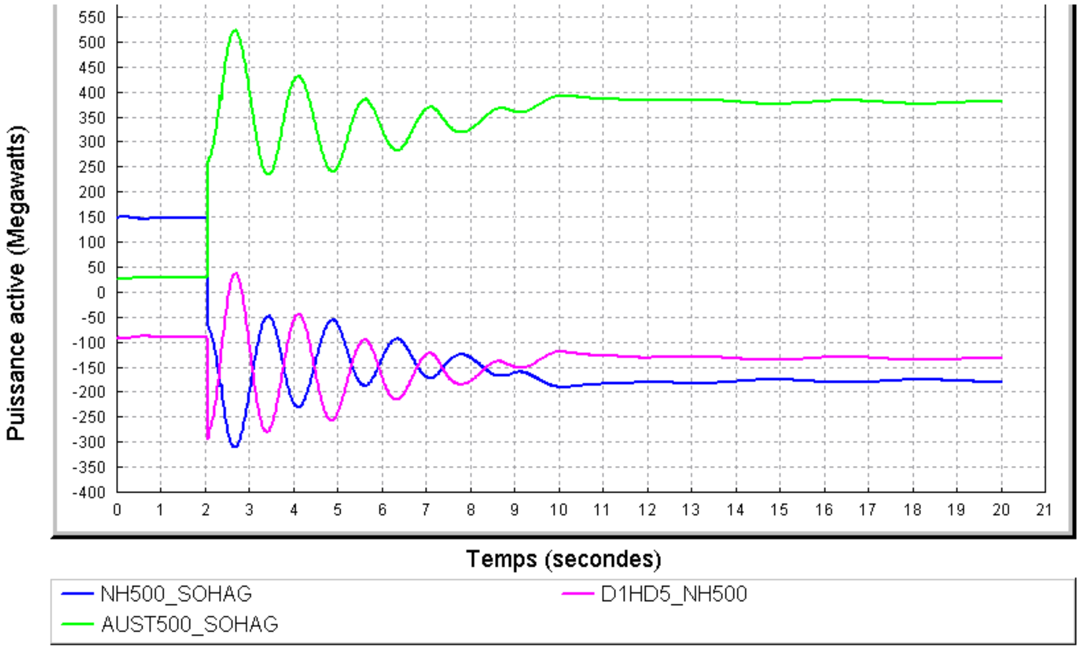


2.1.2 POWER FLOW VARIATION ON INTERCONNECTION

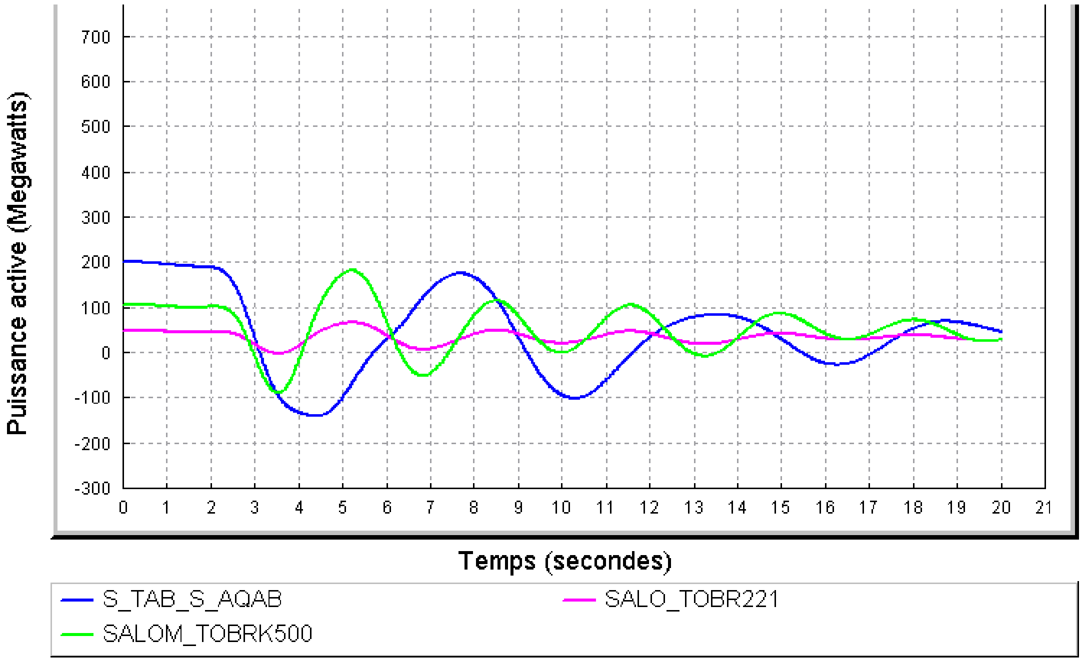




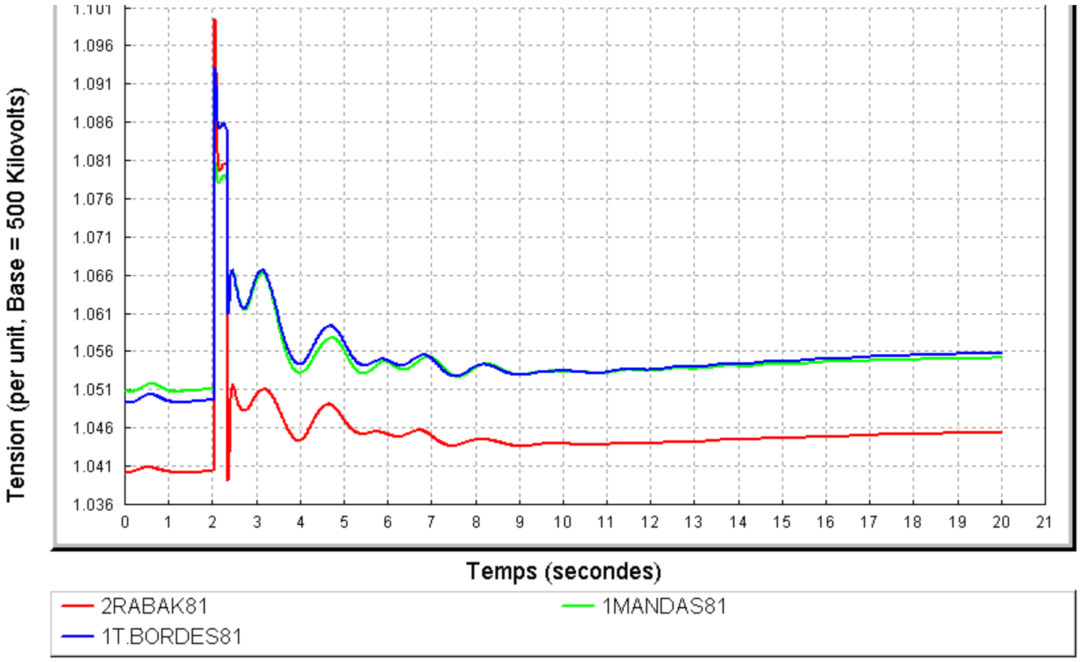
2.1.3 POWER FLOW VARIATION ON NAG HAMMADI 500 KV CIRCUITS

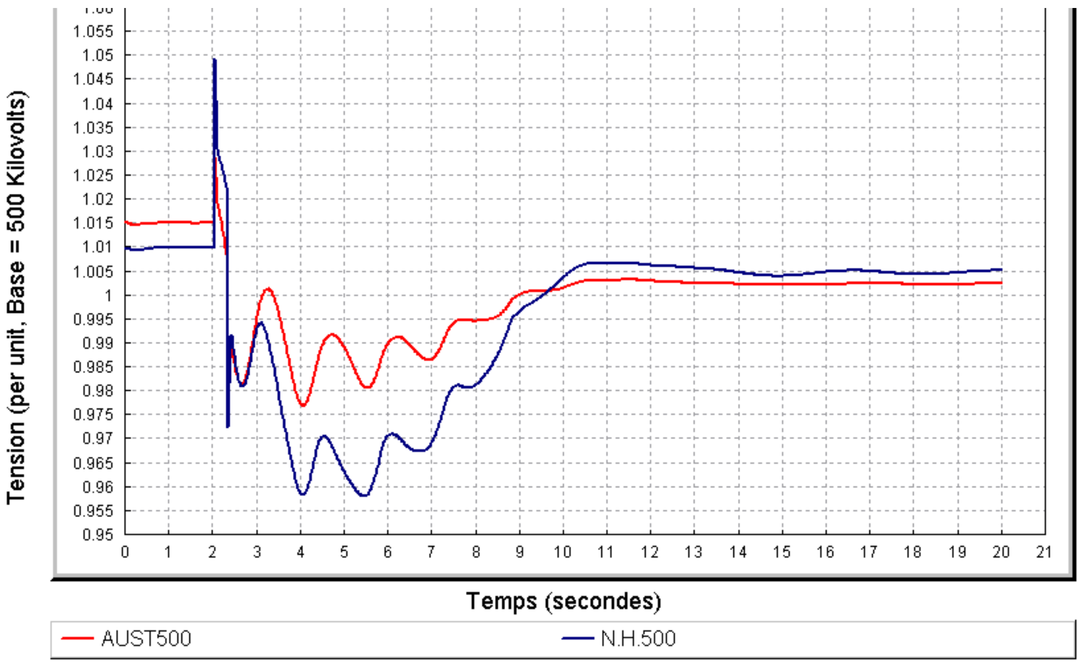


2.1.4 POWER FLOW VARIATION ON EGYPT INTERCONNECTIONS



2.1.5 VOLTAGE VARIATION ON THE 500 KV





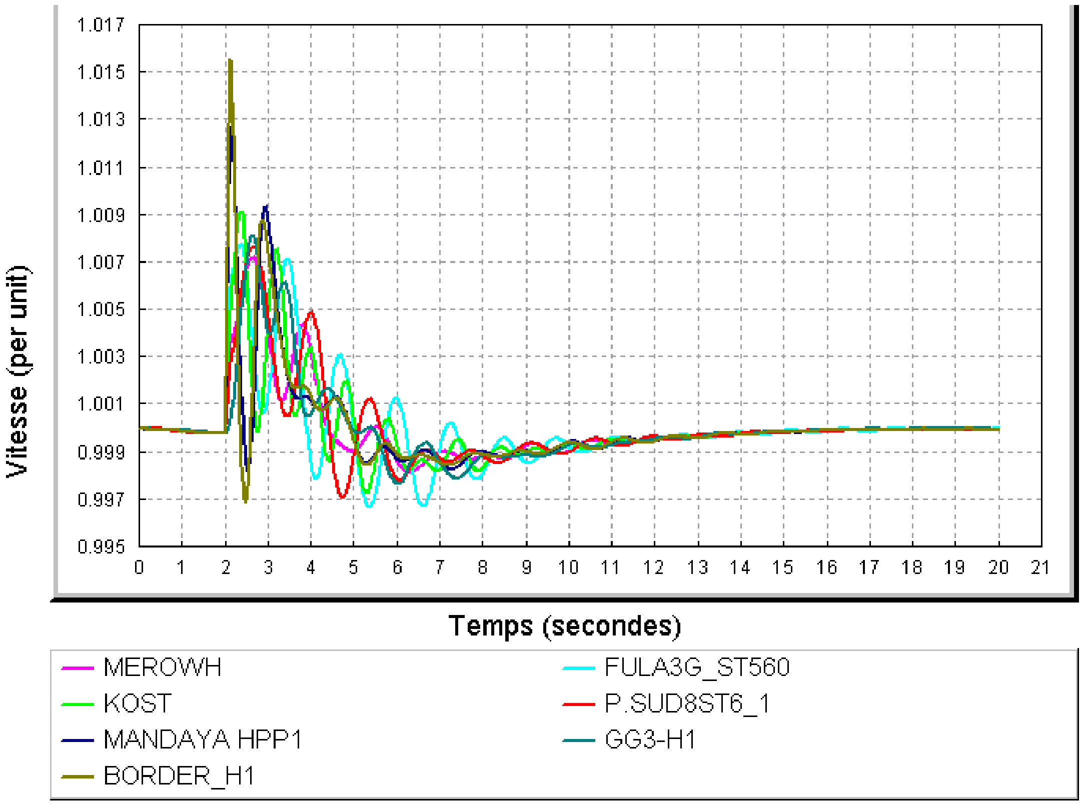
2.2 SHORT-CIRCUIT AT KOSTI ON ONE OF THE 4 KOSTI - T.BORDER CIRCUITS

Event : a 3 phase short-circuit at Kosti end, on one of the 4 circuits T.Border - Kosti, cleared in 120 ms by the opening of the circuit breakers.

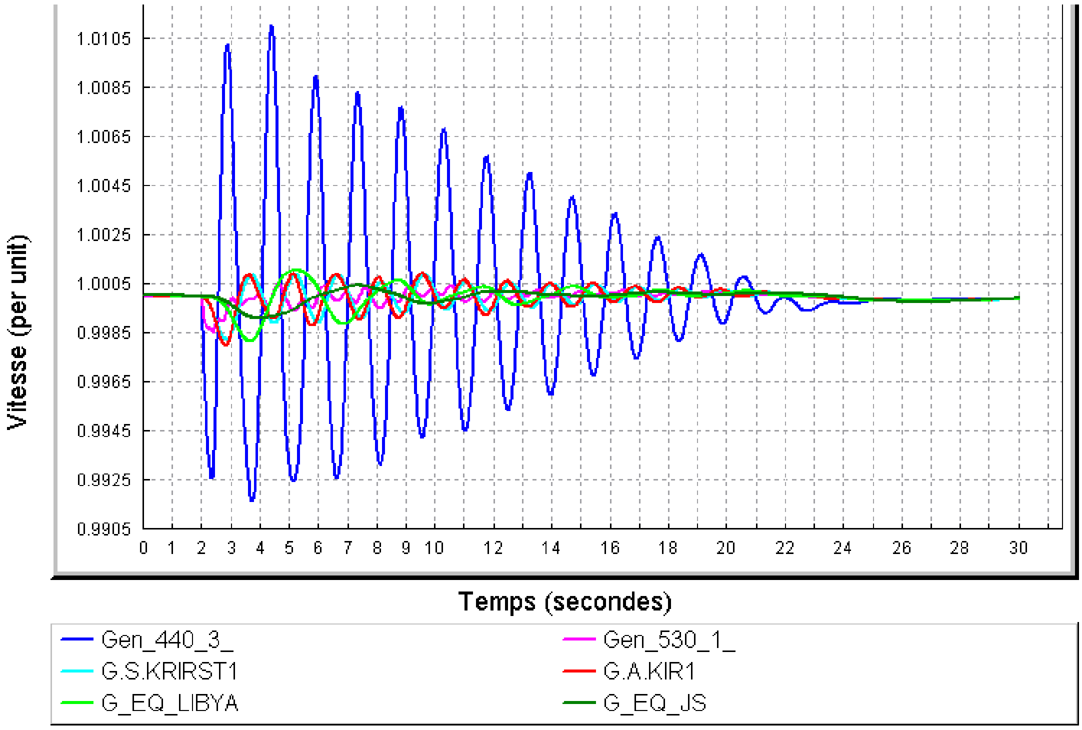
The voltage drop in Kosti (0 pu) led to a transitory blocking of commutation of the inverter station at Kosti. The flow on the DC interconnection is transitory reduced to 0, before recovering its initial value 300 ms after the tripping of the line.

During the transitory blocking of the DC stations, the capacitors bank remained connected.

2.2.1 GENERATORS FREQUENCY VARIATION

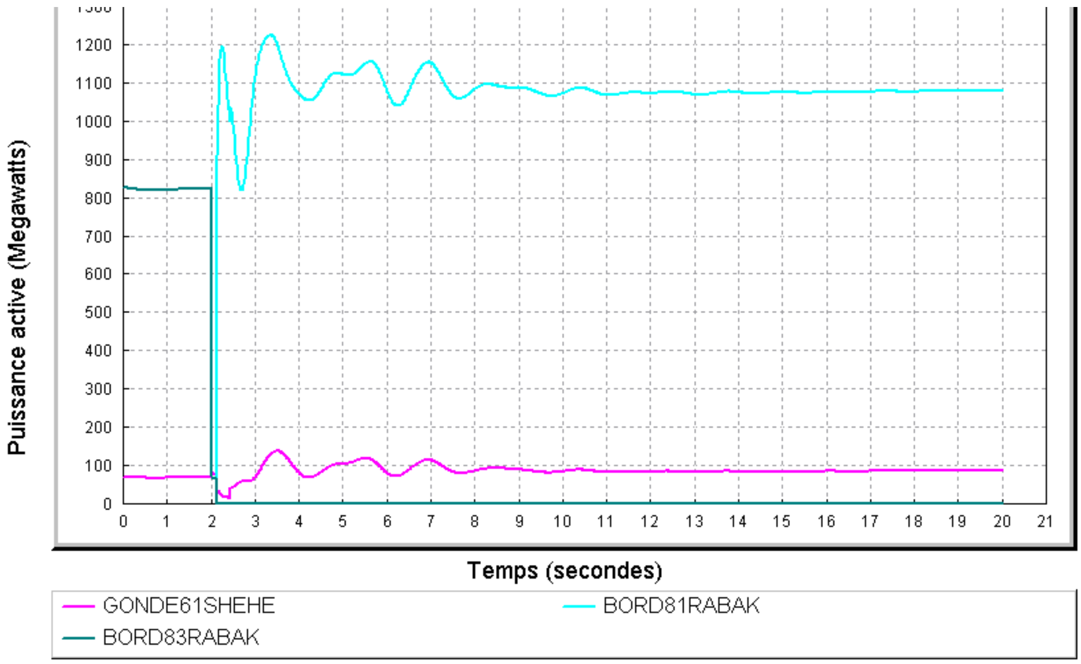


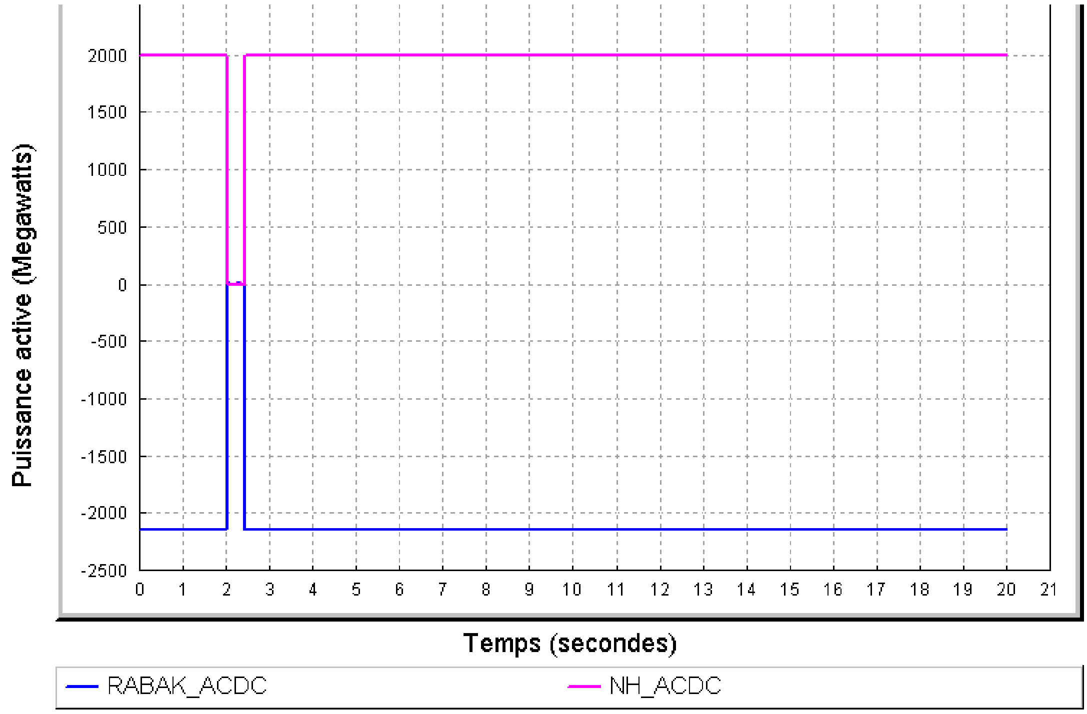
GG3 is Gibe III



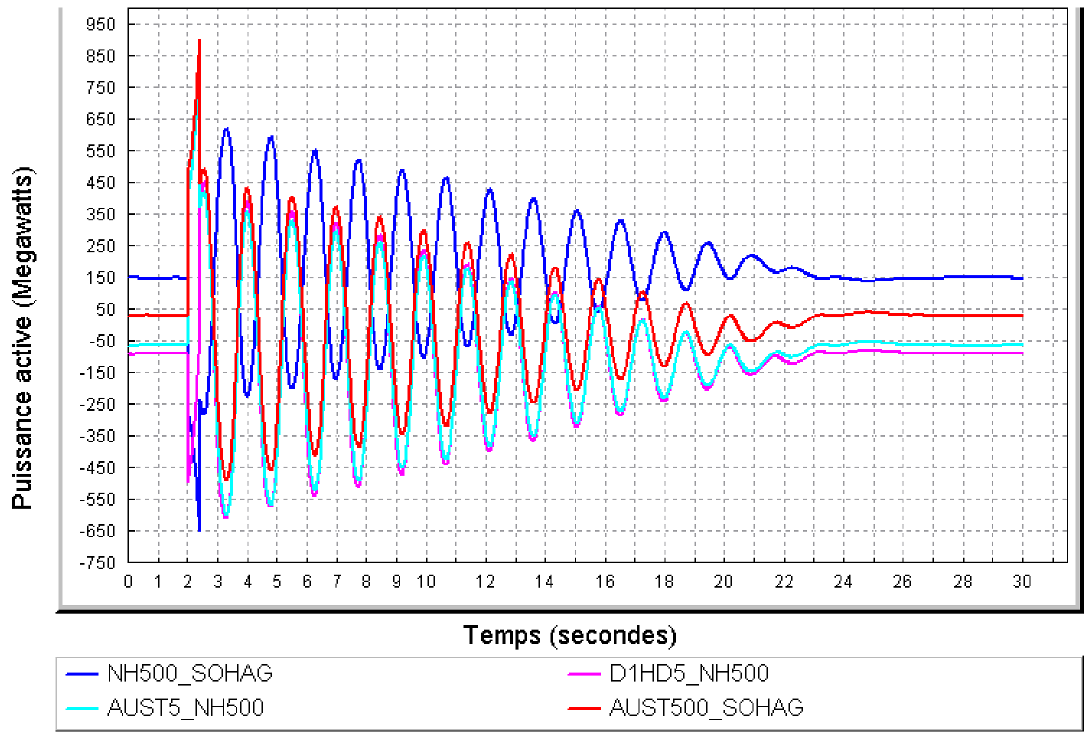
Gen_440_3 is a group of High Dam
Gen_530_1 is group 1 of Kurimat existing steam

2.2.2 *POWER FLOW VARIATION ON ENTRO INTERCONNECTION*

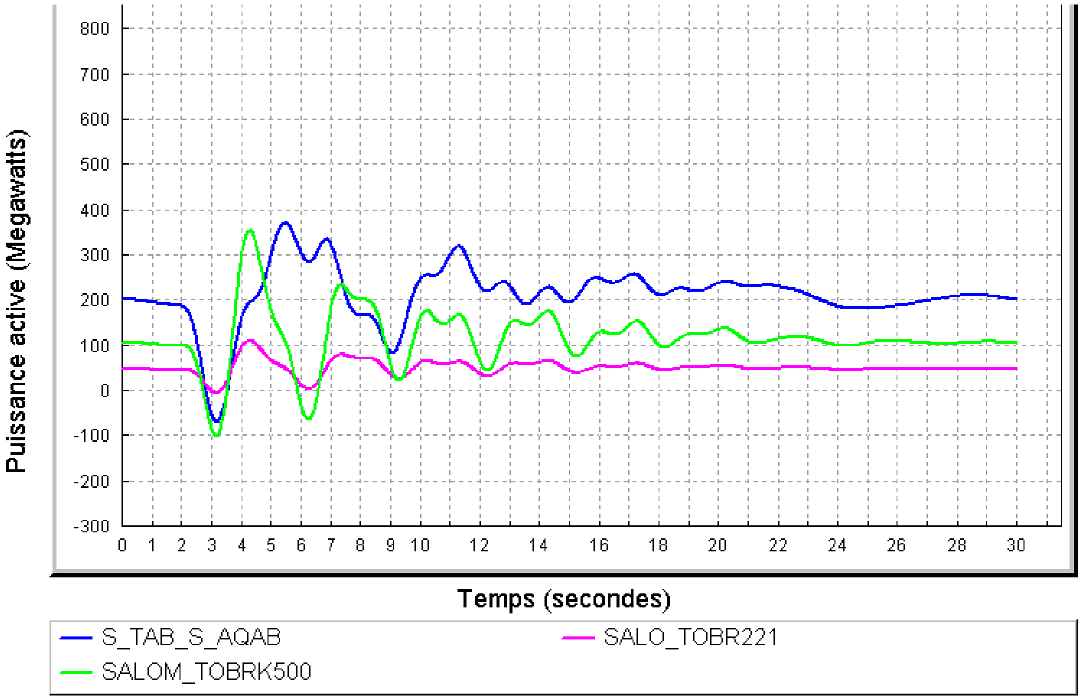




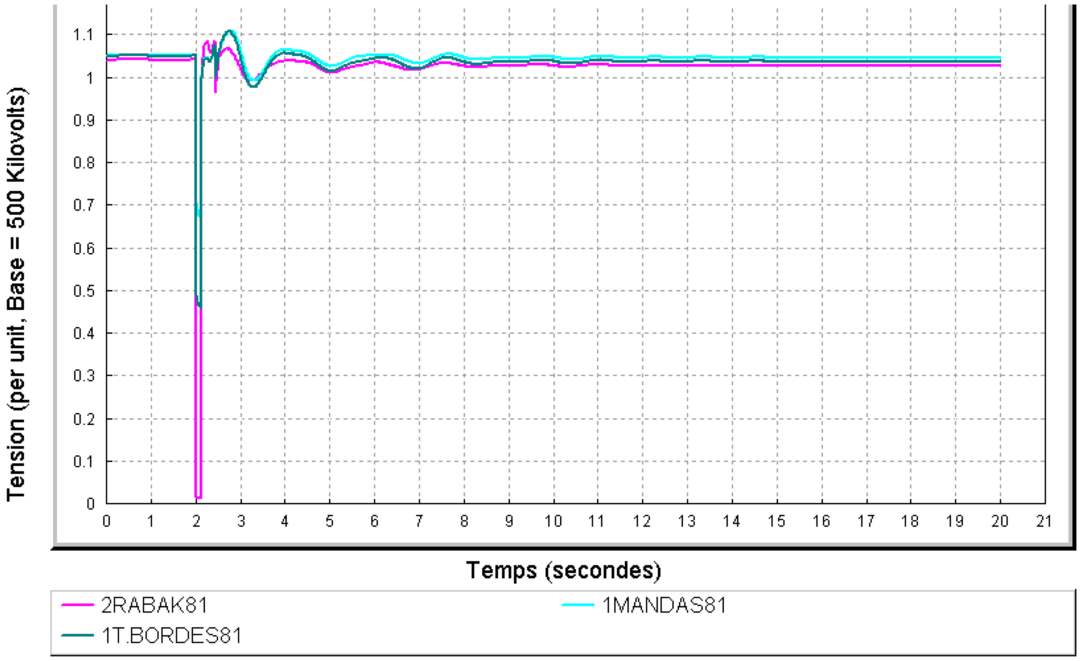
2.2.3 POWER FLOW VARIATION ON NAG HAMMADI 500 KV CIRCUITS

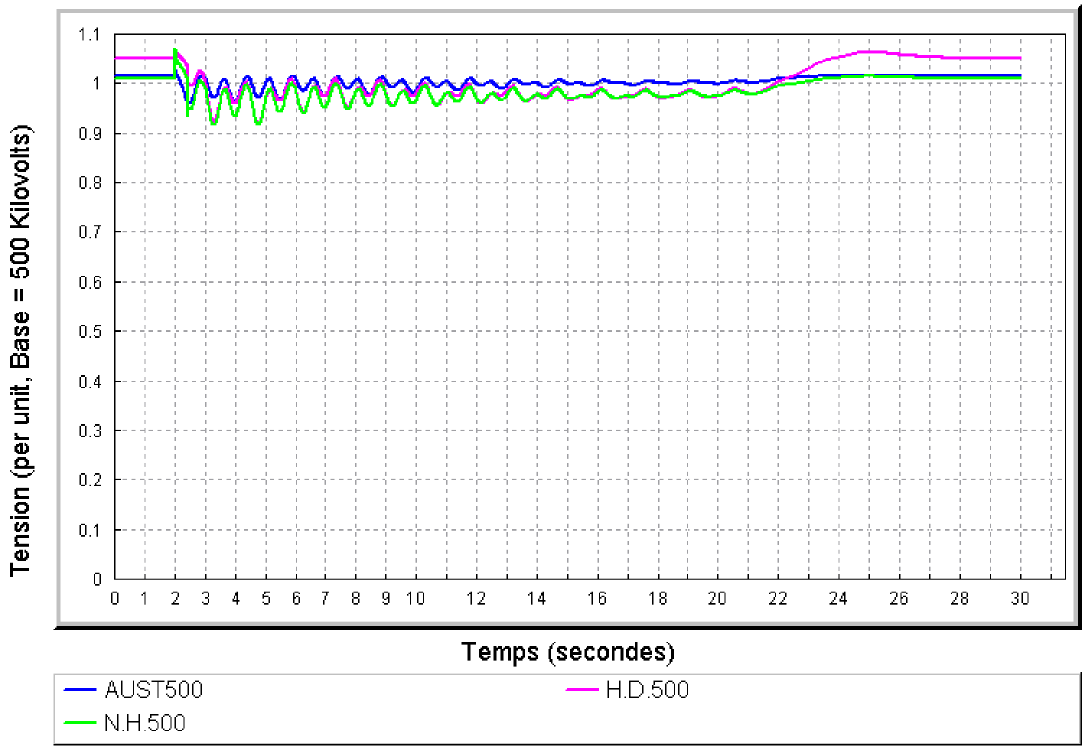


2.2.4 POWER FLOW VARIATION ON EGYPT INTERCONNECTIONS



2.2.5 VOLTAGE VARIATION ON THE 500 KV




Tension (per unit, Base = 500 Kilovolts)
1.1
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0 1 2 3 4 5 6 7 8 9 10 12 14 16 18 20 22 24 26 28 30
Temps (secondes)
AUST500
H.D.500
N.H.500

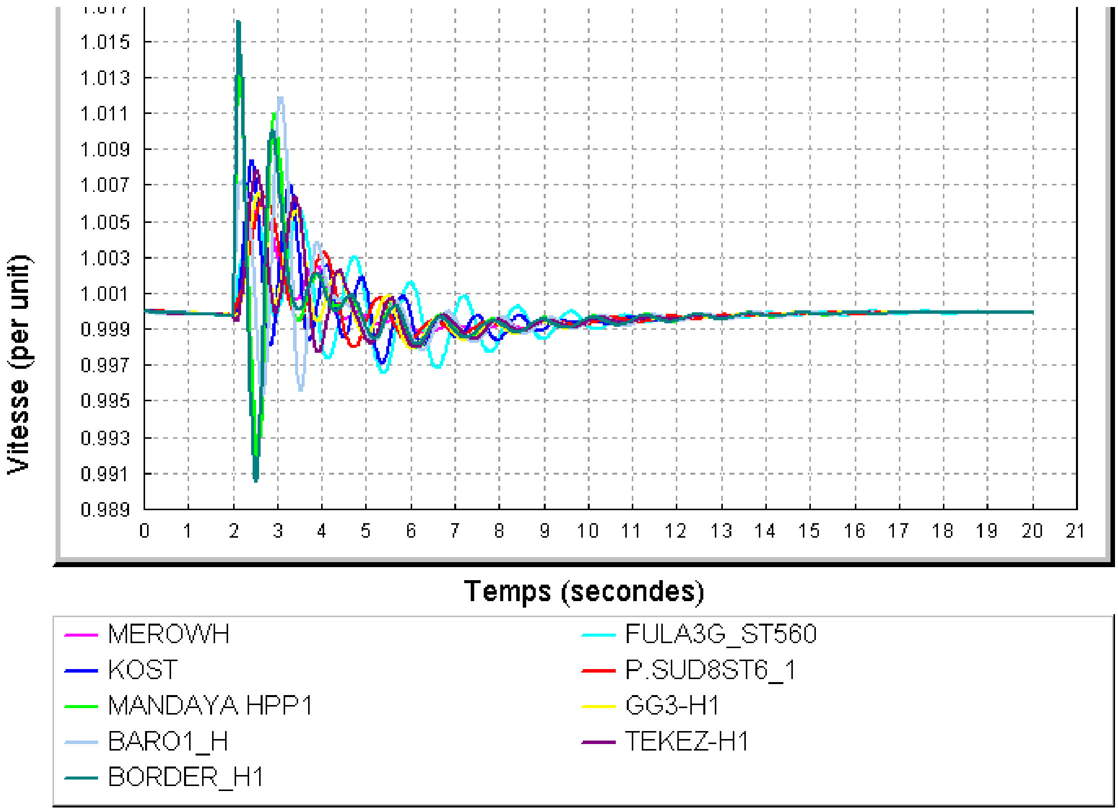
2.3 SHORT-CIRCUIT AT BORDER ON ONE OF THE 4 T.BORDER – KOSTI CIRCUITS

Event : a 3 phase short-circuit at Border end, on one of the 4 circuits T.Border - Kosti, cleared in 120 ms by the opening of the circuit breakers.

The voltage drop in Kosti (0.45 pu) led to a transitory blocking of commutation of the inverter station at Kosti. The flow on the DC interconnection is transitory reduced to 0, before recovering to its initial value 300 ms after the clearing of the fault.

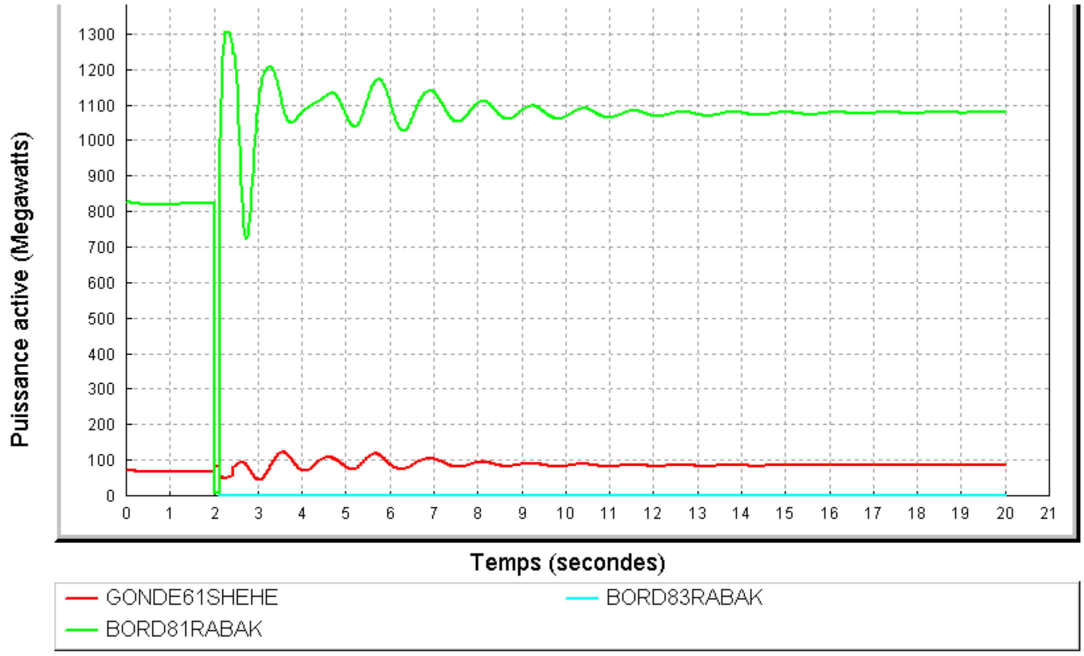
During the transitory blocking of the DC stations, the capacitors bank remained connected.

2.3.1 GENERATORS FREQUENCY VARIATION

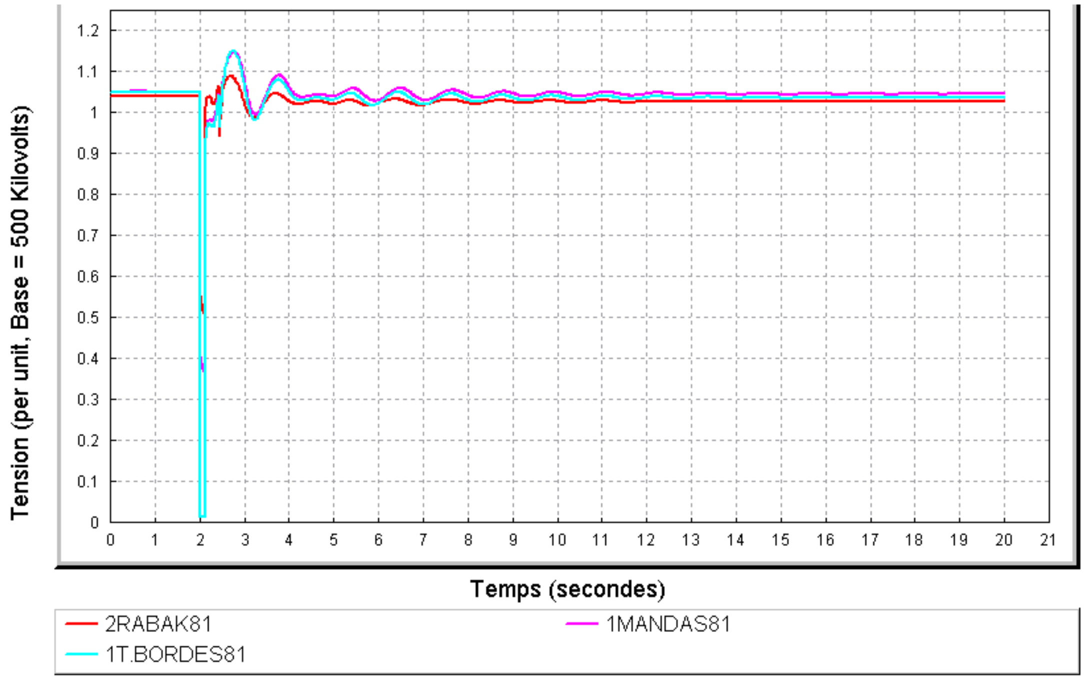


GG3 is Gibe III

2.3.2 POWER FLOW VARIATION ON ENTRO INTERCONNECTION



2.3.3 VOLTAGE VARIATION ON THE 500 KV



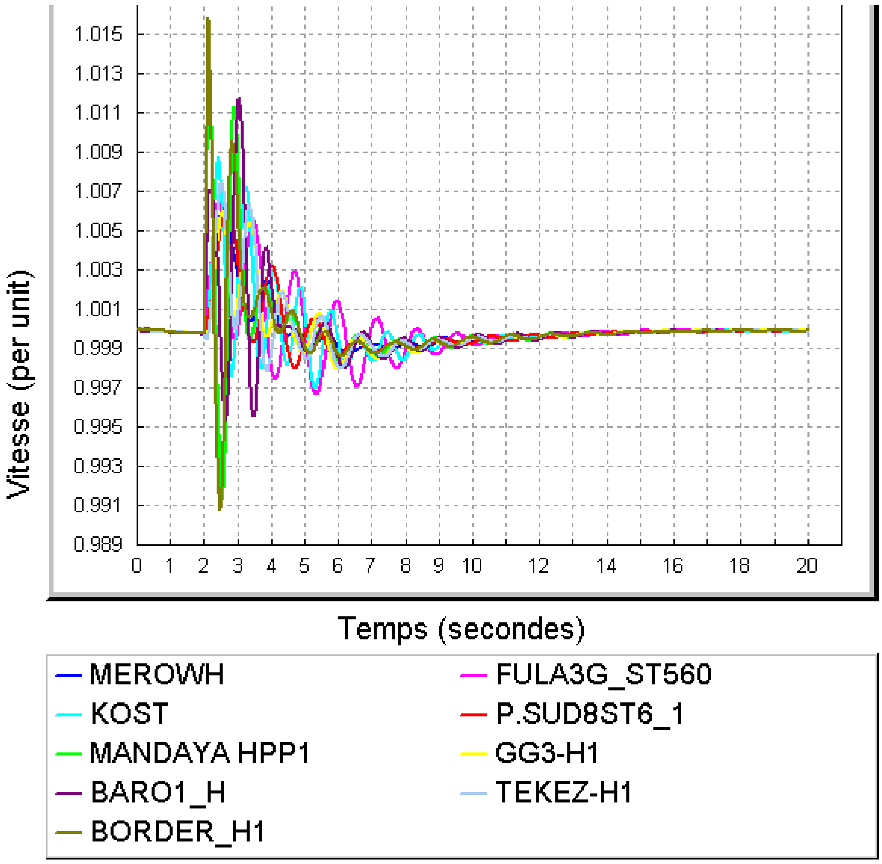
2.4 SHORT-CIRCUIT AT T.BORDER ON ONE OF THE 4 T.BORDER – MANDAYA CIRCUITS

Event : a 3 phase short-circuit at Border end, on one of the 4 circuits T.Border - Mandaya, cleared in 120 ms by the opening of the circuit breakers.

The voltage drop in Kosti (0.44 pu) led to a transitory blocking of commutation of the inverter station at Kosti. The flow on the DC interconnection is transitory reduced to 0, before recovering to its initial value 300 ms after the clearing of the fault.

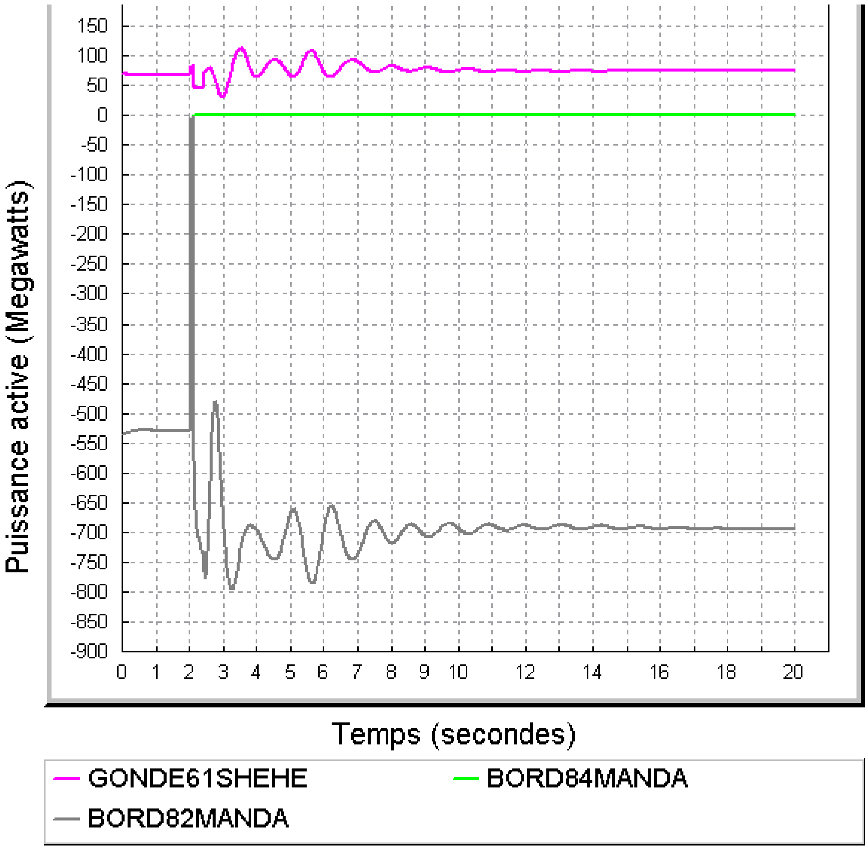
During the transitory blocking of the DC stations, the capacitors bank remained connected.

2.4.1 GENERATORS FREQUENCY VARIATION

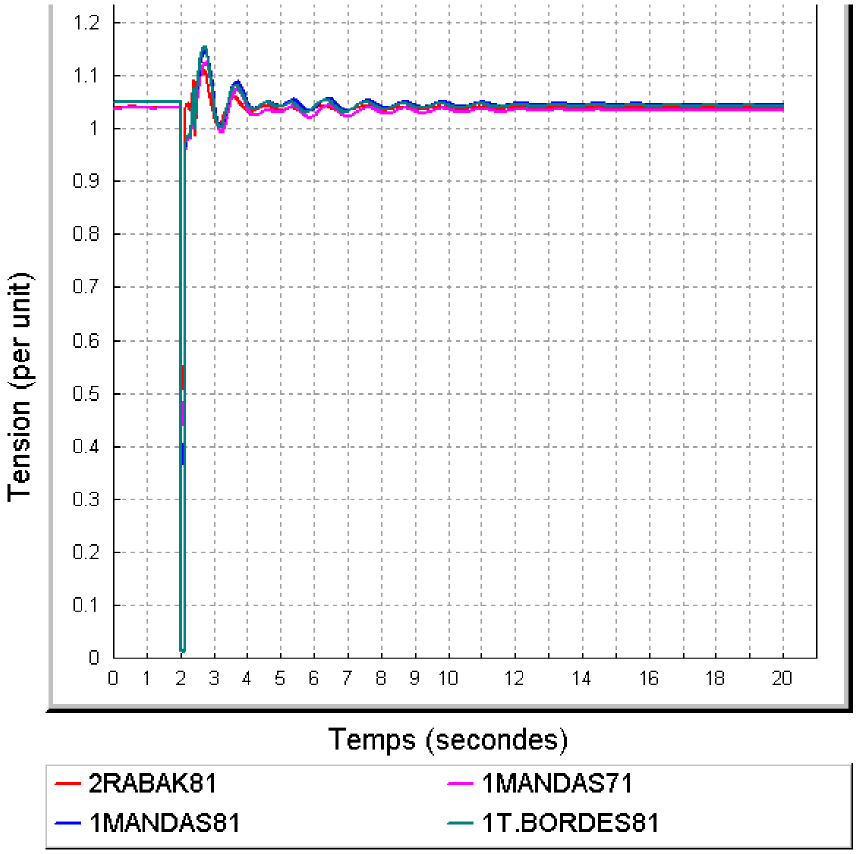


GG3 is Gibe III

2.4.2 POWER FLOW VARIATION ON ENTRO INTERCONNECTION



2.4.3 VOLTAGE VARIATION ON THE 500 KV

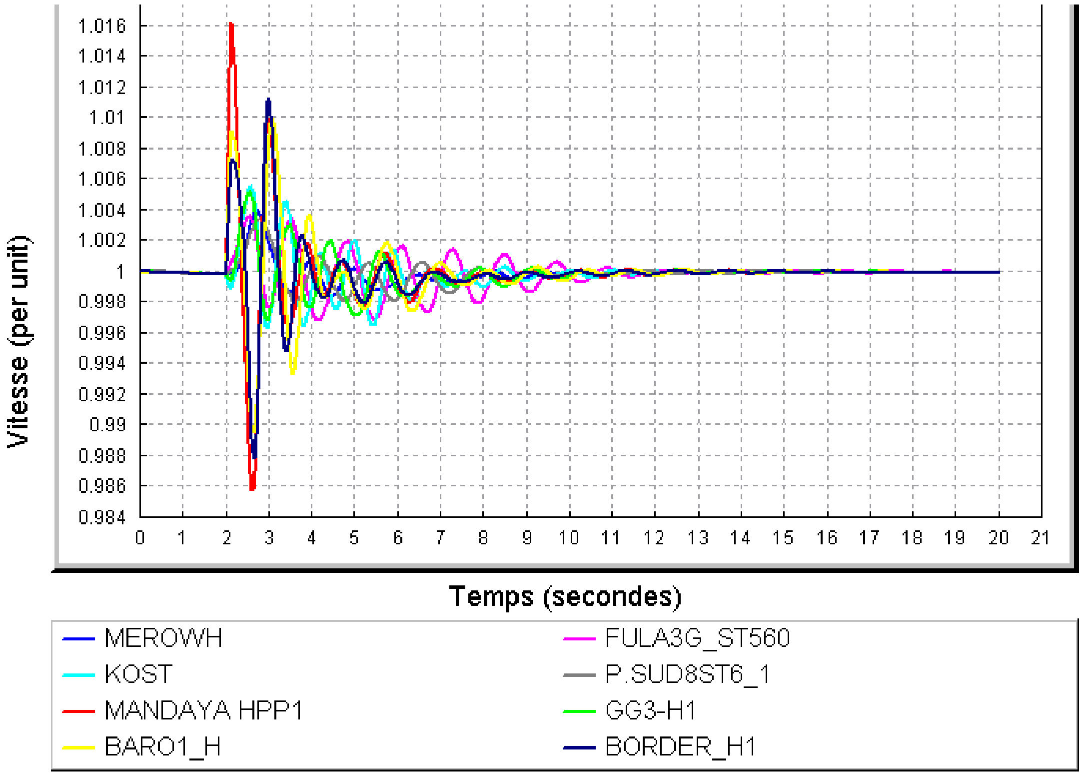


2.5 SHORT-CIRCUIT AT MANDAYA ON ONE OF THE 4 T.BORDER – MANDAYA CIRCUITS

Event : a 3 phase short-circuit at Mandaya end, on one of the 4 circuits T.Border - Mandaya, cleared in 120 ms by the opening of the circuit breakers.

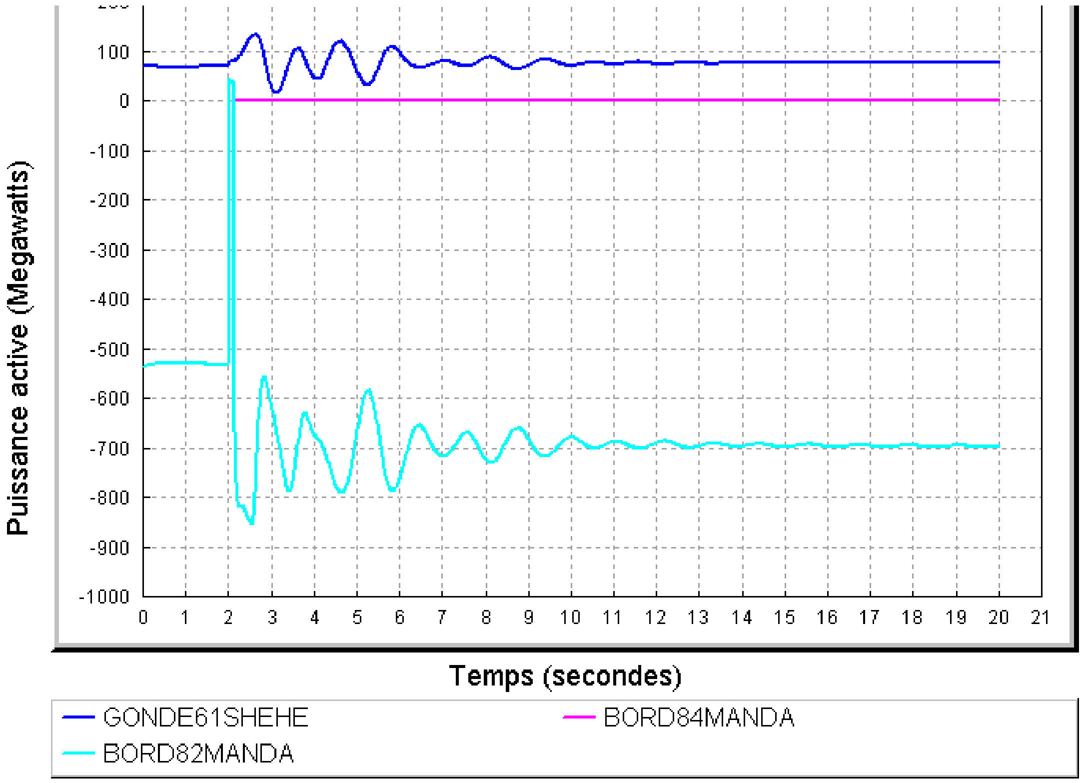
The voltage in Kosti reached 0.64 p.u. There was no transitory blocking of commutation of the inverter station at Kosti.

2.5.1 GENERATORS FREQUENCY VARIATION

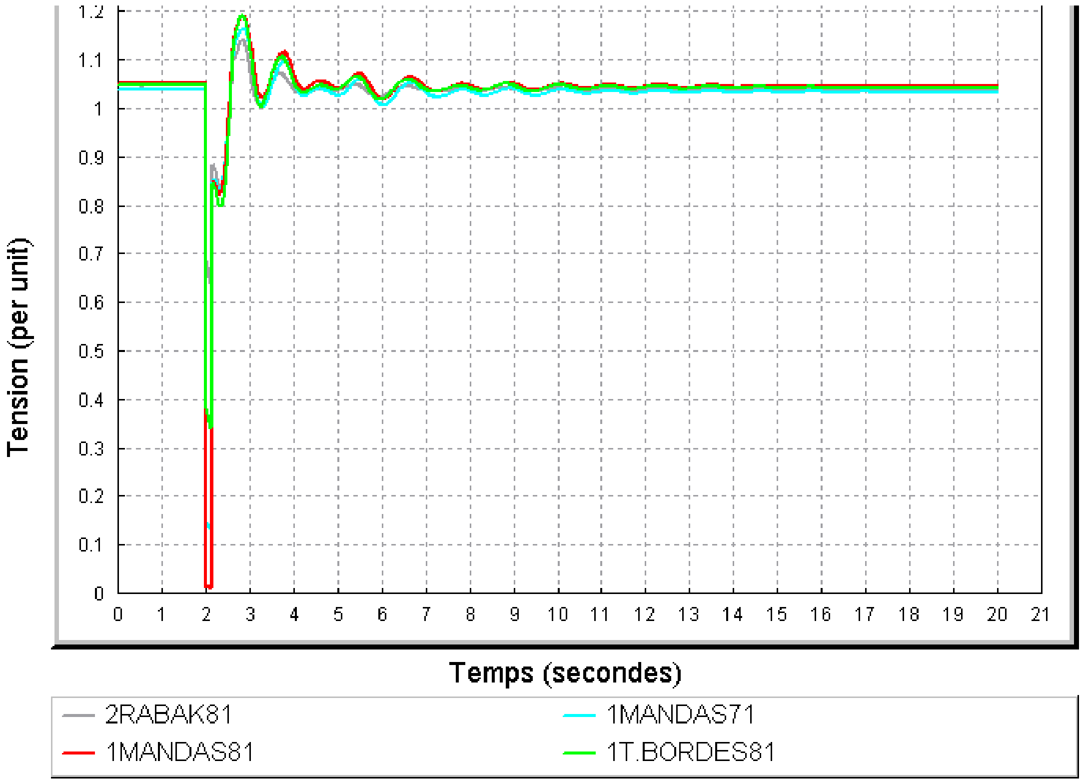


GG3 is Gibe III

2.5.2 POWER FLOW VARIATION ON ENTRO INTERCONNECTION



2.5.3 VOLTAGE VARIATION ON THE 500 KV

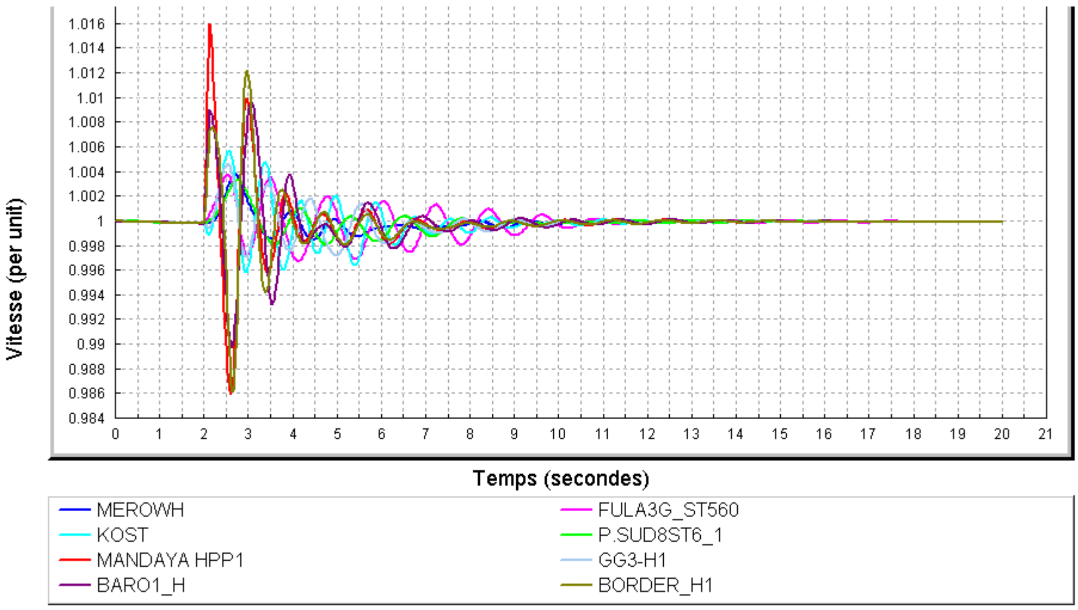


2.6 SHORT-CIRCUIT ON ONE OF THE FOUR 400/500 KV TRANSFORMERS AT MANDAYA

Event : a 3 phase short-circuit at the 500 kV side on one of the four 500/400 kV transformers at Mandaya, cleared in 120 ms by the opening of the circuit breakers.

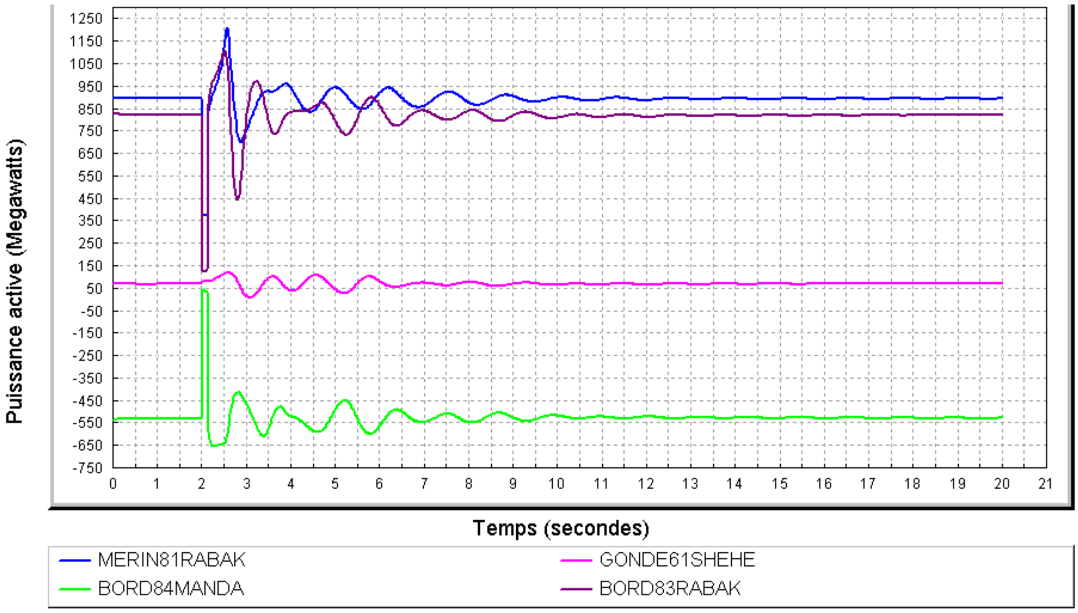
The voltage in Kosti reached 0.64 p.u. There was no transitory blocking of commutation of the inverter station at Kosti.

2.6.1 GENERATORS FREQUENCY VARIATION

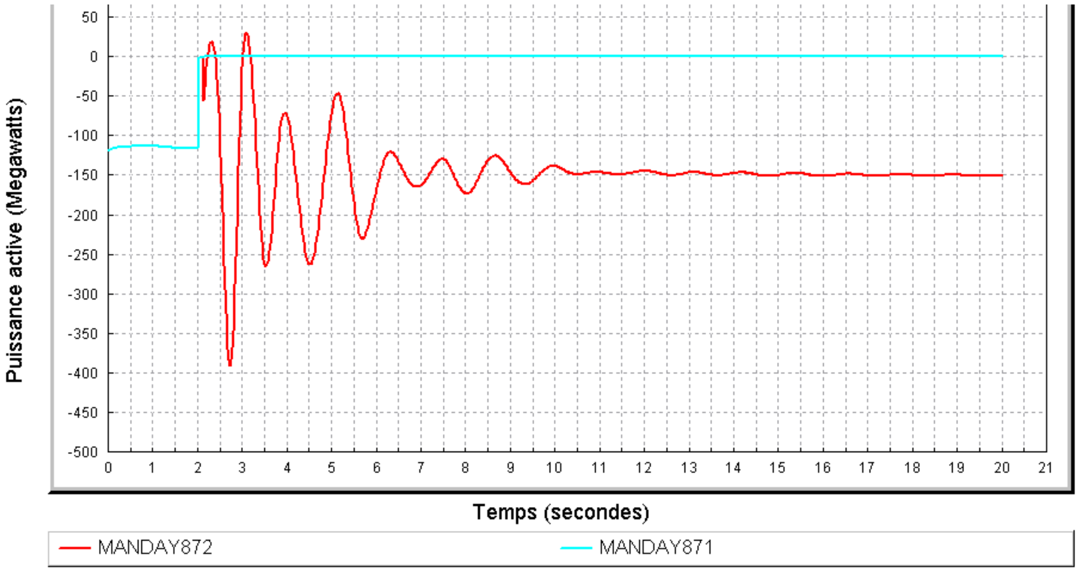


GG3 is Gibe III

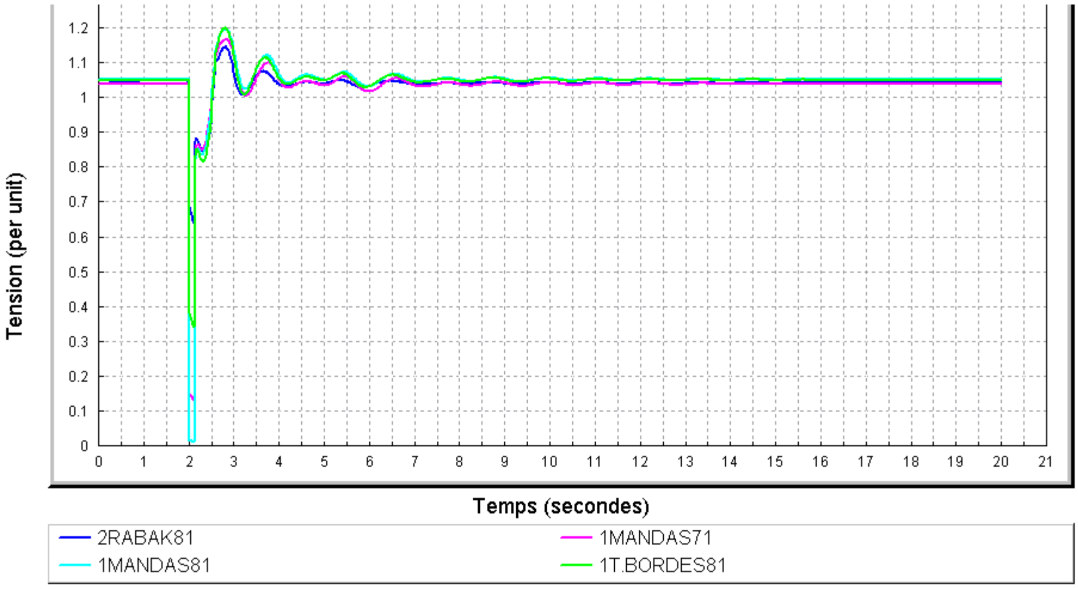
2.6.2 POWER FLOW VARIATION ON ENTRO INTERCONNECTION



2.6.3 POWER FLOW VARIATION MANDAYA 500/400 KV TRANSFORMERS



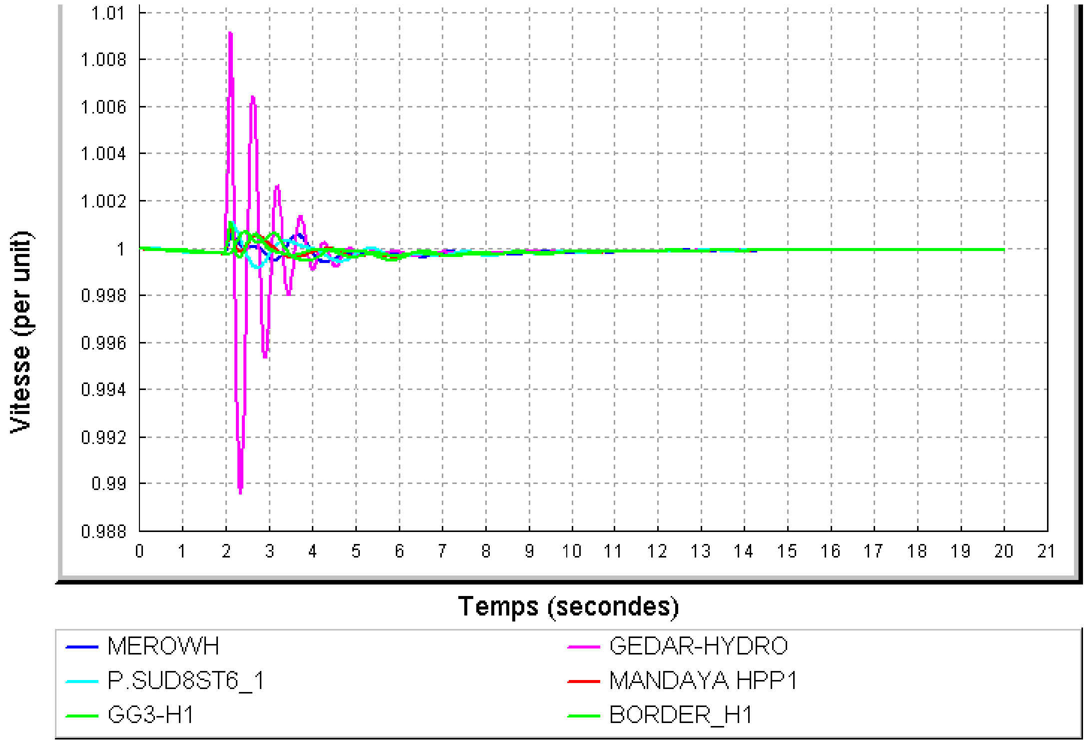
2.6.4 VOLTAGE VARIATION ON THE 500 KV



2.7 SHORT-CIRCUIT AT GEDAREF, ON THE 220 KV PHASE-SHIFT TRANSFORMER

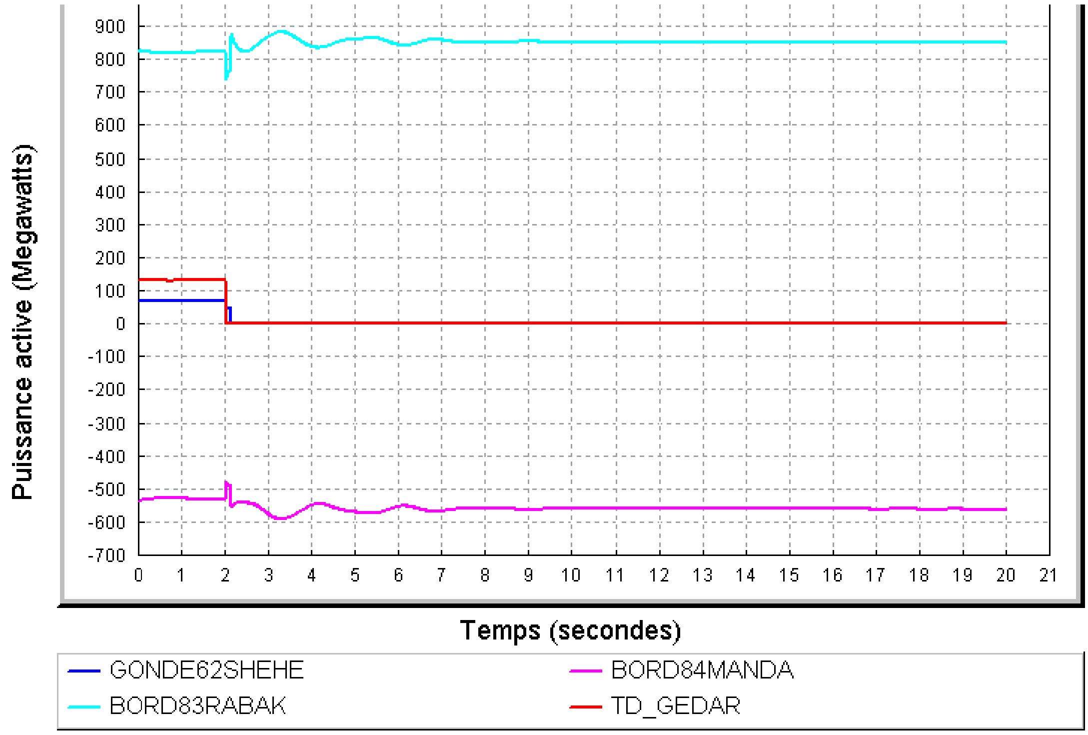
Event : a 3 phase short-circuit at Gedaref 220 kV end, on the 220 kV phase shift transformer, cleared in 120 ms by the opening of the circuit breakers.

2.7.1 GENERATORS FREQUENCY VARIATION

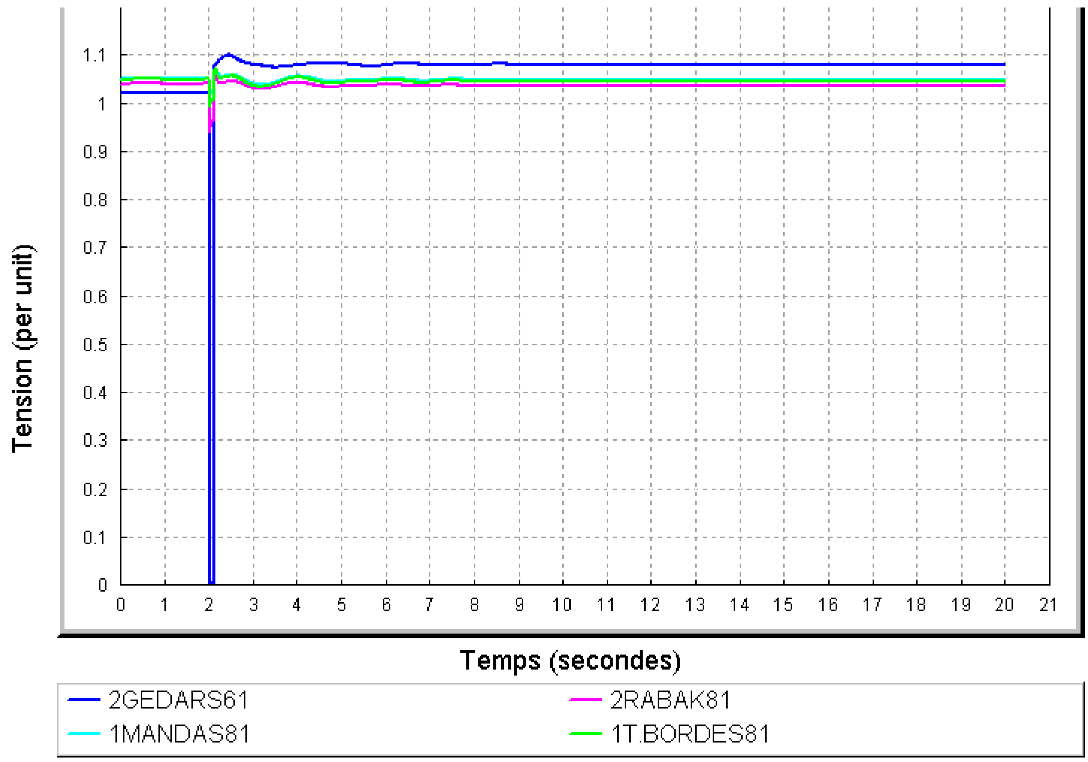


GG3 is Gibe III

2.7.2 POWER FLOW VARIATION ON ENTRO INTERCONNECTION



2.7.3 VOLTAGE VARIATION ON THE 500 KV



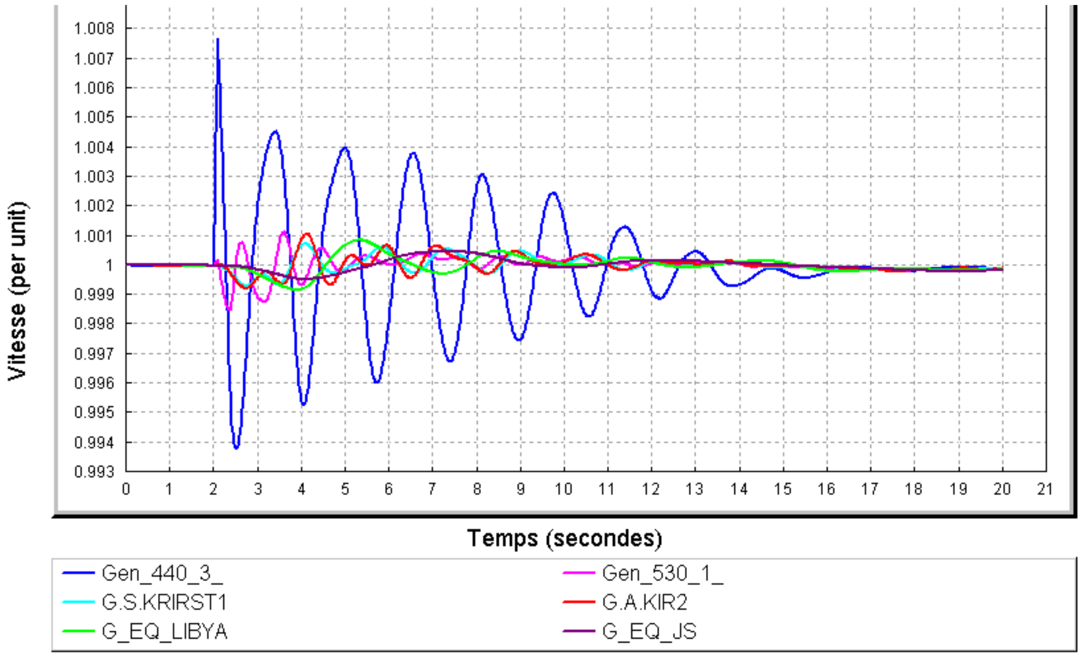
2.8 SHORT-CIRCUIT AT HIGH DAM SIDE, ON ONE OF THE 2 CIRCUITS HIGH DAM - NAG HAMMADI

Event : a 3 phase short-circuit at High Dam end, on one of the 2 circuits High Dam - Nag Hammadi, cleared in 100 ms by the opening of the circuit breakers.

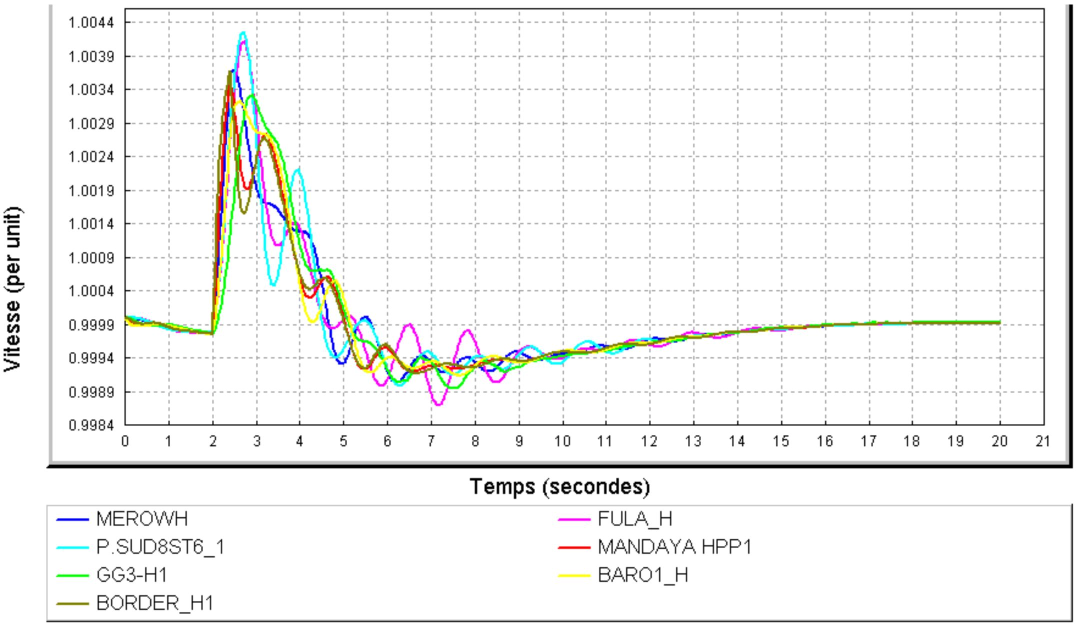
The voltage drop in Nag Hammadi (0.4 p.u.) led to a transitory blocking of commutation of the inverter station at Nag Hammadi. The flow on the DC interconnection is transitory reduced to 0, before starting, 300 ms after the voltage return, its recovery to its initial value.

During the transitory blocking of the DC stations, the capacitors bank remained connected.

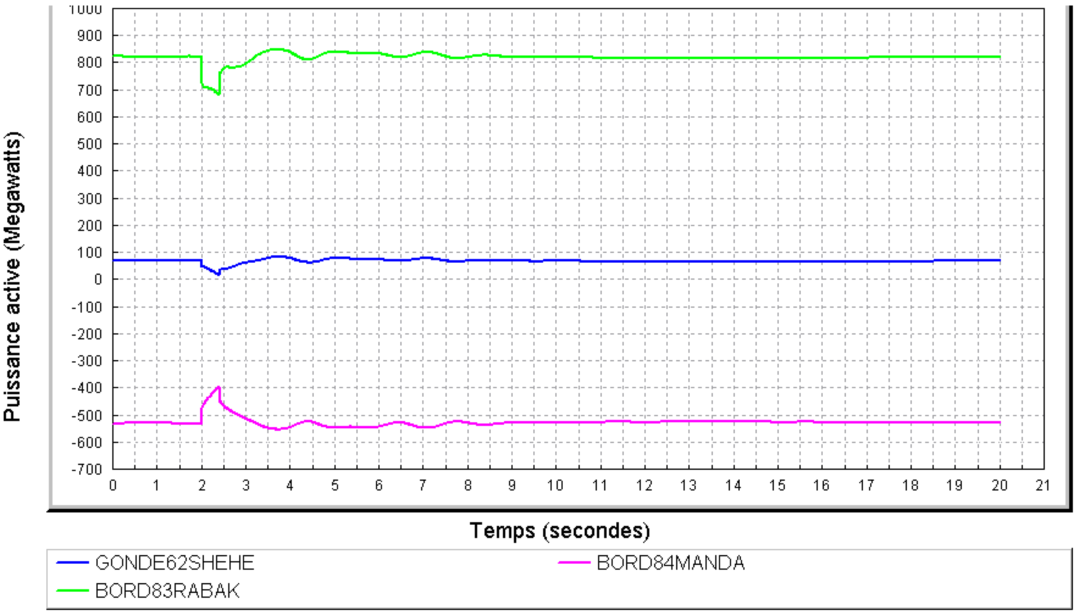
2.8.1 GENERATORS FREQUENCY VARIATION

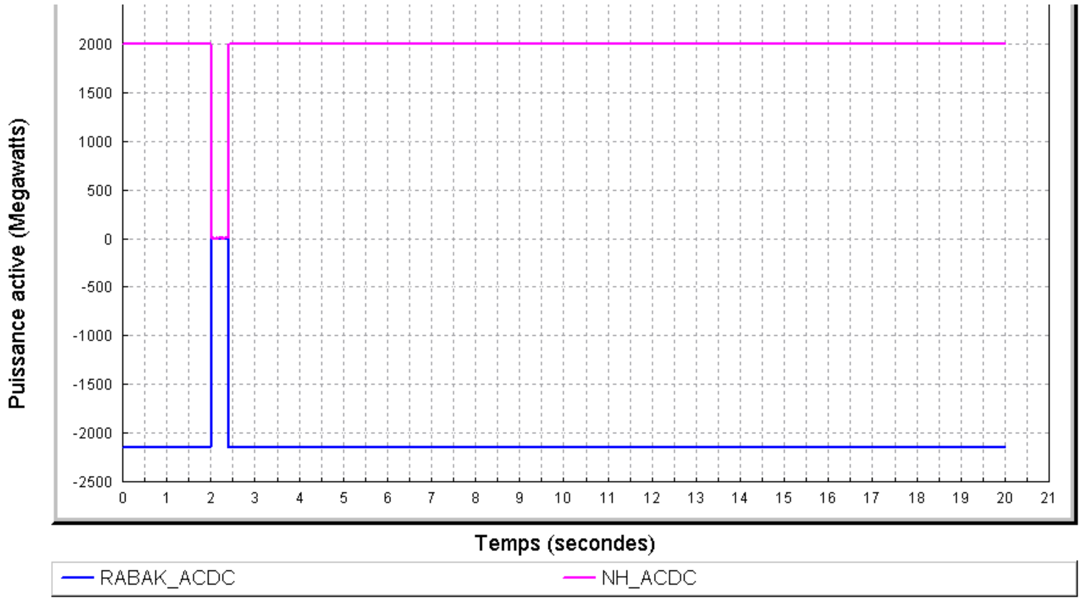


Gen_440_3 is a group of High Dam
Gen_530_1 is group 1 of Kurimat existing steam

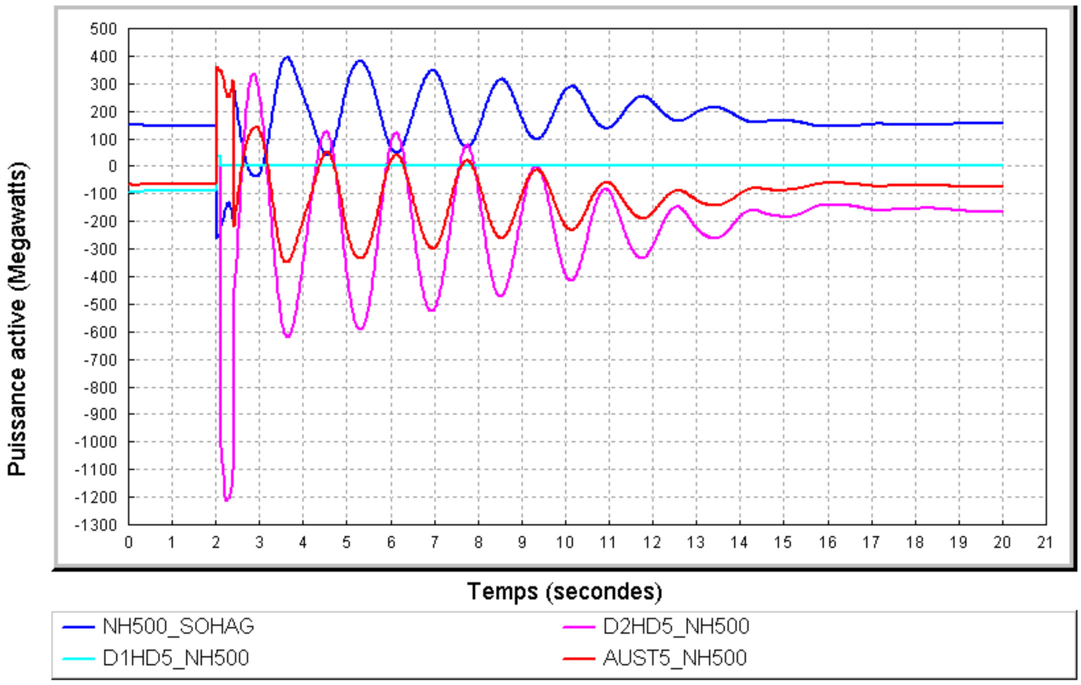


2.8.2 POWER FLOW VARIATION ON ENTRO INTERCONNECTION

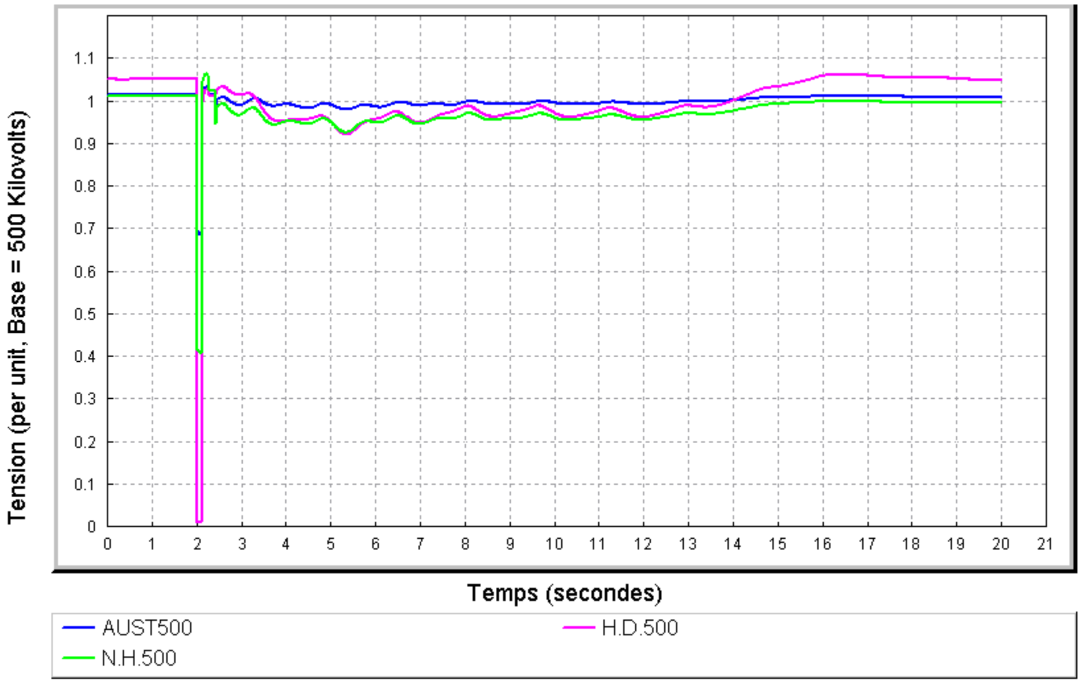


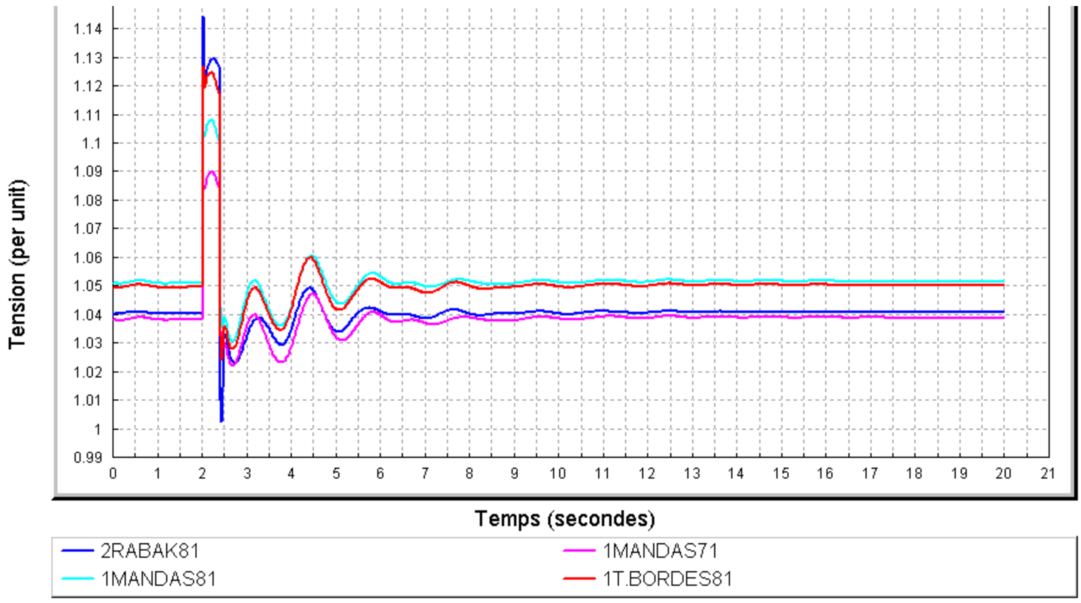


2.8.3 POWER FLOW VARIATION ON HIGH DAM - NAG HAMMADI - ASSIUT



2.8.4 VOLTAGE VARIATION ON THE 500 KV





2.9 SHORT-CIRCUIT AT NAG HAMMADI ON NAG HAMMADI - HIGH DAM

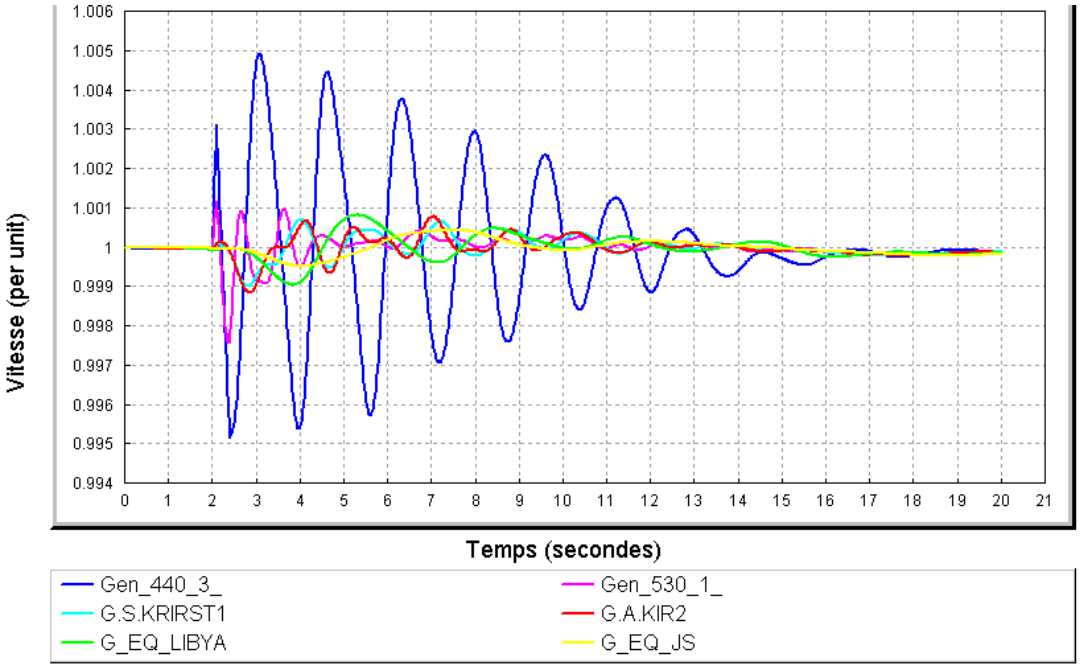
Event : a 3 phase short-circuit at Nag Hammadi end, on one of the 2 circuits High Dam - Nag Hammadi, cleared in 100 ms by the opening of the circuit breakers.

The voltage drop in Nag Hammadi (to 0 pu) led to a transitory blocking of commutation of the inverter station at Nag Hammadi. The flow on the DC interconnection is transitory reduced to 0, The flow on the DC interconnection is transitory reduced to 0, before starting, 300 ms after the voltage return, its recovery to its initial value.

During the transitory blocking of the DC stations, the capacitors bank remained connected.

For the Ethiopian and Sudanese side, the impact on the system and its behaviour is very similar to the case of CC on High Dam - Nag Hammadi, at High Dam.

2.9.1 GENERATORS FREQUENCY VARIATION

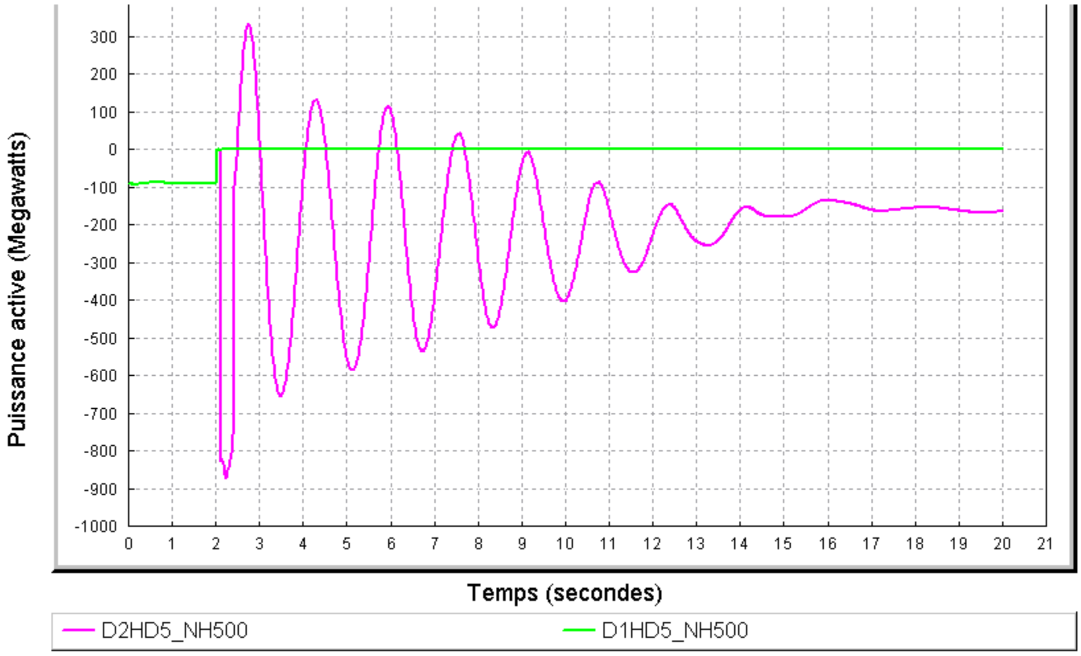


Gen_440_3 is a group of High Dam
Gen_530_1 is group 1 of Kurimat existing steam

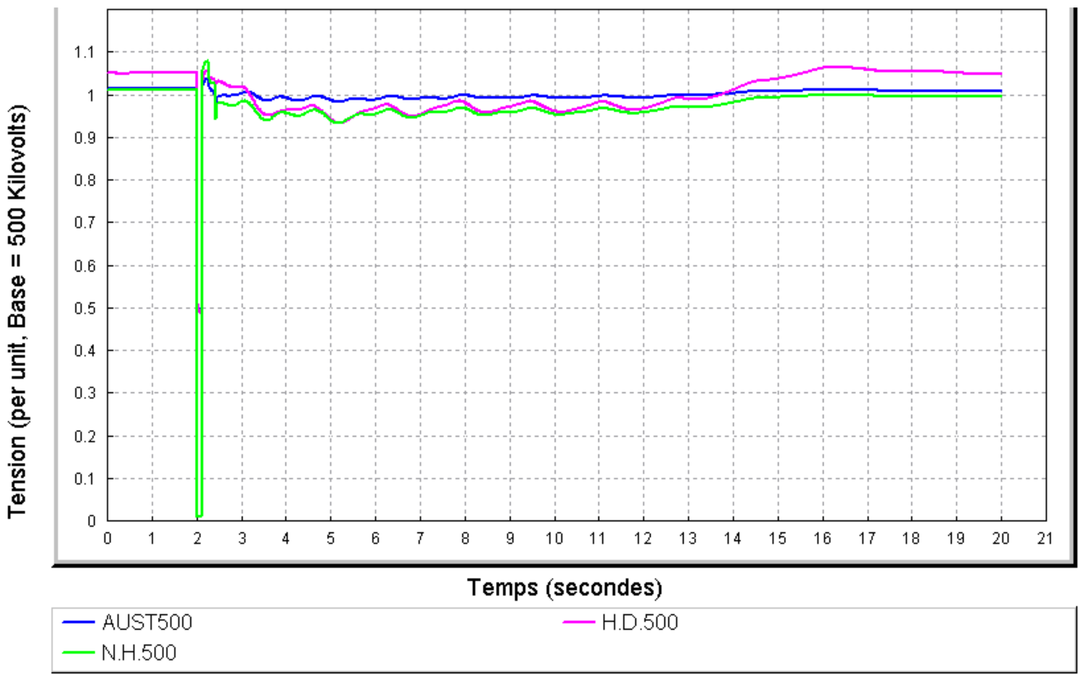
2.9.2 POWER FLOW VARIATION ON ENTRO INTERCONNECTION

For power flow variation on Ethiopia - Sudan interconnection and on the DC interconnection between Sudan and Egypt, the situation is very similar to the case with the SC on High Dam - Nag Hammadi.

2.9.3 POWER FLOW VARIATION ON NAG - HAMMADI - HIGH DAM



2.9.4 VOLTAGE VARIATION ON THE 500 KV



2.10 SHORT-CIRCUIT AT NAG HAMMADI ON NH500 - SOHAG CIRCUIT

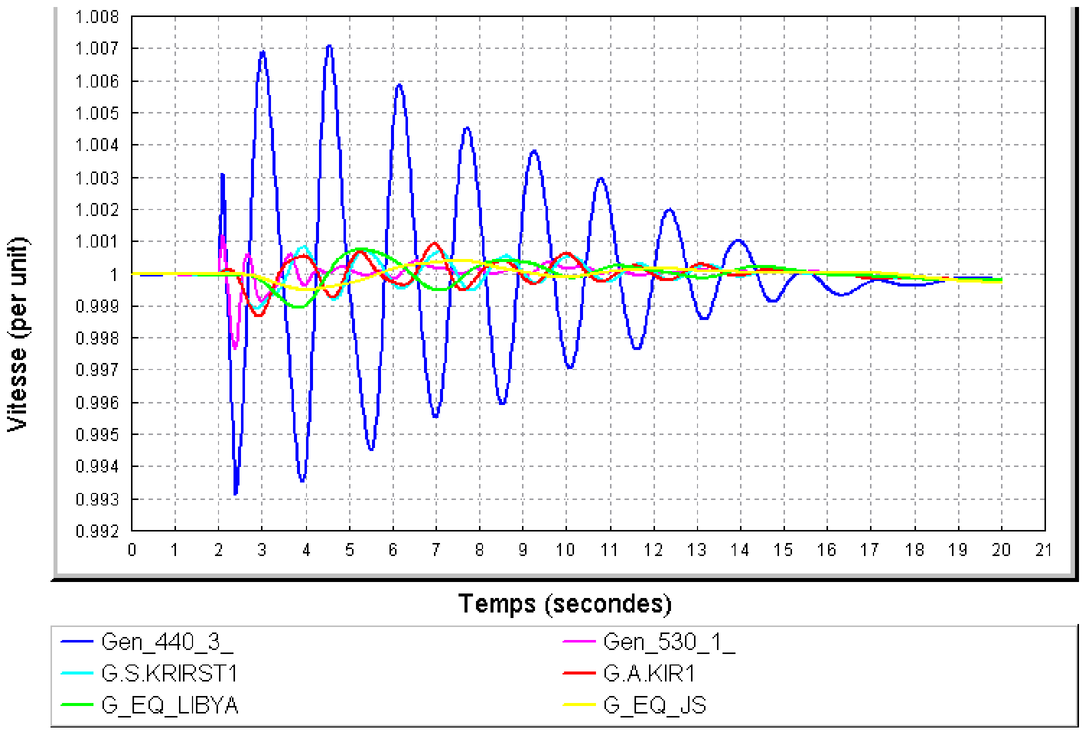
Event : a 3 phase short-circuit at Nag Hammadi end, on the circuit Nag Hammadi - Sohag, cleared in 100 ms by the opening of the circuit breakers.

The voltage drop in Nag Hammadi (to 0 pu) led to a transitory blocking of commutation of the inverter station at Nag Hammadi. The flow on the DC interconnection is transitory reduced to 0, before starting, 300 ms after the voltage return, its recovery to its initial value.

During the transitory blocking of the DC stations, the capacitors bank remained connected.

For the Ethiopian and Sudanese side, the impact on the system and its behaviour is very similar to the case of SC on High Dam - Nag Hammadi

2.10.1 GENERATORS FREQUENCY VARIATION

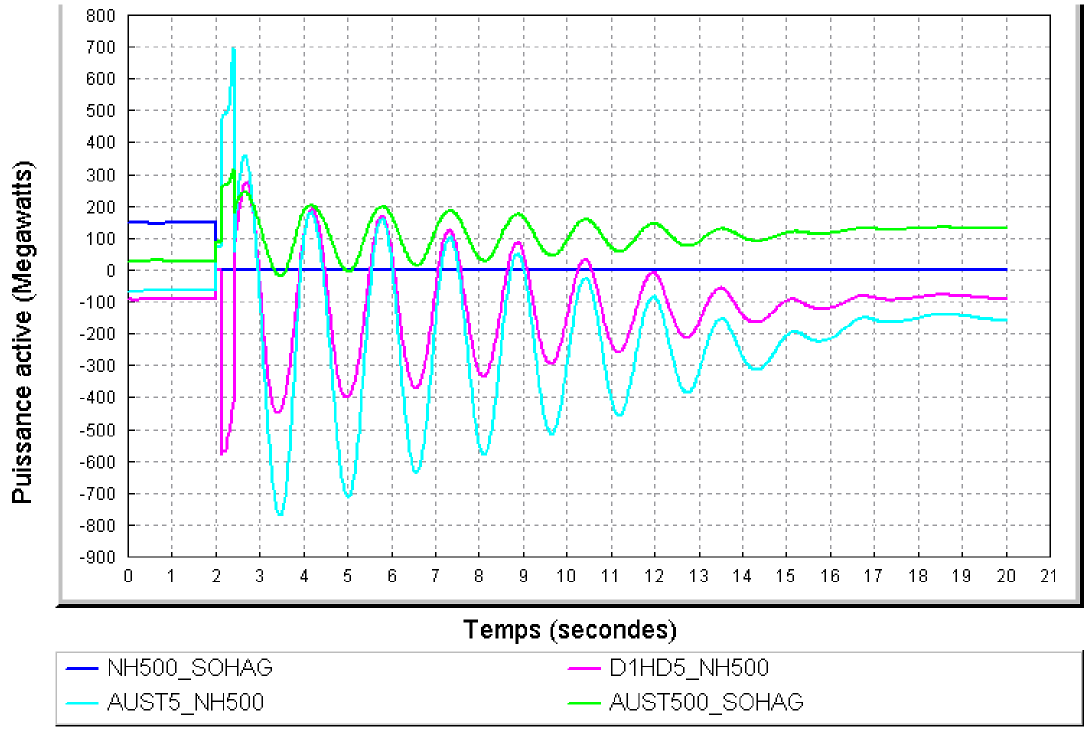


Gen_440_3 is a group of High Dam
Gen_530_1 is group 1 of Kurimat existing steam

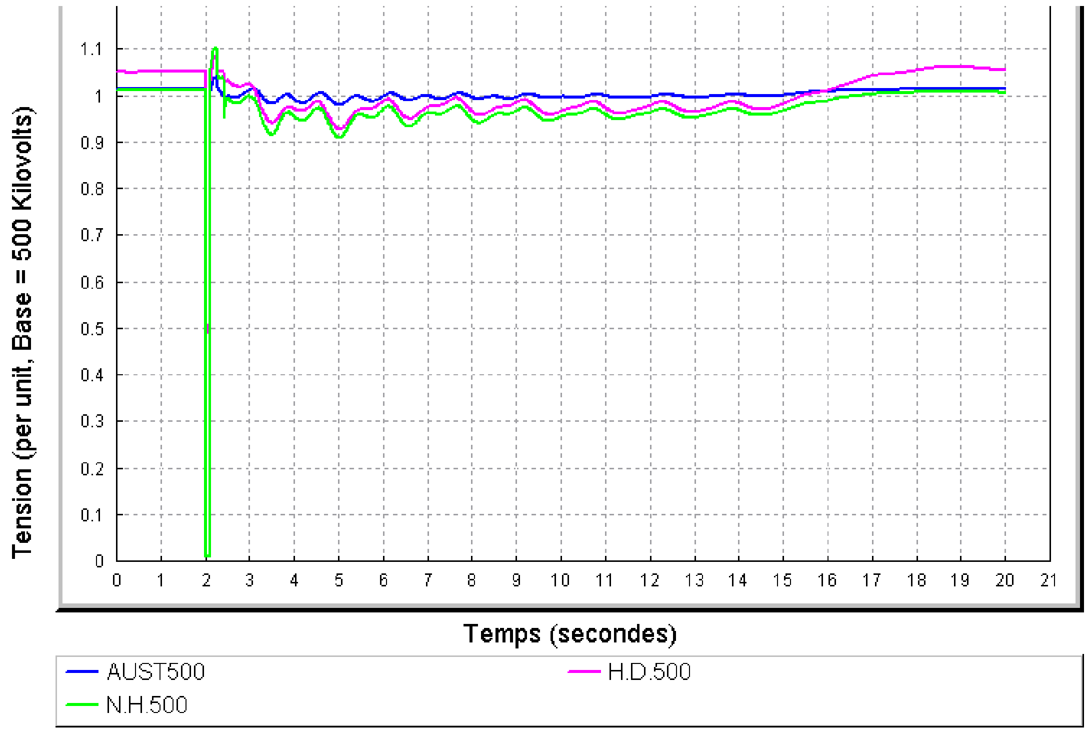
2.10.2 POWER FLOW VARIATION ON ENTRO INTERCONNECTION

For power flow variation on Ethiopia - Sudan interconnection and on the DC interconnection between Sudan and Egypt, the situation is very similar to the case with the SC on High Dam - Nag Hammadi.

2.10.3 POWER FLOW VARIATION ON THE CIRCUIT HIGH DAM - NAG HAMMADI - ASSIUT



2.10.4 VOLTAGE VARIATION ON THE 500 KV

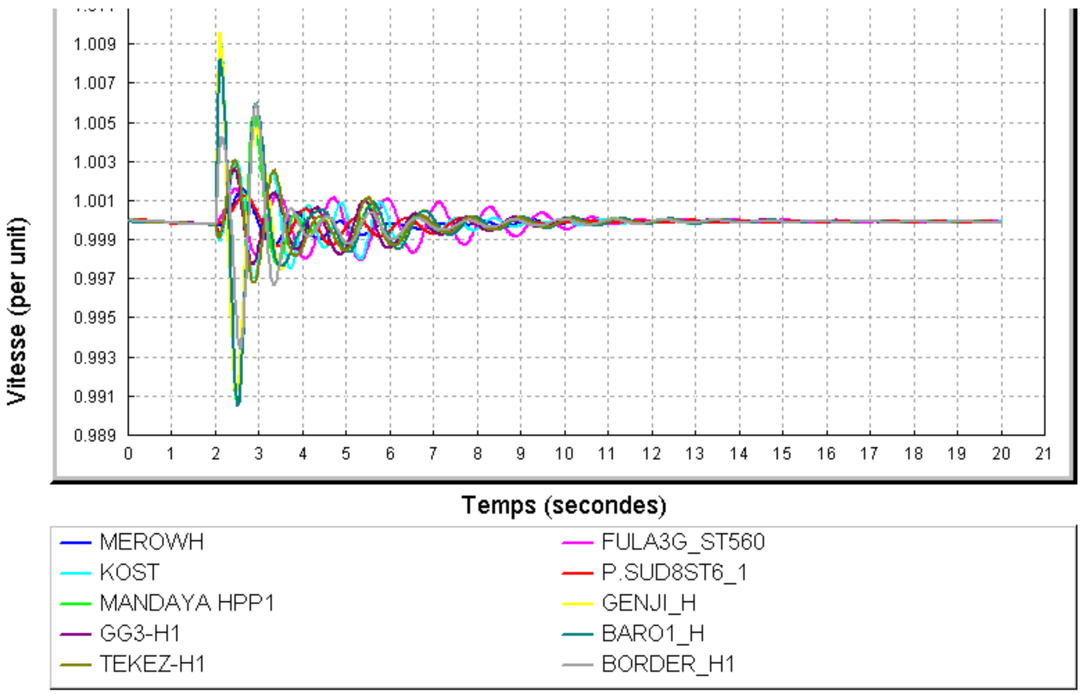


2.11 SHORT-CIRCUIT AT MANDAYA ON ONE OF THE 3 CIRCUITS MANDAYA - GHIMBI

Event : a 3 phase short-circuit at Mandaya end, on one of the 3 circuits Mandaya - Ghimbi, cleared in 100 ms by the opening of the circuit breakers.

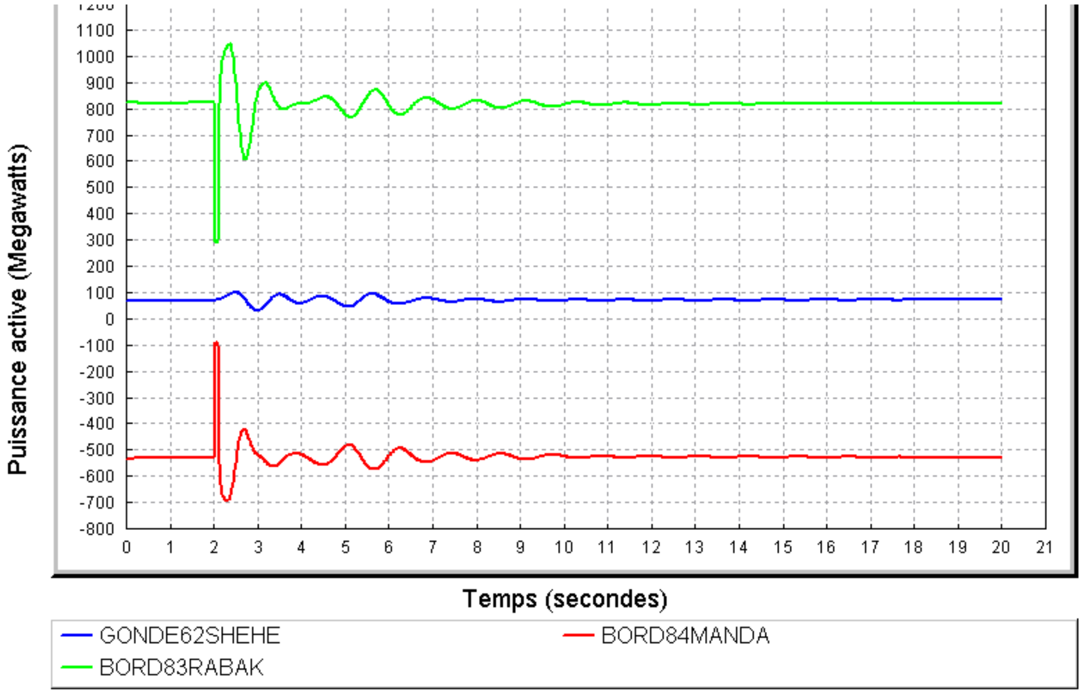
The voltage in Kosti reached 0.74 p.u. There was no transitory blocking of commutation of the inverter station at Kosti.

2.11.1 GENERATORS FREQUENCY VARIATION

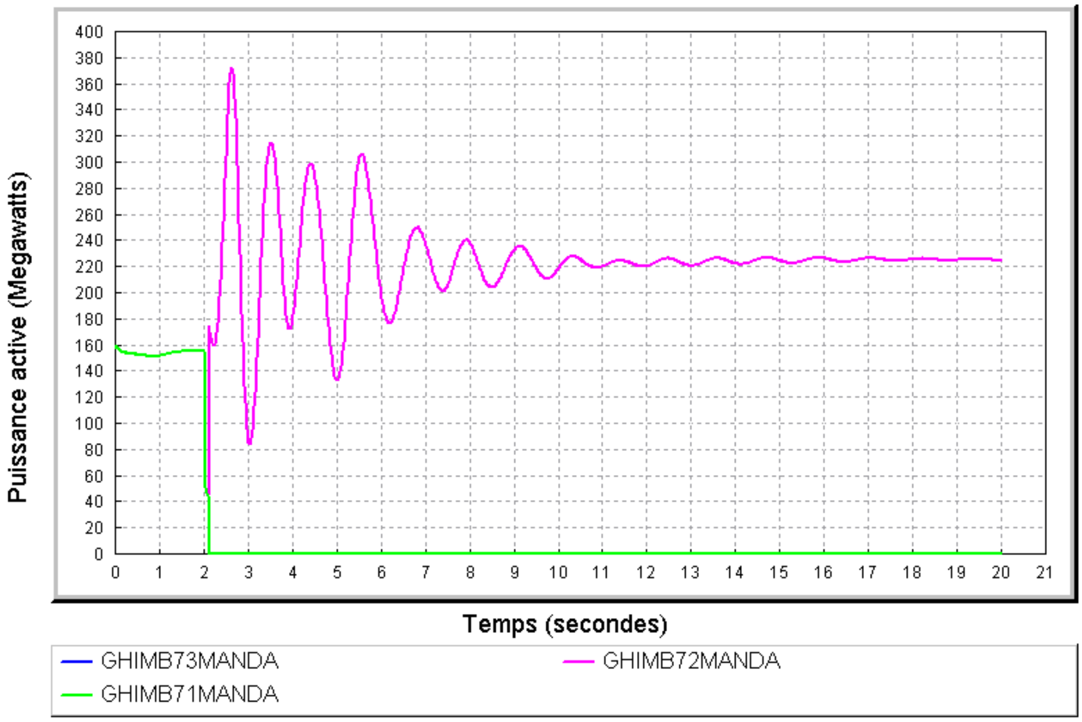


GG3 is Gibe III

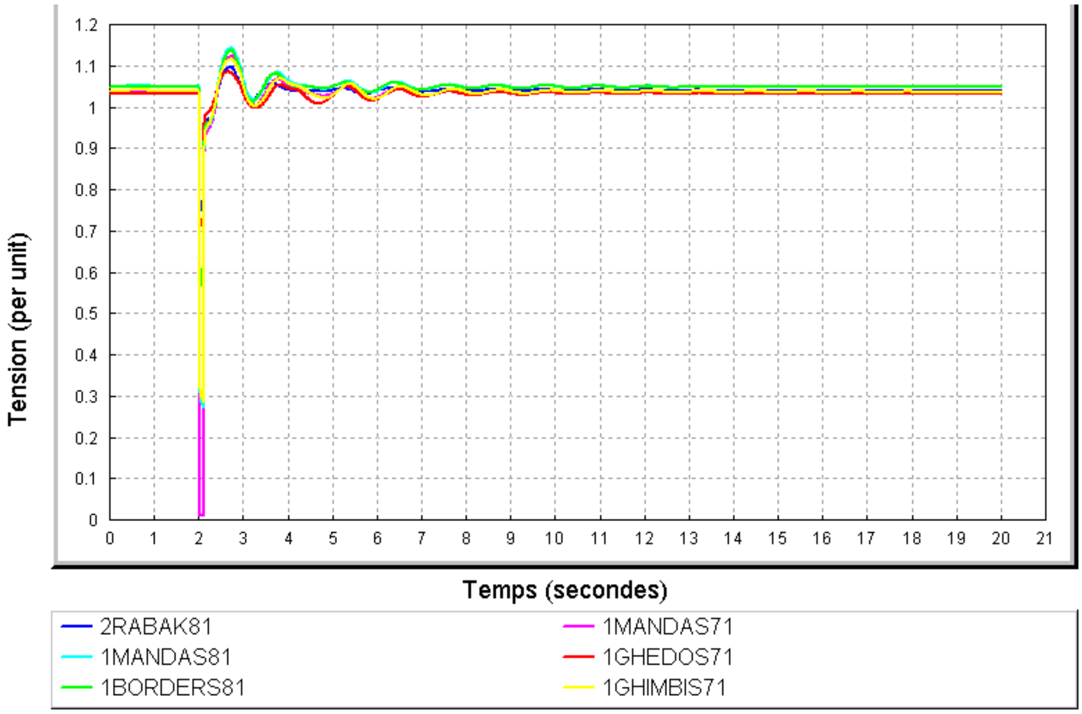
2.11.2 POWER FLOW VARIATION ON ENTRO INTERCONNECTION



2.11.3 POWER FLOW VARIATION ON MANDAYA - GHIMBI



2.11.4 VOLTAGE VARIATION ON THE 500 KV



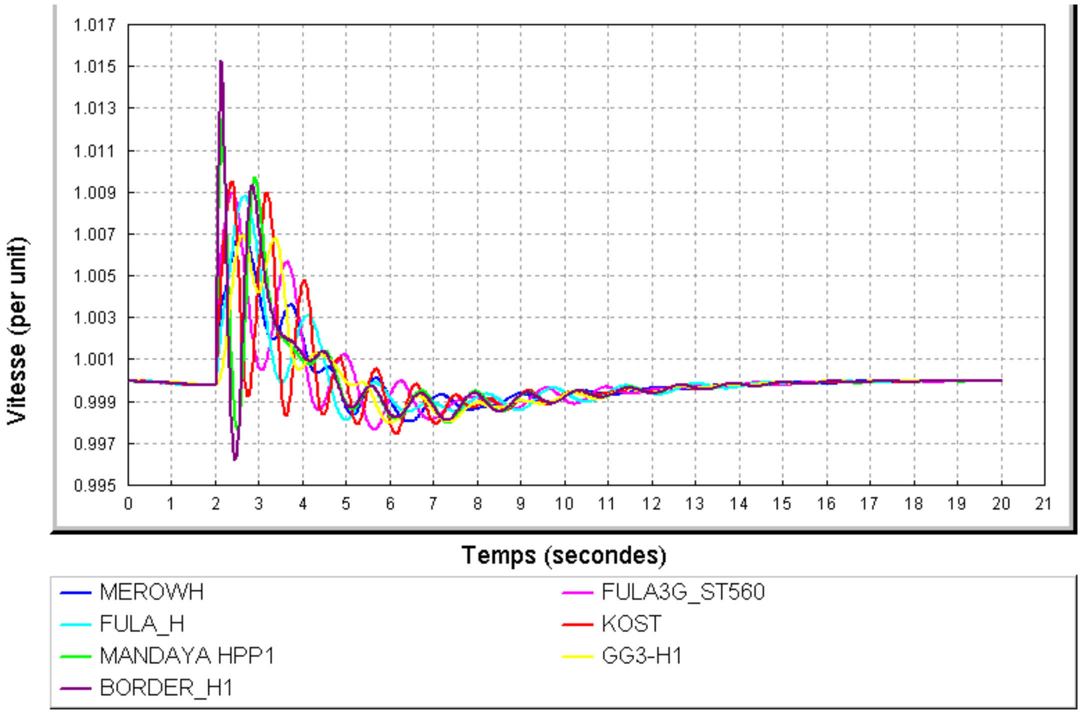
2.12 SHORT-CIRCUIT AT KOSTI ON KOSTI - FULA

Event : a 3 phase short-circuit at Kosti end, on one of the 2 circuits Kosti - Fula, cleared in 120 ms by the opening of the circuit breakers.

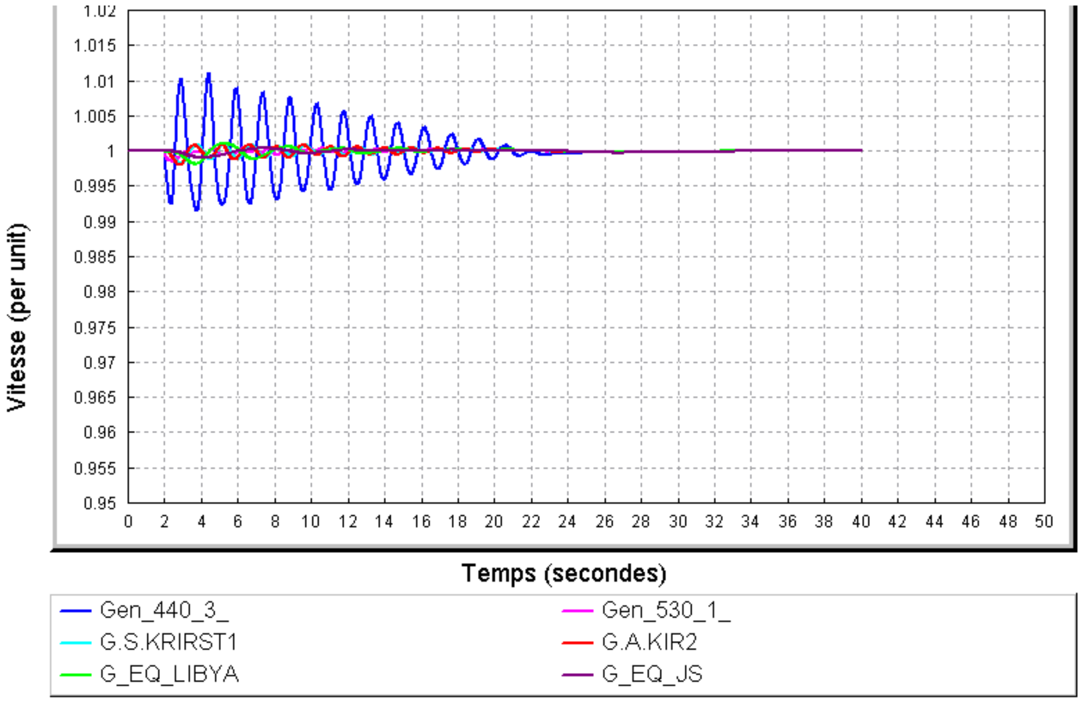
The voltage drop in Kosti (to 0 pu) led to a transitory blocking of commutation of the rectifier station at Kosti. The flow on the DC interconnection is transitory reduced to 0, before starting, 300 ms after the voltage return, its recovery to its initial value.

During the transitory blocking of the DC stations, the capacitors bank remained connected.

2.12.1 GENERATORS FREQUENCY VARIATION

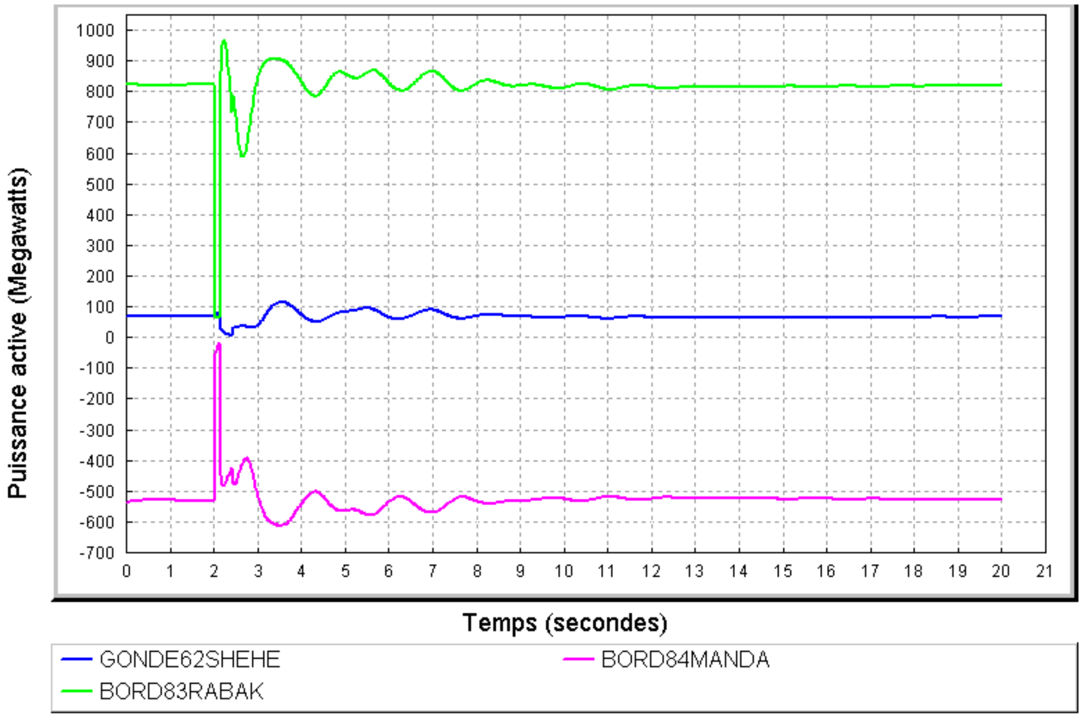


GG3 is Gibe III

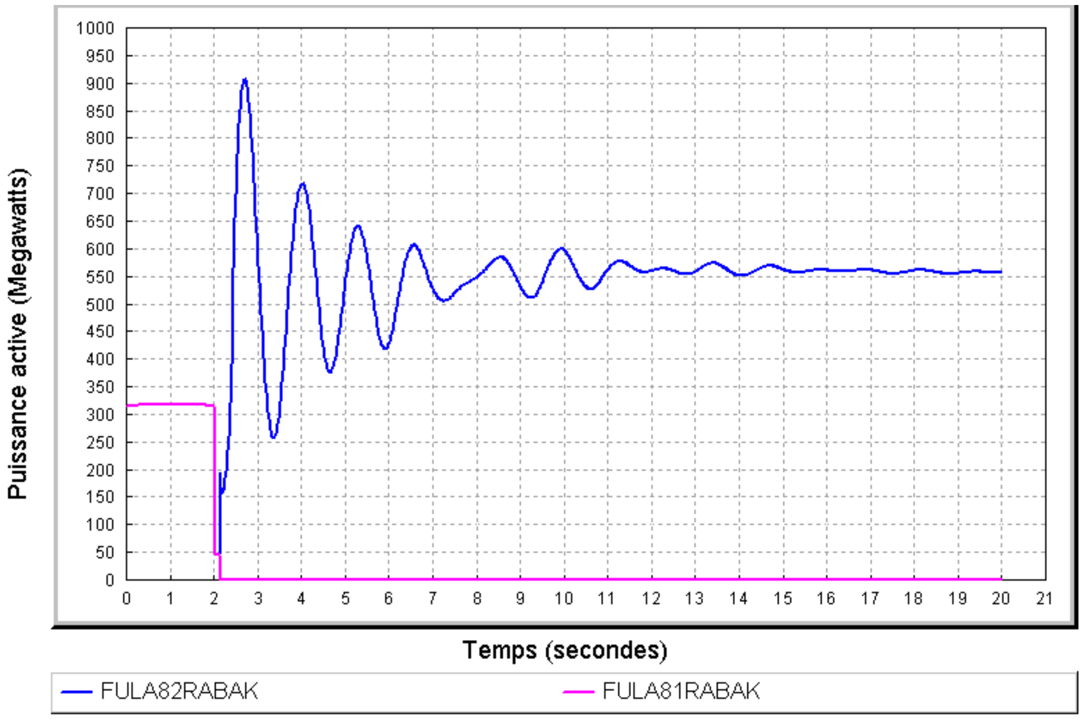


Gen_440_3 is a group of High Dam
Gen_530 is the existing steam turbine in Kurimat

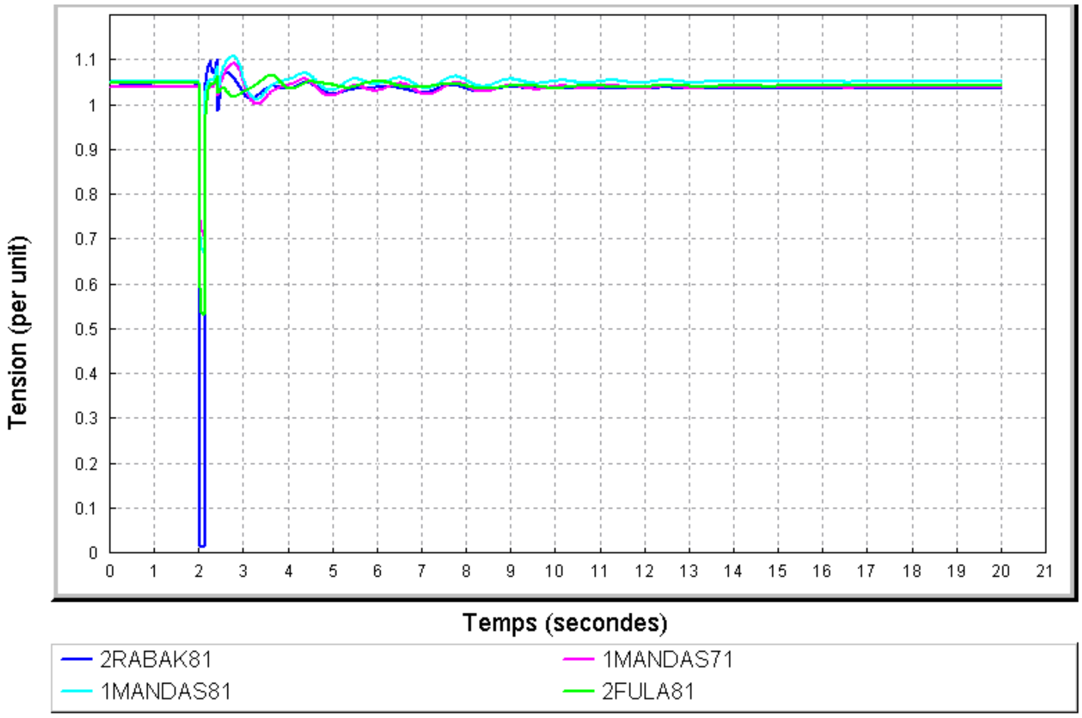
2.12.2 POWER FLOW VARIATION ON ENTRO INTERCONNECTION

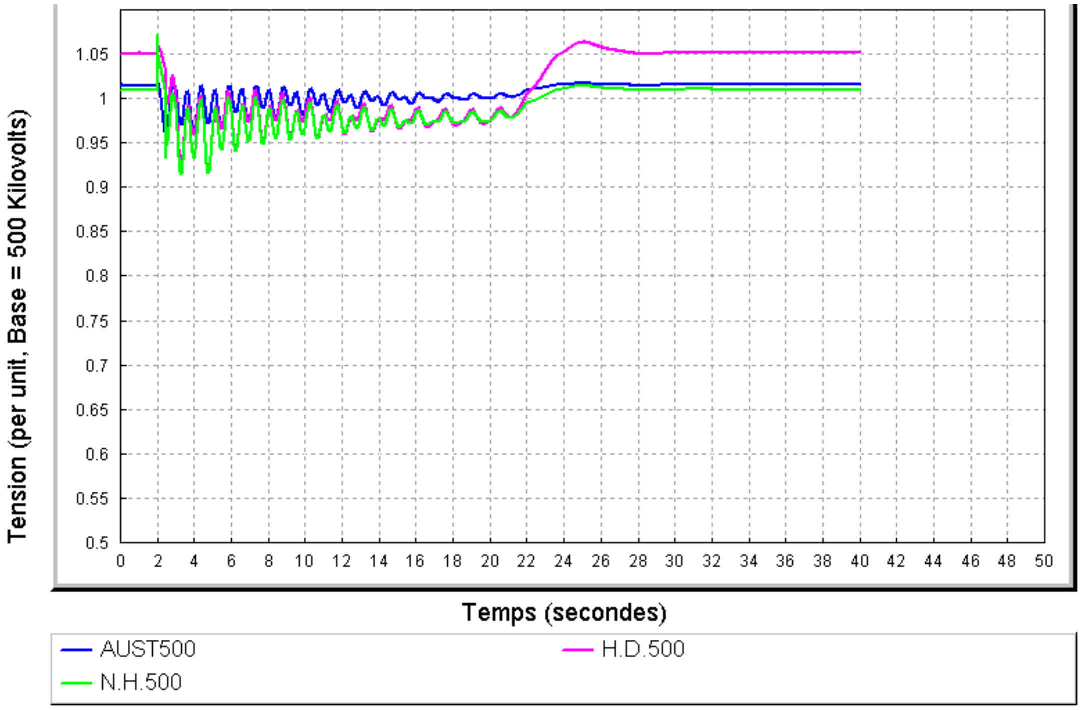


2.12.3 POWER FLOW VARIATION ON KOSTI - FULA



2.12.4 VOLTAGE VARIATION ON THE 500 KV





2.13 SHORT-CIRCUIT AT KOSTI ON KOSTI - MERINGAN

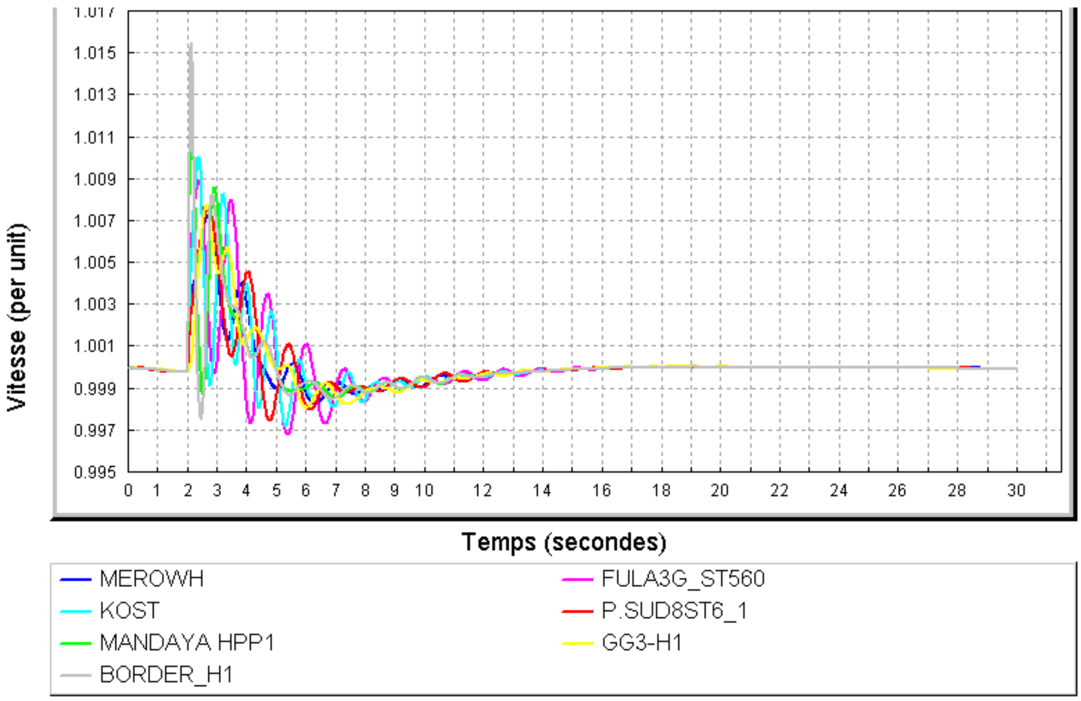
Event : a 3 phase short-circuit at Kosti end, on the circuit Kosti - Meringan, cleared in 120 ms by the opening of the circuit breakers.

The voltage drop in Kosti (to 0 pu) led to a transitory blocking of commutation of the rectifier station at Kosti. The flow on the DC interconnection is transitory reduced to 0, before starting, 300 ms after the voltage return, its recovery to its initial value.

During the transitory blocking of the DC stations, the capacitors bank remained connected.

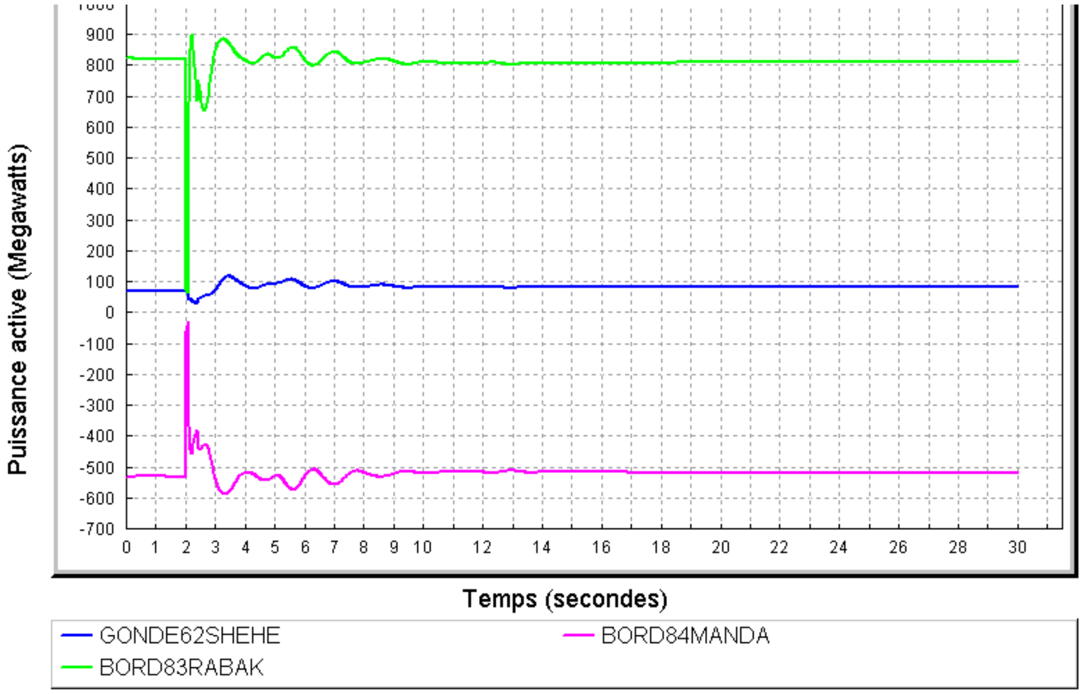
For the Egyptian side, the impact on the system and its behaviour is very similar to the case of SC on Kosti - Fula

2.13.1 GENERATORS FREQUENCY VARIATION

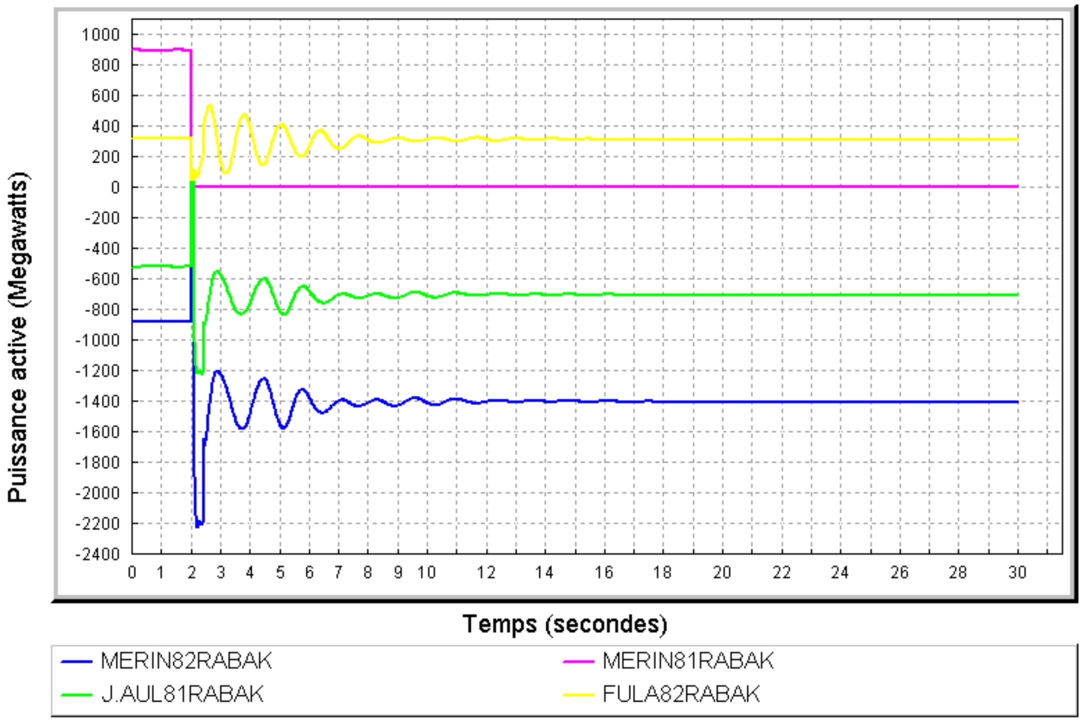


GG3 is Gibe III

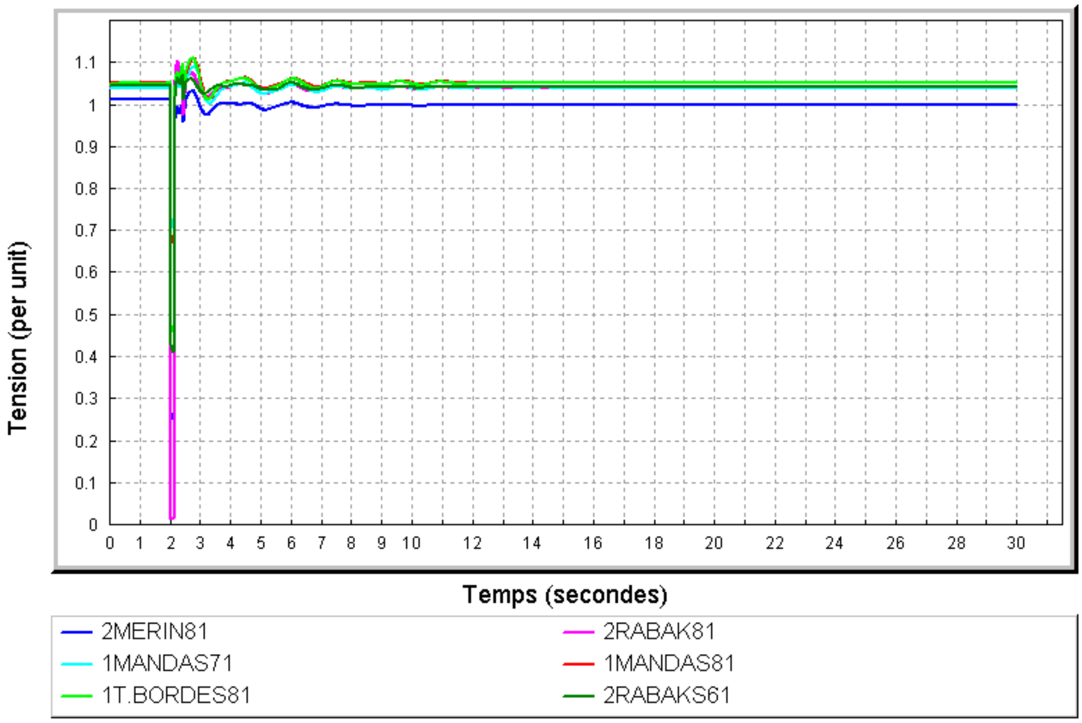
2.13.2 POWER FLOW VARIATION ON ENTRO INTERCONNECTION



2.13.3 POWER FLOW VARIATION ON KOSTI - MERINGAN, KOSTI - FULA AND KOSTI - J. AULIA



2.13.4 VOLTAGE VARIATION ON THE 500 KV



2.14 SHORT-CIRCUIT AT KOSTI ON KOSTI - JEBEL AULIA

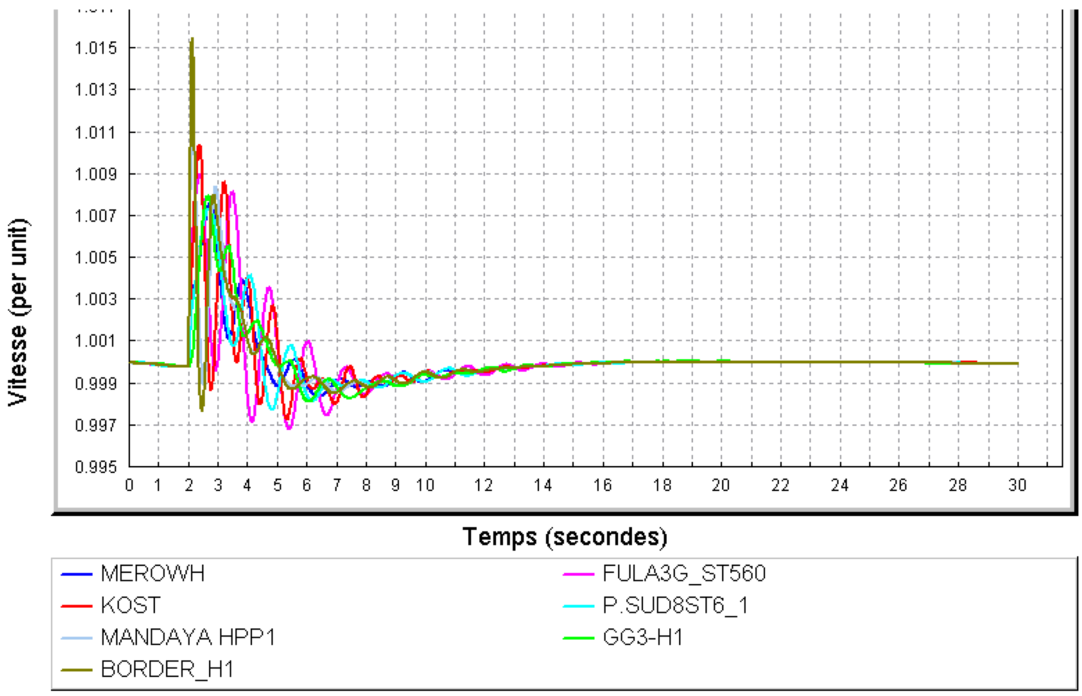
Event : a 3 phase short-circuit at Kosti end, on the circuit Kosti – Jebel Aulia, cleared in 120 ms by the opening of the circuit breakers.

The voltage drop in Kosti (to 0 pu) led to a transitory blocking of commutation of the rectifier station at Kosti. The flow on the DC interconnection is transitory reduced to 0, before starting, 300 ms after the voltage return, its recovery to its initial value.

During the transitory blocking of the DC stations, the capacitors bank remained connected.

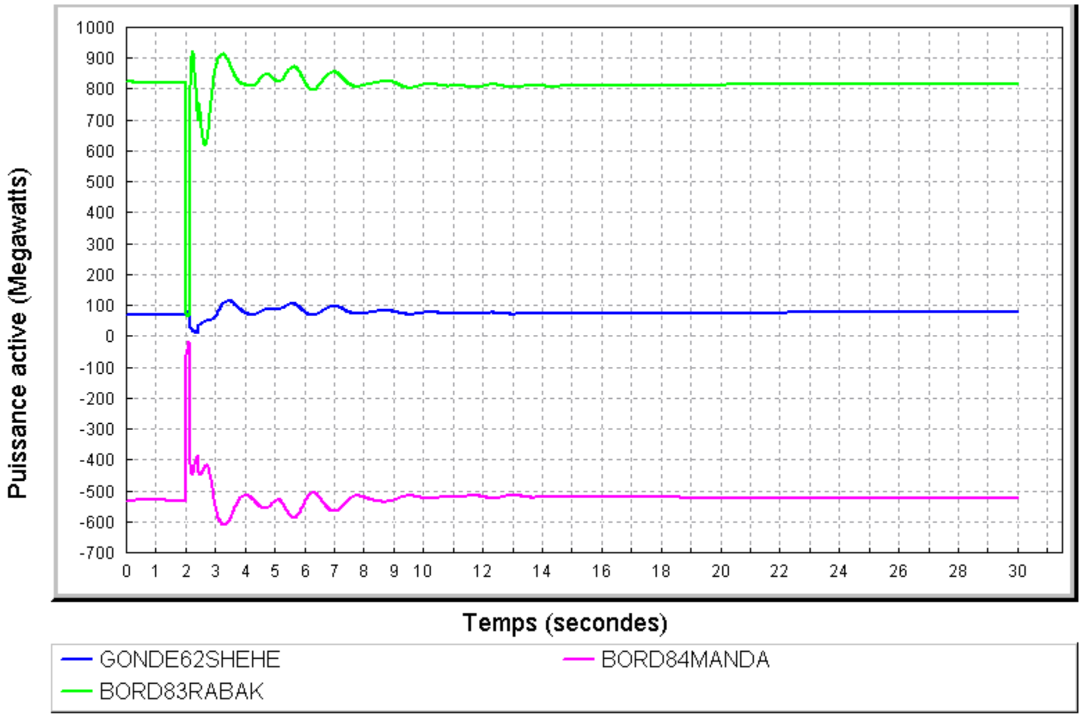
For the Egyptian side, the impact on the system and its behaviour is very similar to the case of SC on Kosti - Fula.

2.14.1 GENERATORS FREQUENCY VARIATION

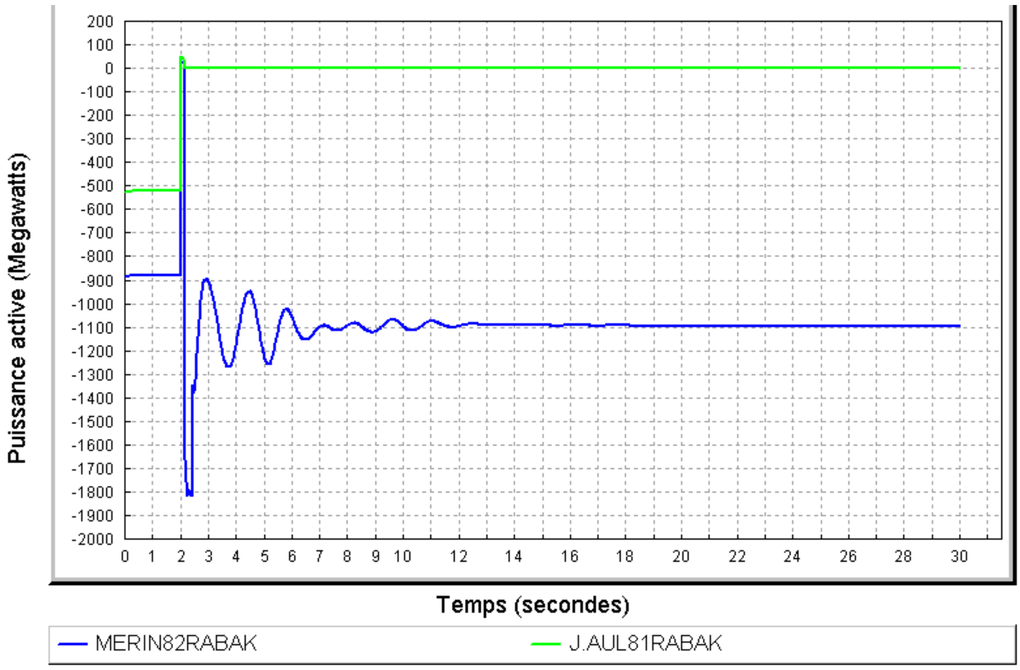


GG3 is Gibe III

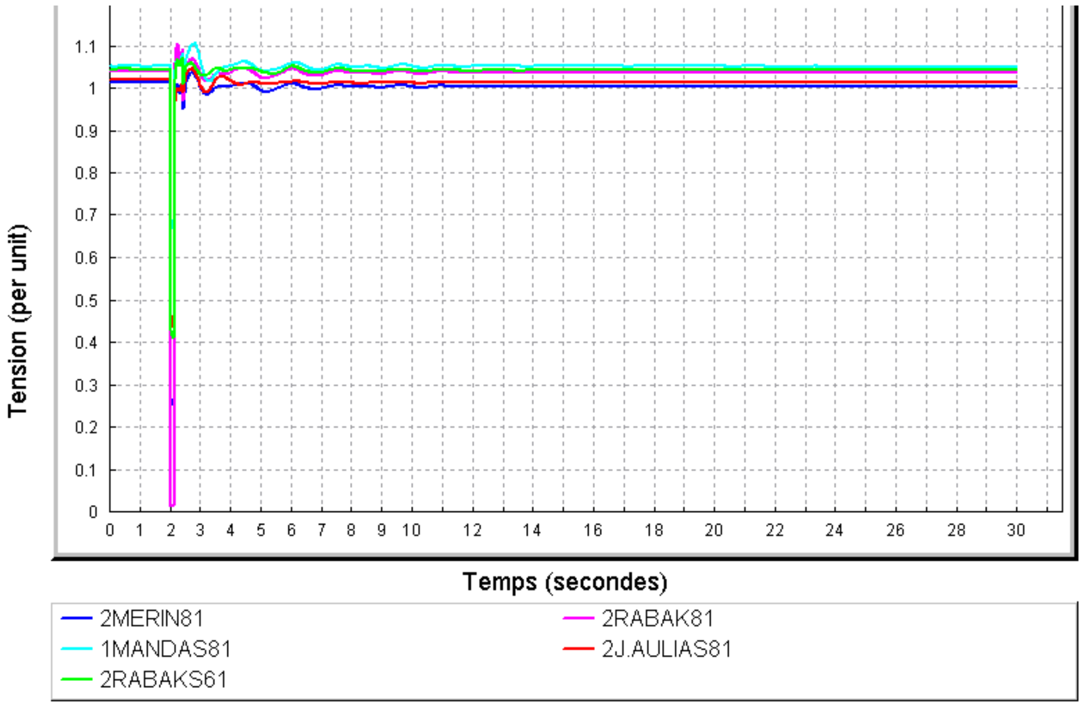
2.14.2 POWER FLOW VARIATION ON ENTRO INTERCONNECTION



2.14.3 POWER FLOW VARIATION ON KOSTI - JEBEL AULIA AND KOSTI - MERINGAN

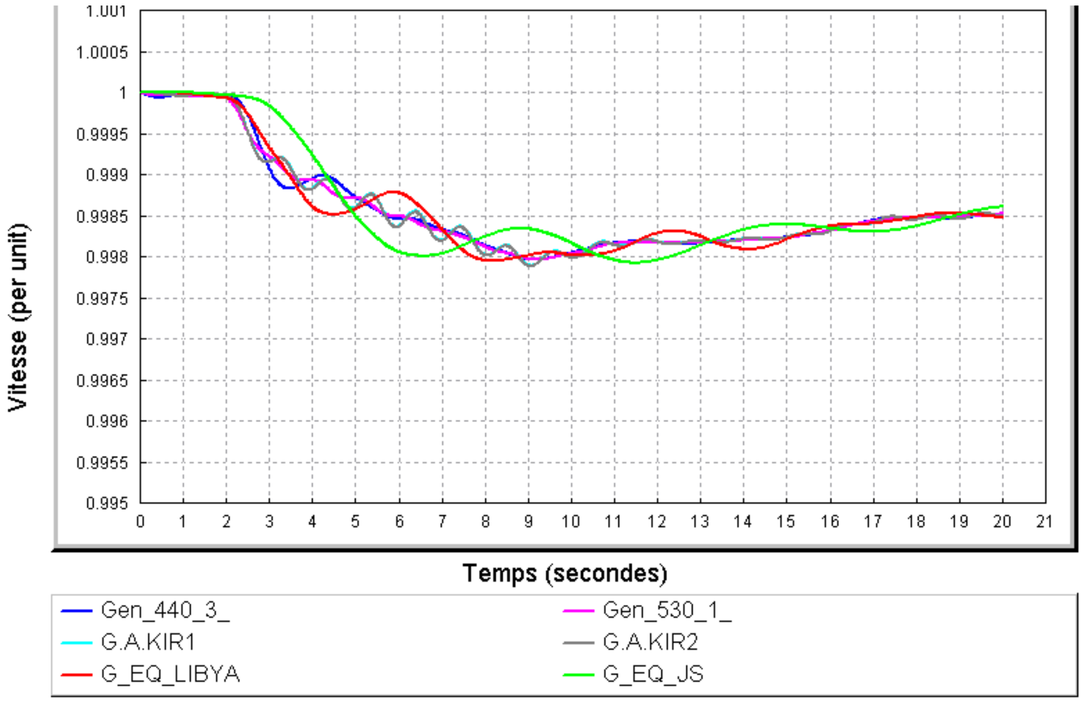


2.14.4 VOLTAGE VARIATION ON THE 500 KV



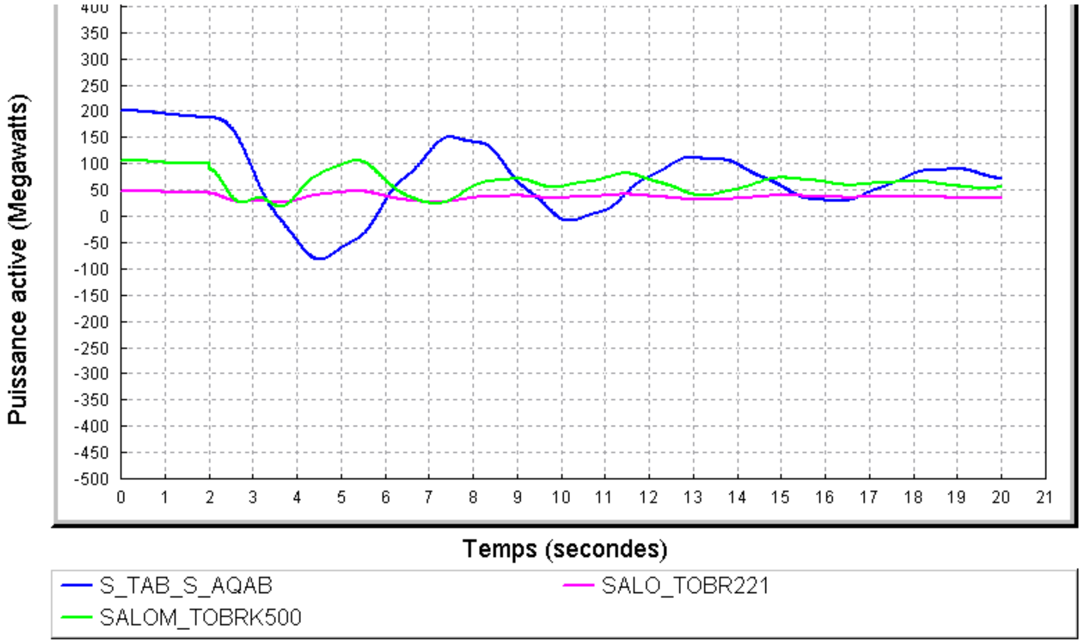
2.15 TRIPPING OF THE MAIN UNIT IN EGYPT : SIDI KRIR 765 MVA STEAM TURBINE

2.15.1 GENERATORS FREQUENCY VARIATION

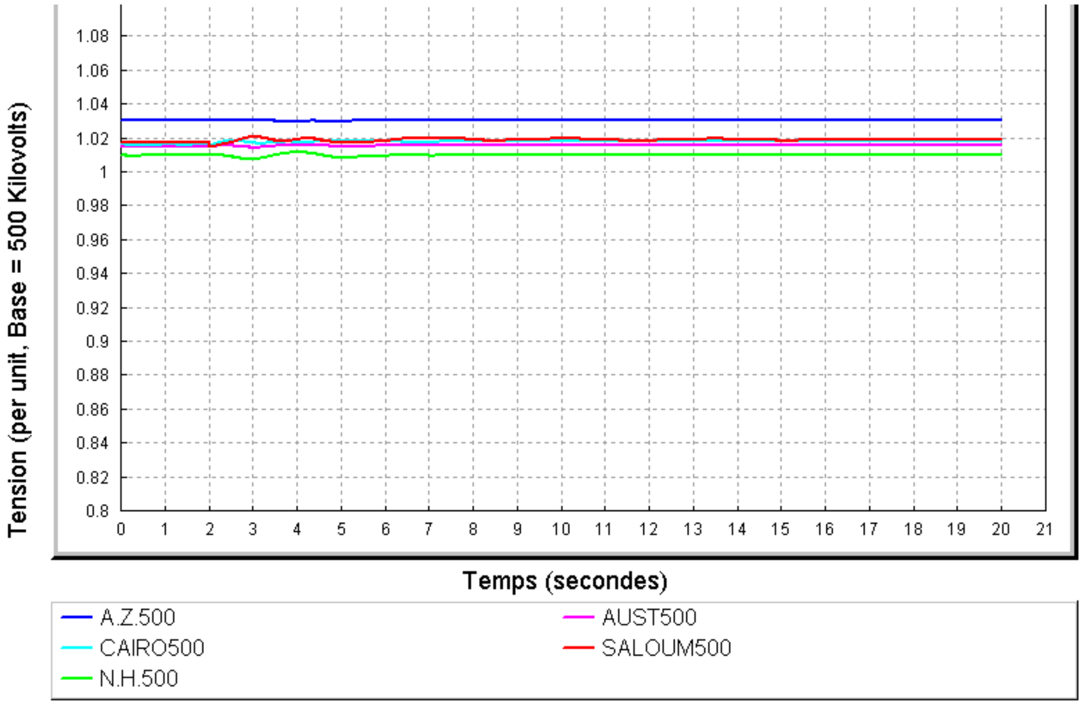


Gen_440_3 is a group of High Dam
Gen_530_1 is group 1 of Kurimat existing steam

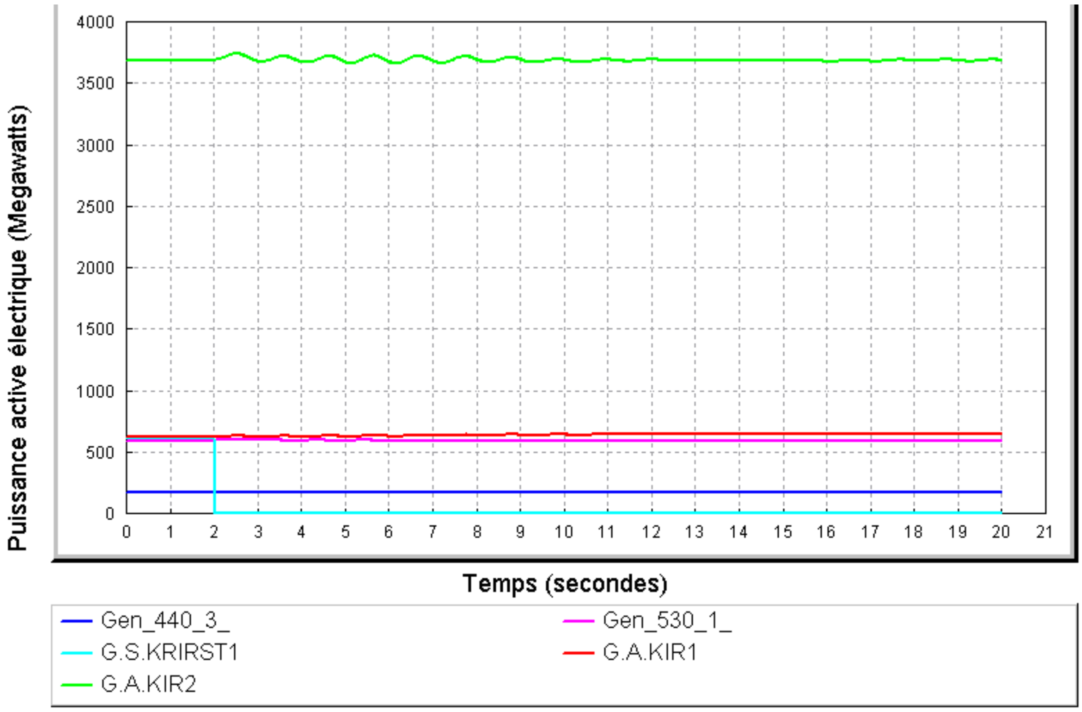
2.15.2 POWER FLOW VARIATION ON EGYPT - LIBYA AND EGYPT - JORDAN INTERCONNECTION



2.15.3 VOLTAGE VARIATION



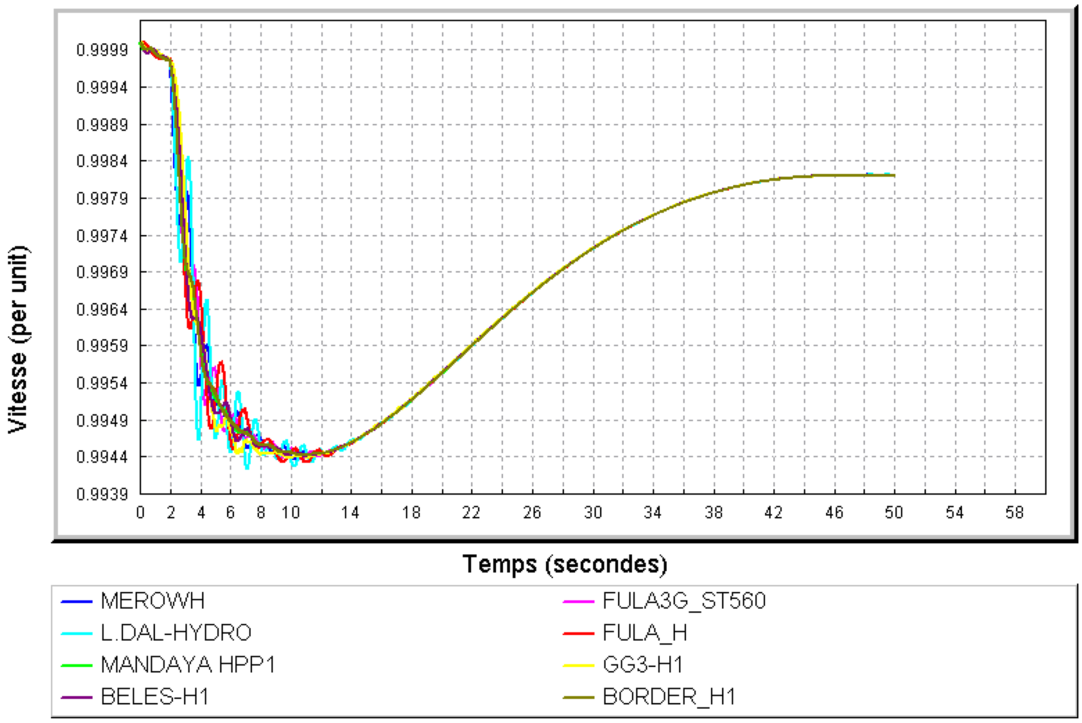
2.15.4 OUTPUT VARIATION OF SOME GENERATION UNITS



2.16 TRIPPING OF THE MAIN UNIT IN SUDAN : PORT SUDAN 670 MVA STEAM TURBINE

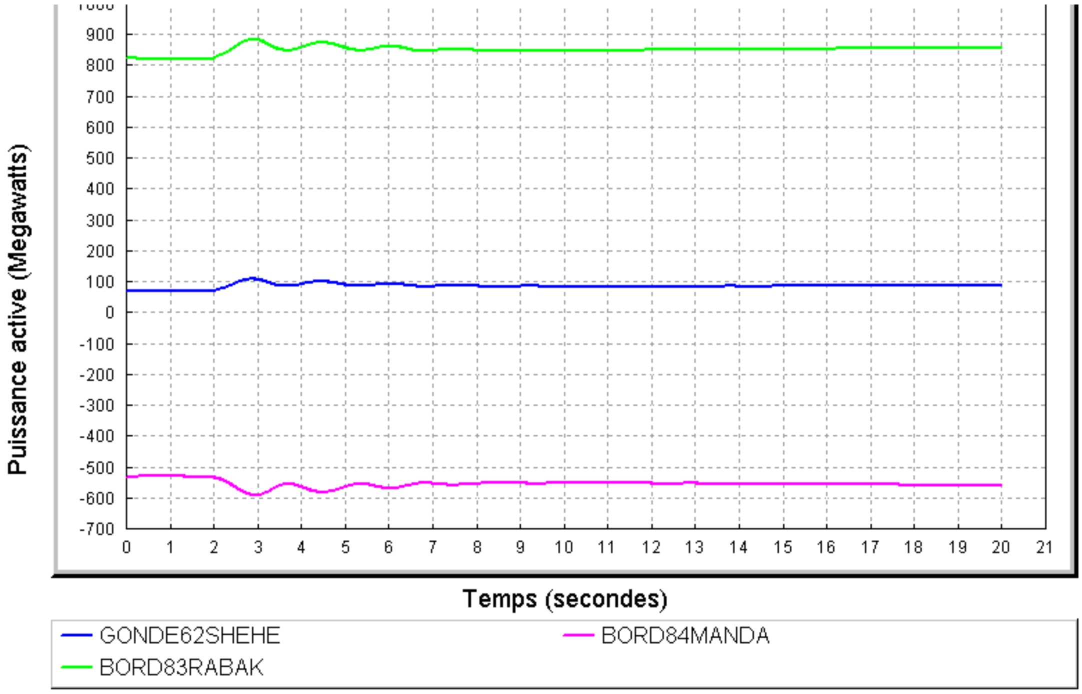
Event : the 670 MVA steam unit of Port-Sudan (the main unit in Sudan) is tripped.

2.16.1 GENERATORS FREQUENCY VARIATION

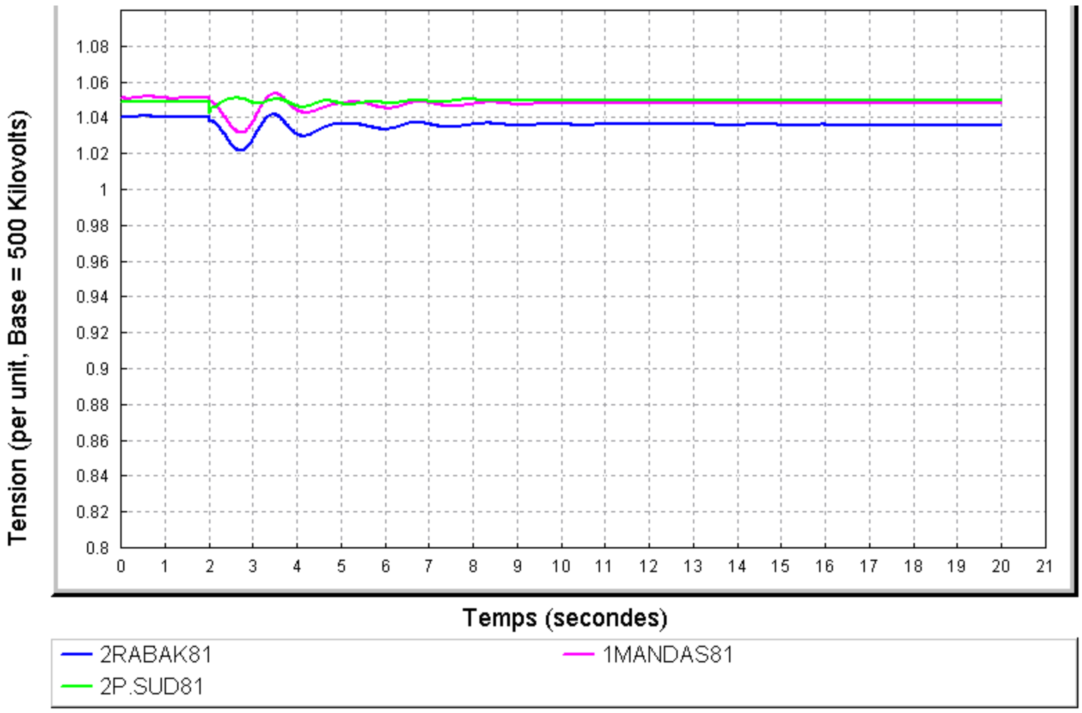


GG3 is Gibe III

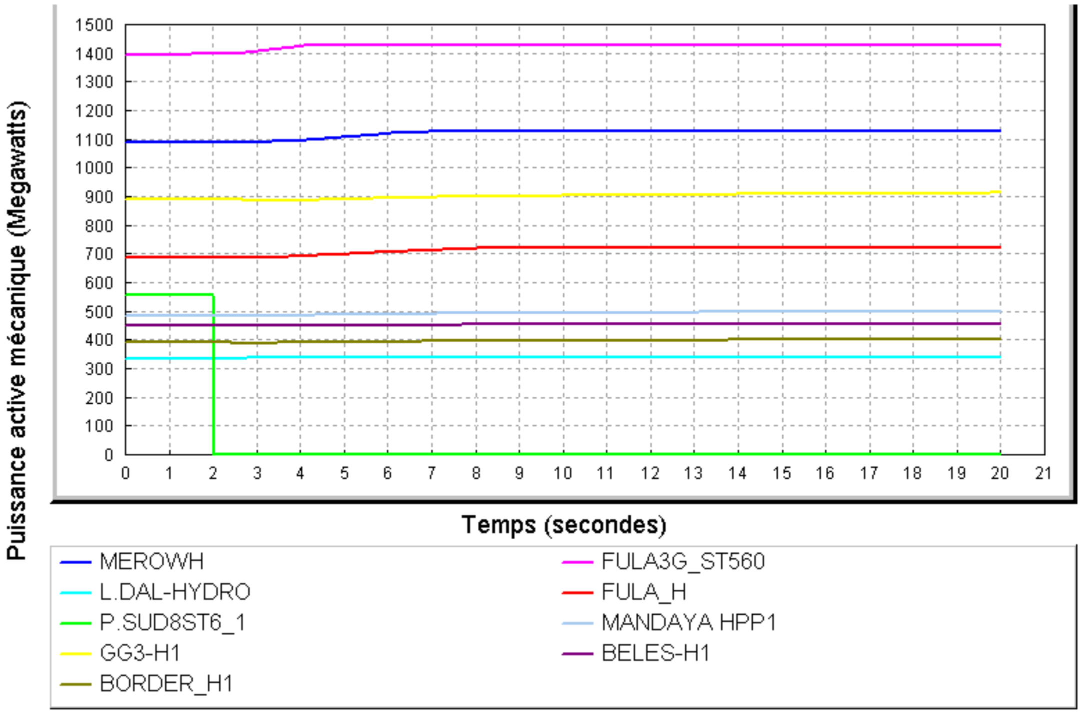
2.16.2 POWER FLOW VARIATION ON ENTRO INTERCONNECTION



2.16.3 VOLTAGE VARIATION

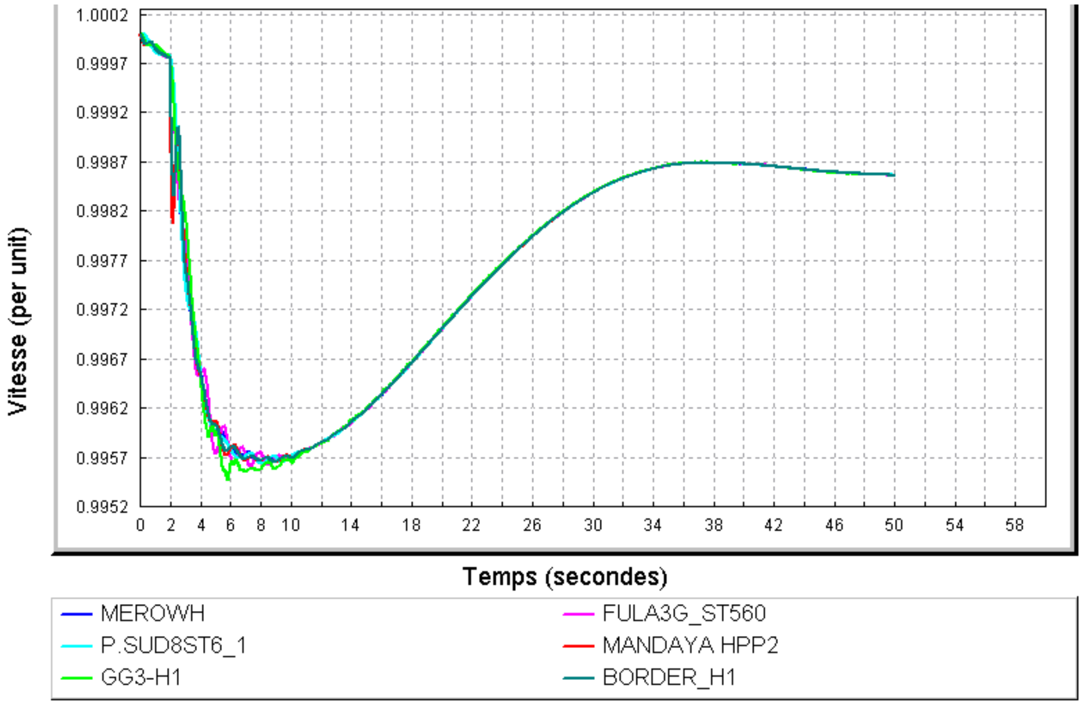


2.16.4 OUTPUT VARIATION FOR SOME GENERATION UNITS



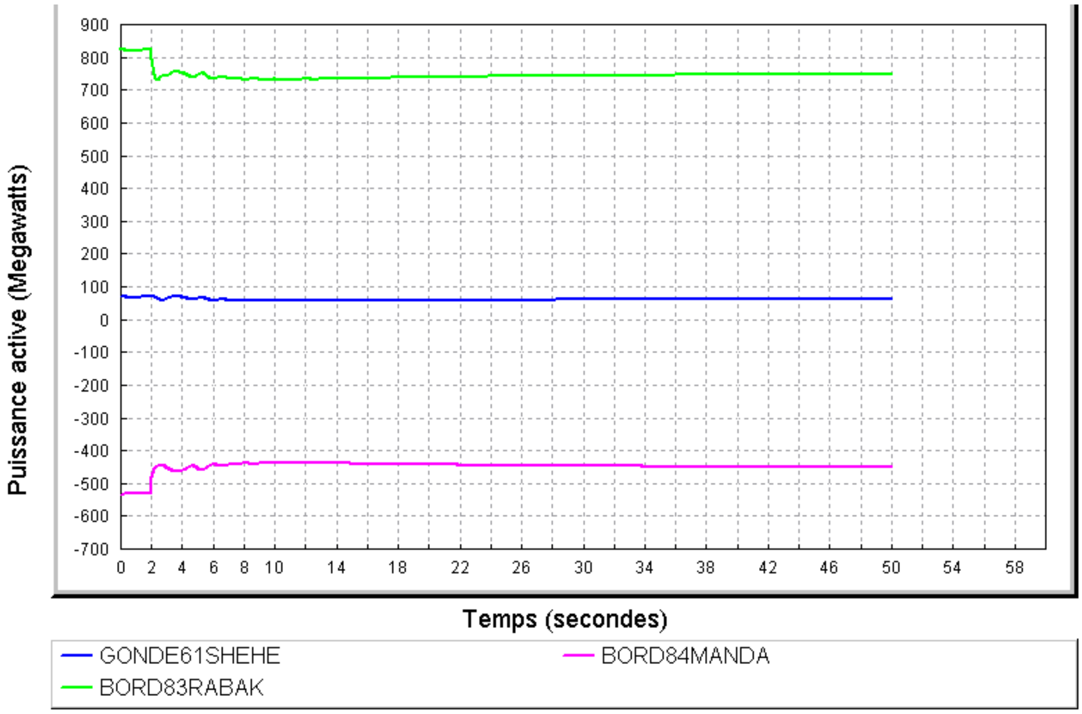
2.17 TRIPPING OF THE MAIN 2 UNITS IN ETHIOPIA : 2 UNITS OF 212.5 MW IN MANDAYA

2.17.1 GENERATORS FREQUENCY VARIATION

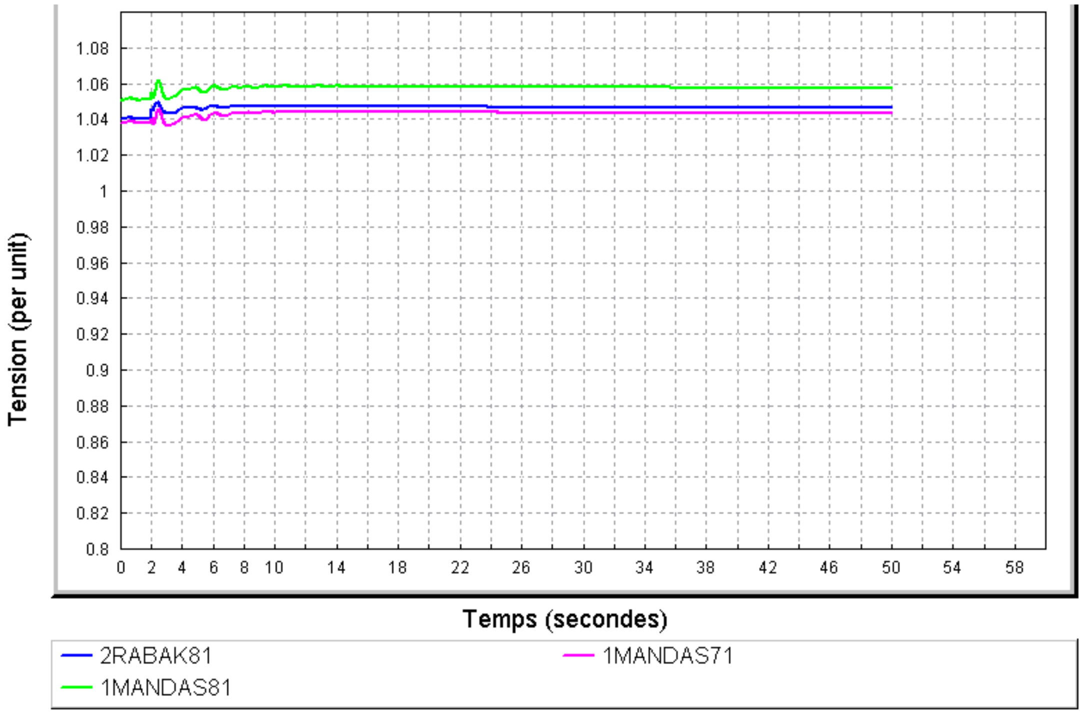


GG3 is Gibe III

2.17.2 POWER FLOW VARIATION ON ENTRO INTERCONNECTION



2.17.3 VOLTAGE VARIATION



2.17.4 OUTPUT VARIATION FOR SOME GENERATION UNITS