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Optimal Location of Facts Controllers For Inter-Area oscillation Damping In Nigerian National Grid Using Minimum Singular Value Decomposition Method

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Abstract: This paper presents a novel method for optimal location of FACTS controllers in the multi-machine power system using Singular Value Decomposition (SVD) method. This research has developed sound analytical framework premised on systematic deployment of unified applications of residue and singular value decomposition techniques as well as eigenvalue and modal analyses to tackle the problem at hand. In order to evaluate the effectiveness of the proposed analytical tools, Kundur Two Area Network and the Nigerian National Grid Network has been selected as test bed systems. Of fundamental requirement in this research effort, are the developments of sufficiently detailed small signal models for the Nigerian interconnected multi-machine system and the Two-Area test system at their respective typical operating states. Both residues and Singular Value Decomposition techniques, that constitute integral parts of the analytical framework, have been applied to the linearized study system models to determine the best locations for FACTS devices as well as for the selections of most effective feedback signals.

I. INTRODUCTION

Inter-area oscillation is a phenomenon that is observed over a large part of the network. It involves two coherent group groups of generators swinging against each other at 1 Hz or less. This leads to large variations in tie-line power, under this condition it is somehow difficult to operate the system without adequate damping. Inter-area oscillation is a complex phenomenon that is influenced by non linear behavior of different components of power system. The damping characteristic of inter-area oscillations is influenced by the tie-line strength, the nature of the loads and the power flow through the interconnection and the interaction of loads with the dynamics of generators and their associated controls. [1]

The popular VSI types FACTS controllers are the static compensator (STATCOM), which is a shunt type controller, the static synchronous series compensator (SSSC), which is a series type and Unified Power Flow Controller (UPFC), which is a combined series-shunt type controller. The VSI type FACTS controller can internally generate both capacitive and inductive reactive power for transmission line compensation. The inverter, which is supported by a DC capacitor, can also exchange active power with the AC system in addition to the independently control reactive power. Because TCSC works through the transmission system directly, it is much more effective than the shunt FACTS devices in the application to power flow control and power system oscillation damping control. [2]

The SVD is typically used to determine the rank of a matrix, i.e. the maximum number of independent rows or columns, and it can be used as a measure of how close a matrix is to the set of singular matrices.

II. LITERATURE REVIEW

The location of these FACTS controllers has been an enormous challenge confronting the transmission utilities. Many research activities have been made on the optimal location of FACTS devices in order to improve the system dynamic behaviour and enhance its reliability. In reference [3], the author indicated that the effectiveness of the controls for different purposes mainly depends on the location of the control devices, this underscores the need for optimal placement. There are researches that optimally allocate FACTS devices for damping inter-area oscillations and stability enhancement by employing eigen-value analysis [4]. In references [3-4] the author introduced a modal analysis of the voltage stability which determines the placement of FACTS based on a participation parameter.

Furthermore several heuristic methods exist for optimal placement of FACTS Devices which include Genetic Algorithm [5], Particle Swarm Optimization [6], Simulated Annealing [7], and Gradient Descent Search [8].

Each one has its own merits and drawback. This research work will rely and improve on the earlier work [9] which considered the issues of location of FACTS devices in the Nigerian power system.

In recent years, the use of the UPFC for oscillation damping has received increased attention [10]. Several approaches have been adopted to the modeling and control of the UPFC. One of the most common approach is to model the UPFC as a power injection model. The power injection model neglects the dynamics of the UPFC and uses the UPFC active and reactive power injection as the control inputs into the power system [10]. This approach has the advantages of simplicity and computational efficiency since the fast dynamics of the UPFC are neglected.

Static interaction measures derived from decentralized control theory such as the relative gain array (RGA) and controllability and observability have been applied in determining both the best location and the best input signals for multiple FACTS devices [11]. Several papers also deal with the combined application of controllability and observability using the Singular Value Analysis [12], [13].

III. DESCRIPTION OF TEST SYSTEM

Figures 1 and 2 shows the single line diagram of the test systems used. Details of system data are given in [14]. The sub-transient models of the systems synchronous machines were used with the detailed dynamic model of other embedded system components.

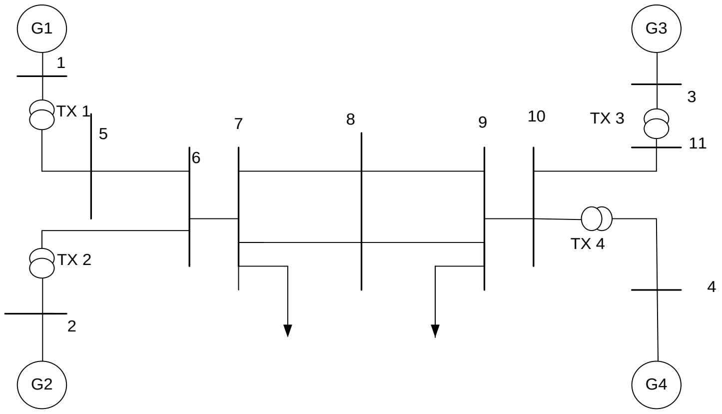

Figure 1: Kundur System

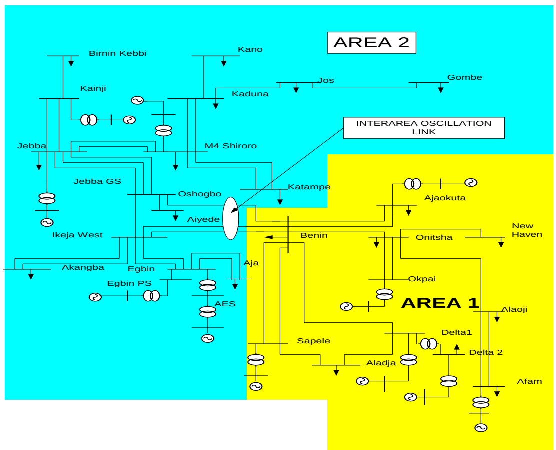

Figure 2: The Nigerian 39 Bus System

IV. PROBLEM STATEMENT

Analysis of local and inter-area oscillations requires detailed representation of the entire interconnected power system, models of excitation systems and loads, in particular, should be accurate, The problem at hand can be best described on the platform of multi-dimensional nonlinear differential algebraic equations (DAE) describing an interconnected power system with embedded FACTS devices controlled by PODs as well as excitation systems incorporating PSSs. The nonlinear vector dimensioned DAE can be cast as follows:

$$\dot{x} = F(x, y, \zeta, u) \quad (1)$$
$$0 = G(x, y, \zeta, u)$$

where x is n-vector state variables that adequately model the dynamics of all electrical machines along with their respective auxiliary control structures, FACTS devices, PODs and PSSs; y is m-vector non-state variables associated with network topology, load representations and distributed FACTS devices' models; ζ is a k-vector of load disturbances; and u is r-vector control inputs of PODs and PSS; and $F(.)$ and $G\,(.)$ are nonlinear mapping functions.

In order to tackle the problem of oscillations in interconnected power system, it is necessary to linearize equation (1) at different operating points to obtain the system A-matrix.

V. PROPOSED APPROACH

The equivalent circuits and the corresponding mathematical description for various FACTS devices considered herein are presented in Figure 3 [3]

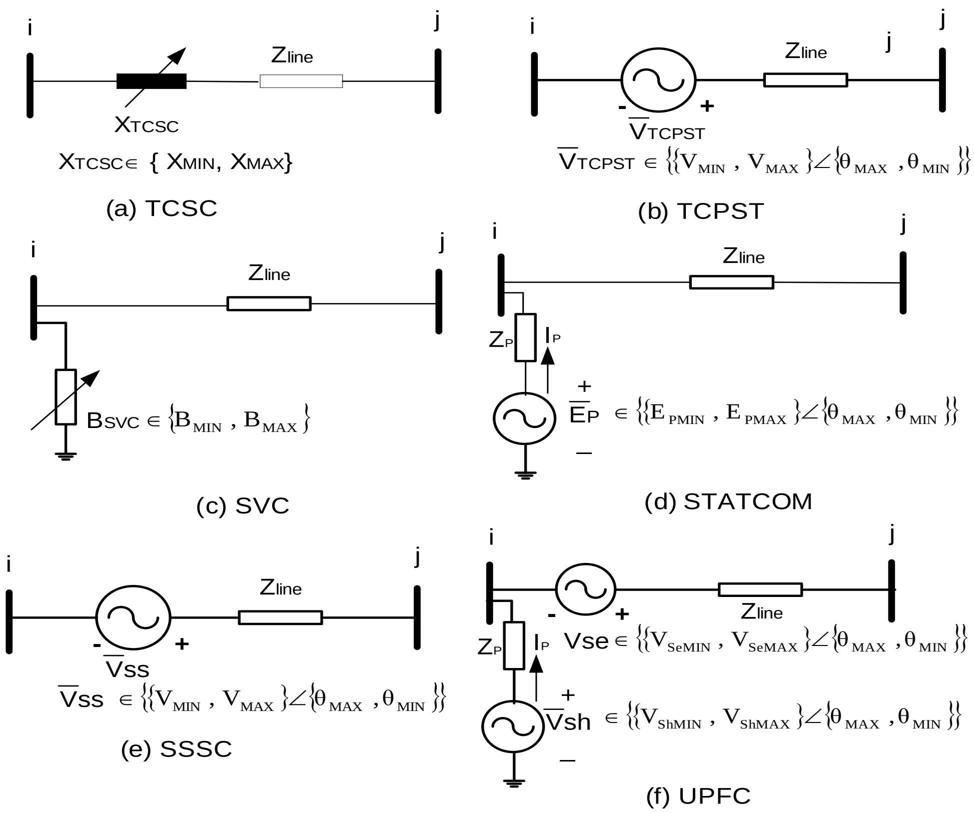

Figure 3: Equivalent Circuit of Various FACTS Devices

VI. SINGULAR VALUE DECOMPOSITION

A singular value and pair of singular vectors of a square or rectangular matrix Aare a nonnegative scalar σ and two nonzero vectors u and v so that

$$Av = \sigma u \quad (2)$$
$$A^H u = \sigma v \quad (3)$$

The superscript on A^H stands for Hermitian transpose and denotes the complex

conjugate transpose of a complex matrix.
Let $\lambda_1, \lambda_2 \ \lambda_3, \lambda_4 \dots \dots \lambda_n$ be the eigenvalues of a matrix A,
let $x_1 \, x_2 \, x_3 \dots \dots \dots x_n$ be a set of corresponding eigenvectors,
let Λ denote the n-by-n diagonal matrix with the λ_j.
on the diagonal, and let X denote the n-by-n matrix whose jth column is x_j . Then

$$\mathrm{AX} = \mathrm{X}\Lambda \qquad (4)$$

$$\mathrm{A} = \mathrm{X}\Lambda\mathrm{X}^{-1} \qquad (5)$$

with nonsingular X. This is known as the eigenvalue decomposition
Any m × n complex matrix can be factored as

$$A = U\Sigma V^H \qquad (6)$$

where U is an m×m unitary matrix whose columns are the eigenvectors of AA^H, V is an n×n unitary matrix whose columns are the eigenvectors of $A^H A$, and Σ is an m×n diagonal matrix of the same size as A that is zero except possibly on its main diagonal. with values $\sigma_1 \geq \sigma_2 \geq \sigma_3 \dots \dots \dots \geq \sigma_r > 0$ and r = rank(A).
In the above, $\sigma_1, \dots \dots \dots \sigma_r$ are called the singular values of A.

An electric power system can be represented by a set of non-linear differential-algebraic equations (DAE), as follows [131]

$$\begin{aligned} \dot{x} &= f(x, y, u) \\ 0 &= g(x, y, u) \\ w &= h(x, y, u) \end{aligned} \qquad (7)$$

Linearizing equation (7) at an equilibrium point yields equation (8)

$$\begin{bmatrix} \Delta\dot{x} \\ 0 \\ \Delta w \end{bmatrix} = \begin{bmatrix} F_x & F_y & F_u \\ G_x & G_y & G_u \\ H_x & H_y & H_u \end{bmatrix} \begin{bmatrix} \Delta x \\ \Delta y \\ \Delta u \end{bmatrix} \qquad (8)$$

$F_x = \nabla_x^F f$, $F_y = \nabla_y^F f$, $F_u = \nabla_u^F f$, $G_x = \nabla_x^G g$, $G_y = \nabla_y^G g$, $G_u = \nabla_u^G g$, $H_x = \nabla_x^H h$, $H_y = \nabla_y^H h$, $H_u = \nabla_u^H h$

Eliminating Δy , and assuming that power flow Jacobian G_y is non-singular (i.e. the system does not show a singularity induced bifurcation), the state matrix A ($A \in \mathcal{R}^{nxn}$) of the system is given by $A = F_x - F_y G_y^{-1} G_x$ and the state space representation of equation (8) is

$$\begin{aligned} \Delta\dot{x} &= A\Delta x + B\Delta u \\ \Delta y &= C\Delta x + D\Delta u \end{aligned} \qquad (9)$$

The open loop transfer function of its single-input-single-output (SISO) is obtained by taking the Laplace transform of equation (9) as follows:

$$\begin{aligned} \Delta \mathrm{x}(\mathrm{s}) &= (\mathrm{sI} - \mathrm{A})^{-1}\mathrm{B}\Delta\mathrm{u}(\mathrm{s}) \\ \Delta\mathrm{y}(\mathrm{s}) &= \mathrm{C}\Delta\mathrm{x}(\mathrm{s}) \end{aligned} \qquad (10)$$

substituting for $\Delta x(s)$ and rearranging we have

$$G(s) = \frac{\Delta y(s)}{\Delta u(s)} = C(sI - A)^{-1}B = \mathrm{C}\Phi[\mathrm{sI} - \Lambda\,]^{-1} \qquad (11)$$

$$\Delta\boldsymbol{x}(s) = (s\boldsymbol{I} - \boldsymbol{A})^{-1}\boldsymbol{B}\Delta\boldsymbol{u}(s) \qquad (12)$$

generating a set of n simultaneous linear equations, where the matrix **B** is n x r. The m component system output vector $\Delta\boldsymbol{y}$(s) may be found by substituting this solution for $\Delta\boldsymbol{x}(s)$ in the output equation.

$$\Delta\boldsymbol{y}(s) = \boldsymbol{C}(s\boldsymbol{I} - \boldsymbol{A})^{-1}\boldsymbol{B}\Delta\boldsymbol{u}(s) \qquad (13)$$

rearranging the MIMO transfer function is obtained as:

$$\boldsymbol{G}(s) = \frac{\Delta\boldsymbol{y}(s)}{\Delta\boldsymbol{u}(s)} = \boldsymbol{C}(s\boldsymbol{I} - \boldsymbol{A})^{-1}\boldsymbol{B} \qquad (14)$$

For a system with r inputs: $\Delta u_1(s)$, $\Delta u_2(s)$ ………… $\Delta u_r(s)$ and outputs $\Delta y_1(s)$, $\Delta y_2(s)$, ………… $\Delta y_r(s)$. **G**(s) is a m x r matrix whose elements are individual scalar transfer functions relating a given component of the output $\Delta\boldsymbol{y}(s)$ to a component of the input $\Delta\boldsymbol{u}(s)$.
G(s) can be written as:

$$\boldsymbol{G}(s) = \begin{bmatrix} \Delta y_1(s) \\ \Delta y_2(s) \\ \vdots \\ \Delta y_m(s) \end{bmatrix} = \begin{bmatrix} G_{11} & G_{12} & \dots & G_{1r} \\ G_{21} & G_{22} & \dots & G_{2r} \\ & \vdots & & \\ G_{m1} & G_{m2} & \dots & G_{mr} \end{bmatrix} \begin{bmatrix} \Delta u_1(s) \\ \Delta u_2(s) \\ \vdots \\ \Delta u_r(s) \end{bmatrix} \quad (15)$$

To measure the controllability of the electromechanical mode by a given input the singular value decomposition (SVD) is employed in this study. It gives a very detailed description of how a matrix acts on the input vector at a particular frequency. Mathematically, if G is an m x n complex matrix then there exist unitary matrices U and V such that G can be written as [12]:

$$\boldsymbol{G}(s) = U\Sigma V^H \quad (16)$$

where

$$\Sigma = \begin{bmatrix} \Sigma_1 & 0 \\ 0 & 0 \end{bmatrix} \quad (17)$$

$$\Sigma_1 = \text{diag}(\sigma_1, \dots \dots \dots . \sigma_r) \text{ with } \sigma_1 \geq \cdots \geq \sigma_r \geq 0$$

$r = \min\{m, n\}$ and $\sigma_1, \dots \dots \dots . \sigma_r$ are the singular values of G

The minimum singular value σ_r represents the distance of matrix G from all the matrices with a rank of r-1. This property can be used to quantify modal controllability. In this study the matrix H can be written as $H = [h_1, h_2, h_3]$ where h_i is the column of matrix H corresponding to the i^{th} input. The minimum singular value σ_{min} of the matrix $[\lambda I - A \ \ h_i]$ indicates the capability of the i^{th} input to control the mode associated with the eigenvalue λ [13].

A system MIMO transfer function $\boldsymbol{G}(s)$ can be represented as:

$$\boldsymbol{G}(s) = U\Sigma V^H \quad (18)$$

U: is a n x n unitary matrix of output singular vectors, u_i

V: is a n x n unitary matrix of output singular vectors, v_i

Diagonal elements $\sigma_k \geq 0$ of Σ are the singular values of G, this is also obtainable from square root of eigenvalues of $G^H G$:

$$\sigma_i = \sqrt{\lambda_i : (G^H G)} \quad (19)$$

VII. RESULTS AND DISCUSSIONS

This session provides in-depth discussions of all the major results obtained. More specifically, the major results comprehensively discussed encompass the following methodologies evolved to obtain the most effective FACTS Device for damping power system oscillation using SVD:

6.1 Result of Modal Analysis of Test System 1

Figure 4 shows the compass plot of the right eigenvectors of the speed state components of the 4 generators in the system. The plot is an indicator of the machines oscillating coherently in an area for the selected poorly damped inter-area mode

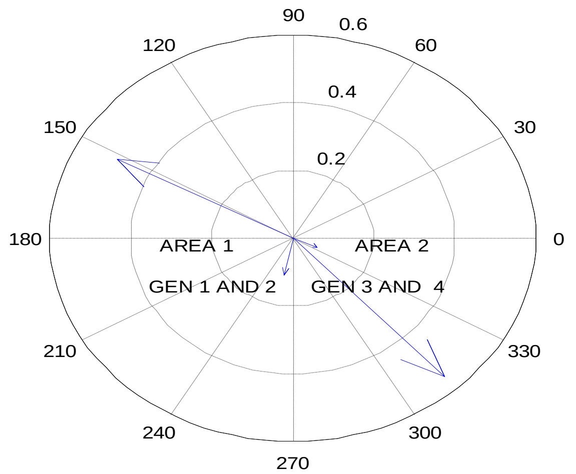

Figure 4: Mode Shape of Kundur two Area System

6.2 Result of Singular Value Decomposition for Kundur System

Figure 5 shows the maximum SVD to real power output. From this graph we concluded that UPFC is the most appropriate FACTS device that would guarantee maximum damping.

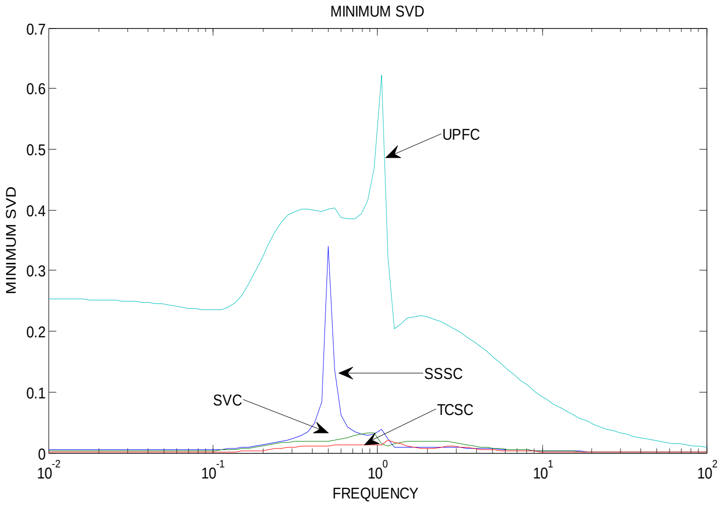

Figure 5: Maximum SVD to Real Power Output

6.3 Result of Modal Analysis of Nigerian System

Figure 6 shows the compass plot of the right eigenvectors of the speed state components of the 11 generators in the system the result shows the numbers of generators oscillating coherently in the two areas.

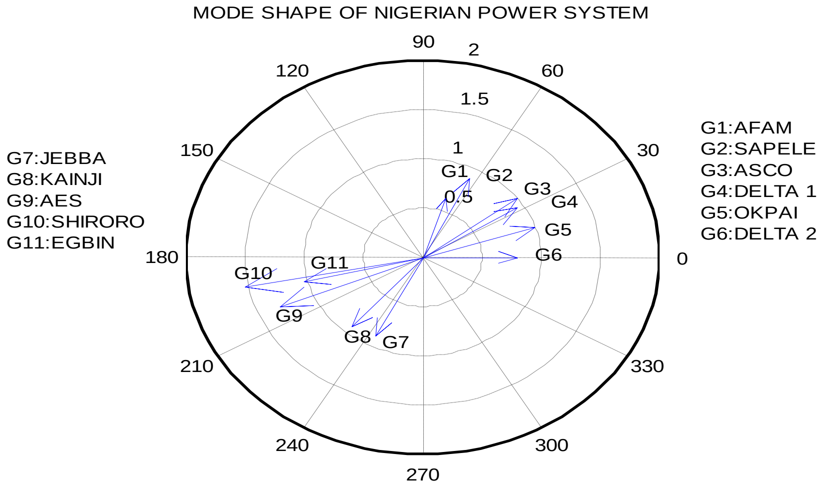

Figure 6: Mode shape of Nigerian Power System

6.4 Result of Singular Value Decomposition for Nigerian Syste

The minimum singular value decomposition for UPFC, SVC, TCSC, and SSSC are as plotted in Figures 7 and 8 for active power and reactive power feedback respectively the effectiveness of UPFC compared to other FACTS devices is revealed in the two Figures from the values of its Minimum Singular Values.

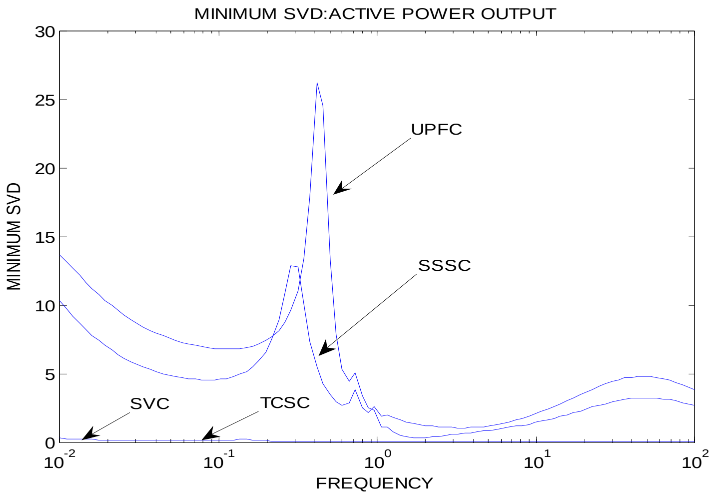

Figure 7: Minimum SVD for Active Power Feedback

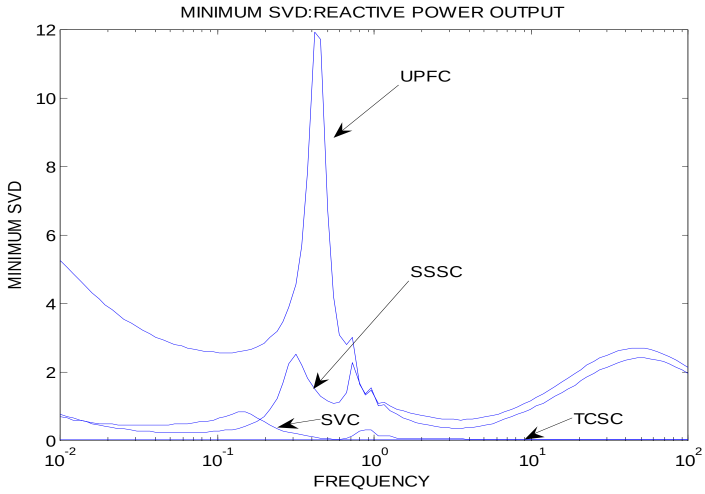

Figure 8: Minimum SVD for Reactive Power Feedback

VIII. CONCLUSION

In this work the generalized small signal model for the Nigerian national grid with embedded FACTS devices has been developed to constitute the main case study system and the method of modal analysis was deployed to determine the Generators oscillating coherently for the case study systems. The method of singular value decomposition was deployed to determine the best candidate among the popular FACTS devices for optimal damping of power system oscillations.

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