PLACEMENT OF POWER SYSTEM STABILIZER (PSS) IN NIGERIA 28-BUS POWER NETWORK FOR EFFECTIVE VOLTAGE AND DYNAMIC STABILITIES EVALUATION

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ABSTRACT- Nigeria power network has been facing voltage, steady-state and transient stability problems with increasing load demand and high population growth. The major causes of power network instability include loading of the generators or tie line, power transfer capability of transmission lines, leading power factor operation of the generator and automatic voltage regulator (AVR) gain. The objectives of this work include overview analysis of the existing Nigeria 10 generators 330kV, 28-bus power network without introduction of PSS model and develop a workable power network that can provide dynamic and transient voltage control during placement of PSS model in order to enhance the totality of power network stability. The paper presents a cost-effective and satisfactory design of power system stabilizers (PSS) capable of solving problems of voltage, network oscillatory instability and damping for generator rotor oscillations. The designed PSS are incorporated into two generators, 3-bus and 10 generators, 28-bus, 330kV Nigeria power network using MATLAB/SIMULINK Power System Toolbox (PSAT) program to evaluate voltage and network instability problems. The dynamic or voltage collapse stability results obtained from PSAT load flow analysis revealed that the maximum loading points (MLP) for the network with and without PSS are 10.1501 pu and 4.5674 pu respectively.

KEYWORDS: Power System Stabilizers (PSS), Nigeria 28-bus power network, voltage problems, steady state problems, transient stability problems, instability problems, MATLAB/SIMULINK Power system Toolbox (PSAT) program, maximum loading point (MLP).

1 INTRODUCTION

The behavior of synchronous machines following perturbation lies at the heart of the stability challenge in the power system. After a change in power, machines should revert to their former condition if it doesn't alter. A new operational state is required whenever a change in load, generation, or network circumstances causes an imbalance between supply and demand. No matter what happens, if the system is stable, all linked synchronous machines should be functioning at the same pace, in parallel, and in synchronism [1,2]. Even though synchronous machines and tie lines tend to have stability issues, other types of power systems with large capacitances may also have instability. Arrangements must be taken to avoid damaging equipment and self-excitation of machinery by avoiding high voltages under light load situations. Modern synchronous generators require high-performance excitation systems in order to maintain steady-state and transient stability. Instabilities caused by power system disturbances can lead to system shutdowns. In the event of disruptions, such as three-phase faults, loss of generators, loss of lines, and loss of loads, stabilizing measures or controls must be implemented in the power network to optimize system performance. The energy supply sector has had its work cut out for it when it comes to stabilizing and improving power system oscillators. 330kV Nigeria 28-bus power network electromagnetic oscillation stability issues may be addressed using an effective power system stabilizer (PSS).

Low-frequency power system oscillations were among the first issues that arose in power systems. Small signal stability in a power system is compromised by these low frequency oscillations (LFOs), which jeopardize efforts to maximize power transmission and secure the power system. The stability issue was put on hold for a while after the damper windings on the generator rotors and turbines were confirmed to be adequate. A poor synchronizing torque among the generators was shown to be a substantial contributor to system instability as power systems were operated closer to their stability limitations. Improved steady-state stability was achieved by the use of automatic voltage regulators (AVR). Concerns about long-distance transmission lines emerged with the development of massive, interconnected power networks.

Low frequency oscillations can be reduced by adding a supplemental controller to the control loop, such as the addition of power system stabilizers (PSS) to the AVRs on generator. Designed for a certain network topology and steady-state circumstances, the power system stabilizers are excellent at their job. However, as the system grows more crowded, its performance suffers [3,4,5,6].

With the introduction of high-speed exciters and continuously-acting voltage regulators, the possibility to manage synchronous machine angular stability through the excitation system was discovered. Hydraulic and thermal equipment increasingly employ bus-fed static exciters with thyristor controllers. Because of improvements in thyristor controllers, they have a strong initial reaction and better dependability [7,8,9,10].

A power system analysis toolkit, MATLAB/SIMULINK, is used to model the voltage and dynamic stability of two generators, three-bus and ten generators, 28-bus 330kV Nigeria power networks (PSAT).

2. MATHEMATICAL ANALYSIS OF POWER SYSTEM STABILIZER (PSS)

The concepts of stabilization in the power network is described by a set of non-linear differential and algebraic equations as follows [4,5]:

$$PX = F(X, Z), \quad P = d/dt \quad s \qquad (1)$$

$$Y = H(X, Z) \qquad (2)$$

$$0 = G(Y, Z) \qquad (3)$$

The oscillatory instability can be viewed as stability of the operating point, subjected to small, random perturbations which are always present. The analysis can be performed by linearizing the system equations around the operating point ($X = X_0$, $Y = Y_0$, $Z = Z_0$). Where X are the state variables, Y represent active and reactive power injections (at buses), Z represent voltage magnitudes and angles at various buses.

Expressing

$$X = X_0 + \Delta X, \; Y = Y_0 + \Delta Y, \; Z = Z_0 + \Delta Z \qquad (4)$$

It is possible to obtain the following equation:

$$P\Delta X = [A]\Delta X \qquad (5)$$

Where

$$[A] = \left[\frac{\partial F}{\partial X} - \frac{\partial F}{\partial Z}\left(\frac{\partial G}{\partial Y}\frac{\partial H}{\partial Z} + \frac{\partial G}{\partial Z}\right)^{-1}\frac{\partial G}{\partial Y}\frac{\partial H}{\partial X}\right] \qquad (6)$$

The elements of A are functions of the operating point. The stability of the operating point can be judged by the location of the eigenvalues of the matrix A. If all the real points of the eigenvalues are negative, the system is stable. If one or more has positive real parts, then the system is unstable

Assuming that the classical model is used to represent the generators in a multi-machine system, the linearized system equations may be expressed as follows:

$$[M]\rho^2\Delta\delta = -[K]\Delta\delta \qquad (7)$$

Where [M] is diagonal matrix $M_{jj} = 2H_j / \omega B$ (H_j is the inertia constant of the jth synchronous machine). $K_{ij} = \frac{\partial P_{ei}}{\partial \partial_j}$, where P_{ei} is the power outputs of the ith machine, ∂_j is the rotor angle of jth machine referred to a rotating reference frame (with the operating speed ω_0). If the network can be reduced by retaining, only the internal buses of the generators and the losses in the reduced network can be neglected,

$$K_{ij} = \frac{E_iE_j}{X_{ij}}\cos(\partial_i - \partial_j) \bumpeq \frac{1}{X_{ij}} \qquad (8)$$

Where X_{ij} is the reactance of the element connecting the generator buses i and j; E_i and E_j are the generator voltages.

The solution of equation (7) is represented as

$$\Delta\delta^R = \sum_{j=1}^{m-1} V_j\left(C_j \cos\omega_j t + d_j \sin\omega_j t\right) \qquad (9)$$

Where $\Delta\delta^R = [\Delta\delta_{21}, \Delta\delta_{31}, \cdots, \Delta\delta_{m1},]^t$is the vector of relative angles ($\Delta\delta_{i1} = \Delta\delta_i - \Delta\delta_1$), $C_1, \ldots, C_{m-1}, d_1, d_2, \ldots, d_{m-1}$ are scalars depending on the initial conditions, V_1, V_{m-1} are vectors. The structure of a vector V_j depicts the participation of various machines in the oscillation mode whose frequency is ω_j. For a 'm' machine system, there are (m-1) oscillatory modes whose frequency varies in the range of 0.2 to 3Hz. The frequencies are obtained as square roots of the non-zero and real eigenvalues of the matrix$[M]^{-1}[K]$.

The various modes of oscillation are grouped into three broad categories [9] as follows:

- Power plants can operate in intra-plant modes, in which only the generators are involved. It is common for the oscillation frequencies to be rather high, ranging from 1.5 to 3.0Hz.
- Local modes, in which a number of generators in a given region collaborate. The oscillations occur at frequency ranging from 0.8 to 1.8 hertz (hertz).
- I Inter-area modes, in which generators located throughout a large geographic region participate. The oscillation frequencies are modest, ranging from 0.2 to 0.5 hertz (cycles per second).

3. DESIGN AND IMPLEMENTATION OF POWER SYSTEM STABILIZERS

In its most basic form, a power system stabilizer (PSS) is a device that dampens the oscillations of a generator rotor by managing the excitation of the generator with supplementary stabilizing signals. A component of electrical torque in phase with the rotor speed variations must be produced by the stabilizer in order for it to offer dampening. The PSS is intended to enhance the amount of power that can be sent through a network, which is currently restricted by oscillatory instability. When the network is subjected to major disruptions such as the development of a three-phase fault, the unexpected loss of a line, or the sudden application or removal of loads, the PSS must function effectively. The block diagram of the PSS design used in the power network is shown in figure1.

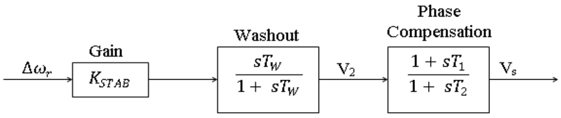


Fig. 1: Block diagram of power system stabilizer.

Power system stabilization is now presented using the thyristor excitation system, as seen in Fig 2, as a case study. The AVR and power system stabilizer are included in the excitation block diagram for correct modeling. In this study, small-signal performance, stabilizer and exciter output limitations, and other parameters, are taken into consideration. Here's a quick rundown of the criteria that go into creating different power system stabilizer setups.

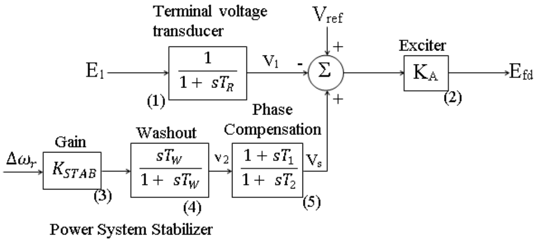


Fig. 2: Thyristor excitation system with AVR and PSS.

Phase correction, signal washout, and gain blocks make up the power system stabilizer seen in figure 2.

(i) For the exciter-to-generator electrical (air-gap) torque phase lag, the phase correction block gives the required phase lead characteristic. A single first-order block is shown in the diagram. It is possible to obtain the needed phase compensation by using two or more first-order blocks. Second-order blocks with complicated roots have been employed in several instances.

Phase correction for the Power System Stabilizer [3] is based on the following criteria:

a) The compensated phase lag (phase of P(s) = GEP(s)PSS(s)) should pass through 90° at frequency around 3.5Hz. For frequency input signal, this can be reduced to 2.0Hz.
b) The compensated phase lag at local mode frequency should be below 45°, preferably near 20°.
c) The gain of the compensator at high frequencies (this is proportional to $\frac{T_1T_3}{T_2T_4}$) should be minimized.

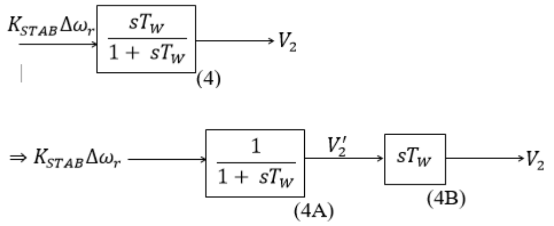
The first requirement must be met in order to avoid instability of intra-plant modes at higher frequencies in the future. Typically, the frequency range of interest is 0.1 to 2.0Hz, and the phase-lead network should offer compensation throughout the whole frequency range of interest.

(i) The signal washout block serves as a high-pass filter, with the time constant T_w high enough to allow signals associated with oscillations in w_r to pass unchanged. Washout it, steady changes in speed would modify the terminal voltage. It allows the PSS to respond only to changes in speed. The value of T_w is not crucial from the perspective of the washout function, and it can be anything between 1 and 20 seconds in duration. In particular, it must be long enough to allow stabilizing signals at the frequencies of interest to pass through intact, but not so long that it causes undesired generator voltage excursions during system-islanding situations.

(ii) The stabilizer gain, denoted by the letter KSTAB, regulates the amount of damping that is introduced by the PSS. (3) The gain is set to the value that corresponds to the greatest amount of dampening.

The power system stability should be considered when applying the PSS to the power network, rather than merely the small-signal stability, because the overall system stability should be improved [3].

Using perturbed values, block 4 of figure 2 is considered to be made up of two blocks:



In this case, $\Delta V_2'$ becomes the state variable, with

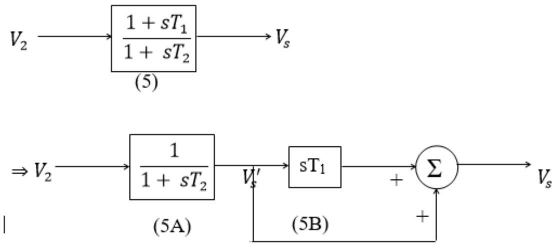
$$\rho\Delta V_2' = \frac{1}{T_W}(K_{STAB}\Delta\omega_r - \Delta V_2') \qquad (10)$$

and the output ΔV_2 of the block is given by

$$\Delta V_2 = T_W\,\rho\Delta V_2'$$

$$= K_{STAB}\Delta\omega_r - \Delta V_2' \qquad (11)$$

Similarly, block 5 of figure 2 is treated as follows:



In this case, V_s' is the state variable, with

$$\rho\Delta V_s' = \frac{1}{T_2}(\Delta V_2 - \Delta V_s') \qquad (12)$$

and the output ΔV_s is given by

$$\Delta V_s = T_1\rho\Delta V_s' + \Delta V_s' = \frac{T_1}{T_2}\Delta V_2 + \left(1 - \frac{T1}{T_2}\right)\Delta V_s' \quad (13)$$

The basis for the choice of the time constants of the phase compensator can be analysed with reference to the block diagram of the single machine system when PSS is added as shown in figure 3

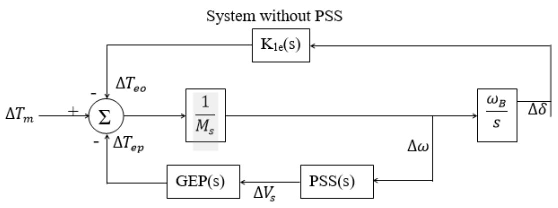


Fig. 3: Stabilizer with speed input: system block diagram.

To produce pure damping torque at all frequencies, the phase characteristics of the power system stabilizer (PSS) must, in the ideal case, balance the phase characteristics of the general purpose generator (GEP) at all frequencies. Specifically, the phase compensator used in this application is composed of two lead-lag states and has the following transfer function.

$$T(s) = \frac{K_s(1+sT_1)(1+sT_3)}{(1+sT_2)(1+sT_4)} \qquad (14)$$

Where K_s is the gain of the PSS and the time constants, T_1, to T_4 are chosen to provide a phase lead for the input signal in the range of frequencies of interest (0.1 to 3.0 Hz). With static exciters, only one lead-lag state may be adequate. In general, the phase compensator can be chosen with the following transfer function

$$T(s) = \frac{K_S N(s)}{D(s)} \qquad (15)$$

Where:

$N(s) = 1 + a_1 s + a_2 s^2 + \ldots + a_p s^p$

$D(s) = 1 + b_1 s + b_2 s^2 + \ldots + b_p s^p$

The zero of D(s) should lie in the left half plane. They can be complex or real. Some of the zeros of N(s) can lie in the right half plane making it a non-minimum phase. The time constants, T_1 to T_4 in equation (14) are to be chosen from the requirements of the phase compensation to achieve damping torque. The gain of PSS is to be chosen to provide adequate damping of all critical modes under various operating conditions.

The different values of the centre frequency, f_c the compensator of equation (14) are computed by

$$f_c = \frac{1}{2\pi}\frac{1}{\sqrt{T_1 T_2}} \qquad (16)$$

It is assumed that

$$\frac{T_1}{T_2} = \frac{T_3}{T_4} = n \qquad (17)$$

The plant transfer function, GEP(s) is computed by

$$\mathrm{GEP(s)} = \frac{\Delta T_e}{\Delta V_s}\Big|_{\Delta\omega=0} \qquad (18)$$

Where V_s is the output of the PSS

4. APPLICATION OF PSS TO NIGERIA POWER NETWORK

Power system stabilizer behavior is studied using the current 330kV, 28-bus, 10 generator Nigeria network. Niger's 28-node, 28-bus system has 10 generators and 18 load (PQ) buses; 16 transformers; 12,426MW grid capacity and 5,988km transmission lines as seen in fig 4. The lower reactance and smaller inertias between the two machines make it possible for the intra-plant oscillations to have a greater frequency since they are linked in parallel between the two producing stations in

Nigeria's 3-bus power network. Afam and Calabar are the locations of the two generators. At Alaoji bus 23, fig 5 shows the two generator buses connected to each other at Afam and Calabar buses 7 and 10 and the line linking bus-bars. There are two generators at Afam bus 7 and at Calabar 10, each with a producing capacity of 726 megawatts and 155 megawatts, respectively, and the transmission line distances between them and Alaoji bus 23 are 25 kilometers and 38 kilometers.

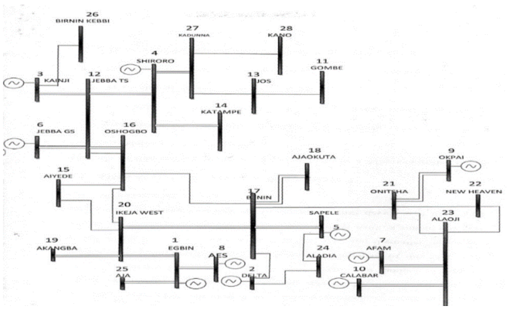


Figure 4: The existing 28 bus 330KV Nigerian transmission grid.

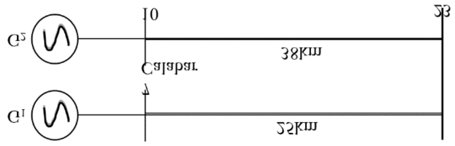


Fig. 5: Two generating stations, 3-bus power network.

The two generators located at Afam bus7 and Calabar bus 10 swing together during oscillation. A Power System Analysis Toolbox (PSAT) specialized tool in MATLAB environment is deployed for assessing the behavior of power system stabilizer of 2 generators 3-bus Nigeria power network. MATLAB/SIMULINK circuit designed using electrical blocks contained in the SIMULINK library for 2 generators 3-bus and 10 generators 28-bus Nigeria power networks connected with power system stabilizers are illustrated in figures 6 and 7 respectively.

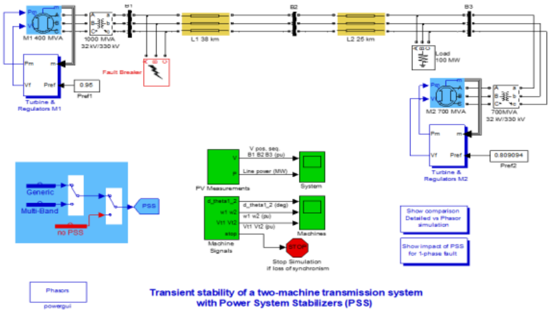


Fig. 6: Simulink block representation of two generators, 3- bus power network connected with power system stabilizer.

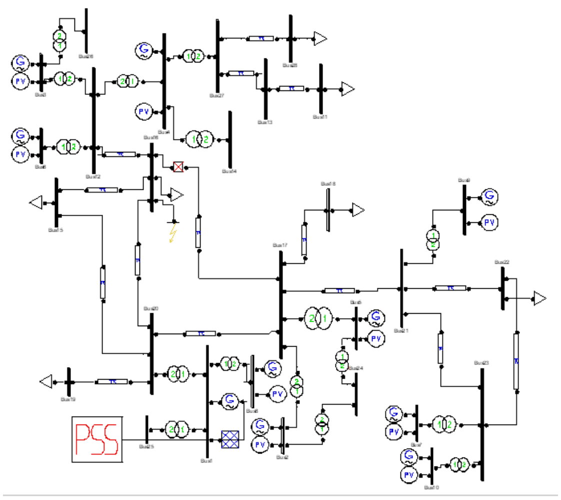


Fig. 7: MATLAB /SIMULINK circuit design for investigating voltage stability of 10 generators 28-bus Nigeria power network with PSS connected.

5. RESULTS AND DISCUSSION

Using two generators connected in a three-bus power network without a power system stabilizer, the transient behavior of line voltage (kV), line power (MW), angle (°), angular speed (ω), and reference voltage were demonstrated in Figures 8 and 9. The findings of the simulation for a two-generator, three-bus power network following the occurrence of a three-phase failure revealed that the network is unstable in the absence of the use of a power system stabilizer. When the PSS design is connected to the network, the line power settles after 2.5 seconds, the angle after 4 seconds, the angular speed after 3 seconds, and the terminal voltage after 2.5 seconds, as illustrated in figures 10 to 11, respectively.

The 10 generators 28-bus power network with PSS recorded 14 low and high voltage violations with total power loading and maximum power factor values of 6.5585pu and 10.1501pu, whereas when this power network was not connected to a PSS, all buses of the network recorded voltage violations with total power loading and maximum power factor values of 2.9501pu and 4.5674pu, as shown in table 1 and figures 12 to 15, respectively.

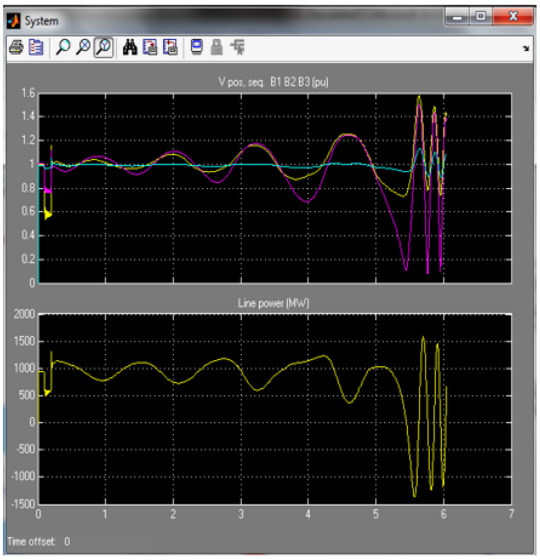


Fig. 8: line power and V_{pos} for two generators 3-bus power network without power system stabilizer.

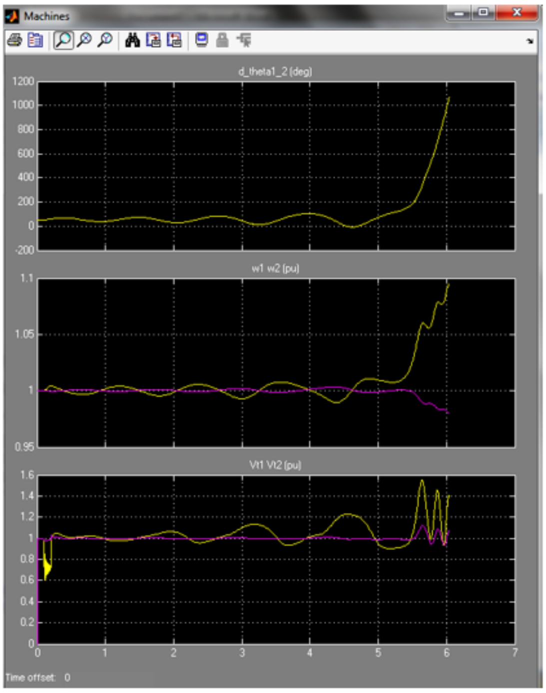


Fig. 9: Angle, angular speed and reference voltage for two generators 3-bus power network without power system stabilizer.

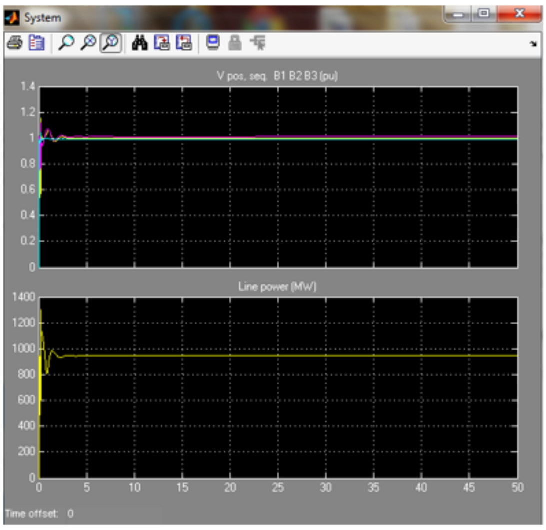


Fig.10: line power and V_{pos} for two generators 3-bus power network with power system stabilizer.

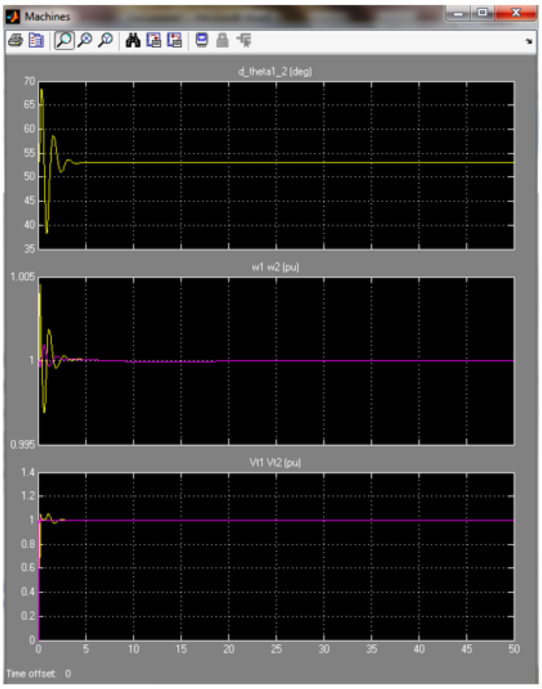


Fig. 11: Angle, angular speed and reference voltage for two generators 3-bus power network with power system stabilizer.

Table 1: PSS Stability analysis result for Nigeria 10 generators, 28-bus power network .

PSS Designed scheme	Voltage profile	Maximum loadability/collapse point(PU)	Total power loading(PU)
Without PSS	All buses violated	4.5674	2.9501

With PSS	14	10.1501	6.5585

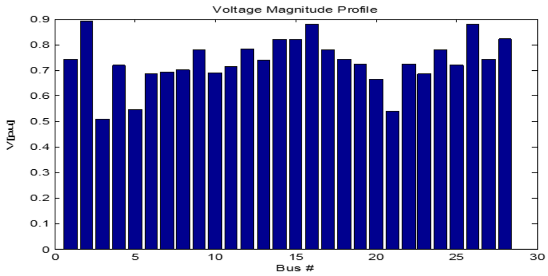


Fig. 12: Voltage profile for10 generators, 28-bus power network without PSS.

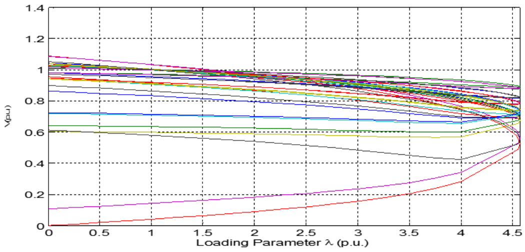


Fig. 13: P-V curve for 10 generators, 28-bus power network without PSS.

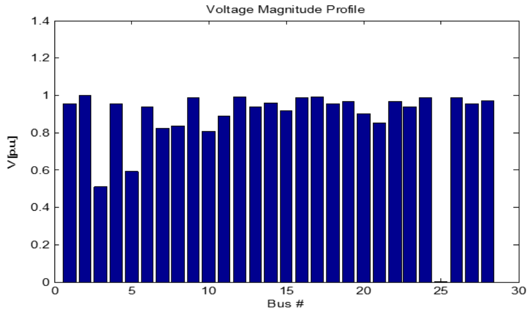


Fig. 14: Voltage profile for 10 generators, 28-bus power network with PSS.

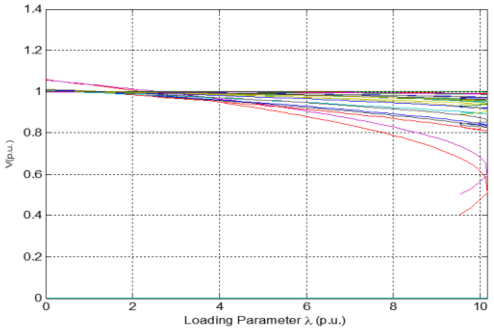


Fig. 15: P-V curve for 10 generators, 28-bus power network with PSS.

6. CONCLUSION

Modern synchronous generators require high performance excitation systems in order to regulate the terminal voltage quickly and ensure stable and transient stability. Two 3-bus and 10 generators, 28-bus 330kV Nigeria power network electromagnetic damped oscillation, or swing, of the rotor instability concerns following disturbances are tackled using MATLAB/SIMULINK Power System Analysis Toolbox to create and simulate effective power system stabilizer models (PSAT). Using power system stabilizers, the 3-bus Nigeria power network with two generators and a rotor angle of 4 seconds, angular speed of 3 seconds, and terminal voltage of 2.5 seconds all settled after 2.5 seconds. There were 14 voltage violations, 6.5585PU total power loading, and 10.1501PU maximum power factor in the 330kV Nigeria power network simulated with the power system stabilizer. Without the PSS, all buses had low and high voltage violations with total power loading points and maximum power factors of 2.9501PU and 4.5674PU, respectively.

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