Modelling of a System Collapse in the Nigerian National Power System using Frequency Disturbance Recorder Data

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***Abstract*—This paper exploits the availability of frequency disturbance recorder (FDR) measurements and knowledge of the underlying operational data from the Nigerian National Power System to develop a model capable of reproducing the most important characteristics of one of the many collapses in the Nigerian grid during the last recent years. The collapse investigated in this paper was captured on December 2nd, 2006, with an FDR unit installed at Abubakar Tafawa Balewa University (ATBU). Using operational information from the National Control Center (NCC) at Osogbo, three models representing the Nigerian power system were developed to capture the most relevant dynamics of the grid during the cascading failure. These models include both detailed representations of the different network components, as well as average frequency dynamics only. Comprehensive simulation results show how the models are capable of representing the most important features of the collapse of the system, and hence, their continuous improvement through model validation may allow their use in the development of load shedding mechanisms which are needed for mitigating cascading failures in the Nigerian system.**

***Index Terms*—Frequency disturbance recorder, power system monitoring, model validation, system collapse, average frequency modelling, Nigerian power system models**

I. Introduction

Rensselaer Polytechnic Institute (RPI) and Abubakar Tafawa Balewa University (ATBU) have established a collaboration to study the dynamics of loosely regulated and rapidly growing power systems, with particular interest in the Nigerian power system. A frequency disturbance recorder (FDR) [1] has been installed at ATBU and, being operational since April 2006, several recordings have been made. In two previous papers we have reported on FDR data analysis from disturbance events and proposed a university-based frequency monitoring network for the Nigerian power system[2], [3], [4].

This paper exploits the availability of frequency disturbance recorder (FDR) measurements and knowledge of the underlying operational data from the Nigerian National Power System to develop a model capable of reproducing the most important characteristics of one of the many collapses in the Nigerian grid during the last recent years. The collapse investigated in this paper was captured on December 2nd, 2006, with an FDR unit installed at Abubakar Tafawa Balewa University (ATBU) since April 2006 as part of a US-Africa collaborative research effort. The preliminary analysis of the available frequency recordings and another system collapse recorded on January 2007 were reported in [2], [3], [4]. The Nigerian power system has suffered a large amount of systems collapses between 2002 and 2005 as documented in [5]. The aim of this investigation is to develop several models, capable of replicating the collapse of the December 2nd, 2006; in three different simulation environments: PSCAD [6], PSAT [7], and MATLAB/Simulink [8]; the computer models are shown in Fig. 11, Fig. 12 and Fig. 13, respectively, in pp. 7—8. For this purpose, valuable operational information from the National Control Center (NCC) at Osogbo, available from [9] was also used for developing the models:

- At 14:00 Hrs. frequency dropped sharply from 50.34 to 47.8 Hz. followed by a system collapse. Efforts made to clear load at the Osogbo 132 kV transmission station failed — telephone calls were unanswered. On the operator's display, it was observed that circuits G3B, B1T, B5W, B6W and B12J as well as S3B at the Benin 132 kV transmission station were in "open" status.
- At 14:20 Hrs. on inquiry, the Benin control center reported an explosion with fire on circuits G3B — yellow phase of the circuit breaker (CT). As a result, circuits B5W, B6W, B1T and B12J were opened to remedy the situation.

The developed models and simulation results obtained in this article where aimed to capture the most important dynamic characteristics of the collapse. The time-based events obtained from the operator's daily report of NCC [9], and FDR, as well as other operational databases on network/generator parameters that included all ancillary electrical and mechanical subsystems.

The reminder of this paper is organized as follows. In Section II a preliminary analysis highlighting the main characteristics of the system collapse are given. Section III shows the analysis procedure developed for inspecting the available FDR measurements. Next, in Section IV, the simulation approach for replicating the system collapse is outlined, while Section V presents the results from the different simulation studies carried out. Discussions on these results are summarized in Section VI, and conclusions are drawn in Section VII.

II. Characteristics and Preliminary Analysis of the System Collapse

Prior to the system collapse, the committed generating units that fed the National Grid on the 2nd of December, 2006 and their loading status, as declared by NCC, are reproduced in Table I. The total system real power demand varied between 2346 MW and 2870 MW before the system collapse. The Nigerian Transmission Grid network is shown in Fig. 1a, while the extant network structure on 2nd December, 2006 is shown

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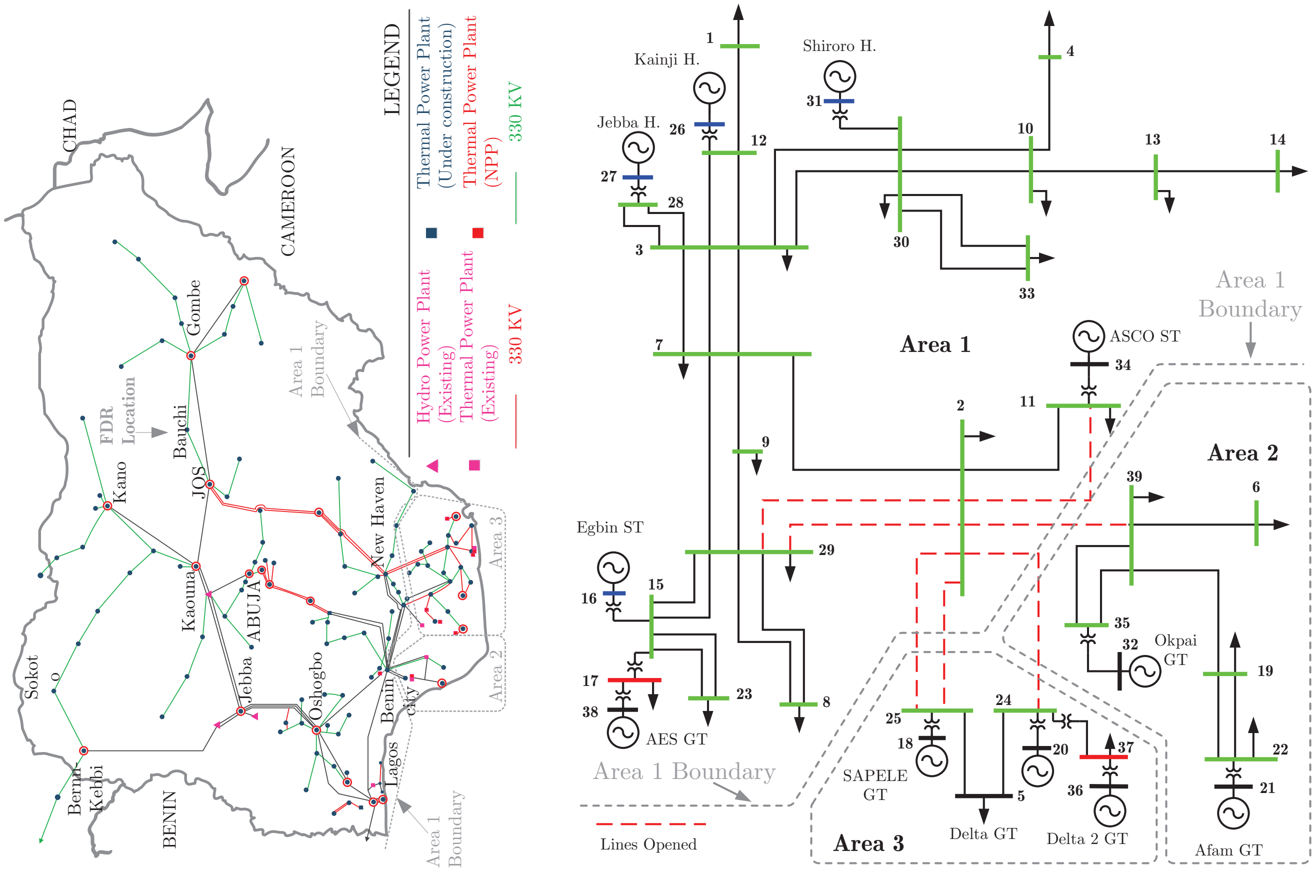


(a) Nigerian Transmission Grid

(b) One-line diagram of the Nigerian Transmission Grid as at December 2nd, 2006; showing three islanded areas.

Figure 1. Complete Nigerian Transmission Grid, and One-line Diagram and 11-Machine 39-Bus Model

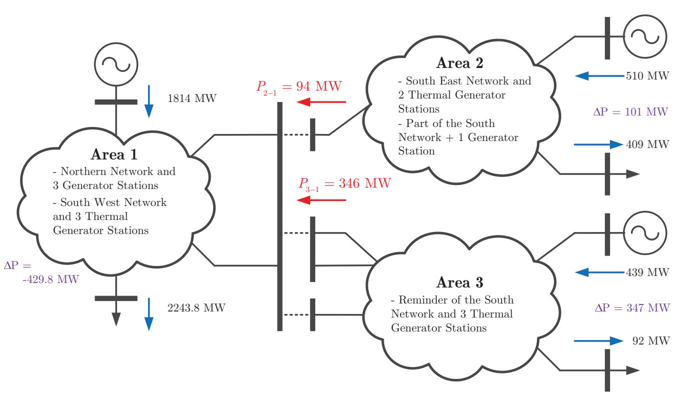


Figure 2. Three Islanded Areas due to the System Collapse in the Nigerian Grid

in Fig. 1b with the transmission lines that tripped, due to an explosion at the Benin 330 kV bulk substation, depicted using dotted red lines. As a consequence of the explosion, several lines tripped, and as recorded by NCC, the National Grid was split into three islanded areas which, in the absence of coordinated load shedding mechanisms, led to the ultimate collapse of the entire national grid. The three islanded areas are depicted conceptually in Fig. 2.

The simulation study in Section V focuses on Area 1 — not only because it forms the largest block, but also because the FDR installed at Bauchi, central to system collapse simulation replication task, is electrically located near Bus 13. Furthermore, the NCC at Oshogbo could only provide information pertinent to Area 1 for simulation studies. Due to the lack of availability of FDR measurements in Areas 2 & 3, their respective frequency response characteristics can only be inferred through system simulations. It is worth to note that that total system collapses rarely occur in well established power systems but when they occur, they are accompanied by detailed investigations to forestall their future occurrences [10]. Although the Nigerian power system has experienced large number of system collapses, not a single one has attracted detailed investigation as attempted in this article.

III. FDR Measurement Data Analysis

The flowchart in Fig. 3 depicts the procedure used for the analysis of captured FDR data. This procedure was developed to navigate through the FDR data captured during the 2nd of December of 2006, and from which the data along the duration of the system collapse period were extracted and benchmarked against the daily report of the NCC during that day.

The GPS time-stamped measurements of the FDR captured the system collapse shown in Fig.4a (the measurements are shown after necessary processing). It is worth mentioning that during the time of system collapse, the FDR installed at Bauchi recorded the frequency decay of Area 1 delineated in Fig. 4b. In the next Section, we outline the simulation procedure

Table I
FDR-BASED AND PMU-BASED MONITORING SYSTEMS

STATION	AVAILABLE UNITS	INSTALLED AVAILABLE CAPACITY (MW)	ACTUAL GENERATION CAPACITY (MW)	GENERATION AT 06:00 HRS.
Kainji Hydro	1G6 - 10 & 12	540	420	386
Jebba Hydro	2G1 - 6	578.4	540	258
Shiroro Hydro	411G1, 2 & 4	450	450	300
Egbin Steam	WT1 - 3 & 5	880	880	574
Ajaokuta (ASCO)	ST1 & ST2	110	90	88
A.E.S (GAS)	GT202 - 205, 207 - 211	287.1	287.1	287.1
Sapele ST	ST1	120	67	67
Okpai Gas/Steam	GT12 & ST1	320	236	236
AFAM (Gas)	GT19 & 20	276	276	274
Delta (Gas)	GT6 - 15, 18 & 20	525	471	471
Total	47	4086.5	3717.1	2941.1
Units on max. capacity	—	—	2991.1	—

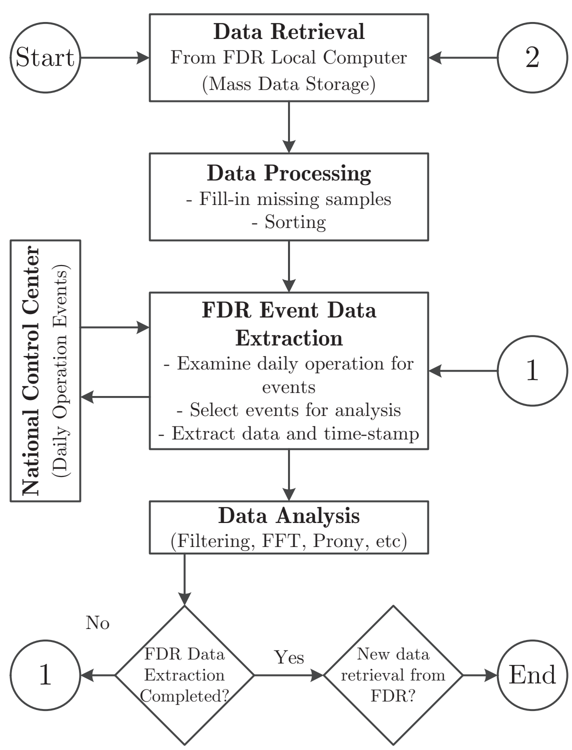
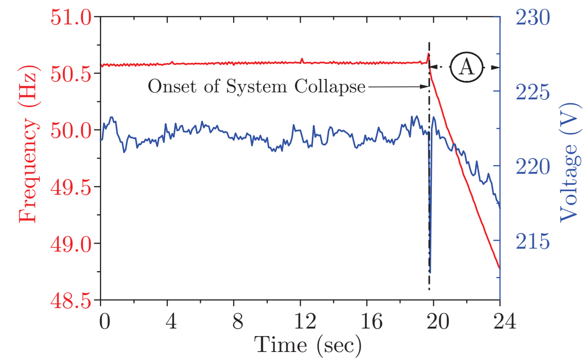


Figure 3. Flowchart Depicting the FDR Measurement Data Analysis Procedure used for this Study

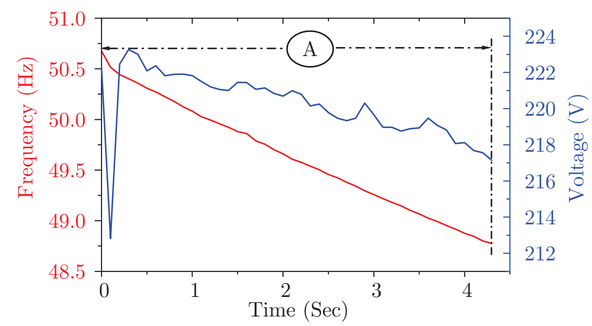
employed to replicate the hypothesized cascading events that led to the system collapse of 2nd December, 2006.

IV. SIMULATION APPROACH

Three models of the Nigerian grid, replicating its operation on December 2nd, 2006 were developed using the following software:



(a) FDR Measurements During during the System Collapse



(b) Expanded view of Fig. 4a after the onset of the system collapse

Figure 4. FDR Measurement Data from the Dec. 2nd, 2006 System Collapse

- PSCAD version 4.2 [6];
- PSAT version 1.3.4 [7]; and
- MATLAB/Simulink 6.0 [8].

The Nigerian grid model developed in PSCAD is a significantly modification of the existing model employed in [11], [12], while its PSAT model is an update of the model developed in [13]. For proper modelling, all the electrical generators that included governors and excitation systems were adequately represented with available system parameters and where necessary typical parameters were used. The 330 kV transmission network status during December 2nd, 2006, parameters, and loading conditions just before the on-set of the system collapse period were used. Following similar approach in [14], [15], an average frequency model shown of the Nigerian grid in Fig. 5 was also developed and used to emulate the frequency measurements from the FDR installed at Bauchi. The relevant parameters used to implement this model in MATLAB/Simulink were derived from the equivalent detailed system model in Fig. 1b using the parameter aggregation approach in [16].

Because information on the complete system operating state was not readily available, we relied on our engineering knowledge and Monte-Carlo based power flow studies to arrive at credible system loading scenarios and generation levels before the occurrence of the system collapse. We finally established the most probable loading scenarios, as well as the generation levels for the three areas as depicted in Fig. 2, with total power transfer of approximately 450 MW from Areas 2 and 3 to Area 1. The initial operating state of the detailed Nigerian power system models in PSCAD and PSAT was computed on the

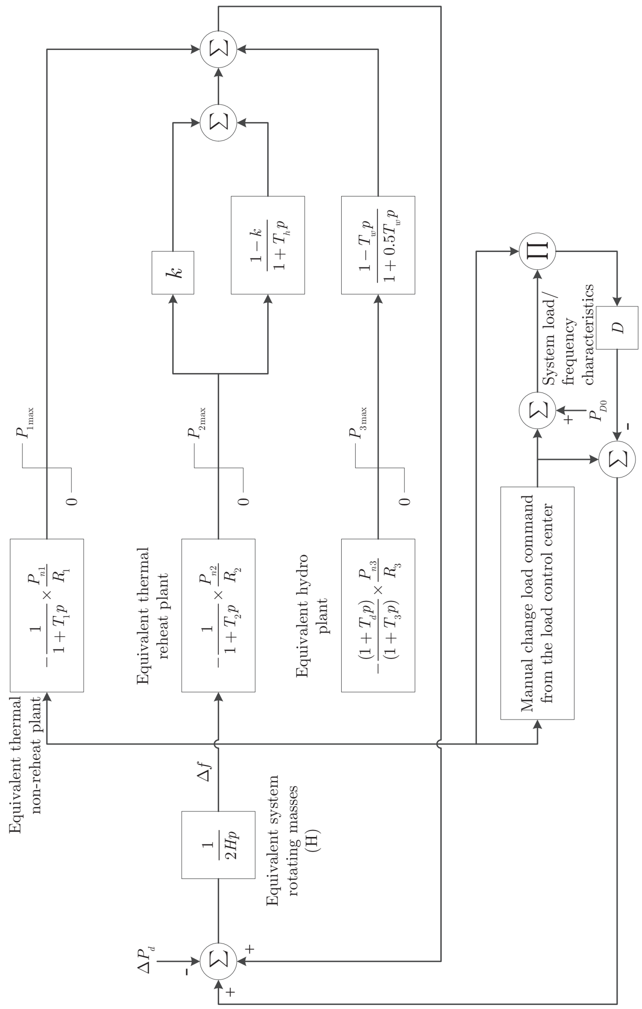


Figure 5. Three Area Average Frequency Model

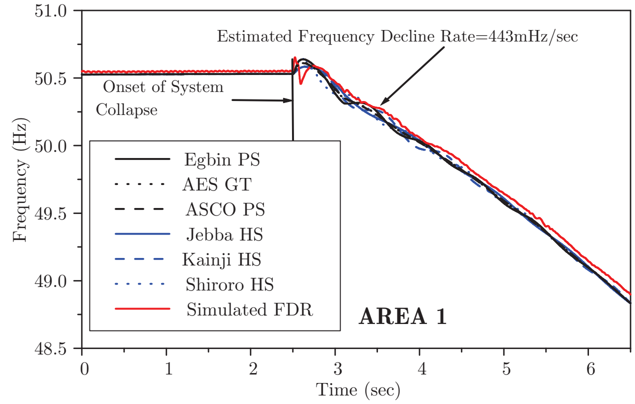


Figure 6. Bus Frequency Responses in Area 1 computed from the PSCAD Model of the Nigerian Grid — Simulated FDR refers to the bus frequency at Bus 13 of Fig. 1b

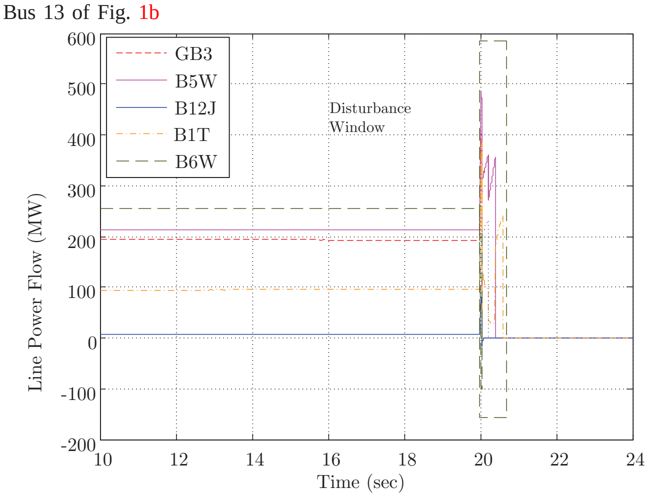


Figure 7. Line power flows computed from the PSAT Model simulated using a spanning window of 30 cycles

hypothesized generation levels, system loading patterns and inter-area power transfer. Finally, the cascading failures that led to the system collapse of the national grid on December 2nd, 2006 were simulated by implementing the following sequence of events:

- A bolted fault to ground on line (GB3) of 3 cycle duration was used to simulate the explosion at Benin Transmission Substation as reported by NCC, this was followed by
- A sequential opening of lines GB3, BIT, B5T, B6T, B12J and S3B.

The sequential opening of the lines was completed within a time span of 30 cycles starting from the initial presumed faulted line (GB3). The simulation procedure also made use of the existing knowledge of the Nigerian power system operating philosophy, which was found advantageous to obtain good simulation results.

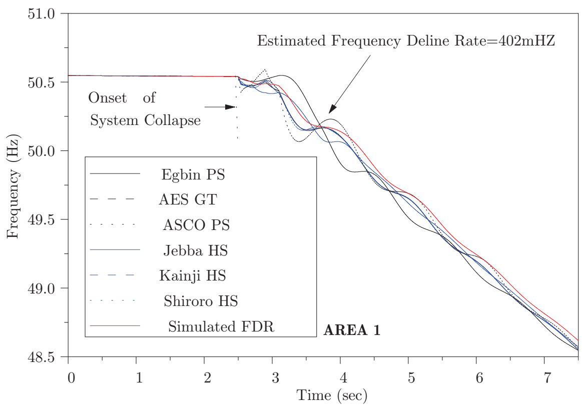
V. Simulation Results

The simulation results obtained from the models described in the preceding section are presented next. Figure 6 presents the simulation results obtained from the PSCAD model of the Nigerian National grid when subjected to the system disturbances experienced on December, 2nd 2006. Similar results obtained from the PSAT model of the Nigerian national grid are presented in Figs. 7, 8a-8c. Note from the FDR plots of Fig. 4a and Fig. 4b that the steady state frequency was 50.5 Hz just before the onset of sudden frequency decline. Consequently, the initial operating system frequency for both models was ramped to 50.5Hz through predetermined load shedding after which the hypothesized system disturbances were implemented. A frequency measurement unit attached to Bus 13 (see Fig. 1b) for each aforementioned model essentially simulated the actual FDR located at Bauchi. Figures 8b and 8c portray the frequency responses of the generating units feeding Areas 2 and 3, respectively, just before and immediately after the onset of the collapse of the Nigerian grid.

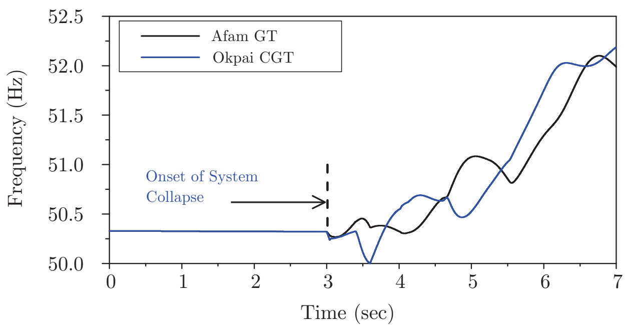
VI. Discussion of Simulation Results

The simulation results obtained from both the PSCAD and PSAT detailed models of the Nigerian power system clearly replicated the total system collapse of 2nd December, 2006 as captured by the FDR installed at Bauchi. Several other loading scenarios of the Nigerian grid system were explored with similar simulation results recorded when subjected to the same system disturbances. The adequacy of the Nigerian grid system models deployed for this study appeared satisfactory.

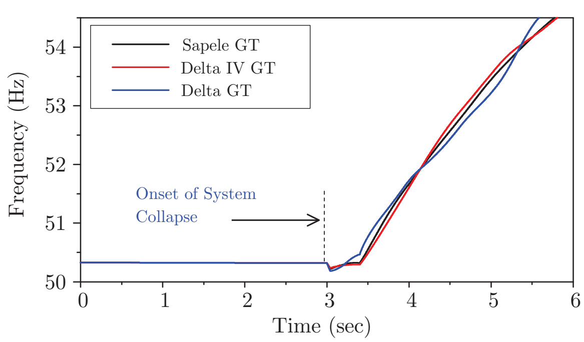
The anatomy of the system collapse simulated in this article depends on knowledge about the grid status and the



(a) Frequencies in Area 1



(b) Frequencies in Area 2



(c) Frequencies in Area 3

Figure 8. Frequency Responses in each Area computed from the PSAT Model of the Nigerian Grid — Simulated FDR refers to the bus frequency at Bus 13 of Fig. 1b

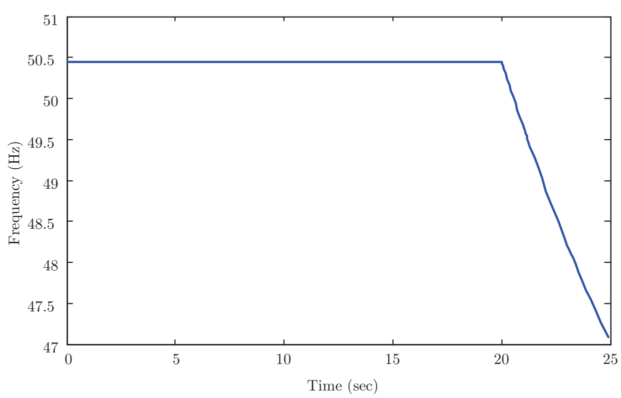


Figure 9. Frequency Response in Area 1 computed from the Three Area Average Frequency Model

resulting three islanded areas created by cascaded tripping of several transmission lines after an explosive fault at the Benin substation, near Benin (Bus 29 in Fig. 1b). The actual

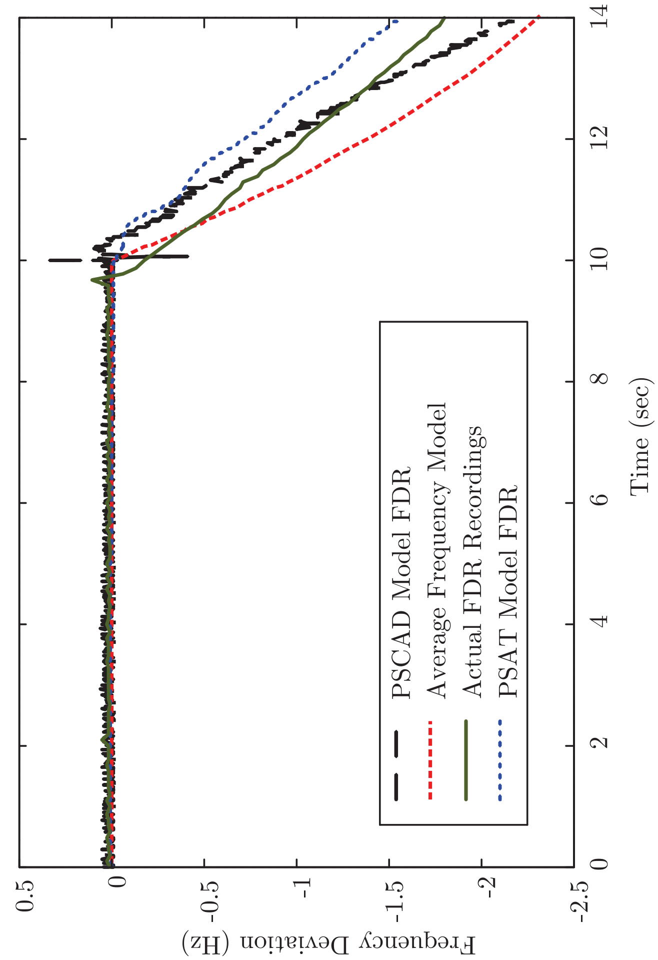


Figure 10. Comparison of Frequency Responses between Simulation Models and FDR Measurements — PSCAD Model FDR and PSAT Model FDR refers to the bus frequency at Bus 13 of Fig. 1b, for each corresponding model.

cause of the explosion was not immediately known. However, it is suspected to be either due to a poor maintenance culture, or exposure to prolonged high voltage stress, resulting on an inadvertent opening of a CT burden circuit. In the absence of functional system event recorders, we relied entirely on the NCC daily report which stated that the explosion was remedied by opening several transmission lines within Benin Transmission Substation, carried out by the system operators. It is also suspected that the operators' counteractive actions were not carried out with sound engineering judgement. This is because the uncoordinated line tripping of several lines led to the creation of three isolated areas (see Fig. 2) with the following characteristics:

- Area 1, covering the south-west and northern sub regions, which had deficiency in generation of approximately 400 MW at the on-set of system collapse;
- Areas 2 and 3 covering east and south-south sub regions, respectively had excess generation of 400 MW.

As should be expected, without adequate load shedding mechanisms, Area 1 suffered from a severe frequency decline, as captured by the FDR recording located in Area 1. The FDR recording as plotted in Figs. 4a and 4b was corroborated by similar sharp frequency decline measurements recorded at

National Control Center at Oshogbo. The results of Figs. 6-8c, obtained using two different models and simulation platforms, are essentially plots of bus frequency responses of generating units connected on-line within Area 1 and the simulated FDR. It is clearly seen that all the generating units' frequency responses declined with time, and dropped to below 48.5 Hz within 4.5 seconds.

The average frequency model developed in MATLAB/Simulink for Area 1 of the Nigerian grid, also revealed a bus frequency decline versus time characteristic similar to the FDR measurements when subjected to load perturbation of approximately 400 MW, as shown in Fig. 9. Comparisons of all the bus frequency decay characteristics from the simulation models and the FDR measurements are made in in Fig. 10. Note that the frequency decay patterns are relatively similar, thus confirming the ability of the developed Nigerian simulation models to predict the particular system collapse studied in this article.

VII. Conclusions

This paper presented detailed models of the Nigerian grid implemented in the PSCAD and PSAT software which were deployed to carry out extensive simulation of the system collapse experienced on December 2nd, 2006. In addition, an average frequency model was developed for the Nigerian power system, this model allows to obtain an approximate system frequency response when subjected to load perturbations. The detailed PSCAD and PSAT models of the Nigerian power system were found to replicate satisfactorily the frequency response characteristics of the grid when subjected to the system disturbance and cascaded transmission line outages that led to system collapse of December 2nd, 2006. The simulation results satisfactorily agreed with the FDR measurements in capturing the major characteristics of the system collapse analysed. The next challenging task, currently on-going, is to develop pragmatic load shedding schemes for the mitigations of total system collapses that have plagued the Nigerian power system in the last decade. Hence, this paper should be seen as an initial step on developing detailed models of the Nigerian National power system; such models will allow for the development of much needed load shedding methodologies that can aid in the mitigation of cascading collapses in this power system.

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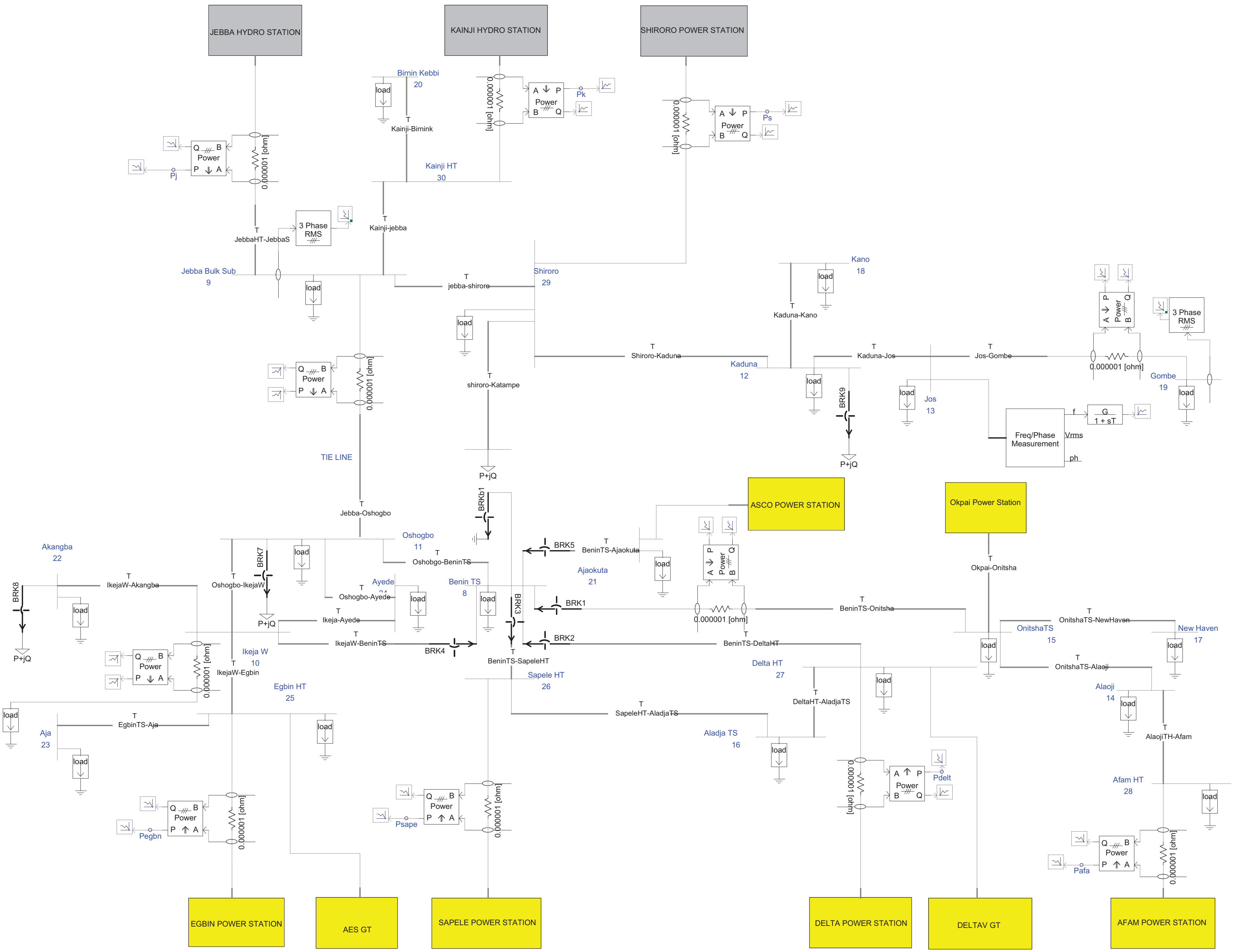

Figure 11. PSCAD Model

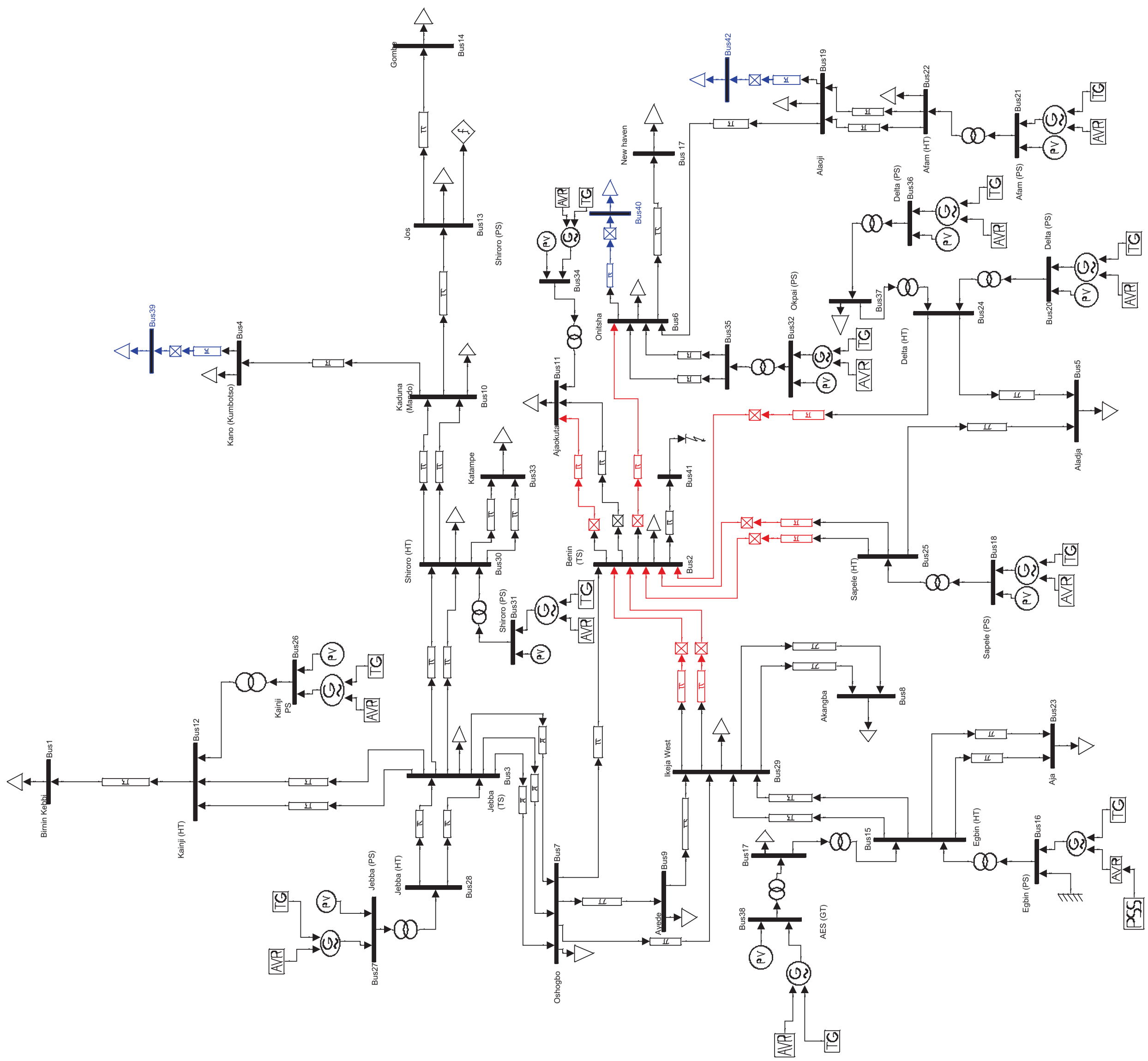

Figure 12. PSAT Model

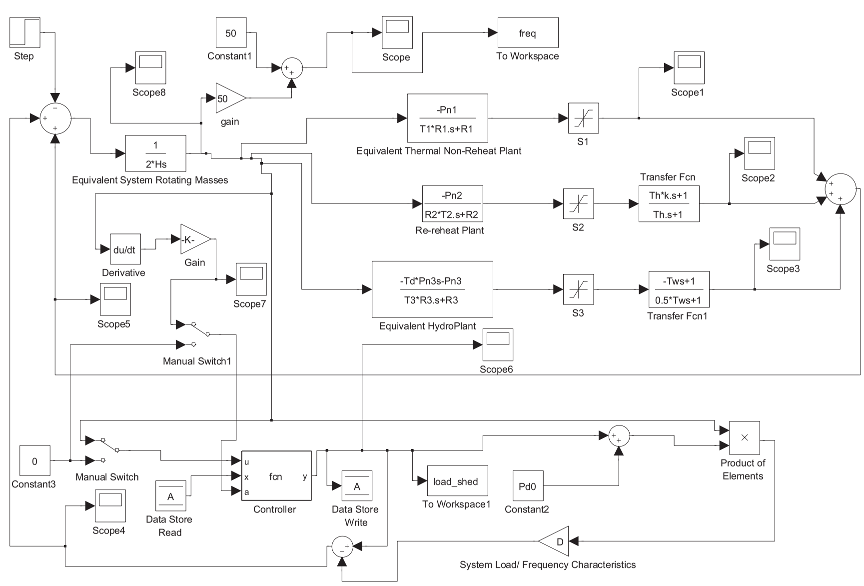

Figure 13. MATLAB/Simulink Average Frequency Model