Building a Frequency Monitoring Network to Study Dynamics of Rapidly Growing Power Systems

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***Abstract*— Frequency is one of the most important measures of the status of a power system, especially for structurally weak and rapidly growing power systems. Thus, frequency monitoring is a desirable practice to ensure reliability and provide data for analysis. This paper reports the joint work between Rensselaer Polytechnic Institute (RPI) and Abubakar Tafawa Balewa University (ATBU) to study frequency dynamics of small power systems. We describe the Frequency Disturbance Recorder (FDR) implementation experience at ATBU, Bauchi, Nigeria, and present analysis on the digital recordings provided by the FDR installed at this location. A proposal for a university-based frequency monitoring network for Nigeria's power system is also presented. Such monitoring system will allow further investigations on the Nigerian system and ultimately enhance the understanding of the dynamics and control of structurally weak and rapidly growing power systems found in some developing countries.**

***Index Terms*— Technology transfer, developing nation, Frequency Monitoring Network, Frequency Disturbance Recorder, Phasor Measurement Unit**

I. Introduction

Monitoring of frequency in power networks provides insight on the characteristics of system dynamics, due to the fact that frequency is a common measure throughout the system [1]. In particular, in a rapidly growing power system constrained by insufficient generating capacity, frequency can be very sensitive to disturbances and control actions.

Rensselaer Polytechnic Institute (RPI) and Abubakar Tafawa Balewa University (ATBU) have established a collaboration to study the dynamics of a rapidly growing power network typified by the Nigerian grid system. The frequency disturbance recorder (FDR) has been installed at ATBU and several recordings have been made, some of which are analyzed in this paper, revealing interesting operation and dynamic characteristics.

The characteristics of the Nigerian power grid as described by the recordings obtained with ATBU's FDR suggest the need for improvement of frequency control, this is a major concern because Nigeria is embarking on deregulating its electricity market [2]. Tighter frequency control is crucial to provide adequate signals to the real time market and avoid fluctuating energy prices.

To enhance the understanding of the Nigerian grid and to generalize this knowledge to other rapidly growing power networks, we propose a university-based frequency monitoring network that would enable further investigations of Nigeria's transmission system, and thus, enlighten the current understanding of rapidly growing power networks dynamics and control.

In order to achieve full coverage of the Nigerian grid system for the purpose of in-depth characterizations of the system frequency behavior engendered by various system disturbances, we have proposed, in this paper, a university-based frequency monitoring network. The Nigerian frequency monitoring network, if and when fully operational, could be replicated for other electric utilities in developing nations for the sole aim of deepening the current understanding of the dynamics and control of structurally weak electric power networks.

The remainder of the paper is organized as follows. Section II presents a brief summary on wide-area monitoring systems, and the justifications for the selection of an FDR-based system. In Section III we provide the background on the RPI-ATBU collaboration, describe the implementation experience gained at ATBU, and present some FDR data analysis from recordings made at Bauchi, Nigeria. A proposal for a university-based frequency monitoring network is made in Section IV, where logistic and reliability issues of this monitoring system are also discussed.

II. Wide area monitoring systems

A. FNET

FNET (Frequency Monitoring Network) [3] was conceived by VTech (Virginia Institute of Technology and State University) Power IT (Information Technology) Laboratory. The FNET project has developed a less expensive alternative recording device to Phasor Measuremet Units (PMUs) [4]. Its main goal was to create a wide-area measurement system that could be quickly deployed, be economical, and cover large geographic areas without the need of a dedicated communication infrastructure.

FDRs provide single-phase GPS synchronized voltage measurements at a sampling rate of 10 samples per second. They can be used individually to obtain on-site recordings (as currently used in Nigeria) and also within a Frequency Monitoring Network (as in the US).

FNET consists of two major components. The first is the FDR which performs GPS synchronized frequency data measurement, network interface, and data transmission. It is also a node of the FNET system. The Information Management System (IMS) server is the second component, performing data storage, management, analysis, and user interface. The Internet provides the integrated wide area communication media between the FDRs and the IMS server.

A detailed description of the characteristics and architecture of the FNET system can be found in [3].

B. PMU-based System

PMUs digitally record GPS synchronized three-phase voltage and current measurements. These units use a high internal sampling rate which writes and exports data at 10-60 samples per second. Measurements are time stamped with a GPS

TABLE I
FDR-BASED AND PMU-BASED MONITORING SYSTEMS

FDR-Based	**PMU-Based**
Low Voltage	High Voltage
Home/office/lab.	Substation
GPS Synchronized *single phase* $V_{1\phi}$ measurements	GPS synchronized *three phase* $V_{3\phi}$, $I_{3\phi}$ measurements
f is derived from $V_{1\phi}$	f is derived from $V_{3\phi}$
Easy to install and relocate	Installation and relocation might be time consuming
Internet based communication network	Secure dedicated communication network (*Data has to be protected with restricted access*)
Internet communication	Dedicated network
Sample rate is 10 samples/sec (Higher rate is available)	Sampling rate 10-60 samples/sec

signal, accurate to within fractions of a degree. PMUs require a communication network and a data concentrator to store and transmit measured data. Such a network has been deployed in the US Western Power System and is known as Wide-Area Monitoring System(WAMS). The US Eastern Interconnection Phasor Project (EIPP) is currently under development.

The interested reader is referred to [4] for a detailed description of the characteristics and architecture of PMU-Based wide-area monitoring systems.

C. FDR Based System vs PMU Based System

The most relevant features of both FDR and PMU-based wide-area measurement systems are summarized in Table I. The main justifications for the selection of the FDR over the PMU in this research project were the ease of installation and portability features of the FDR which are suitable for a university laboratory. Also important is the fact that while a PMU needs a dedicated communicated infrastructure to send and process the data which makes it more costly. Because the FDR is Internet ready, the communication infrastructure is less expensive and readily available.

III. FDR IMPLEMENTATION AND DATA ANALYSIS

A. FDR Implementation Experience

To obtain actual dynamic system and control characteristics of the Nigerian Power System, researchers from RPI provided a frequency disturbance recorder manufactured at Virginia Institute of Technology and State University to ATBU researchers. The FDR digitally records the voltage from a 230 V socket outlet. The voltage measurement is time tagged using the GPS signal. From the voltage measurement, frequency can be computed. The data rate of 10 samples per second is captured with a personal computer and/or transmitted over the internet to the frequency monitoring network (FNET) server at Virginia Institute of Technology and State University.

Figure 1 shows the low-voltage power supply installation and data transfer set-up adopted by the ATBU's researchers.

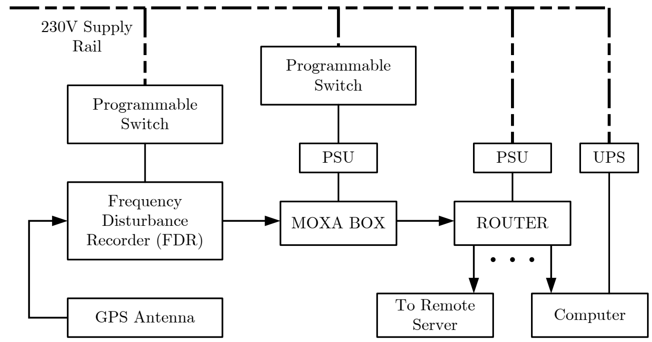

Fig. 1. ATBU FDR Installation Set-up

The power supply for the FDR consists of a 230 V supply rail, two programmable switches, two PSU (Power Supply Unit) and an UPS (Uninterruptible Power Supply). The programmable switches are used to switch on the FDR for scheduled data gathering. The PSU units are used to convert voltage and frequency from a 230V/50 Hz to a 110V/50 Hz supply. Note that the FDR was designed for operation at either power supplies, however, the Ethernet devices (serial device server and router) used in the installation are not designed for 200V/50 Hz. The data transfer set-up consists of a serial device server (MOXA Box [5]) extracting data from the FDR through the serial port and sending it to a router. The router is enabled to send data to VTech's IMS server and allows a dedicated PC to receive the information for local storage.

Several difficulties were encountered for the implementation of the FDR. Aside from the logistic problems, there were two major drawbacks that are worthy to mention here. Initially, it was desirable to have a continuous stream of data flowing from ATBU to VTech's IMS server. This would have populated a major database of disturbances and would have provided a better insight on the behavior of the system. Nevertheless, it was found after several tests that the data transfer from Africa to the US contained large amounts of information loss. Therefore, it was decided that the data would be locally

Fig. 2. FDR small server program retrieving data at ATBU

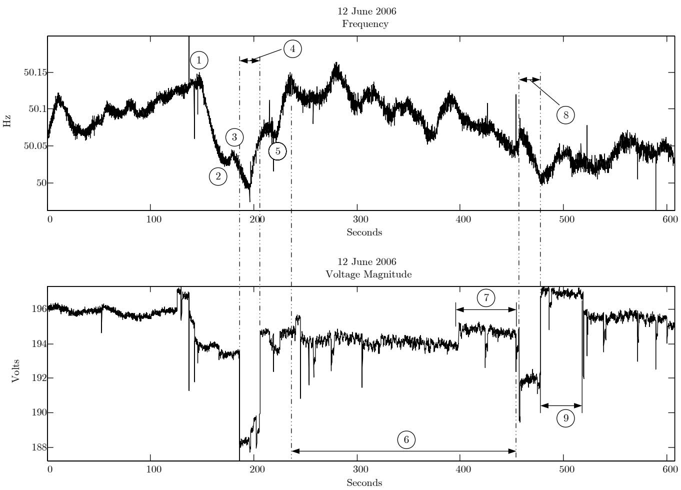

Fig. 3. FDR Recording of June 12, 2006

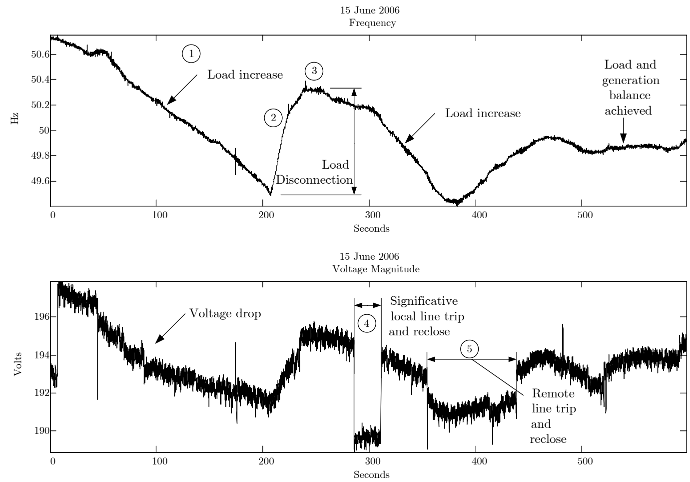

Fig. 4. FDR Recording of June 15, 2006

recorded with a PC at ATBU and then the recordings were sent to RPI via email. Figure 2 shows a screen shot of the FDR small server program retrieving data from ATBU's FDR.

The second obstacle concerns the identification of lost data. The initial installation of the FDR had large amounts of lost information due to the loss of GPS signal. Initially it was difficult to identify the missing samples in the data because the FDR *small server* did not had a sample tagging capability. The pinpointing of lost data was possible after this deficiency in the software was presented to VTech's researchers who created a *time index* feature, allowing pinpointing of the missing samples in the data. The GPS signal loss was solved by simply relocating the FDR to another area with better signal reception.

B. Analysis of FDR recordings

From several recordings made at ATBU, two representative ones were analyzed and presented here.

1) Event on June $12, 2006$*:* Figure 3 shows the recording of a disturbance event. The description enlisted below corresponds to the circled numbers in Figure 3. An interpretation of the event follows:

1. At 147.3 seconds frequency (50.15 Hz) begins to drop due to a load increase, such as switching in loads.
2. Frequency decays at a 4.6 mHz/sec rate at 175.3 seconds where the frequency is 50.02 Hz.
3. At 179 seconds a major load increase produces a rapid decay in frequency (4.7 mHz/sec) which is followed by a voltage dip also.
4. Load continues to increase until 196 seconds (49.97 Hz) where a large amount of load is disconnected. This is followed by a frequency rise with a 5.6 mHz/sec rate.
5. More load is disconnected at 221.3 seconds where the frequency is 50.05 Hz; frequency rises at a rate of 4.4 mHz/sec.
6. Gradual overall system load increase takes place system frequency regulation is present.
7. Nearby reactive power changes produce voltage jumps.
8. Local load switching.
9. Local load switching.

2) Event of June $15^{th}, 2006$*:* Figure 4 shows the recording of a disturbance event. An interpretation of the event follows:

1. From 0 to 200 seconds, there was a load increase in the system, indicated by a decline in frequency and a decline in voltage. Neither the active power nor the reactive power from the generators was able to follow the load.
2. At this point frequency reached 49.5 Hz. Some new generation was connected and the frequency and voltage both went up. This could not be a load trip since the variable is continuous.
3. At about 250 seconds, the frequency reached a plateau, most likely due to the added new generation having been used up. After that time, the frequency and voltage both start to drop.
4. Just before 300 seconds, the voltage dropped sharply and 15 seconds later, the voltage increased sharply. This would not be a load switching because the frequency was quite smooth. The most likely explanation is that there was a close-by transmission or distribution line that got switched out and reclosed.
5. Similar but smaller voltage drop and increase where observed at 360 second and 450 second, respectively. A reasonable explanation is that the line tripped and reclosed occurring farther away.

C. Operation Practices

The interpretations made on the recordings from the FDR are coupled to the operation practices of the grid operators for the Nigeria power system. Generally speaking, frequency control is very loose and load shedding is done manually, which significantly affects the system behavior. To better understand the recorded data, system operation practices at Nigeria are described below.

Load is mostly controlled manually. Whenever there is a lack of generation (generation deficiency) the control center

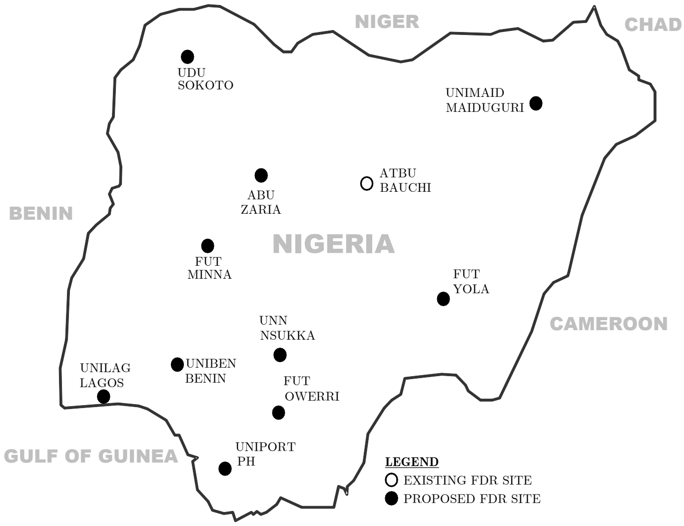

Fig. 5. FDR locations for the proposed FNET

TABLE II
LIST OF HOST UNIVERSITIES OF THE NIGFNET

Acronym	Host University	City
UDU	Usumanu Dan Fodio University	Sokoto
UNIMAID	University of Maiduguri	Maiduguri
ABU	Ahmadu Bello University	Zaria
ATBU	Abubakar Tafawa Balewa University	Bauchi
FUT YOLA	Federal University of Technology, Yola	Yola
FUT MINNA	Federal University of Technology, Minna	Minna
UNN	University of Nigeria	Nsukka
UNILAG	University of Lagos	Lagos
UNIBEN	University of Benin	Benin City
FUT OWERRI	Federal University of Technology, Owerri	Owerri
UNIPORT	University of Port-Harcourt	Choba

calls load centers (substations) to manually disconnect a certain amount of MW to bring up the frequency. The frequency deviation acceptable by control center operators is 2.5% of nominal 50 Hz, that is, $\pm$ 1.25 Hz. The voltage deviation acceptable is 6% of nominal 230 Volts that is, 13.8 Volts. SCADA is set up in the control centers, from which frequency is monitored, but no automatic load shedding mechanisms are used. Load shedding is manual. In general, control center operators have a good idea of what the demand is in each load area. They can sequentially connect or disconnect loads. Substations can later disconnect smaller loads within their feeders at their discretion.

Load disconnection when frequency shows a high rate of decay is frequently done at 49.5 - 49.8 Hz. Frequently, the source of this problem is that substation operators are not able to follow the control center instructions promptly.

IV. PROPOSED FREQUENCY MONITORING NETWORK

A. Prospective locations and hosts

Figure IV shows a proposed university-based frequency monitoring network in Nigeria (NigFnet). The FDRs will be located at each of the universities in offices or laboratories of the various research collaborators. Table II annotates the acronyms used in Figure IV.

Other recommended institutional hosts of FDRs not shown in the map include Obafemi Awolowo University (OAU) at Ile-Ife, University of Uyo at Uyo, and University of Abuja at Abuja because of their well established information technology infrastructures. Without any doubt, other institutions of higher learning within the country having the requisite facilities and researchers can subsequently hook to the network for the purpose of participating in this collaborative research effort. For the avoidance of doubt, one of the criteria used in proposing host institutions is the availability of reliable internet facilities amongst others. This is because data transfer from wide area distributed FDRs to the IMS server at a location, require internet communication infrastructure as previously mentioned.

B. IMS Server Location

The issue of the IMS server location is central to the successful implementation of the frequency monitoring network in Nigeria. The ideal location of the IMS server should be one of the proposed host universities with the best internet facility from a reliability standpoint as well as maximum commitment to the success of the project within the overall framework of US-Africa research collaboration initiative. In the recent past, University of Benin has served as the Nigerian hub for the US-Africa research collaboration effort and, against the backdrop of her reliable internet facility, should naturally be the best candidate to host the IMS server. It should be mentioned that the Nigerian electric utility also monitors the grid system frequency on continuous basis at its load control center, Oshogbo which is within the same geographical zone as the University of Benin.

C. Reliability of the proposed FNET

The proposed FNET when fully implemented should not be expected to capture frequency measurements for 24-hours from all the FDRs on continuous basis due to different operational constraints of the internet facilities at various institutions and other infrastructural deficiencies. Firstly, all the internet facilities at the proposed institutions mostly offer services during daytime. Secondly, the strength of GPS signals at different locations in Nigeria has not been studied but could significantly affect the recordings of FDRs. The experience gained from FDR installation at ATBU, Bauchi, indicates that frequent loss of GPS signal is principally responsible for most of the data gaps noticed in some of the recordings so far carried out. The GPS signal strength is adversely affected mostly during heavy cloud overcasts and rainfall. The improvement in the sensitivity of GPS to weak signal is a possible solution to overcome the problem of missing data in FDR recordings. Although some of these institutions have dedicated feeders from utility bulk substation, they still suffer from frequent power supply cuts. Depending on where the

FDRs are located at the various host institutions, they may suffer further from phase failure within the local distribution networks. All these factors will impact somewhat on the reliability of the proposed FNET. However, the expected power supply improvement and deployment of more reliable internet facilities with higher bandwidths in the future will most likely improve the reliability of the proposed Nigerian FNET to enable in depth characterization of the dynamics and control of the Nigerian grid system.

V. Conclusions

In this paper we have presented the initial results of the joint work of Rensselaer Polytechnic Institute (RPI) and Abubakar Tafawa Balewa University (ATBU) to study frequency dynamics of rapidly growing power systems. A description on wide area measurement systems and justifications for the selection of a FDR-based frequency monitoring network have been provided. The implementation of the FDR at ATBU has provided background information on possible future problems of GPS signal drop and data retrieval. Analysis of data recordings from Bauchi, Nigeria, shows the need for an improvement on frequency control; this highlights a major concern for the deregulation plans of the electricity market at Nigeria. Finally, we have presented a proposal for a university-based frequency monitoring network at Nigeria which would enable researchers from the US and Africa to embark into further research on the understanding of frequency dynamics of rapidly growing power systems.

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