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Stability study of the interconnection of electricity networks of WAPP countries - case of control zone II (Ghana, Togo & Benin)

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***Abstract*— In the context of the ECOWAS power transmission networks interconnection project led by WEST-AFRICAN POWER POOL (WAPP), a master plan was drawn up in 2004 and updated in 2011. This plan recommended the partitioning of the ECOWAS area into five (05) control zones to ensure effective control of the stability parameters of the interconnected network. This paper is a study of the functioning and stability of the power network of control Zone 2 composed of Benin, Togo and Ghana. After an inventory of the production and transmission infrastructures and the survey of the load curves of each country, the network of the control zone 2 is modeled with the CYME software version 8.1.6 and analyzed with the Newton-Raphson algorithm. With the voltage plans taken from steady state simulation and transient stability tests, technical solutions have been proposed and implemented to improve the zone 2 power network stability.**

Keywords—Interconnection, Modeling, Network, Simulation, Stability

I. INTRODUCTION

The Economic Community of West African States (ECOWAS) comprises fifteen (15) countries. Fourteen (14) are located on the continent with a population very unevenly distributed within this economic area. [1] The main energy resources available in West Africa are also unevenly distributed over the Region's territory, which means that electricity costs are prohibitive for citizens. So, the 15 countries of the Economic Community of West African States (ECOWAS) took the initiative to interconnect their power networks with a view to ensuring long-term security of supply and optimal use of energy resources in the region. To this end, WAPP has been created and becomes the institutional framework of the regional electricity system aimed at integrating the operation of national power networks into an unified regional market. WAPP's power network is composed of national power grids of the 14 continental countries. The various studies undertaken by WAPP have retained the establishment of 5 control zones in the ECOWAS area, namely: Zone 1: Nigeria, Niger; Zone 2: Ghana, Togo, Benin; Zone 3: Ivory Coast, Burkina-Faso; Zone 4: Senegal, Gambia, Mali; Zone 5: Guinea Conakry, Sierra Leone, Liberia, Guinea Bissau. [2] Each adjustment zone has several network managers including a zone operator. Zone operators are : Zone 1: Nigeria; Zone 2: Ghana; Zone 3: Ivory Coast; Zone 4: Senegal; Zone 5: Guinea Conakry.

II. PROBLEM

The interconnection of large power networks such as the network of ECOWAS requires prior studies, especially with regard to the stability of the interconnected network. We note with regret, some difficulties of synchronization between the networks of zone 1 and 2 due to the instability of the network frequency of Nigeria, and to the relatively low voltage level on the 161kV network. Apart from these problems for which solutions are sought, one of the preoccupations of the network operators and zone operators will be to maintain the stability and security of the interconnected network. The issue of the stability of the WAPP interconnected network is a research opportunity that will enable us to analyze the behaviour of the network and to propose subsequent solutions.

III. MÉTHODOLOGY

The objective of this work is to perform a stability study of the interconnected network and propose improvement solutions. For this purpose, the methodology adopted consists of: (i) collecting the data, (ii) modeling the network, (iii) defining the basic assumptions of the study, (iv) studying the power flow with CYME software using the Newton-Raphson algorithm, (v) analyzing the result from the obtained voltage plan and from the transient study curves, (vi) proposing solutions, implementing them and drawing conclusions. The choice of the Newton-Raphson method is due to its ability to solve all types of networks including balanced, unbalanced, radial or highly meshed networks.

IV. DATA COLLECTION

The collected data come mainly from the registrations or archives of the electricity companies and also from the studies commissioned by the WAPP respectively in 2011 and 2015 for the update of its master plan and the realization of the master plan development of the SRDO (Senegal River Development Organization) transmission network [3]. The data collected in the archives of the electricity companies are complementary and in adequacy with informations from the master plans. The infrastructures of zone 2 are summarized in tables I and II below.

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TABLE I. TRANSMISSION AND GENERATION INFRASTRUCTURES OF GHANA

GHANA		
Transmission Infrastructures		
Type	***Voltage (kV)***	***Length (km)***
LINE	161	2694
	225	484
	330	475
TOTAL		3603
Power Generation Infrastructures		
Location	***Fuel***	***Power (MW)***
TAPCO	DDO/NG	300
TICO	DDO/NG	300
CENIT	DDO/NG	100
TT1PP	DDO/NG	23.4
TT2PP	DDO/NG	21.6
KTPP	DDO/NG	200
AKSA	HFO	345
KARPOWER III	HFO	646
AMERI	NG	230
SUNSON ASOGLI	NG	420
AKOSSOMBO	HYDRO	900
KPOMG	HYDRO	200
BUI	HYDRO	
WINEBA & NAVRONGO	PV	22.5
TOTAL		3708,5

The peak power of Ghana is estimated in 2018 at 2225 MW; that suggests a sufficient reserve of energy if all sources are available.

TABLE II. TRANSMISSION AND GENERATION INFRASTRUCTURES OF TOGO AND BENIN

TOGO & BENIN		
Transmission Infrastructures		
Type	***Voltage (kV)***	***Length (km)***
LINE	161	1640
	330	190
TOTAL		1830
Power Generation Infrastructures		
Location	***Fuel***	***Power (MW)***
TAG CEB	JET A1/NG	40
SBEE NATI-PARA	DDO	8
SBEE PORTO N	DDO	6
MRI	DDO	25
AGGREKO	DDO	100
CAI	DDO/NG	00
CONTOURGLOBAL	HFO/NG	90
CEET LOME	DDO	5
CEET KARA SOK	DDO	5.5
NANGBETO	HYDRO	65
YERIPAO	HYDRO	0.5
DJOUGOU	PV	1.5
MARIA GLETA	HFO/NG	120
TOTAL		466,5

The synchronous peak power in Togo and Benin is estimated at 530 MW far exceeding the available power. Hence, both countries must import electricity from Ghana and Nigeria to supplement their needs.

Fig. 1 and 2 below illustrate the load curve forecasts of Ghana and Togo / Benin from 2019 to 2025.

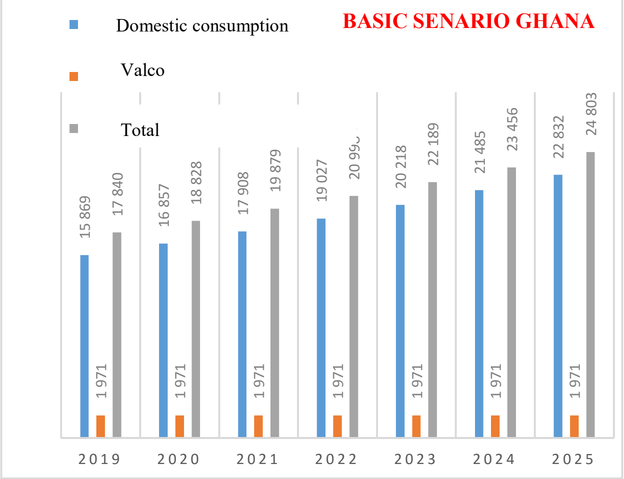

Fig. 1. Forcast Curve of loads in Ghana - Basic Scenario

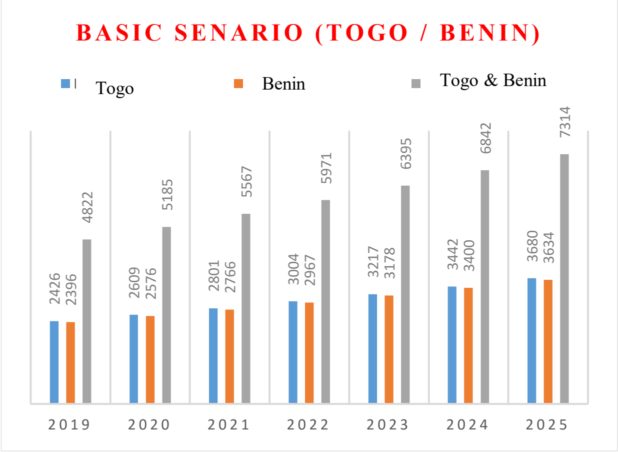

Fig. 2. Forecast Curve of loads in Togo/Benin - Basic Scenario

The network analysis software we used to do this work is CYME V8.1 Rev3. [4]. Regarding the load balancing analysis, the CYME software uses the following algorithms: the voltage drop method, the Fast Decoupled method, the Newton-Raphson method, and the Gauss-Seidel method. [4]. Fig. 3 below is an extract of the single-wire representation of the power networks from the CYME software.

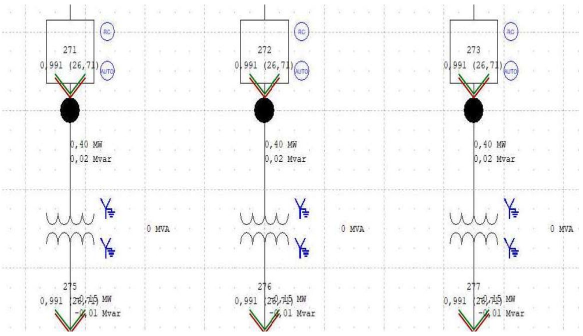

Fig. 3. Illustration of electrical diagrams made from CYME 8.1 rev3

V. BASIC AND MODELING ASUMPTIONS FOR ZONE 2 POWER NETWORK STUDY

For our study, the following basic assumptions, presented in tables III, IV, V and VI below, were defined as the operating criteria:

A. Permissible voltage range and short-circuit current

TABLE III. RANGE FOR VOLTAGE SELECTED FOR STUDIES

Nominal Voltage	**Operation Voltage**	**Vmin**	**Vmax**	**Icc Permissible (kA)**
	± 5%	-10%	+10%	
330kV	315-345	300	360	50
225kV	214-236	200	245	50
161kV	153-169	145	175	40

B. Allowable load of structures

TABLE IV. ALLOWABLE LOAD OF STRUCTURES

Structure	**State N (Normal situation)**	**State N-1 (After incident)**
	% nominal power	***% nominal power***
Line	100 %	110 %
Transformer	105 %	120 %

C. Permissible frequency range

TABLE V. PERMISSIBLE FREQUENCY RANGE

State	**Frequency range (Hz)**	**Note**
Normal Situation	49.5-50.5	
Loss of a generator or loss of an import line	Quasi-stationary deviation < -200 mHz	deviation observed 30 seconds after the incident
	The transient deviation < 0.5Hz or fdyn < 500mHz	

D. Network Modeling Rules

TABLE VI. MODELING ASSUMPTIONS

N°	**State**	**Solution applied**
1	Location Transformer Control	Primary side with Y connection to earth
2	Tap changer for generator transformers	No
3	Type of winding of generators transformers	Δ side for the generator and Y at earth for side HT
4	Transformer tap changer position	median
5	Line Impedances	Supplied by Manufacturers
6	Transformer Power	Last cooling stage
7	Value of transformer impedance	10%
8	Value of resistance R1	X1 / 12 if S <20MVA; X1 / 20 if 20MVA <S <60MVA and X1 / 30 if S> 60MVA

VI. CALCULATION OF POWER FLOW

A. Theoretical approach of resolution using the Newton-Raphson algorithm

The most widely used method for solving nonlinear algebraic equations is the Newton-Raphson method. This method is a successive approximation procedure based on an initial estimate that uses the Taylor series decomposition. Consider the nonlinear equation:

$$f(x) = c \tag{1}$$

If x_0 is an initial estimate of the solution, and is a small deviation from the correct solution, we have:

$$f(x_0) + \Delta x_0 = c \tag{2}$$

Taylor's series in the neighbourhood of x_0 gives:

$$x_0 + \Delta x_0 = f(x_0) + \left(\frac{df}{dx}\right)_0 \Delta x_0 + \frac{1}{2!}\left(\frac{d^2x}{dx^2}\right)(\Delta x_0)^2 + ... = c \tag{3}$$

We neglect the terms of large order and we add Δx_0 to the initial estimate and we have:

$$x_1 = x_0 + \Delta x_0 = x_0 + \frac{\Delta c_0}{\left(\frac{df}{dx}\right)_0} \tag{4}$$

The successive use of this procedure gives the Newton-Raphson algorithm :

$$x_{(k+1)} = x_k + \Delta x_k \tag{5}$$

The main equation used by the Newton method is defined by the equation: [6]

$$j_k \Delta x_k = -f\left(x_k\right) \tag{6}$$

For more complex and desequilibrated networks calculation, the main system of equations is constructed from the formulation of Modified and Augmented Nodal Analysis (MANA) below: [6]

$$\begin{bmatrix} Y_n & V_{adj}^t & D_{bdepc} & S_{adj}^t \\ V_{adj} & 0 & 0 & 0 \\ D_{bderl} & 0 & 0 & 0 \\ S_{adj} & 0 & 0 & S_z \end{bmatrix} \begin{bmatrix} V_n\, I_n \\ I_{vs}\, V_s \\ I_{vd}\, 0 \\ I_{vs}\, 0 \end{bmatrix} = \begin{bmatrix} I_n \\ V_s \\ 0 \\ 0 \end{bmatrix} \tag{7}$$

Where :

Y_n: *Linear network admittance.*

V_{adj}: *Proximity matrix of the voltage source*

D_{bdepr}: *Relations depending on the branch.*

D_{bdepc}: *Relations depending on the branch.*

S_{adj}: *proximity matrix of closed switch type devices.*

S_z: *Diagonal and unitary matrix for open switch type devices.*

V_n: *Vector tensions of unknown nodes.*

I_{Vs}: *Vector currents of unknown voltage sources.*

I_{Vd}: *Vector unknown currents in the branches of the dependent voltage sources.*

I_{SW}: *Vector unknown switching currents.*

I_n: *Vector known nodal current injections.*

V_s: *Vector known voltages.*

The Jacobian matrix gives the linearized relationship between small changes in voltage angle and voltage magnitude with the small changes in real and reactive power. In short form, it can be written as: [7]

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} J_{11} & J_{12} \\ J_{21} & J_{22} \end{bmatrix} \begin{bmatrix} \Delta \delta \\ \Delta V \end{bmatrix} \qquad (8)$$

Where:

ΔP: small change in real power

ΔQ : small change in reactive power

ΔV : small change in voltage magnitude

$\Delta\delta$: small change in voltage angle

J_{MN}: Jacobian matrix

B. Modeling and simulation of the network with the CYME software, implementation of the proposed solutions

1) Power flow analysis

a) Voltage plan analysis

The voltage plans in Ghana substations and in the Togo and Benin substations are presented in the following figures:

GHANA POWER NETWORK

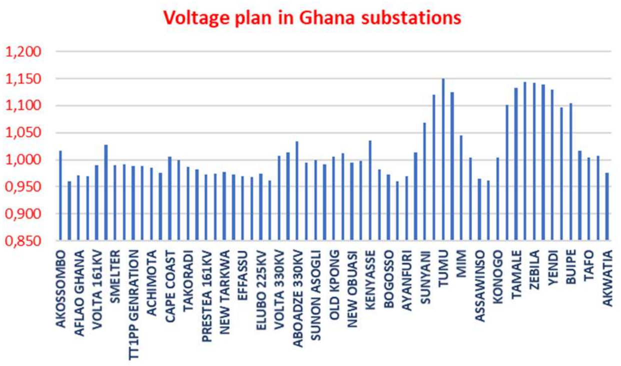

Fig. 4. Voltage plan in steady-state for substations in the Ghana network

The zone 2 network is isolated from the network of Nigeria and Ivory Coast during testing. So, it was operating as islanded network. The voltage plan of Ghana (Fig.4) shows voltage levels higher than 105%Vn in the Sunyani, Tumu, Mim, Tamale, Zebila, Yendi and Buipe substations. However, several substations have a low voltage level set in the permissible limit higher than 95% Vn. To correct the high level of the voltage in these substations, we implemented the installation of shunt inductors on the Techiman-Buipe and Sunyani-Sawla lines. The value of the reactive power of each inductor is -18MVAR. The result of this implementation is shown in Fig.5 below. We can see that the voltage levels in all HV bus are now comprised between 0.96 p.u and 1.050p.u.

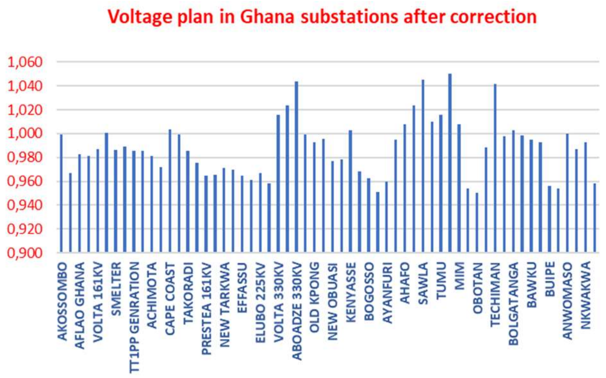

Fig. 5. Illustration of the voltage plan of Ghana network after correction

TOGO & BENIN POWER NETWORK

Fig. 6. Voltage plan of substations in steady state in CEB network

The network is still operating in islanded network. The voltage plan of the CEB network (Togo & Benin) shown in Fig. 6 above, reveals that most substations have a voltage level lower than the permissible limit (95% Vn). To solve this problem, two solutions have been implemented. The first is to connect the Zone 2 network to the Nigeria power grid. This first solution enables to align the voltage level on the HV bus of the southern substations in the allowable voltage range. However, the voltage level in the northern substations (Parakou, Kandi, Malanville, Bembereke) has increased dramatically. To correct this situation, we have adopted a second solution which consists of implementing the installation of shunt inductors on the Parakou-Onigbolo line. Thus, the voltage level on the HV bus of the CEB power network is restored between 0.96 p.u and 1.013p.u. (see Fig.7 below).

Fig. 7. Illustration of the voltage plan of Togo and Benin network after correction

In general, we noted that no equipment is overloaded including generators, lines and transformers which are loaded within the limits of their nominal operation.

b) Frequency stability analysis test results

In stable condition, the frequency in different points of the network is recorded during 0 to 30 seconds. It reveals that the network frequency is identical everywhere and quasi-stable, varying between 49.9993Hz and 50.0007Hz (See Fig. 8 below).

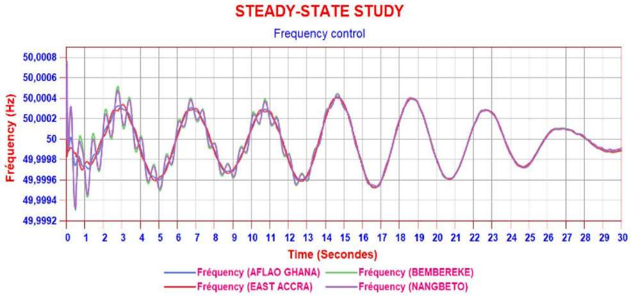

Fig. 8. Measurement of the speed of production units during 30 seconds

2) Tansient and dynamic stability

a) Load transfer stability test results

This consists to access the risks of loss of stability of the installation during changes in operating patterns of the transmission network. So, while the network is in normal operation, the overall network load has been varied first at + 5% and secondly at -20%. We can note, through Fig.9 and 10 below that, in the first case (increase of 5% of the overall load) the production units reacted by taking charge through their primary reserves, in the second case (decreased by -20% of the overall load), the groups reacted by decreasing their active power as well. Similarly, the network frequency curve has been plotted to see the effect of disturbances on the network frequency. Fig.11 and 12 illustrate the frequency curve of the network respectively in the first case (increase by + 5%) and in the second case (decrease by -20%). In the first case, we note that the frequency drops immediately after the fault at 49.30Hz but has gradually increased to reach 49.70Hz in 13 seconds. In the second case, we note that the frequency rises immediately after the fault at 52.6Hz but has gradually returned around 50.8Hz in 13 seconds. All these tests confirm the good performance of the production units and consequently the good performance of the power network.

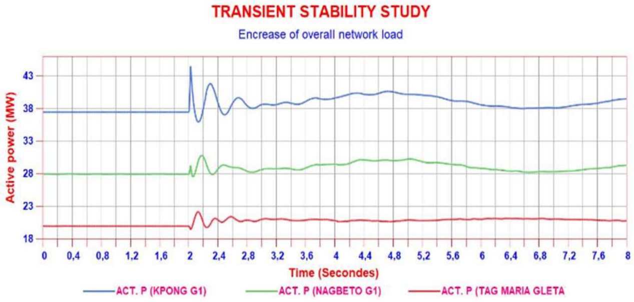

Fig. 9. Illustration of the healthy units reaction following the sudden increase of the overall network load

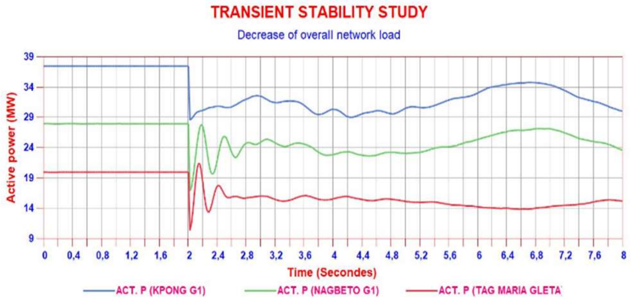

Fig. 10. Illustration of the healthy units reaction following the sudden decrease of the overall network load

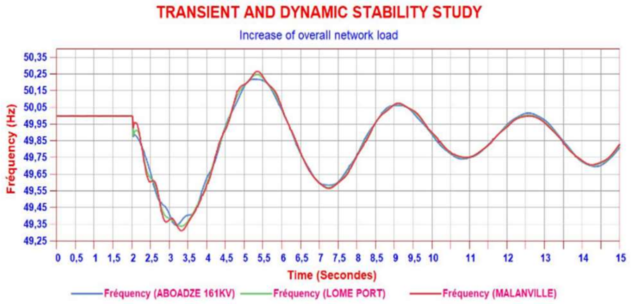

Fig. 11. Frequency curve following the sudden increase of the overall network load

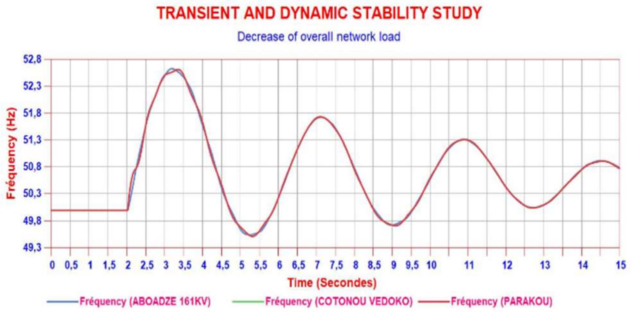

Fig. 12. Frequency curve following the sudden decrease of the overall network load

b) Loss of the largest production unit test results

The interconnected network of Benin, Togo and Ghana is still operating in islanded network. This test consisted of the sudden stop of one of the largest unit (Akossombo G5, 170MW) and the analysis of the behavior of the healthy production units in the network. The power curves of the production units G3-AKOSSOMBO and G2-BUI shown in Fig. 13 below, reveal that each unit reacted through its primary reserve by taking a part of the lost load. This confirms that there has been a load shift on healthy units.

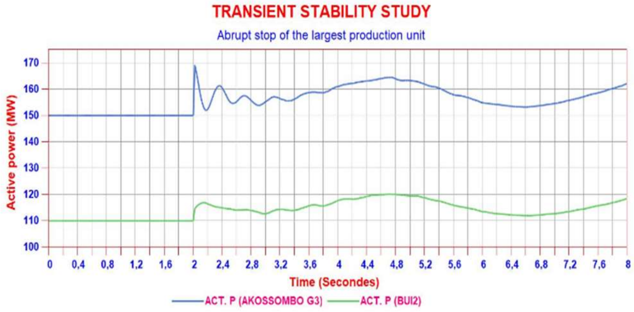

Fig. 13. Load deferral illustration on healthy generators

c) Determination of the production units dumping time

During normal network operation, a transient fault opens the breaker of one of the largest production unit (G6-AKOSSOMBO) for 5ms and closes it again. We have visualized in Fig.14 and 15 below, the oscillation curves of speeds and angles of generators G3-AKOSSOMBO, G1-BU2 and G1-NANGBETO. We note that the three generators regain their stability after 2.4 seconds.

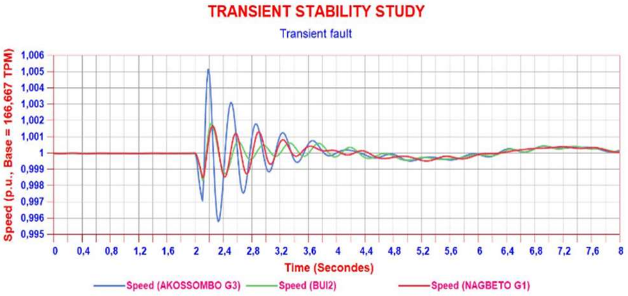

Fig. 14. Speed curves of healthy production units following a transient fault

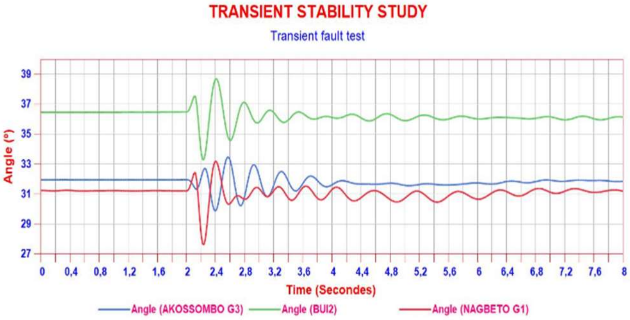

Fig. 15. Angle curves of healthy production units following a transient fault

VII. CONCLUSION

In this paper, after having inventoried the existing power generation and transmission infrastructure in Togo, Benin and Ghana, we have modeled the network and performed stability tests with CYME software. The results obtained during the various tests show that the network is stable expect some rise of voltage level in several substations in Ghana and in northern Benin. The implementation of shunt inductors installation on some lines allowed correcting the voltage plan. Concerning the transient and dynamic stability, the tests reveal that the network reacts correctly to the various transient faults which have been simulated. All our tests were performed by the NEWTON RAPHSON method.

The plausible prospect would be to extend this study to the whole ECOWAS zone. We also plan to do very soon a comparative study using Fast Decoupled algorithm.

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