Hybrid Transient Stability Analysis Solution for Power System Stability Studies

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Abstract*- Power system transient instability has become inevitable in recent times, due to geometrically increasing electrical energy demand leading to more complex networks. This is of paramount importance to power system utility engineers and other energy players in the industry. In lieu of this, this article carried out a complete survey of power system transient stability methods developed over the past ten decades. The research revealed that, the following methods; the Time Domain Simulation Method (TDSM), Direct Method (DM), and Automatic Learning Method (ALM) have so far been developed. While considering the strength and weakness of each method; hybrid solutions leading to combination of two methods which takes advantage of the merit of each method while evading their corresponding demerits were explored and developed. However, despite the maturity of all the methods developed so far, there is yet to exist a general-purpose transient stability analysis method because they were designed to operate independently. To fill this gap, this research article deployed structural design and algorithmic method to develop a novel Hybrid Transient Stability Analysis Solution (HTSAS) geared at taking advantage of the strength of the three methods so far developed; TDSM, DM, and ALM in conjunction with real-time computing through Supervisory Control and Data Acquisition (SCADA) System. The HTSAS structure was designed and an algorithm developed to illustrate the functionalities expected of the solution. These include, ability to sieve out power system network states, in the form of voltage, current and power delivery through the SCADA interface, parallel computation between TDSM//DM and seamless data storage to the associated database. The generated database is made available to the ALM module automatically, which then analyses them and produce accurate controllability and stability margins. This solution represents the first attempt to combine and synchronize TDSM, DM and ALM operations in a single solution. The programming languages used for the HTSAS development is web 3.0 languages which is a universal platforms that powers platform independent and mobile friendly solutions. The developed solution was tested in the laboratory using power system assembly which supplied current, voltage and power to the solution. The solution computed network parameters state and stored same with the associated data file in the control database. The output of the HTSAS unit was found to learn the pattern of network state variation and thus able to develop the necessary actuation signal required by the control unit. Given these results and further future refinement and adaptation, this solution is envisaged to be a general-purpose transient stability analysis solution.

Indexed Terms*- Hybrid Transient Stability Analysis Solution, parallel computation, seamless data storage, database, real-time computing, software algorithm.

I. INTRODUCTION

The inherent instability experienced by the power system networks in the course of its operations are of great vitality to power system engineers responsible for utility companies. Power system networks encounters Transient State or Steady State conditions depending on the nature of the impinging operations. Loss of high-power synchronous alternator, transmission line(s) or heavy short circuit, introduces transient instability. The more common stability state ambient with the power system networks is the steady state which encompasses load variation, transformers tap-changing action, and other associated small network perturbations. Researches over the years and common usage experience had clearly pointed that transient stability imposes more stringent requirement.

This is partly due to its non-linear nature and catastrophic tendencies within a short period. Authors in [1] and [2], wrote; *"Power system stability is its ability to remain in equilibrium state under normal operating condition and regain acceptable equilibrium state after undergoing system disturbance"*. Transient state results to large excursion of synchronous alternator's rotor angle, leading to loss of synchronism and possible system collapse in the event of system protection failure. [3], defined different stability study category such as voltage, rotor angle and frequency stability with further but overlapping classification depending on the size of network disturbance and timeframe of its occurrence. The goals of the power system stability assessment therefore entail accurate implementation of power system security constrained solutions that ensure proper power system network resources and elements utilization without compromising the security of the entire system. Transient Stability Analysis is the foundation of Power System Transient Stability Control leading to stable operation in power system networks [4]. Methods involving analytical computations and algorithmic development such as the traditional and the direct transient stability methods were highlighted in [5], with its inherent drawback. Following technological advancement, [6] posited that more advanced methods based on artificial intelligence system had been developed and is applicable to power system stability studies. Authors in [7], presented Regularized Robust Recursive Least Squares ($3R_sLS$), method previously cited in [8] and a host of others.

Before the advent of computers, TDSM were used to determine dynamic stability of power system networks. Highly simplified versions of system differential equations were evaluated manually to obtain the swing curves of the synchronous machines used in the power system that is the rotor angles as a function of time [9]. TDSM continued to be the universal way of determining system transient stability of general multi-machine power system owing to its intrinsic attractive features such as ability to provide machine swing curves, i.e., rotor angles, speeds, accelerations, power etc., and to reach the required degree of accuracy in a predefined time. However due to its inherent drawback such as inability to provide straightforward screening tools, sound stability margins, sensitivity analysis tools and sound control suggestions, the non-conventional approaches began to receive appropriate attention [10]. The development of direct and automatic learning method both began simultaneously by the late sixties. But while direct method continued to be developed, automatic learning method was halted until two decades after due to limited computational power of computers available as at that time. Harnessing the advantages of direct method which involves reducing the Time domain simulations to the barest minimum during fault, sound stability margins and suitable sensitivity analysis, the authors [11] and [12] made tremendous breakthrough in the development of this method for transient stability studies. Three decades after it became clear that the direct method surfers from two main difficulties which include over simplification of model to ensure construction of good Lyapunov function and poor computational efficiency and accuracy of the transient stability assessment of large systems [13]. Among the many interesting attempts made to circumvent these difficulties include the "structure preserving modeling" [14] and the "pseudo-Lyapunov approaches" which involved the use of TDSM with detailed modeling together with pseudo-Lyapunov functions with simplified modeling [15]. Furthermore, other solutions proposed to tackle the second difficulty encountered by direct method includes; the method of [16], the acceleration approach [17], the exit point strategy of authors in [12], and other methods contributed by authors in [18] and [19].

Despite the inventive nature of these solutions, they were not able to completely overcome the limitations of direct method as the resulting solutions were overly conservative with unpredictably varying degrees of conservativeness and on the other hand computationally heavy, thereby removing the computer gains expected of direct method, making them much heavier than TDSM even.

However further research and development which combined theoretically pure approaches with rational engineering solutions led to the approaches that circumvented the aforementioned limitations of direct method. This approach proposed the use of single or two machine equivalents to represent large power system and hybrid DM /TDSM to carry out the associated modeling for the purpose of stability domain estimation. These solutions resulted on one hand to Bellman decomposition-aggregation approach and the Vector Lyapunov functions, where the multi-machine power system is reduced to 2-machine subsystems [13] and or the single machine equivalent approach [20], and [21]. On the other hand, the modeling aspect resulted to hybrid approach either of the multi-machine type [22] or of the single-machine equivalent type [23]. In reality, hybrid DM / TDSM of two types ensured visa viz multi-machine type (MME) and single machine type (SIME).

The merits of the resultant hybrid solution include full flexibility with respect to power system modeling, first-swing and multi-swing transient stability assessment, effective screening tool design, computation of stability margins, yielding sensitivity analysis and the identification of the relevant machines parameters which opens avenue for real-time emergency control [10].

The automatic learning models such as the Decision Tree, Artificial Neural Networks, k-nearest Neighbors and Fuzzy Decision Trees had received considerable attention of researchers in the past and this had given rise to identification of their individual weakness and merits. To further standardize the AL models so far developed, hybridization was carried out resulting to models such as DT-ANNs, DT-kNNs and Fuzzy DTs, the aim of which being to utilize their individual benefits while evading their weaknesses [10]. Since ALM depends on accurate database generation or bank of statistical data generated by experts in the system, it then become imperative that appropriate tools be made available, else the result of the model may be inaccurate.

To that effect, [24], proposed a probabilistic solution approach to power system dynamic performance subject to various severe fast and slow perturbations. The authors modeled the potential causes resulting to extreme cases such as voltage collapse, loss of synchronism, loss of transmission lines or synchronous machine and line overloading, probabilistically taking into cognizance design uncertainties. To be able to handle bulky data associated with the process, the authors developed a database generation tools which exploited parallel computation techniques to simulate in details the considered scenarios and a statistical data mining tool specially adapted for very large databases composed of impermanent data. The approach yielded a very promising result, although much work is still underway to achieve the ultimate goal of synthetic stability analysis and control.

Improvement in computer technology had led to rapid development of ALM applied to transient stability as well as voltage stability to a lesser extent. The success recorded so far were made possible by close collaboration with research and design engineers who provided their expert knowledge and critical judgment. Their efforts had resulted to generation of accurate databases which serves as precursor to ALM, further standardizing the operation of this method and gearing it towards universal acceptance by the key players in the power system utility industry [25].

From the literature reviewed, it is obvious that power system transient stability assessment or generally power system stability is a complex task which requires critical and advanced approach to deal with. Presently various methods have been developed which are capable of handling power system stability cases not possible within the past few decades due to limited computational prowess of available computers then. The implementation of these methods was made feasible by the combined effort of researchers, developers and practicing engineers in the field of power system engineering. These methods include the TDSM, DM and ALM.

TDSM remained the universal method of determining power system stability [26] due to its ability to produce machine swing curves; i.e., rotor angles, speed, acceleration and power, modeling flexibility, ability to reach the degree of accuracy in a predefined time [9]. However, to achieve sufficient accuracy, time deviation of differential curve approximation must be very small [27]. The reduction in time step by the use of predictor-corrector method which is a modified form of Euler's method, resulted to various shortfalls such as inability to self-start, and use of large computer memory as well as heavy computational time, when compared to other higher-order methods, example the Runge-Kutta method.

In summary, the TDSM is unable to provide straightforward screening tools, sound stability margins, sensitivity analysis tools and sound control suggestions or real-time emergency control. These shortfalls paved way for development of non-conventional methods: The DM and ALM [10].

In direct method, the researcher explored the possibility of reducing the time of simulation to the barest minimum during fault to achieve a good stability margin and suitable sensitivity analysis [11]. Authors in [28] gave an excellent treatment of the direct method based on the equal area criteria applied to the power system under consideration. This criterion simply relates the kinetic energy acquired by the rotor of a synchronous machine during faulty state to the potential energy attained by the rotor during post-fault state. For stability, the gained kinetic energy must be converted to potential energy at the instance the machine reverses it motion which enables it to return to new steady state. [29] Used the first integral of energy to obtain stability criterion, while [30] developed a technique for system stability using the classical model with zero transfer conductance. Not quite long into the development of direct method, it became obvious that the power system network model must be oversimplified to make feasible construction of good Lyapunov function which is the heart of direct method. Among efforts made to shape the Lyapunov's direct method includes [31], application to single machine infinite bus system and [32], application of the method to multi-machine system. Also, computational efficiency of the resulting model applied to transient stability analysis of large systems was poor [13]. Several efforts were made to circumvent these difficulties by authors such as [14], using structure preserving models and pseudo-Lyapunov's approach. However, despite the inventive nature of these solutions, they did not remove the weakness of direct method completely, due to the conservative nature of the resulting models, unpredictability and computational cumbersomeness. However, further research resulted to hybrid versions of DM/TDSM where the multi-machine power system is reduced to two-machine systems [13] and or the single machine equivalent approach [20] and [21].

The merit of the resulting solution includes full flexibility with respect to power system modeling, first-swing, and multi-swing transient stability assessment, effective screening tools, design, computation of stability margins which gave rise to sensitivity analysis, thereby opening avenue for real-time emergency control [10].

Following the hybridization of various ALM developed due to their individual weakness, the three main intrinsic characteristics of ALM ensured. These include interpretability of the given phenomena, extraordinary online computational efficiency and the ability to manage uncertainties which stems from its statistical nature where the uncertain situation is suitably randomized. This asset is very crucial in the real-world scenario where unpredictability always abound. Some of the hybrid ALM includes Fuzzy DT, hybrid ANN, and hybrid *k*-NNs. These hybrid solutions are indeed able to meet stringent need of power system stability assessment with the help of genetic algorithm but at the expense of heavy computational time [33]. For ALM methods to be fully implemented and adopted in the real world, it must develop a routine process of accurate database generation in the context of operation [34], and in the context of real-time, and automatic operation [35]. The second limitation which ALM method must overcome to stand the test of time is to eliminate over-dependency on the conventional method for its input data.

Now the obvious is the final goal which should be a solution capable of unifying the highlighted three types (TDSM, DM and ALM) of stability assessment approaches instead of piecewise approaches. This solution is yet to be developed but it is currently undergoing active research and development. To help tackle the identified problem, this research article proposes a Hybrid Transient Stability Analysis Solution which is intended to be a general-purpose transient stability analysis solution for power system engineers and utility players. The proposed solution is to be built on the core of TDSM with DM and ALM incorporated such that each module will be able to access the necessary data required for its operation, at any point in time.

II. TECHNICAL CONSIDERATION

Transient instability of power systems can be investigated using single machine infinite bus system, two machine system, or multi-machine system. Single machine infinite bus system consists of an alternator delivering power to a large system denoted by a vast bus through transmission lines or circuits. Infinite bus represents voltage source of constant voltage magnitude and constant frequency. Two machine systems consist of two machines of comparable sizes connected to each other through a transmission link. Multi-machine systems incorporate numerous synchronous machines similar in characteristics, closely coupled electrically, and connected to high-capacity utility system. This type of power system representation which mimics practical or real-life power system scenario is very complex to analyze especially when detailed and precise analysis is required [36]. However, in practice under most type of perturbations, machines remain in synchronism with each other, though they can fall out of step with the utility grid. This condition is similar to a single synchronous machine connected through impedance to an infinite bus. With this apparent simplification, further stability analysis carried out in this dissertation will involve single machine infinite bus system. For illustration purpose, let us consider single machine infinite bus system shown in figure 2.1. The concept and principles of transient stability is presented by analyzing the system's response to large perturbation, using simple machine model. Under this condition, all resistances, the speed governor effects are neglected and synchronous machines are represented by classical model.

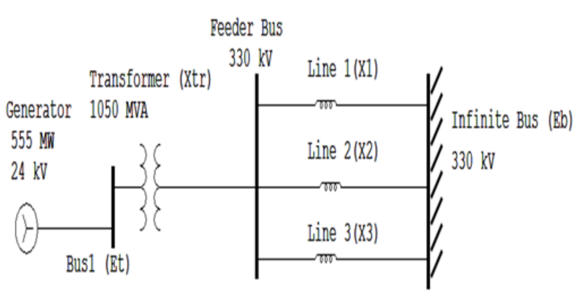


Figure 2.1: Single machine infinite bus system (Source: adapted from [1]

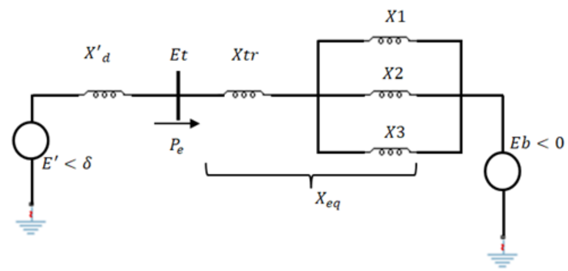


Figure 2.2: Equivalent circuit (Source: adapted from [1],

Figure 2.2 shows equivalent circuit representation of the single machine system of figure 2.1. The voltage behind the transient reactance(X'_d)is represented by E'. The rotor angle δ indicates the angle by which E'leads Eb, the infinite bus voltage. When the system is disturbed, the magnitude of E' remains constant at its pre-perturbation value and δ changes as the generator rotor speed departs from synchronous speed ω_0. The reduced system model is shown in figure 2.3.

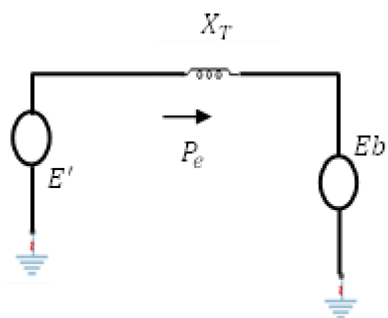


Figure 2.3: Equivalent circuit in reduced form. (Source: [1])

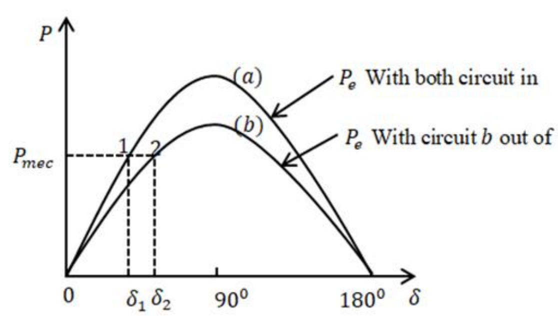


Figure 2.4: Power Angle Relationship of figure 2.3, equation (1) (Source: adapted from [1]).

The reduced circuit of figure 2.3 can be examined using analytical method which is helpful in understanding the basic transient stability phenomenon. Here the alternator's electrical power output P_e can be represented with equation (2.1).

$$P_e = \frac{E'Eb}{X_T} sin\delta = P_{max} sin\delta \qquad (2.1)$$

Where $P_{max} = \frac{E'Eb}{X_T}$ (2.2)

With stator resistance neglected, air-gap power is the same as terminal power each equals P_e. Figure 2.4 curve (a) illustrates graphically, the power angle relationship of circuit of figure 2.3 and equation (1) with both transmission circuits in service (InS). With mechanical power input P_{mec}, the steady-state electrical power output P_e is equal to P_{mec}. The operating condition is denoted by point (1) on the curve and the corresponding rotor angle is δ_1.

If one of the transmission lines is out of service (OofS), the effective reactance X_T increases resulting in reduced maximum power. This condition is shown with curve (b). With a mechanical power input of P_{mec}, the rotor angle becomes δ_2 corresponding to the operating point 2 on curve (b). In order to transmit the same steady-state power, the rotor angle is higher with increased total reactance. During perturbation, the oscillation of rotor angle δ is superimposed on the synchronous speed ω_0 but the change in speed $(\Delta\omega_r = d\delta/dt)$ is very small compared to ω_0. Hence the generator speed is virtually equal to ω_0 and the per unit (pu) air-gap torque becomes equal to pu air-gap power. This forms the basis of swing equation or equation of motion of generator rotor shown in equation (2.3).

$$\frac{2H}{\omega_0}\frac{d^2\delta}{dt^2} = P_{mec} - P_e \qquad (2.3)$$

Where P_{mec} is the mechanical power input in (pu), $P_e = P_{max} sin\delta$, P_{max} is the maximum electrical power output in (pu), H is the inertia constant in (MW-seconds/MVA$_{(base)}$), δ rotor angle in (electrical radian) and t is the time of operation in seconds (s).

2.2.1 Equal Area Criteria

In stability analysis of a single-machine infinite bus system, the information regarding the maximum angle excursion (δ_m) and stability limit (δ_L) can readily be obtained graphically from the power angle curve of figure 2.5 (a) without formally solving the swing equation. From equation (2.3), the relationship between the rotor angle and the accelerating power can be written as follows:

$$\frac{d^2\delta}{dt^2} = \frac{\omega_0}{2H} P_a \qquad (2.4)$$

Where $P_a = P_{mec} - P_e$. At the initial condition, the alternator operates at synchronous speed with rotor angle δ_0 and mechanical power P_{mec0}. At this point $P_{mec} = P_e$. When fault occurs, difference in power which must be accounted for by rate of stored kinetic energy change in rotor masses occurs [37]. This is as a result of increase in speed caused by constant accelerating power P_a. For any time less than the clearing time t_c, the acceleration is constant as seen from equation (2.4).

While the fault subsists, the velocity increase during fault can be obtained by integrating equation (2.4) as follows with respect to time:

$$\frac{d^2\delta}{dt^2} = \int_0^t \frac{\omega_0}{2H} P_a dt => \frac{d\delta}{dt} = \frac{\omega_0}{2H} P_a t \qquad (2.5)$$

A further integration of equation (2.5) with respect to time yields the rotor angle position as follows:

$$\frac{d\delta}{dt} = \int_t^{t_c} \frac{\omega_0}{2H} P_a(t) dt => \delta = \frac{\omega_0 P_a}{4H} t^2 + \delta_1 \qquad (2.6)$$

Equations (2.5) and (2.6) shows that the velocity of the rotor, relative to the synchronous speed increases linearly with time, while the rotor angle moves from $\delta_0 or\ \delta_1 to\ \delta_2$, the clearing angle as in the case of figure 2.5.

At the instance of fault clearing, equation (2.6) can be written as equation (2.7), from where the critical clearing time can be obtained.

$$t_c = \sqrt{\frac{4H(\delta_2 - \delta_1)}{\omega_0 P_a}} \qquad (2.7)$$

We can define the angular velocity of rotor ω_r relative to synchronous speed ω_0 from the swing equation for a single machine connected to an infinite bus, or two machine system of equation (2.3) as follows:

$$\omega_r = \frac{d\delta}{dt} = \omega - \omega_0 \qquad (2.8)$$

Differentiating equation (2.8) with respect to time *t* and substituting in the swing equation of equation (2.3) we obtain;

$$\frac{2H}{\omega_0}\frac{d\omega_r}{dt} = P_{mec} - P_e \qquad (2.9)$$

Hence multiplying both side of equation (2.9) with $\omega_r = \frac{d\delta}{dt}$, equation (2.10) is obtained.

$$\omega_r \frac{2H}{\omega_0}\frac{d\omega_r}{dt} = (P_{mec} - P_e)\frac{d\delta}{dt} \qquad (2.10)$$

Rearranging equation (2.10), multiplying both side by dt and integrating, we obtain equation (2.11).

$$\frac{H}{\omega_0}\frac{d(\omega^2{}_r)}{dt}.dt = \int_{\delta_1}^{\delta_m}(P_{mec} - P_e)\frac{d\delta}{dt}.dt \qquad (2.11)$$

The change in rotor angular acceleration $d(\omega^2{}_r)$ corresponds to the rotor angle excursion limit $\delta_1 and\ \delta_m$. Since ω_r is the difference between the rotor angular speed and the synchronous speed, we can deduce that if the rotor angular acceleration is synchronous at the two-machine angle limits considered, $d(\omega^2{}_r)\ or\ \omega^2{}_{r2} - \omega^2{}_{r1}$ equals zero. Hence equation (2.11) reduces to equation (2.12) which applies to any two points $\delta_1$and $\delta_m$or boundary condition on the power angle curve provided the rotor speed is at synchronous speed.

$$\int_{\delta_1}^{\delta_m}(P_{mec} - P_e)d\delta = 0 \qquad (2.12)$$

Integrating equation (2.12) in parts or steps produces equations (2.13) and (2.14) when the accelerating part is equated to the decelerating part.

$$\int_{\delta_1}^{\delta_2}(P_{mec} - P_e)\,d\delta + \int_{\delta_2}^{\delta_m}(P_e - P_{mec})\,d\delta = 0 \qquad (2.13)$$

$$\int_{\delta_1}^{\delta_2}(P_{mec} - P_e)\,d\delta = \int_{\delta_2}^{\delta_m}(P_e - P_{mec})\,d\delta \qquad (2.14)$$

This entails that the area under the function $(P_{mec} - P_e)$ plotted against δ equals zero for the system to be stable and is achievable when areaA_1 equals area A_2. Splitting the integral function of equation (2.13) into accelerating and decelerating kinetic energy (KE) periods, we obtain equations (2.15) and (2.16).

$$KE_1 = \int_{\delta_1}^{\delta_2}(P_{mec} - P_e)\,d\delta = area\ A_1 \text{ ...accelerating} \qquad (2.15)$$

$$KE_2 = \int_{\delta_2}^{\delta_m}(P_e - P_{mec})\,d\delta = area\ A_2 \text{ ...decelerating} \qquad (2.16)$$

Since energy losses had not been considered, the kinetic energy gained is equal to that lost; thus area A_1 is equal to area A_2. This is the basis of equal area criterion which enables the maximum swing of δ and hence the stability of the system to be determined without explicitly computing the time response through formal solution of swing equation [28].

This criterion can readily be used to determine the maximum permissible increase in P_{mec} for the system under consideration. The value of A_1depends on the fault clearing time. Delay in fault clearing increases clearing angle δ_c or δ_2 as shown in figure 2.5, consequently increasing area A_1. A stability criterion requires that area A_2 increase at the expense of larger rotor maximum excursion angle δ_m.This system is considered stable only if area A_2equal to A_1 is located above P_{mec}. For values of A_1 greater than A_2, A_2 located any other place apart from above P_{mec}along the curve or vice versa, the system becomes unstable. At this point$\delta_m > \delta_L or\ \delta_{max}$, the maximum permissible rotor angle deviation the system can withstand. Stability is lost owing to the fact that the net torque at this time is generative instead of degenerative.

Hence in order to satisfy the requirements of the equal-area criterion for stability, there is a critical angle for clearing the fault called the *critical clearing angle* δ_{cr}. The corresponding critical time for removing the fault is called the *critical clearing time* t_{cr}.δ_{cr} and t_{cr} can be calculated. Thus, from equation (2.15)

$$A_1 = \int_{\delta_1}^{\delta_{cr}} P_{mec}\,d\delta = P_{mec}(\delta_{cr} - \delta_1) \qquad (2.17)$$

Where δ_1 is the initial rotor angle. At this instance $P_e = 0$ and from equation (2.16)

$$A_2 = \int_{\delta_{cr}}^{\delta_{max}} (P_e - P_{mec})\, d\delta => \int_{\delta_{cr}}^{\delta_{max}} (P_{max} \sin\delta - P_{mec})\, d\delta \qquad (2.18)$$
$$=> A_2 = P_{max}(\cos\delta_{cr} - \cos\delta_{max}) - P_{mec}(\delta_{max} - \delta_{cr}) \qquad (2.19)$$

Equating the new expression for A_1 and A_2, that is equations (2.17) and (2.19), we can obtain the critical clearing angle as follows:

$$P_{mec}\delta_{cr} - P_{mec}\delta_1 = P_{max}\cos\delta_{cr} - P_{max}\cos\delta_{max} - P_{mec}\delta_{max} - P_{mec}\delta_{cr} \qquad (2.20)$$

$$\cos\delta_{cr} = -\frac{P_{mec}}{P_{max}}\delta_1 + \cos\delta_{max} + \frac{P_{mec}}{P_{max}}\delta_{max} \qquad (2.21)$$
$$\cos\delta_{cr} = \frac{P_{mec}}{P_{max}}(\delta_{max} - \delta_1) + \cos\delta_{max} \qquad (2.22)$$

But $\delta_{max} = \pi - \delta_1 (elec\ rad.)$ from figure 2.5 and $P_{mec} = P_{max}\sin\delta$, hence substituting these into equation (2.22) produces equation (2.23).

$$\cos\delta_{cr} = \sin\delta_1(\pi - 2\delta_1) + \cos(\pi - \delta_1) \qquad (2.23)$$

Recalling the trigonometry identity $\cos(\pi - x) = -\cos x$, equation (2.23) becomes

$$\delta_{cr} = \cos^{-1}[(\pi - 2\delta_1)\sin\delta_1 - \cos\delta_1] \qquad (2.24)$$

Substituting the value of δ_{cr} into equation (2.7) and setting $\delta_2 = \delta_{cr}$, t_{cr} becomes

$$t_{cr} = \sqrt{\frac{4H(\delta_{cr} - \delta_1)}{\omega_0 P_a}} \qquad (2.25)$$

We can solve for δ_0 from the pre-fault swing equation, (with 0 acceleration) according to equation (2.3) from where δ_{max} can be obtained.

$$\frac{2H}{\omega_0}\frac{d^2\delta}{dt^2} = P_{mec} - P_{max}sin\delta => 0 = P_{mec} - P_{max}sin\delta_0 \qquad (2.26)$$

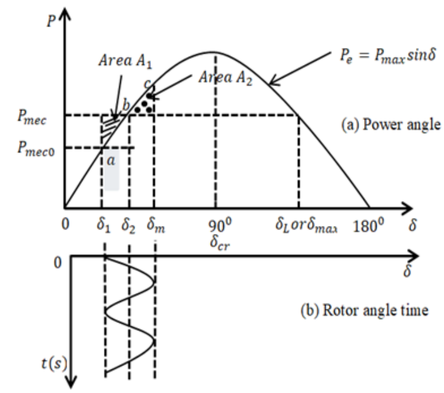


Figure 2.5: Equal area criteria illustration (Source: Adapted from [1]).

2.3 Transient Stability Analysis Method.

Broadly classified, there are two main classes of Transient Analysis method, visa vis Conventional and Non-Conventional method. The Time Domain simulation method forms the basis of conventional method while the Direct and the Automatic Learning method belong to the non-conventional method [10]. Due to the complex nature of power system network, accurate transient analysis of this system requires detailed modeling of each individual unit.

2.3.1 Time Domain Simulation Method (TDSM)

Time-Doman simulation is the most developed and currently the method that gives a close approximation of the characteristics of power system network under transient condition. This method involves the use of step-by-step numerical integration or differentiation approach, to determine system stability. Some of the common numerical integration technique used for system stability assessment include the Euler Method, Modified Euler Method (Predictor-Corrector Method), and the Runge-Kutta (R-K) Method. These methods are referred to as explicit method. The differential equations governing the behaviour of power system is a non-linear ordinary differential equation with known initial conditions or values as represented in equation (2.27).

$$\frac{dx}{dt} = f(x, t) \qquad (2.27)$$

Where $|x|$ the state is vector of n dependent variables and $|t|$ is the independent variable$(time)$. The objective here is to solve x as a function of t, with the initial values of $x\ and\ t$ equal to $x_0 and\ t_0$respectively [1]. This method is based on successive approximation of the slope of the tangent drawn at any point in the system curve or characteristics. For example, at $x = x_0, t = t_0$, we can approximate the curve representing the time solution by its tangent having a slope;

$$\frac{dx}{dt}|_{x=0} = f(x_0, t_0) \quad (2.28)$$

Therefore, $\Delta x = \frac{dx}{dt}|_{x=0} . \Delta t$ (2.29)

The value of x at $t = t_1 = t_0 + \Delta t$ is given by

$$x_1 = x_0 + \Delta x = x_0 + \frac{dx}{dt}|_{x=x_0} . \Delta t \quad (2.30)$$

In the same manner, the value of x_2 can be obtained as follows;

$$x_2 = x_1 + \frac{dx}{dt}|_{x=x_1} . \Delta t \quad (2.31)$$

Successive application of this technique results to various values of x corresponding to different values of t being computed. This is a first-order method because it considers only the first derivative. To achieve sufficient accuracy for each step Δt must be very small [27]. This increases round-off error, and the computational efforts required.

The modified Euler method was introduced to correct the over approximation inherent in Euler method. This is done by using the average of the derivatives at two points of reference. The operation is carried in two steps.

(a) The Predictor step,

$$x_1{}^p = x_0 + \frac{dx}{dt}|_{x=x_0} . \Delta t \quad (2.32)$$

Where $x_1{}^p$ is the value of x at predicted point.

(b) Corrector step,

$$x_1{}^c = x_0 + \frac{1}{2}(\frac{dx}{dt}|_{x=x_0} + \frac{dx}{dt}|_{x=x_1{}^p}) . \Delta t \quad (2.33)$$

Where $x_1{}^c$ is the corrected value of x obtained by taking average of the derivates at the beginning and at the end of the steps considered. This process can be repeated successively until a more accurate value with the desired accuracy is achieved [1]. The simplest Predictor-Corrector Method (PCM) is the modified Euler method. Other PCM include Adams-Bashforth method, Milne method and Hamming method [38]. Authors in [39], investigated the feasibility of this method in power system stability analysis and found out that it suffers from a number of limitations, which includes inability to self-start, use of large computer storage and less time steps, in comparison to other higher-order method such as (R-K) methods.

The R-K method, makes use of the Taylor series in its approximation, but does not require explicit evaluation of derivate higher than the first term [38]. The effect of higher derivatives is taken into consideration by repetitive evaluations of the first derivatives [1]. Depending on the number of terms effectively retained in the Taylor Series, there are several other higher order methods such as second-order R-K methods, fourth-order R-K method etc.[40]. For the explicit method, the value of the dependent variables x is evaluated from the knowledge of the previous state of x and the previous state of time step t. Despite its simplicity,it surfers from poor numerical stability [27]. Numerical stability is related to the stiffness of the set of differential equations governing the system [1], and the stiffness is associated with the range of time constants in the system model. Another time domain simulation method used for system stability analysis involves the use of implicit integration method. The simplest of this method is the trapezoidal rule which uses linear interpolation. Unlike the previous methods described, the trapezoidal rule is numerically A-stable (Asymptotically stable) [27]. The stiffness of the system

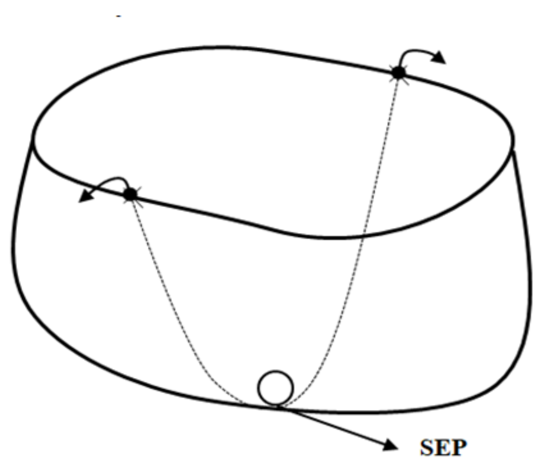


Figure 2.6: A ball rolling on the inner surface of a bowel (Source: adapted from [1])

Under equilibrium state, the ball is stationed at the bottom of the bowel; a condition referred to as Stable Equilibrium Point (SEP). It will remain in that state, until kinetic energy of a given magnitude and direction is injected into the system causing the ball to move up the bowel in the direction determined by the kinetic energy injected. Depending on the magnitude of the kinetic energy injected, the ball could rise and fall back to equilibrium point or escape the bowel through the rim to state of instability. The surface inside the bowel represents the Potential Energy Surface (PES), and the rim of the bowel represents the Potential Energy Boundary Surface (PEBS) [41]. With reference to power system, the application of Transient Energy Function (TEF) method to power system transient analysis is synonymous to that of a ball rolling in a bowel, briefly described above [1]. Prior to the presence of fault in the power system, it is operating at stable equilibrium point. When fault occur, the system gains kinetic energy which causes the synchronous machine to accelerate. While the fault persists, the power system gains kinetic energy and potential causing it to move away from SEP.

being analyzed affects accuracy but not numerical stability [1].

2.3.2 Direct Method (DM)

This method evaluates system stability without explicitly solving the system set of differential equations [1]. It uses transient energy for assessment of system transient stability. A more general Lyapunov's second method called the direct method uses the energy-based method. The transient energy method makes use of rolling ball analogy [15], for its implementation. As shown in figure 2.6, the area inside the bowel represents the region of stability and the area outside is the region of instability [1]. The bowel has irregular rim surface representing different heights.

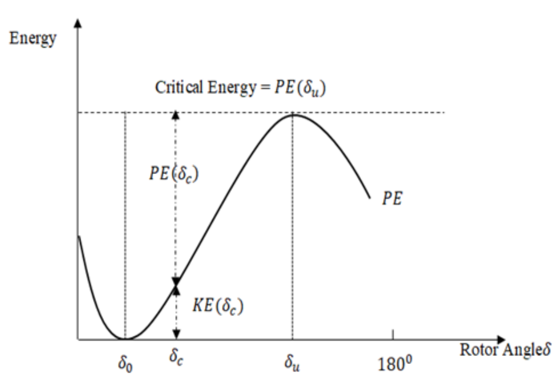


Figure 2.7: Energy angle relationship (Source: [1])

When the fault is cleared, the kinetic energy is converted into potential energy like in the case of rolling ball system. For stability, the criterion is that the system must be capable of absorbing the kinetic energy at a time when the forces on the generators tends to bring them toward a new equilibrium point [1]. This depends on the potential energy-absorbing capacity of the post-disturbance system. For a given post disturbance system, there is a maximum or critical amount of transient energy that the system can absorb. Thus, transient stability assessment requires two considerations.

(a) Functions that adequately describe the transient energy required for one or more machines to fall out of synchronism.
(b) A good estimation of the critical energy required for the machines to lose synchronism.

For a two-machine system, the critical energy is uniquely defined [1], and the TEF analysis is equivalent to the equal area criterion described in section 2.2.1. See figure (2.7) which shows a plot of transient energy to rotor angle (δ)[15]. Figure (2.7) can be used to specify the critical clearing angle in terms of potential and kinetic energy.

To determine stability, the sum of the kinetic energy and the potential energy gained by the system during fault at a given rotor angle, is compared to the critical potential energy$PE(\delta_u)$, equation (2.34).

$$PE(\delta_c) + KE(\delta_c) = PE(\delta_u) \qquad (2.34)$$

For a given disturbance, there is a stable equilibrium point for the post fault system. Figure (2.8) shows region of attraction for a given post fault condition / SEP. Any state of the system at fault clearing (x_{cl}) inside the region of attraction will eventually converge to SEP, thus the system is said to be stable. But if the state of the system at (x_{cl}) lies outside the region of attraction, the system is said to be unstable. The state of the system at fault clearing (x_{cl}) can be described by the value of the energy function evaluated at x_{cl} i e. $V(x_{cl})$. Hence the direct method solves the stability problem by comparing $V(x_{cl})$ to the critical energy V_{cr}. The system is stable if $V(x_{cl})$ is less than V_{cr} and the quantity $V_{cr} - V(x_{cl})$ is a good measure of the systems relative stability defined as the transient energy margin. The quantity $V(x_{cl})$ measures the amount of transient energy injected into the system by the fault while the critical energy measures the strength of the post fault system.

With reference to figure (2.8), if the rotor oscillates within the range δ_{u1} and δ_{u2}, the system will remain transiently stable. If it swings out of this region, instability sets in. Hence, the two points δ_{u1} and δ_{u2} on the potential energy curve form a boundary to all stable rotor angle trajectories. This boundary is called the PEBS and the points on the boundary are local potential energy peaks.

The boundary of the stability region is usually approximated locally by a constant energy surface $\{K = V(x)|_x\}$ as shown in figure (2.8), where K represents the critical energy V_{cr} of the post-fault system.

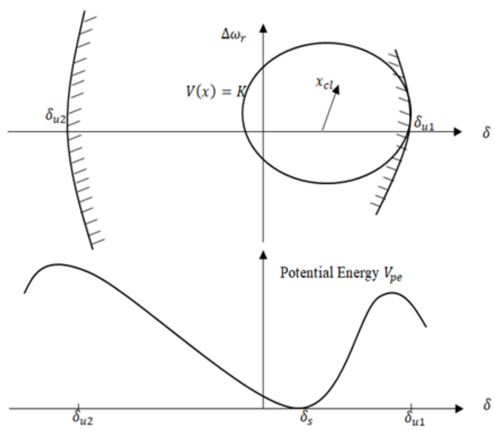


Figure 2.8: Region of stability and its local approximation (Source: [1]).

2.3.3 Automatic Learning Method (ALM)

This method deals with supervised learning only in which there exist three families; visa viz the Machine Learning (ML), the Decision Tree (DT), and the k-Nearest Neighbors (kNNs) and the Fuzzy DTs. The Statistical Pattern Recognition (SPR) is a form of machine method which is concerned with discovering patterns or making inference from perceptual data using statistical, probability and or computational geometry tools [42]. The interesting thing about all ALM is that they all aim at extracting the vital data imbedded in a learning set of pre-analyzed or pre-classified cases.

The DTs compress the extracted data into synthetic rules or models (e.g., for classification), while the kNNs learn in a case-by-case or stepwise fashion, aiming at figuring out similarities with the cases of the majority class of its k-nearest neighbors [10]. Figure (2.9) shows the general principle of ALM, identifying that the principles comprise of three sequential processes; two offline and one online.

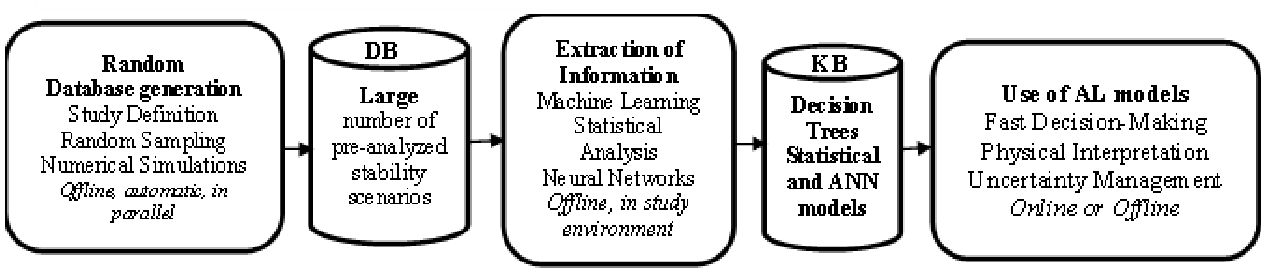


Figure 2.9: General principle of ALM for stability studies. (Source: adapted from [25])

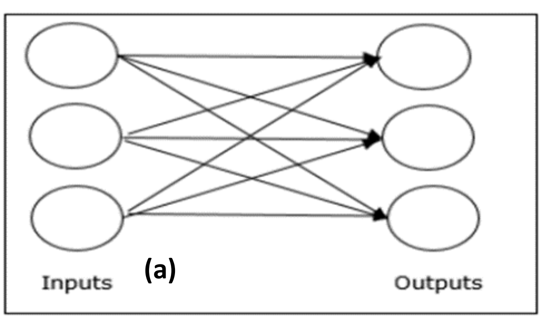
The life wire of ALM is database generation. This is basically the first step in the context of power system transient stability. The databases are states generated so as to cover all foreseen situations, using one or a few numbers of base cases and random though realistic variations of the parameters which are likely to influence the transient stability phenomena [10]. The stability of each one of these states with respect to a given disturbance is then assessed either in terms of margins e.g., stability limit –Critical Clearing Time (CCT) or Power Limit (PL), or simply as stable or unstable with respect to a selected criterion, previously determined from Time Domain Simulation (TDS) transient stability program simulations, with desired degree of accuracy and power system modeling details.

The data set generated and pre-analyzed are then sub-divided into two independent sets; visa vis, the Learning Set (LS) and the Test Set (TS). The first set is used to learn the rules of the selected ALM, while the second sets are used to assess their quality that is test and validation process [35].

Owing to the relative assets and weakness of individual ALM, hybrid approaches were adopted to take advantage of their merits while evading their drawbacks. Two of such hybridization includes DT-ANNs and DT-kNNs in which DTs were utilized for their unique interpretability characteristics, test attributes and information quality. The data provided by the TDs serves as input to the associated ALM which then generates a more accurate control margin. It is very vital to note that the quality of database data depends on the expertise of human elements associated with the power system under consideration and the transient behaviour of the system. Since the databases are generated offline, there exist more time to perfect the result. Also, the quality of resulting ALM strongly depends on the combined effort of the power system engineer and the ALM designer's expertise [10].

2.4 ANN Building Block

The operation of ANN depends on the network topology, adjustment of weights or learning and application of activation function [43]. Network topology is the arrangement of a network along with its nodes and connecting lines. Based on topology ANN can be classified into feed-forward network and feedback network. Feed-forward is a non-recurrent network having processing units/nodes in layer(s)with all the nodes in a layer connected to the nodes of the previous layer(s). The connection has different weights upon them and it does not have any feedback loop attached. Figure (2.10-a) shows a single layer feed-forward network while figure (2.10-b) shows multilayer feed-forward network. The concept of hidden layers is obtainable in multilayer networks.



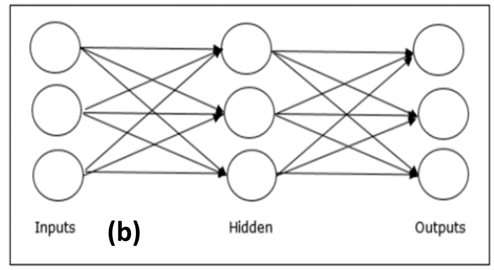
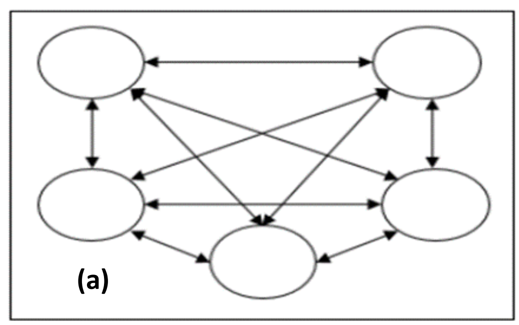


Figure 2.10: (a) Single layer feed-forward network (Source: [43])
(c) Multilayer layer feed-forward network (Source: [43])

The feedback network is a recurrent network with feedback loop attached. The action of the feedback mechanism makes it a non-linear dynamic system, which changes continuously until it reaches a state of equilibrium. The feedback network is divided into fully recurrent and Jordan network. The former is the simplest form in which all nodes are connected to each other with each node working as both input and output, while the latter is a closed loop network in which the output is fed back to the input as shown in figure 2.11-b. Figure 2.11-a illustrates a fully recurrent network.



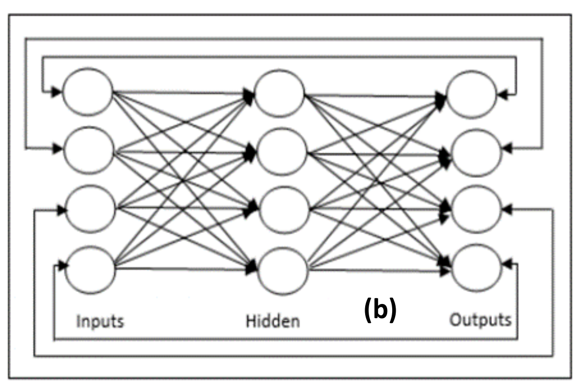


Figure 2.11: (a) Fully recurrent network (Source: [43])
(c) Jordan network (Source: [43])

III. MATERIALS AND METHOD

3.1 Material

The materials or software tools used include, Notepad++ for software code development and editing, Hypertext Markup Language (HTML), Cascaded Style Sheet (CSS) and JavaScript (JS) for graphical user interface design, Hypertext Pre-processor (PHP), for software logic and server-side/backend development, Supervisory Control and Data Acquisition – Phasor Measurement Unit (SCADA-PMU) software to transfer power system network state to the HTSAS solution, MATLAB, standard Universal Serial Bus cable (USB 2.0/3.0) cable for data communication and Personal Computer (PC) running Windows or Linux or Mac 64 bits operating system with 4 gigabit RAM, 250 gigabit hard disk, 2.0 GHz processor or above; to host and run the HTSAS.

3.2 Method

The method employed in this dissertation is structural design and algorithmic development.

3.3 Hybrid Transient Stability Analysis Solution (HTSAS) Structural Model

The primary aim of carrying out transient stability studies is to ascertain the robustness of a given power system network or device. However, this action is tied to effective control of the power system to ensure sustainability. The HTSAS proposed in this dissertation is a composite software solution which is designed to take advantage of the three major and fully developed transient stability analysis methods; visa viz Conventional Method, Direct Method and Automatic Learning Method.

Although there are still some research in-progresses in the area of ALM, to bring it up to industrially acceptable standard, it has developed to a fairly stable solution ready for adoption by the main stream power system utility players. In line with the current research in this area, this dissertation introduced HTSAS which is a common solution capable of hosting TDSM, DM, and ALM. This is intended to operate in two modes; the *Real-time-mode* and the *Education-mode*. When in Education mode, the individual module can be operated independently with data exchange initiation activated manually, but in the Real-time mode, all actions are automated and the computer or device hosting the HTSAS is connected to the live power system network through Supervisory Control and Data Acquisition (SCADA) system, with help of its Phasor Measurement Unit (PMU). When in Real-time mode, the network states, i.e., voltage and current distribution representing the pattern of system variation are feed into the solution through the data exchange interface and the system stability criteria such as critical clearing time, angle and maximum energy are computed and stored. The time-domain module and the direct method module simultaneously compute these criteria and store them in the database over a given period of time. The ALM module is designed to have automatic access to this database such that it can pull data set and utilize it for its operation. The judgment provided by the ALM module is coupled to the control unit for mitigation purposes.

At specific intervals which may be determined by frequency of network fluctuation, the TDSM, and DM module re-computes system stability criteria. The computed data is compared with data already stored in the database before storage system is initialized. If there exist data variation of up to 5% or more, the database content is refreshed and the ALM module initializes automatically to compute a new control state. This process is implemented so as to save time and storage space in the application and increase efficiency. Block diagram illustration of HTSAS is shown in figure (3.1).

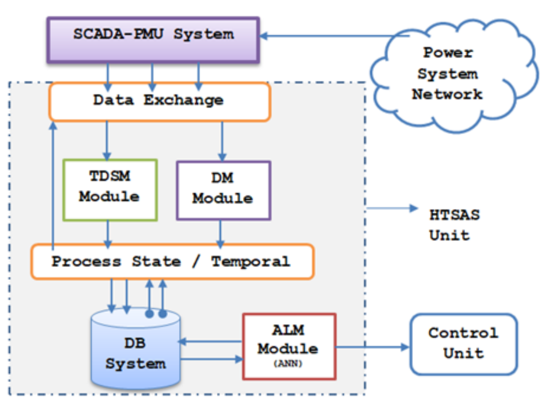


Figure 3.1: Hybrid Transient Stability Analysis Solution block diagram illustration.

3.4 Operation Principle

The HTSAS algorithm begins by reading system state from the SCADA-PMU output terminal or data file. This terminal acts as the input to the data exchange unit, the point at which the HTSAS initializes. The TDSM module which is the core of the application initializes simultaneously with the DM module, owing to the hybridization existing between DM and TDSM which has been fully developed, according to figure 3.4.

These modules compute the system stability criteria such as critical clearing time, maximum excursion angle, maximum power or energy deliverable at critical clearing time and store them in the software database alongside the system state responsible for them as at the time of computation. The storage is initiated if the database state differs from the incoming data sets by 5% or more and discarded if not. When the database state is not different from the incoming data sets by 5%, the application sends a refreshing command which instructs the program to go back and monitor the state of the input parameters at the data exchange unit.

Now the automatic learning method module, constantly monitors the state of the software database to readily generate control signal required to deactivate the faulted network or line, compensate or augment generation when necessary.

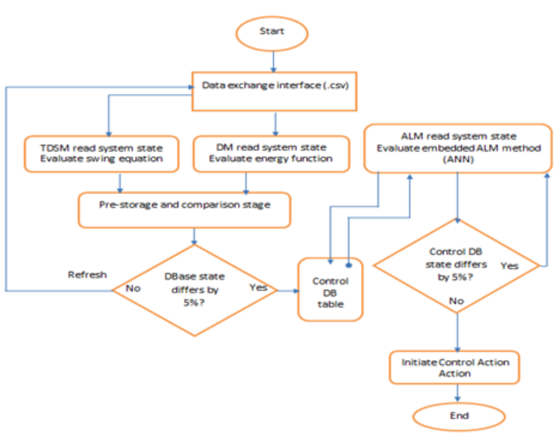


Figure 3.2: Hybrid Transient Stability Analysis Solution algorithm flow chart.

The ALM control module recalculates its control signal or pointer when the database state changes by 5% or more and so the process continues.

In summary as highlighted earlier, the HTSAS is meant to operate in two modes; the education mode and the real-time mode. This action can be adjusted in the settings file of the solution. When operating in education mode i.e., real-time off mode, the csv file generated by the SCADA-PMU system can be modified manually or with data randomizer developed for such purpose, and used as input to the HTSAS. Under this mode, students or research/design and development engineers can experiment with the solution observing various control actions initiated by the ALM module for various stability criteria generated as a result of randomized input variables. This is a vital tool for power system planning purposes.

When operating in the real-time mode, i.e., education off mode, the entire process from network state generation by the SCADA-PMU system through HTSAS initialization to control actions are all coordinated automatically. Once setup and powered-on, the system operates without human supervision.

3.5 Hybrid Transient Stability Analysis Mathematical model

From equation (2.1), the electrical power output of the alternators connected to the network P_e, can be represented in the vector form as follows:

$$\bar{P}_e = \frac{\bar{E}'\overline{Eb}}{\bar{X}_T} \sin\bar{\delta} = \bar{I}\bar{V}\sin\bar{\delta} => \bar{P}_e = P_{max}\sin\bar{\delta} \quad (3.1)$$

For a 3-phase system, equation (3.1) in matrix form is shown in equations (3.2) and (3.3).

$$\begin{bmatrix} P_{e11} & P_{e12} & P_{e13} \\ P_{e21} & P_{e22} & P_{e23} \\ P_{e31} & P_{e32} & P_{e33} \end{bmatrix} = \begin{bmatrix} I_{11} & I_{12} & I_{13} \\ I_{21} & I_{22} & I_{23} \\ I_{31} & I_{32} & I_{33} \end{bmatrix} \begin{bmatrix} V_{11} & V_{12} & V_{13} \\ V_{21} & V_{22} & V_{23} \\ V_{31} & V_{32} & V_{33} \end{bmatrix} \sin \begin{bmatrix} \delta_1 \\ \delta_2 \\ \delta_3 \end{bmatrix} \quad (3.2)$$

$$\bar{X}_T = \begin{bmatrix} x_{11} & x_{12} & x_{13} \\ x_{21} & x_{22} & x_{23} \\ x_{31} & x_{32} & x_{33} \end{bmatrix} \quad (3.3)$$

In terms of admittance

$$\bar{Y}_T = \begin{bmatrix} y_{11} & y_{12} & y_{13} \\ y_{21} & y_{22} & y_{23} \\ y_{31} & y_{32} & y_{33} \end{bmatrix} \quad (3.4)$$

$\bar{X}_T$ and $\bar{Y}_T$ are the transfer reactance and admittance between the synchronous machine and infinite bus respectively, and $\bar{I}\bar{V} = P_{max}$. From equation (2.11), which is the swing equation expressed in terms of the machine rotor angular speed, we obtain equation (3.5), which reduces to equation (3.6) when rotor speed synchronizes with the system reference speed at the chosen boundary conditions.

$$\frac{H}{\omega_0}\frac{d(\omega^2{}_r)}{dt}.dt = \int_{\delta_1}^{\delta_m}(P_{mec} - \bar{I}\bar{V}\sin\bar{\delta})\frac{d\delta}{dt}.dt \quad (3.5)$$

$$\int_{\delta_1}^{\delta_m}(P_{mec} - \bar{I}\bar{V}\sin\bar{\delta})d\delta = 0 \quad (3.6)$$

At the instance the rotor angle is at initial stage, $P_e = P_{max}\sin\bar{\delta} = \bar{I}\bar{V}\sin\bar{\delta} = 0$ thus from equation (2.17) under area 1,

$$A_1 = P_{mec}(\delta_{cr} - \delta_0) \quad (3.7)$$

The solution of critical clearing angle can be obtained from equation (2.24) restated here for clarity.

$$\delta_{cr} = \cos^{-1}[(\pi - 2\delta_0)\sin\delta_0 - \cos\delta_0] \quad (3.8)$$

The initial rotor angle δ_0 can be obtained from the pre-fault swing equation, (with 0 acceleration) according to equation (2.3), modified to obtain equation (3.9) from where δ_{max} can be calculated.

$$\frac{2H}{\omega_0}\frac{d^2\delta}{dt^2} = P_{mec} - P_{max}sin\delta => 0 = P_{mec} - \bar{I}\bar{V}sin\delta_0 \quad (3.9)$$

Or $$\delta_0 = \sin^{-1}\frac{P_{mec}}{\bar{I}\bar{V}} \quad (3.10)$$

$$\delta_{max} = \pi - \delta_0(elec\ rad.) \quad (3.11)$$

The critical clearing time can be computed using equation (2.25) restated here for clarity

$$t_{cr} = \sqrt{\frac{4H(\delta_{cr}-\delta_0)}{\omega_0 P_a}} \quad (3.12)$$

From these relations, the power angle relation of the network under consideration can be deduced and the power angle curve plotted, given voltage (V) and current (I) measured or obtained from network state through the SCADA-PMU or LVDAC-EMS.

In direct method, the system stability is accessed using the method of transient energy. Here, to determine stability, the sum of the kinetic energy and the potential energy gained by the system during fault, at any given rotor angle is compared to the critical potential energy $PE(\delta_u)$, see equation (2.34) restated here for clarity. That is

$$PE(\delta_c) + KE(\delta_c) = PE(\delta_u) \quad (3.13)$$

In simple terms, electrical energy is defined as the work done in an electric circuit. This is synonymous to the work done in moving one coulomb of charge within the circuit. Charged particles hold potential energy which is released when attractive or repulsive force is applied in the form of heat energy. Since movement of charge in electric circuit constitutes current, we can say that energy required to generate electric current is called electrical energy. Now for three phase star connected circuit, if (V) is the potential difference or pressure or attractive or repulsive force causing the current of (I) to flow when a charge (Q) is moved, work done becomes;

$$W = Q\sqrt{3}V \quad (3.14)$$

But $Q = it\ or\ I = Q/t$, therefore

$$W = \sqrt{3}VI\cos\theta.t = PE = \sqrt{3}VI\cos\theta.t(W - S\ or\ Joule) \quad (3.15)$$

Where $\cos\theta$ is power factor. The potential energy of the system at any point in time must equalize the injected kinetic energy due to fault for the system to maintain stability, thus critical clearing energies;

$$PE(\delta_{cr}) = KE(\delta_{cr}) \quad (3.16)$$

Or

$$KE(\delta_{cr}) = \sqrt{3}VI\cos\theta.t_{cr}(\delta_{cr}) \quad (3.17)$$

In terms of power, work done per unit time or 1 joule of energy expended per unit time is defined as power. From equation (3.15), it follows that;

$$\frac{W}{t} = \frac{E}{t} = \sqrt{3}VI\cos\theta = P \quad (3.18)$$

Or

$$E = Pt \quad (3.19)$$

Where *E* is the energy expended and the *P* is the power consumed in *t* time.

With stator resistance neglected, air-gap power is same as the terminal power. That is $P_{mec} = P_e = \bar{I}\bar{V}\sin\bar{\delta}$. Hence, expressing the terminal power in terms of energy potential of the system, we have;

$$E = P_e t = \bar{I}\bar{V}\sin\bar{\delta}.t \quad (3.20)$$

From where the transient time can be computed as shown in equation (3.21)

$$t = \frac{\overline{IV}\sin\overline{\delta}}{P_e} \qquad (3.21)$$

The rotor speed change $\Delta\omega_r = \frac{\partial\delta}{\partial t}$ can be obtained from equation (3.22)

$$\Delta\omega_r = \frac{\partial\delta}{\partial(IVsin\delta)/P_e}, => \omega_r = \int\left(\frac{(P_{mec}-P_e)\omega_0}{IVsin\delta}\right).d\delta \qquad (3.22)$$

This is synonymous to equation (2.3), after simplification, restated here for clarity; a variant of the swing equation.

$$d(\delta^2{}_r) = \int_{\delta_1}^{\delta_m}\left(\frac{(P_{mec}-P_e).\omega_0}{2H}\right)d\delta \qquad (3.23)$$

$\frac{\omega_0}{IVsin\delta} = \frac{\omega_0}{2H} = costant,$ a measure of the inertia constant of the alternator given in megawatts-seconds per megavolt ampere.

We can solve for δ_0 from the pre-fault swing equation, (with 0 acceleration) according to equation (2.3) from where δ_{max} can be obtained.

$$\frac{2H}{\omega_0}(\delta^2{}_r) = \int_{\delta_1}^{\delta_m}(P_{mec} - P_{max}sin\delta)d\delta =>$$

$$0 = P_{mec} - P_{max}sin\delta_0 \qquad (3.24)$$

This HTSAS model analysis represents a new approach to power system transient stability analysis mathematical modeling in which time domain simulation and direct method is incorporated. The method also eliminated the vague introduced by the term "*construction of good Lyapunov's energy function*". In order words, it simplified the process of energy function determination and extended it to compute the transient time which readily produces the rotor angle-time response characteristics.

The HTSAS module also incorporates the ANN model described in section 3.6 to perform discrimination function which enable it initiate control action in event of fault.

3.6 Artificial Neural Network Model

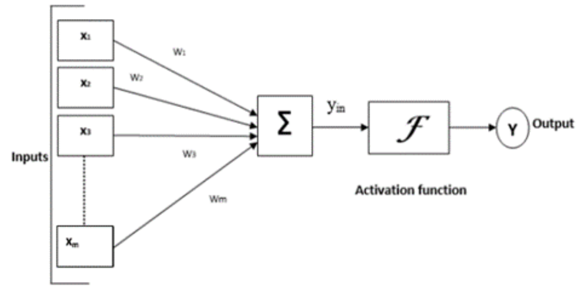


Figure 3.3: General model of Artificial Neural Network (Source: [43], [45]).

The net input for the general ANN model of figure (3.3), can be calculated as follows;

$$y_{in} = x_1.w_1 + x_2.w_2 + x_3.w_3 + \cdots + x_m.w_m \qquad (3.25)$$

$$y_{in} = \sum_i^m x_i w_i \qquad (3.26)$$

Where y_{in} is set of effective or net input parameter, $x_i..x_m$ are sets of input vectors and w_i ... w_m are sets of weight parameter used for training the ANN or learning.

The output parameter (Y) can be calculated by applying the activation function over the net input parameter y_{in} as follows;

$$\boldsymbol{Y} = \boldsymbol{F}(y_{in}) \qquad (3.27)$$

IV. RESULT AND DISCUSSION

4.1: HTSAS Prototype Interface

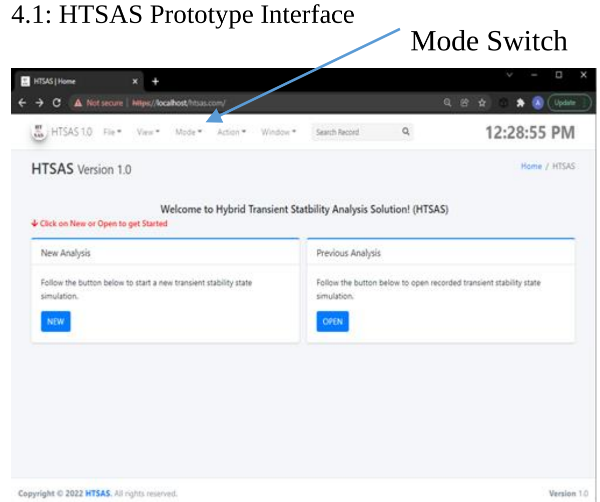


Figure 4.1: Hybrid transient stability analysis solution user interface.

The concept of HTSAS as illustrated in the prototype interface shown in figure 4.1 is simple and user friendly. When the application is opened, the *mode* switch menu as labeled in figure 4.1 is used to toggle the solution operation between *Real-Time-Mode* and *Education-Mode* as explained in section 3.4. When operating in Education mode, the New Analysis, Previous Analysis, as well as Run simulation and Graph plotting utilities under the action menu are activated or functional unlike when operating in Real-Time mode. Under Real-Time mode, all other features apart from mode switch menu are deactivated, while the solution performs synchronized operation utilizing the data found in the database.

4.2 Simulation Results

The developed model is tested on a 9-bus test system, Figure 4.2 (a), which is extracted from [44]. It represents three generators translating to forth (IV) order system, adapted for Nigerian 9-bus test system. Complete data is found in appendix I.

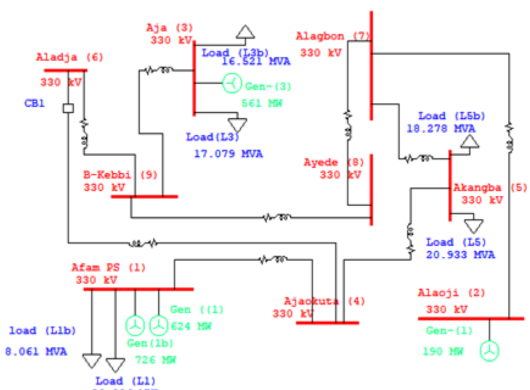


Figure 4.2(a): 9-bus Nigerian test Network

The time domain simulation method according to PSAT software routine potted to HTSAS application framework performs load flow of the network under steady state first before commencing the actual TDSM. The transient state of the network thereafter is initiated by calling differential and algebraic equation DAE.x(Syn.omega(2)) = 0.95, built in function and passing in the bus number whose speed is to be varied due to fault in the network. In this case, its generator at bus two (2) and the value of the machine speed under this condition is 0.95 per unit. This is about 5% reduction from the synchronous speed. See appendix II for results of the steady state power flow simulation.

Figures 4.2 to 4.5 show the network state under steady state.

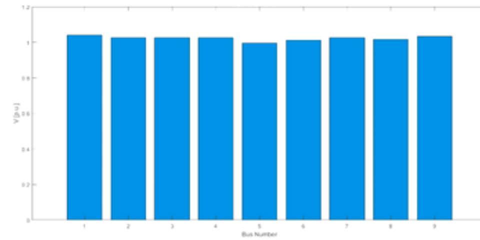


Figure 4.2(b): Voltage magnitude profile of 9-bus Nigerian power system network.

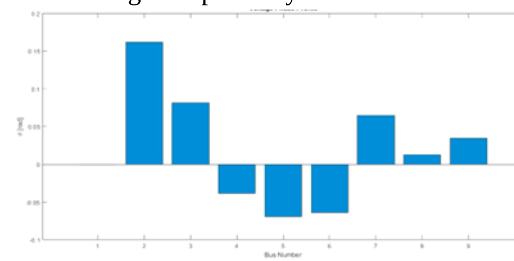


Figure 4.3: Voltage phase profile of 9-bus Nigerian power system network.

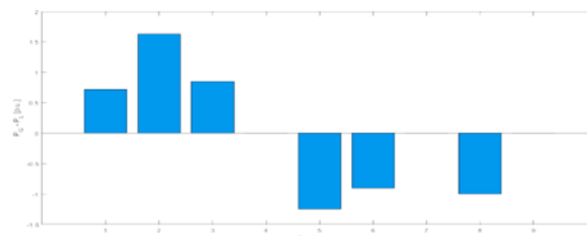


Figure 4.4: Real Power profile of 9-bus Nigerian power system network.

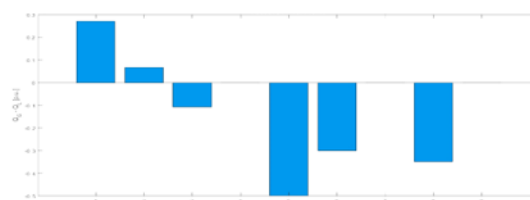


Figure 4.5: Reactive Power profile of 9-bus Nigerian power system network.

Now Applying fault(s) at bus <Alaoji(2)> when t = 1 s, clearing fault(s) at bus <Alaoji(2)> for t = 1.083 s and opening breaker at bus <Alaoji(2)> on line from <Alaoji(2)> to <Aladja(6)> for t = 1.083 s, the transient behaviour of the system is observed. The response time of the control system present in the network is 2.3179 s. The system's transient state is depicted in figures 4.6 and 4.7 in per unit system and with the actual speed of the test system which is 60H_z.

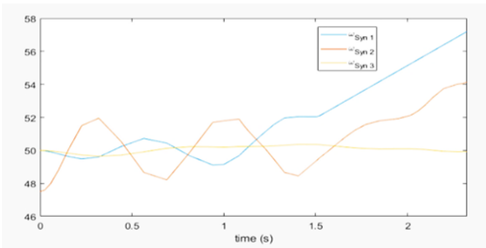


Figure 4.6: Speed-Time curve in per unit of 3 generators connected to the 9-bus Nigerian power system network.

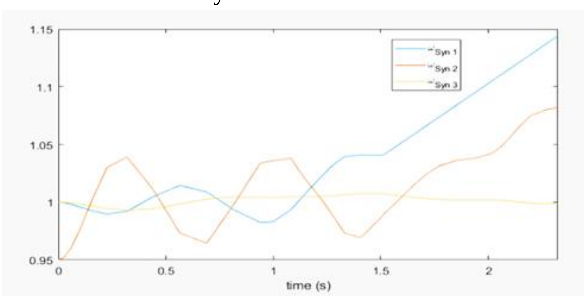


Figure 4.7: Actual Speed-Time curve of 3 generators connected to the 9-bus Nigerian power system network.

The direct method module of HTSAS uses a subroutine to obtain the root mean square value of the current and voltage inherent in the network and further compute the power distribution in the network according to equation (3.18). This value is multiplied with the simulation time stamp obtained from the measurement module to calculate the kinetic and the potential energy distribution of the network according to equation (3.19).

The computed network state energies are stored in the database for ANN reference purposes. The calculated sample network state potential and kinetic energy is shown in appendix IV. The sum of the kinetic energy of the network is always equal to the potential energy at any given time stamp.

Now the ANN module of the HTSAS, monitoring the state of the control database can make control decisions based on the energy function state of the network stored in the database by learning the pattern of network energy distribution overtime.

In real-time mode, the network state stored in the database is overwritten every cycle of measurement. These data are continually monitored by the ANN module of HTSAS to detect pattern changes. The last known control state stored by the HTSAS is maintained for mitigation purposes until the network state changes drastically. This action would result to network state pattern change and consequent re-calculation of the control state by the HTSAS.

We implemented 6 inputs, 10 hidden layers, one output layer ANN, shown in figure 4.8 and ran the generated network data from 3 phase transmission line MATLAB Simulink model, on it. The performance characteristics of the network, was plotted as shown in figure 4.9.

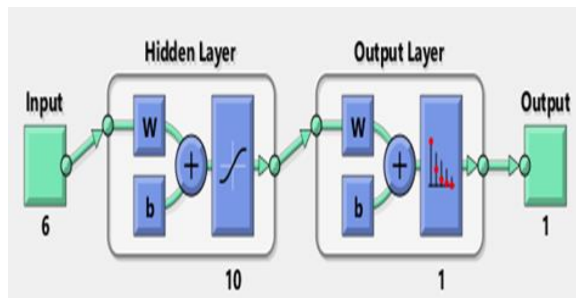


Figure 4.8: 6 inputs, 10 hidden layers, one output ANN model

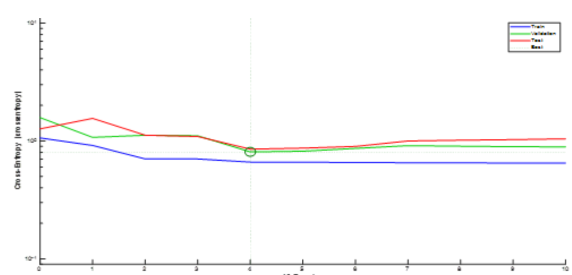


Figure 4.9: Performance characteristic of network of figure 4.8

The 6 inputs are made up of 3 components of the 3 phase current and the voltage obtained from the network, i.e. $I_a, I_b, I_c, V_a, V_b,$ and V_c. Due to slight variation between the training curve, the test and the validation curve of figure 4.11, we increased the complexity of the hidden network to 20 layers and applied the same dataset, figure 4.10. The performance of the network improved considerably as shown in performance curve of figure 4.11.

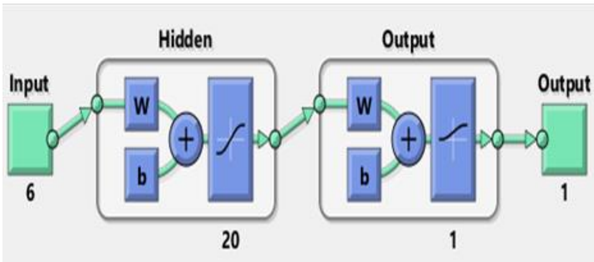


Figure 4.10: 6 inputs, 10 hidden layers, one output ANN model

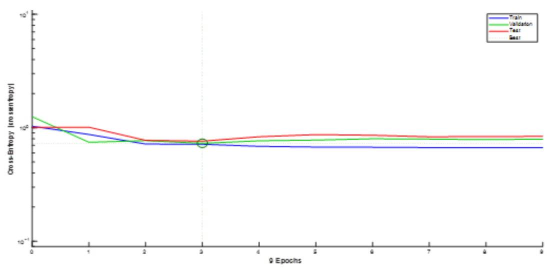


Figure 4.11: Performance characteristic of network of figure 4.10

This is a clear indication that the ANN module of HTSAS designed, learned the pattern of network variation and thus is capable of making informed decision when presented with similar network state variation without having to recomputed the entire network control state every time a change occur in the network.

To validate the HTSAS ANN software routine, Artificial Neural Network pattern recognition module of MATLAB, appendix (v) was used to simulate the same network state generated from the Simulink model and near similar result was obtained as illustrated in figure 4.12 but with slight iteration convergence difference.

Figure 4.12: Performance characteristic of network of figure 4.10 using MATLAB codes

CONCLUSION

The age-long power system network problem referred to as instability remained on the frontline of power system research to date. Over the years, various advances were made which gave insight into the nature and state of the power system network during its operation. The growing complexity of the power system network as world population surges, and new technology develops, made it apparent that monitoring and understanding the state of the network alone won't be enough. These led to the development of automatic controls or control mechanism. On this note, this research article examined the 3 standard method of power system stability evaluation and control mechanisms; TDSM, DM and ALM and came up with HTSAS. The model of HTSAS was clearly specified with real mathematics and a prototype implemented. This solution was based on the TDSM core with modified DM coupled to ANN model. The developed HTSAS offline mode operation was tested using data generated from transmission line modeled in MATLAB Simulink and the results presented and analyzed in section 4.2. Meanwhile the TDSM functionality was tested on a 9-bus Nigerian Network based on the traditional power system stability assessment model.

From the performance curve of HTSAS in comparison with the ANN model of MATLAB; it was noticed that the pattern recognition validation process completed faster in HTSAS, than in ANN-MATLAB module, corresponding to 3 epochs when compared to 4 epochs for the same data sample and same computer configuration. This could be due to the speed of the programming language used, (hypertext preprocessor). This language is known to run faster than the native C-language upon which ANN-MATLAB module is built.

5.1 Further Work

This dissertation presented a prototype software model of HTSAS which is not yet fully functional. It therefore suggests further work on the solution to standardize it into a stand-alone power system stability analysis application that is based on the language of the web or mobile device.

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Appendix I

```
Bus.con = [ ...
1 16.5 1 0 4 1;
2 18 1 0 5 1;
3 13.8 1 0 3 1;
4 330 1 0 2 1;
5 330 1 0 2 1;
6 330 1 0 2 1;
7 330 1 0 2 1;
8 330 1 0 2 1;
9 330 1 0 2 1;
];
%first two items represents from bus to bus
Line.con = [ ...
9 8 100 330 50 0 0 0.0119 0.1008 0.209 0 0 0 0 0 1;
7 8 100 330 50 0 0 0.0085 0.072 0.149 0 0 0 0 0 1;
9 6 100 330 50 0 0 0.039 0.17 0.358 0 0 0 0 0 1;
7 5 100 330 50 0 0 0.032 0.161 0.306 0 0 0 0 0 1;
5 4 100 330 50 0 0 0.01 0.085 0.176 0 0 0 0 0 1;
6 4 100 330 50 0 0 0.017 0.092 0.158 0 0 0 0 0 1;
2 7 100 18 50 0 0.07826087 0 0.0625 0 0 0 0 0 0 1;
3 9 100 13.8 50 0 0.06 0 0.0586 0 0 0 0 0 0 1;
1 4 100 16.5 50 0 0.07173913 0 0.0576 0 0 0 0 0 0 1;
];
% The first item represents line number and the second represents bus number
Breaker.con = [ ...
2 4 100 330 50 1 1.083 4 1 0;
];
% The first item represents bus number
Fault.con = [ ...
6 100 330 50 1 1.083 0 0.001;
];
SW.con = [ ...
1 100 16.5 1.04 0 99 -99 1.1 0.9 0.8 1 1 1;
];
PV.con = [ ...
2 100 18 1.63 1.025 99 -99 1.1 0.9 1 1;
3 100 13.8 0.85 1.025 99 -99 1.1 0.9 1 1;
];
PQ.con = [ ...
6 100 330 0.9 0.3 1.2 0.8 0 1;
8 100 330 1 0.35 1.2 0.8 0 1;
5 100 330 1.25 0.5 1.2 0.8 0 1;
];
Syn.con = [ ...
2 100 18 50 2 0.0521 0 0.8958 0.1198 0 6 0 0.8645 0.1969 0 0.535 0 12.8 0 0 0 1 1 0.002 0 0 1 1;
3 100 13.8 50 2 0.0742 0 1.3125 0.1813 0 5.89 0 1.2578 0.25 0 0.6 0 6.02 0 0 0 1 1 0.002 0 0 1 1;
1 100 16.5 50 2 0.0336 0 0.146 0.0608 0 8.96 0 0.0969 0.0969 0 0.31 0 47.28 0 0 0 1 1 0.002 0 0 1 1;
];
Bus.names = {...
 'AfamPS(1)'; 'Aja(3)'; 'Ajaokuta(4)'; 'Akangba(5)'; 'Aladja(6)';
 'Alagbon(7)'; 'Alaoji(2)'; 'Ayede(8)'; 'B-Kebbi(9)'};
```