Nigerian Power Grid: Model development, validation and standardization for R&D

S. S. Adamu[1], A. A. Sadiq[2*], and J. G. Ambafi[2*]**
[1]Electrical Engineering, Bayero University, Kano, Nigeria.
[2]Electrical and Electronics Engineering, Federal University of Technology, Minna, Nigeria.
[**]Principal corresponding author [*]Corresponding author

Abstract

The Nigerian power grid is characterized by uncertainties ranging from unbalanced load to generation rationing, radial topology, voltage instability, and incessant grid collapse. These uncertainties and their causes require rigorous and time-consuming investigative studies. To adequately studied any phenomena of interest in power systems, due to the complex and physical nature of power systems interconnection and associated control equipment, software-based model development and validation approach are paramount, particularly for research and development (R & D). A significant task in the power system's model development is the validation of the developed models with the actual field measurement. In this paper, some selected publications on the models of the Nigerian power grid were reviewed, and are found to be inconsistent in terms of number of buses modelled, load, and generation profile. Also, the models are often not benchmarked for either static or dynamic simulation studies. Therefore, this paper draws the attention of the various stakeholders in the Nigerian power sector, to as a matter of urgency pay attention to the accurate model development, validation, and benchmarking of the Nigerian power grid for R & D; recommendations were equally proffered in the conclusion section.

Introduction

Due to the improvements in technology and the need for sustainable power delivery, modern power systems have evolved from the conventional and centralised controlled grid structures to a highly interconnected networks. The transition presents new challenges in terms of accurate models of either: the technological change in generating technologies, load growth pattern and models used in simulation studies, and on the other hand the use of Flexible Alternating Current Transmission Systems (FACTS) devices to achieve highly complex and precision control. Furthermore, structural change in power systems operations through the microgrid operations or Islanding operation have made power systems modelling a critical task. The modern power systems, therefore, witness drastic transformation in terms of technology improvement, sophistication and dynamism of power electronics converters, smart grid as well as distributed generation penetration mainly due to support schemes for renewable "———[1][4]. The large size, dimensionality, and risk level involved in physical power grid infrastructure, the prerogative of the unbundled companies (GenCos, TransCos and DisCos) on various aspects of their planning and operations constitute the factors in planning and operations of power grid [5]. Moreover, technology-based solutions such as FACTS control operations often within the transmission network adds to the factors responsible for power grid sectioning in planning and operation studies. The key to adequate planning, operations, the reliable, and economic performance of large power systems rely to a great extent on the integrity, readiness, availability, and access to the power systems' data in all form. The data of the different power grid component enables the development of computer-based models. Hence, computer-based models of power grids are adopted for research and development. The geographical terrain, poor policies, and lack of information management systems make the data acquisition and in extension model development and validation of the Nigerian power grid almost impossible. Long transmission paths, radial grid nature, loose interconnection, and uneven generation to load profiles produce poor power quality, dynamic interactions/oscillations, and many systems collapse far below recommended best practices ———[6][9].

Power systems simulation studies can be classified into two major categories: steady-state (static) and dynamic simulations. The static simulation also referred to power flow or load flow analysis involves the computation of the power systems equilibrium, assuming constant parameter. The simulation assumes a snapshot thereby neglecting the dynamism of faults and other components used for control operation. On the other hand, dynamic system simulation is the computation of power systems response over time; it covers different time scales and is genrally time consuming compared to static simulation [10]. The various simulation studies performed in power systems can be grouped as either static or dynamic simulation and depicted in Figure 1.

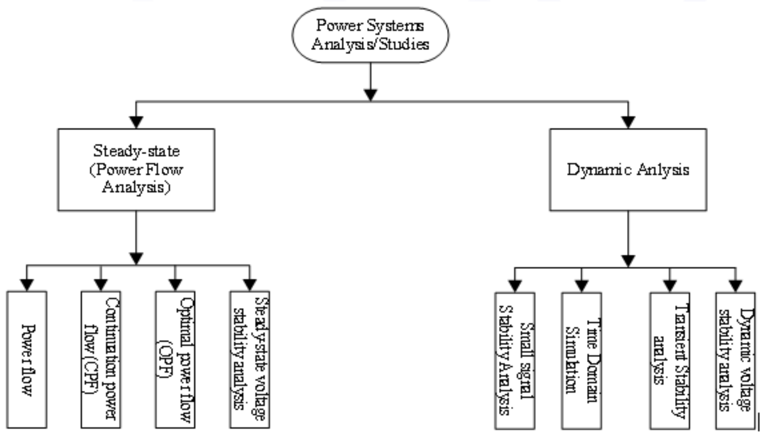

Figure 1: Power systems analysis classification

The major work in power grid modelling and simulation lies in the models' ability to adequately capture the phenomena of interest, either in a steady-state or dynamic state. The foundation of power grids analysis is often hidden in assumptions and methods as well as in model improvement that has resulted from years of experiences and cleverness. In power grid models, there is often a need to strike a balance between techniques and models mixed with power engineering on the one hand and the sophistication of power grids' control system which requires extensive theories on the other hand. The middle ground ensures that theoretically, sound engineering solution models are achieved [11]. All power grid studies (operating limits, planning studies for assessment of new generation and load growth, performance assessments of protection schemes) depend on the mathematical model representations of the various power grids' components: generation, transmission, and load.

However, from the various literature ——[12][16], researchers use significantly different models of the Nigerian 330 kV power grid. Moreover, evidence of the comparison of the performance of these models against actual measured power system data is yet to be reported. As the power grid expands as well as the occurrences of observed phenomena, there is the need for routine model validation such that the model represents significant observed phenomena on the power grid [17]. The techniques for the analysis of power systems have been transformed drastically by the superior computing abilities of the digital world. Various commercial and open sourced research-based software tools are available for the analysis and validation of multiple power systems models [18], [19].

This paper draws the attention of the various stakeholders (in the Nigerian power sector) to the importance of modelling, validation and benchmarking of the Nigerian power grid at a different level for research and development (R&D); thereby ensuring grid security, reliability, quality of supply, safety and economical operation.

Related works on Nigerian power grid models

The Nigerian power grid is majorly a mix of hydro and gas-fired (thermal) generation plant. According to the statistics of the model in [9], the Nigerian grid consists of 5, 523.8km of 330 kV transmission lines and thirty-two (32) 330/132kV substations with installed transformation capacity totalling 7, 688 MVA (which amount to 6, 534.8 MW). The average available capacity on 330/132kV is 7, 364MVA that is about 95.8% of installed capacity. The transmission voltages are 132 kV and 330 kV while 33 kV and 11 kV are nominal distribution voltages.

Statistically, the reviewed literature ———[14][16], [20] claimed to have obtained the network parameters from official sources, yet the models differ considerably as summarized by Table 1. The critical question, however, is how accurate are the data and the genuineness of these data to represent the actual parameters of the network?

Table 1: A tabular summary of different models of the Nigeria 330kV power grid

S/N	Authors	Generating stations	Buses	Tx. Lines	Pgen (MW)
1	(Nkan, Okoro, Awah, & Akuru, 2019)[14]	14	48	48	
2	(Ibe & Odia, 2010)[15]	10	35	40	
3	(Akwukwaegbu, Nosiri, & Ezugwu, 2017)[16]	10	28	32	
4		18	52	64	
5	(Okakwu & Ogujor, 2017)[13]	11	32	27	7461
6	(Sadiq & Nwohu, 2013)[20]	7	32	27	7461
7	(Onojo, Ononiwu, & Okozi, 2013)[12]	11	31	29	6000
8		17	49	64	10000
9	Proposed	14	56	53	5926.8

Generally for large interconnections (like the Nigerian power grid), to study some phenomena of interest, researchers often use reduced model as against the complete detailed mode. The justification for adopting the reduced models include: (i) the necessity of comprehensive models of the far-off section eases with the increase of the electrical distance from the event to be studied; (ii) practical restrictions of the model environment and those of computational resources; (iii) the guidelines and policy on information sharing amongst areas (of large interconnections) owned by different utilities; and (iv) limited resources (such as PMUs) deployed to monitor the system for the purpose of validation [21], [22]. Consequently, those parts of the interconnections remotely located and sufficiently distant from the event of interest are often represented using reduced-size models known as "equivalents".

Similar to power systems analysis, techniques for obtaining reduced model equivalents are broadly divided into static and dyanamic; the choice of either model is based on the phenomena of interest. Some of the model reduction techniques for static analysis includes: Dimo's (REI) method, Kron reduction, Ward reduction, and Zhukov's method [21], [22].

To study the various events which affects the performance of the Nigerian grid, and the radial topology of the grid characterized by long transmission lines (electrical distance of some portions of the grid) as well as limited measurement resources, reduced equivalent models of the grid for different events are important. At present, there exist no equivalent model of the Nigerian grid which provide adequate and comprehensive model, (of the electrical network, power generation, and other control equipment) for at least static studies. In [23], only a portion of the Nigerian grid was used as case study, however, the other sections of the grid were not adequately represented. Hence there is the need for several of such equivalent models validated and benchmarked for R&D. In the reduced equivalent model, the portion of interest are retained while the external areas, buses and portion are represented by an equivalent as depicted in Figure 2.

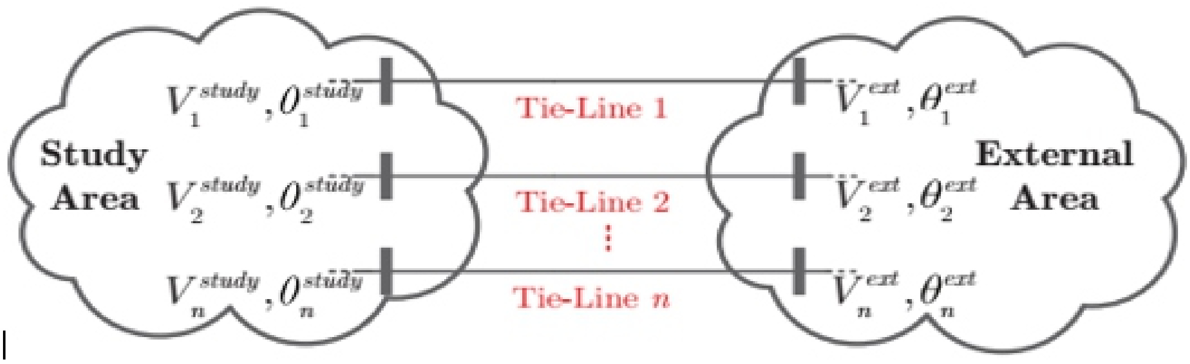

Figure 2: Power system schematic showing study area and external area, for reduction (Source:[24])

Model Development

Power systems' model development and validation form the foundation of all power systems studies. The approach to the development of entire power systems model is such that generators, transformers, loads and other associated components' models are individually obtained. The components' models rely majorly on physical and operational description and the data from the inherent characteristics of each component. Furthermore, the extent of components model representation depends on the phenomena of interest, which classified the model as either in steady-state (power flow) or dynamic simulation. Following the August 14, 2003 blackout in the north-eastern United States and eastern Canada, the recommendation by the U.S. Canada Power System Outage Task Force and NERC, identifies model validation and benchmarking to replicate the system's condition. The validated model permits rigorous investigative studies on the causes of the outage as well as mitigation measure; which resulted to several months of work to develop the power flow model used to study the outage [17].

Generally, steady-state models of the transmission section represent only the positive sequence quantities (in addition to negative and zero sequence for unbalanced short circuit studies), while remote parts of a large interconnections can be represented using the equivalent reduced-size models. The formulation of the model equation of an m-bus power systems network is considered as a set of nonlinear equations [25] given by equation (1).

$$\begin{aligned} \dot{x} &= f(x, y) \\ 0 &= g(x, y) \end{aligned} \qquad (1)$$

Where $y (y \in \mathbb{R}^m)$ are the algebraic variables, voltage amplitudes V and phases θ at the network buses and all other algebraic variables such as generator field voltages, AVR reference voltages, etc. $x (x \in \mathbb{R}^n)$ are the state variables, $g (g \in \mathbb{R}^m)$ are the algebraic equations and $f (f \in \mathbb{R}^m)$ are the differential equations.

In the traditional formulation of the steady-state AC power flow model, the power balance equation is considered under real and reactive components expressed in equations (2) and (3), expressed as functions of the voltage angles θ and magnitudes ${}_mV$ and generator injections ${}_gP$ and ${}_gQ$, where the load injections are assumed constant. The solution of the steady-state or power flow model of the equation (1) involves solving for the set of voltages and flows in a network corresponding to a specified pattern of load and generation [19].

$$g_P(\theta, V_m, P_g) = P_{bus}(\theta, V_m) + P_d - C_g P_g = 0 \quad (2)$$

$$g_Q(\theta, V_m, Q_g) = Q_{bus}(\theta, V_m) + Q_d - C_g Q_g = 0 \quad (3)$$

For each active component, the dynamics of the components need adequate representation. For stability studies, the phenomena of interest usually are time constants dependents and range from a few tens of milliseconds to many seconds. Therefore, the dynamic models denote the performance of power plants and their controls, certain components of loads, power electronic transmission devices (i.e., FACTS and HVDC), and, for some studies, on-load tap changers, PLC controls on shunt devices, remedial action schemes, and other similar control devices. Each component in the steady-state model needs to be matched with their corresponding dynamics models.

As a typical example, Figure 3 depicts the steady-state model of Nigerian 330 kV network for static studies such as load flow, continuation power flow and optimal power flow; which neglects the dynamics of the generator and its associated component —[20].

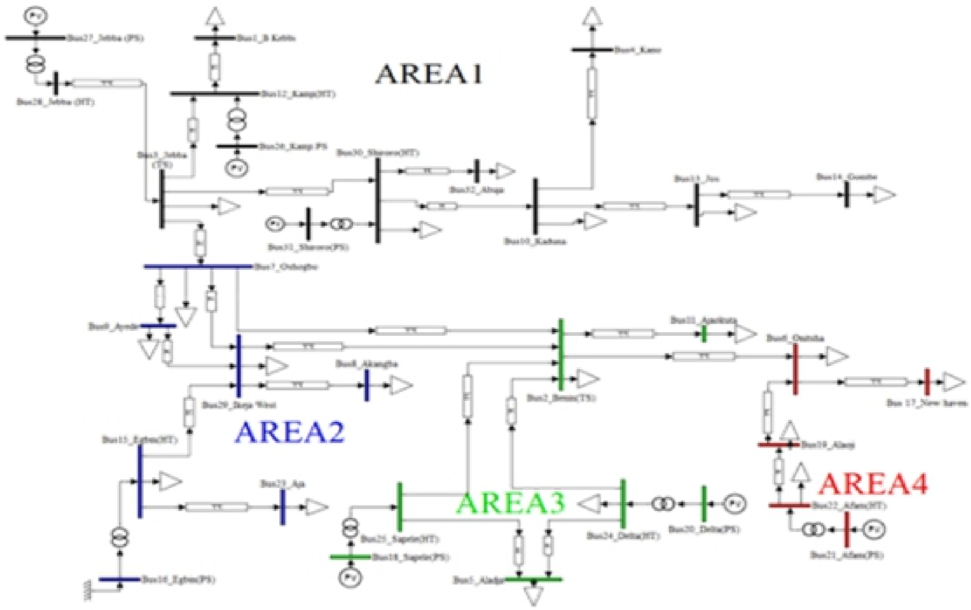

Figure 3: Steady-state model of Nigerian 330 kV power grid (Source: —[20])

For dynamic studies, each of the active components' nonlinearity and dynamic models of the generator, AVR, turbine governors and all other circuit dynamics are modelled as depicted in Figure 4.

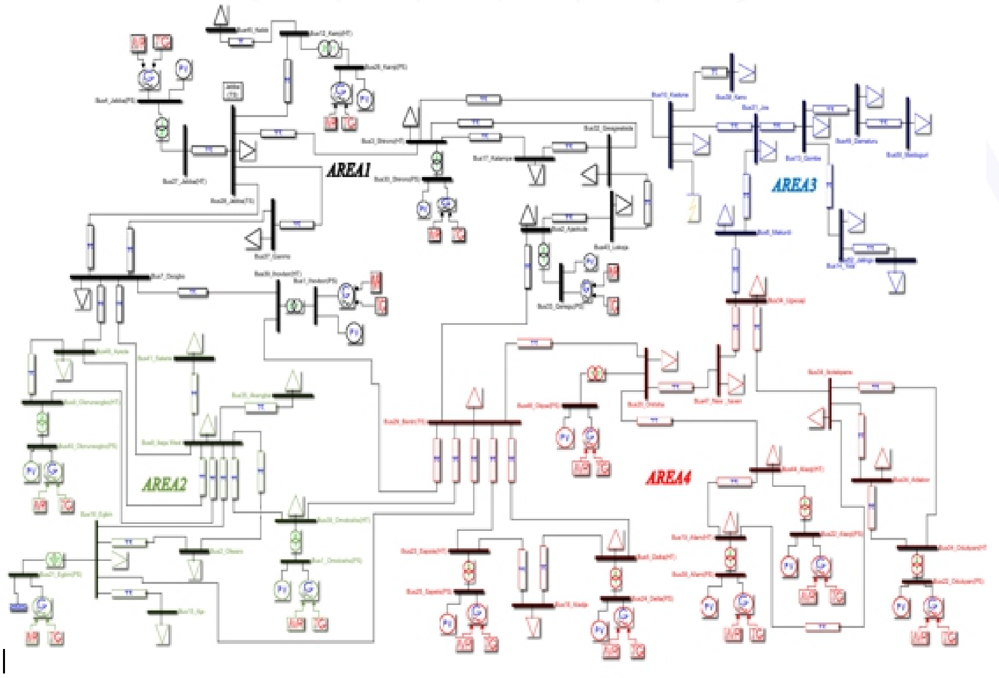

Figure 4: A modified dynamic model of Nigerian 330 kV power grid

Model Validation

The accuracy of each model depends on the extent of validation through comparison with actual field measurement. Periodic model validation is required to ensure its accuracy, keep up to date with the changes, provide a means of planning and expansion, as well as for research and development. The analysis of disturbances present opportunities for model validation as well as identification of improvements necessary in the existing model; hence, power grid planning and operating decisions are obtained from approximate results from the simulation.

The simulations of power systems depend on the adequacy of the model to predict the performance of the grid during phenomena of interest. Therefore, the accuracy and integrity of dynamic components model, as well as their corresponding data, must be up to date. For reliable and economic operations of power systems, realistic models are necessary, which is neither optimistic or pessimistic. Power systems performance prediction requires that all aspects of the performance of the system are model correctly. The power systems performance model requires an understanding of the system's behaviours and the assumptions made during model development. Complete system behaviour is obtained from observations, measurement and analysis, which allows for model validation [17]. A typical need for the Nigerian power grid model development and validation is the incessant power grid collapse [26][28]. The frequency of the grid collapse reported in [26], [28][31] is far below the grid reliability requirement. In the first quarter of 2019, four (4) grid collapses occurred [31]. It is worthy of note here that simulation studies are yet to be conducted on the causes and the necessary mitigation measures of the incessant grid collapse.

A typical illustration of the importance of model development and validation is the 1996 western interconnection outages. Initial attempt to reproduce the event in simulation did not match the actual observation and recordings as depicted in Figure 5.

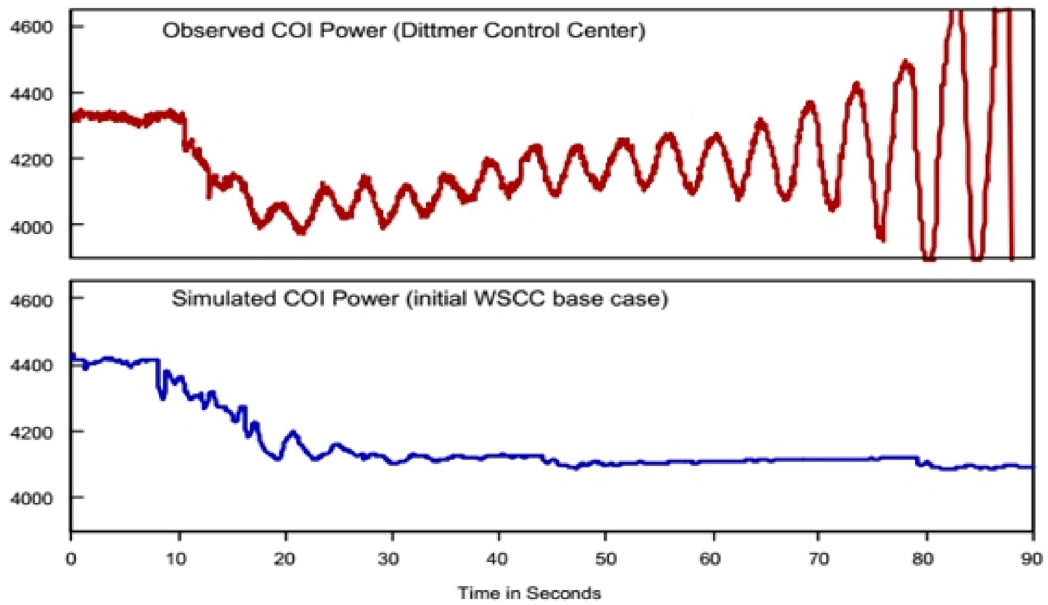

Figure 5: Comparison of observed and simulation results from 1996 WSCC outage (Source: [17])

To effectively implements and simulate different components and the entire power systems model, various software tools/packages are have been developed. The software tools are categorized as either commercial such as NEPLAN, PSCAD, and PSS/E or open sourced such as EMTP, ETAP, MATPOWER, Power World Simulator (PWS), PSAT, and PST. Each of these has been deployed for power systems model implementation, simulations, and validation. The choice of any of the software tools depends on the needs of the events to be studied, availability and adequacy of various component models and the capacity in terms of the maximum number of buses that each software can handle.

Generally, a model of interest that needs validation are Operational cases, Planning cases, Models for the components that make up the cases, and data constants associated with the component models. Power system model validation is carried out both at the component model or system-wide model validation. Figure 6 depicts a flow chart for a typical system-wide model validation process.

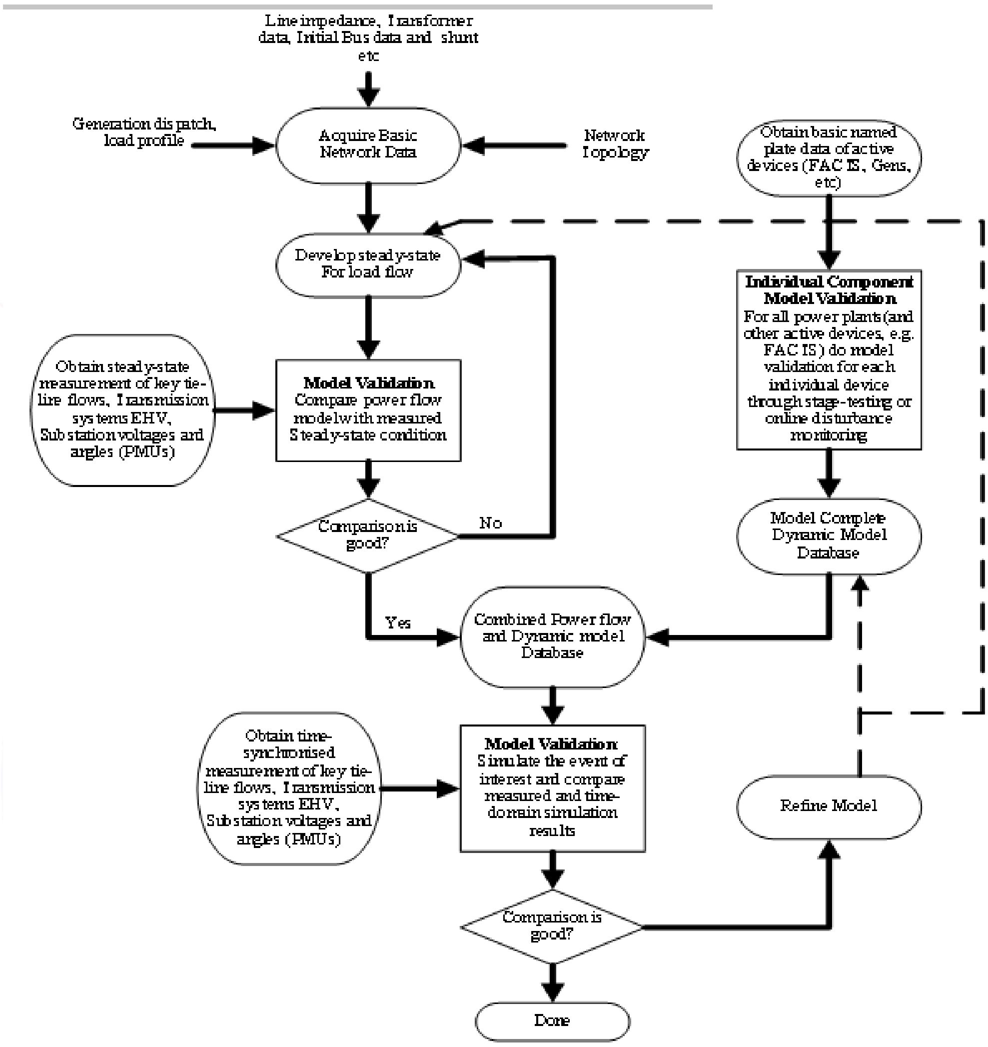

Figure 6: Model development and Validation Process (Source: [17])

Standardization

Depending on the phenomena of interest or the events that need to be studied, parts of large interconnections remote from locations of interest have often represented an equivalent. Therefore, for R&D, and in addition to the events being studied, different system-wide models of the Nigerian power grid is required for both power flow and dynamic studies. For instance, to study various grid collapses caused by generation or line outages in the Nigeria grid, an equivalent system-wide model is required, and upon successful completion, the developed model needs to be benchmarked for future similar events or against new mitigation technologies or methods.

Dynamic simulation of a modified Nigerian grid system

The dynamic model of Figure 4, was simulated under three-phase to ground severe fault at 40 s. The fault simulation is at Kaduna bus 1, throughout 200 ms. Upon clearing the fault, the post-contingencies performance of the dynamic model under voltage profile, generator rotor angle, and frequency responses were examined with and without FACTS devices, particularly SSSC and STATCOM [32]. Figures 7 to 9 depict the voltage profile, all generator rotor angles, and frequency responses under the simulated faults with and without FACTS devices.

As depicted in Figure 7, the voltage profile of the dynamic model under the said fault improves significantly with the FACTS devices. Also, Figure 8 shows that the behaviour of all the generators nose-dived from the start of the simulation without fault; however, with the introduction of SSSC and STATCOM, the system response was normalized.