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Design of Power Oscillation Damper for UPFC Controllers Embeded in the Nigerian National Grid

Dr I. I. Alabi, Dr A. I. Araga, A.O. Anibasa
Department Of Electrical/Electronic Engineering, Nigerian Defence Academy, Kaduna, Nigeria

ABSTRACT: *An issue that is central to effective operation of power system is the damping of power system oscillations. This paper presents the design of Power Oscillation Damper for UPFC controllers embedded in a multi-machine system. This research has developed sound analytical framework premised on systematic deployment of Control System Toolbox and Power System Analysis Toolbox that both works in MATLAB environment. 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 importance in this research effort, is the far reaching insight provided by the results obtained.*

I. INTRODUCTION

A large scale power system can be viewed abstractly as comprising interconnections of several lower order sub-systems typified by geographically dispersed electrical generators, power transformers, transmission lines, substations, bus-bars, electrical loads, etc with high probability of discrete changes in interconnection pattern during operation. With attendant increasing complexity of integrated power system, a corresponding enhancement in its overall damping is desirable via network based control device options so as to achieve improvement in the quality of electric service delivery. The emerging FACTS devices constitute such network based control infrastructures that translate mainly into improved damping of any network initiated transient oscillations as well as increase in power transfer limits of the existing transmission lines. This research intends to design a Power Oscillation Damper that will be fitted to the UPFC Controller so as to improve the Damping capability of UPFC.

II. LITERATURE REVIEW

Electromechanical oscillations have been observed in many power systems [1]-[2].The oscillations may be local to a single generator or generator plant (local oscillations), or they may involve a number of generators widely separated geographically (inter-area oscillations). Electromechanical oscillations are generally studied by modal analysis of the linearized system model [1]. The most common control action to enhance damping of power system oscillations is the use of power system stabilizers (PSS). Although PSSs provide supplementary feedback stabilizing signals, they suffer a drawback of being liable to cause great variation in the voltage profile. Participation factors can be used to help determine whether a power system stabilizer (PSS) is needed to damp system oscillations. If the participation factors for many generators in an area are large, then a PSS placed in that area would dampen the oscillation of the system. However, if the participation factors for generators are negative, then adding a PSS would actually increase the oscillation [1]. A locally designed PSS normally fails to perform effectively during the inter-area oscillations. A carefully tuned PSS may also be effective in damping inter-area modes up to a certain transmission loading. The effectiveness in damping inter-area modes is limited because inter-area modes are not as highly controllable and observable in the generator's local signals as the local modes are [3]. Also, the number of dominant modes in the system is much larger than the number of the controlled devices available [4].

Recently, several FACTS devices have been implemented and installed in practical power systems the type of FACTS devices include static VAR compensator (SVC), thyristor controlled series capacitor (TCSC), and thyristor controlled phase shifter (TCPS) [4]. The emergence of FACTS devices and in particular gate turn-off (GTO) thyristor-based STATCOM has enabled such technology to be proposed as serious competitive alternatives to conventional SVC. Nowadays, series power electronics based controllers FACTS such as Static Synchronous Series Compensator (SSSC), have become one of the best alternatives means to damp power system oscillation [5].

From the power system dynamic stability viewpoint, the STATCOM provides better damping characteristics than the SVC as it is able to transiently exchange active power with the system [5]. A multivariable design of STATCOM AC and DC voltage control is presented in [6]. The coordination between the AC and DC voltage PI controllers was taken into consideration, however, the structural complexity of the presented multivariable PI controllers with different channels reduces their applicability. This seminar presents a comparative study of the effects of PSS and FACTS-based controllers, namely, Static Synchronous Series Compensator (SSSC), and static synchronous compensator (STATCOM) on power system electromechanical oscillations damping. Generally, the damping function of FACTS devices is performed mainly through the changes of the power delivered along the transmission line [7].

With appropriate lead-lag compensation from Power Oscillation Damper [9], the damping torque provided by FACTS damping control is proportional to the gain of the controller. Since FACTS devices are located in transmission systems, local input signals are always preferable. Residue method is an appropriate approach in finding the most proper local feedback signal in the controller design procedure. Moreover, it is also a simple and practical approach for designing of FACTS POD controllers [10]-[12].

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 [12-13]. The sub-transient models of the systems synchronous machines were used with the detailed dynamic model of other embedded system components.

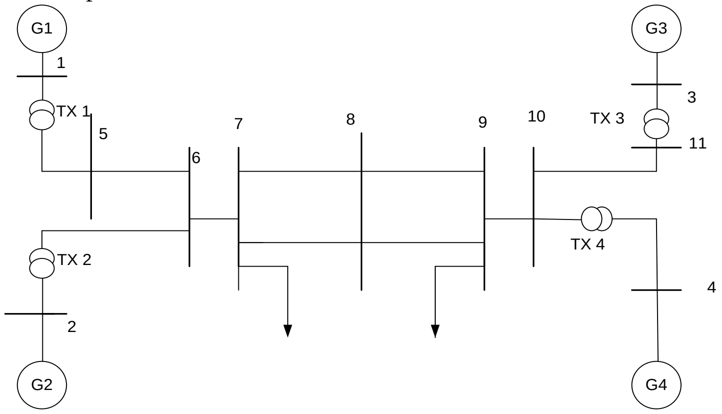

Figure 1: Kundur System

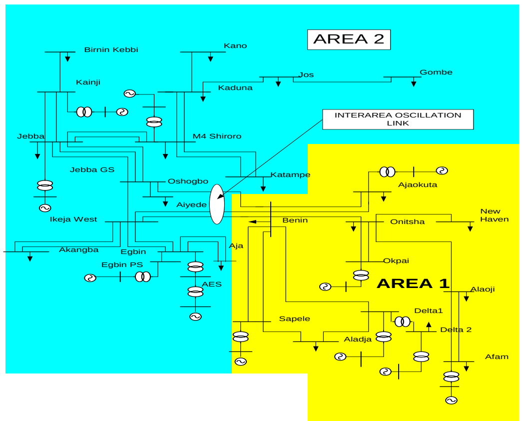

Figure 2: The Nigerian 39 Bus System

IV. PROBLEM STATEMENT

The continuous supply of electric energy is most essential for sustainable economic growth of any developing nation. Due to a combination of increasing energy consumption and various system conditions, the Nigerian Grid System electrical energy delivery to various consumers has been very unsatisfactory from technical viewpoint. The identified operational problems amongst others have motivated this research work to offer alternative solutions to mitigating them. The underlying generalized differential algebraic equations (DAE) that characterize such problems when linearized can be cast mathematically as follows [131]:

$$\begin{bmatrix}\Delta\dot{x}\\0\\\Delta w\end{bmatrix}=\begin{bmatrix}F_x & F_y & F_u\\G_x & G_y & G_u\\H_x & H_y & H_u\end{bmatrix}\begin{bmatrix}\Delta x\\\Delta y\\\Delta u\end{bmatrix} \qquad (1)$$

the state space representation of equation (1) is

$$\Delta\dot{x}=A\Delta x+B\Delta u \qquad (2)$$
$$\Delta w=C\Delta x+D\Delta u$$

The aim of this research is to develop generalized mathematical model for an interconnected power system equipped with distributed FACTS devices as prescribed in equation (1). Starting there from, investigate the effects of the various controllable parameters contributed by the embedded FACTS devices with respect to local, inter and intra area oscillations of the proposed Nigerian national grid and Kundur two area network models when excited by different disturbance scenarios.

V. PROPOSED APPROACH

Figure 3 shows a system G(s) equipped with a feedback control H(s). When applying the feedback control, eigenvalue of the initial system G(s) are changed. It is shown in [14] that when a feedback control is applied, the movement of an eigenvalue can be determined using equation (3).

$$\Delta\lambda_i=R_iH(\lambda_i) \qquad (3)$$

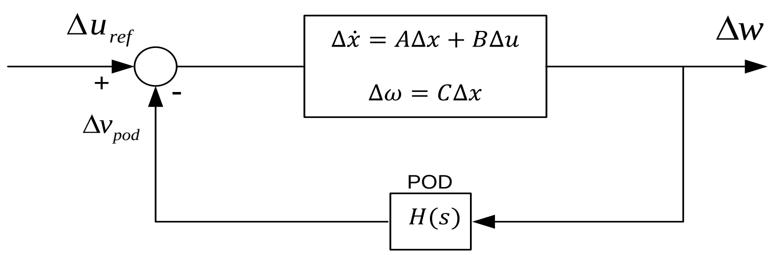

Figure 3: Typical Closed loop system

It can be observed from equation (3) that the shift of the eigenvalue caused by a controller is proportional to the magnitude of the residue. The change of eigenvalue must be directed towards the left half complex plane for optimal damping improvement.

In order to shift the real part of an eigenvalue to the left, FACTS device based POD controller is employed. The desired movement can be achieved with a transfer function consisting of an amplification block, a wash-out block and m_c stages of lead-lag blocks.

$$H(s)=K\frac{sT_w}{1+sT_w}\left[\frac{1+sT_{lead}}{1+sT_{lag}}\right]^2 \qquad (4)$$

Where K: is a positive constant gain. The washout time constant, T_w is typically selected between 5 and 10s [14].

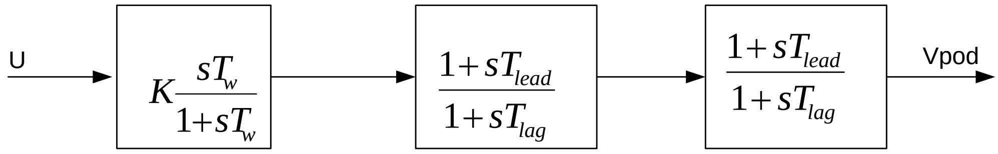

Figure 4: POD Block Diagram

The lead-lag parameters (T_{lead} & T_{lag}) can be determined using the following equations [70]:

$$\varphi_{comp}=180-\arg(R_i) \qquad (5)$$

$$\alpha_c=\frac{T_{lead}}{T_{lag}}=\frac{1-\sin\left(\frac{\varphi_{comp}}{2}\right)}{1+\sin\left(\frac{\varphi_{comp}}{2}\right)} \qquad (6)$$

$$T_{lag}=\frac{1}{\omega_i\sqrt{\alpha_c}} \quad \& \quad T_{lead}=\alpha_cT_{lag} \qquad (7)$$

where $arg(R_i)$ denotes phase angle of residue R_i; ω_i is the frequency of the mode of oscillation in rad/sec. The controller gain K is computed as a function of the desired eigenvalue location. The linearized power system dynamics can be represented by an open-loop transfer function $G(s)$, variable y is used by the POD controller as an input signal, variable u is where the control is fed back, as shown Figure 3. Since the FACTS devices are located in transmission systems, local input signals like power deviation, bus voltages or bus currents, are always preferable. As in case of choosing the feedback signal, the optimal siting of the FACTS device is also very important, since a larger residue results in a larger change of the corresponding oscillatory mode. The process of designing a POD is as follows:

The power flow problem has to be solved, then eigenvalues and the participation factors of the state matrix equation (2) are computed in order to identify the critical modes of the system. The next step consists in computing all output and input matrices (A,B,C and D). The input and output matrices of interest in this research are B matrices for all FACTS devices, and C matrices that have as outputs bus voltage magnitudes, bus voltage angles, line current flows, line active power flows, and line reactive power flows.

The Nyquist plots of the open loop transfer function $\Delta w(s)/\Delta u_{ref}(s)$ of Figure 3 is plotted, the choice available input signals to the POD $\Delta w(s)$ from the selected transmission line are:

i) Sending end real power
ii) Receiving end real power
iii) Sending end reactive power
iv) Receiving end reactive power
v) Sending end current
vi) Receiving end current

The choice with the maximum residue is selected as input to the POD. The variable ω_n which indicates the critical frequency of the applied input signal $\Delta u_{ref}(s)$ is identified. The necessary phase compensation φ, required by the POD to obtain a good phase margin, can be determined based on the critical frequency ω_n. The polar plot encircling the point should be approximately symmetrical with respect to the real axis to yield a good PM [15]. Having determined φ, the parameters of the phase compensator blocks would be obtained using equations (5) to (6). The POD gain K has to be determined in order to provide the desired damping for the closed-loop system.

VI. 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 design Power Oscillation Damper for UPFC: The reports of simulations carried out are also reported herein for the two Test Systems..

Results of POD Design for Kundur Two Area System

The POD controller is designed using the frequency response method through Nyquist plots of a given OLTF. Then, the Nyquist analysis was performed after selecting the POD input parameter with the largest residue $\frac{\Delta P_r}{\Delta v_{pod}}$ as shown in Table 1. The Nyquist plot is shown in Figure 5.

Table 1: Table of Transfer Functions and their Residues

Transfer Functions	Residues
$\frac{\Delta P_r}{\Delta v_{pod}}$	0.2800 - 0.4003i
$\frac{\Delta Q_r}{\Delta v_{pod}}$	0.1055 - 0.3625i
$\frac{\Delta I_r}{\Delta v_{pod}}$	0.0128 – 0.0341i
$\frac{\Delta P_s}{\Delta v_{pod}}$	0.0148 - 0.0357i
$\frac{\Delta Q_s}{\Delta v_{pod}}$	0.0156 – 0.0224i
$\frac{\Delta I_r}{\Delta v_{pod}}$	0.0116 – 0.0326i

The lead and Lag time constants obtained from the procedures of equation (5) to (7) are 0.1861 and 0.3721 respectively.

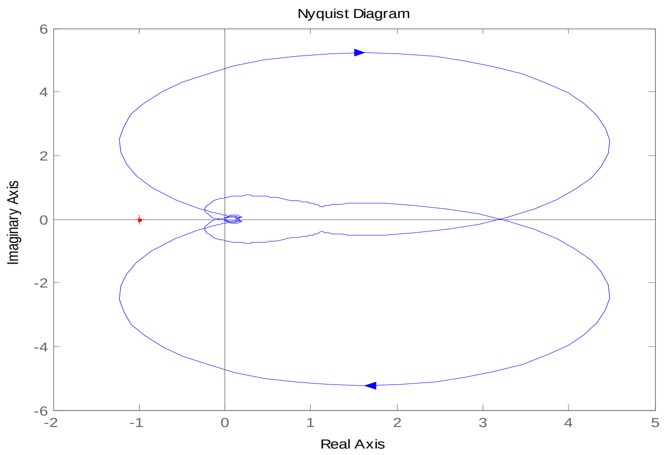

Figure 5: Nyquist Plot of the Open Loop Transfer Function

The last step of the procedure of POD Design consists in defining the POD gain K_{ω} by launching the root-locus editor of the MATLAB Control System Toolbox and by dragging the critical mode to the desired damping as illustrated in Figure 6, the POD gain is 1.94 and the damping ratio under this condition is 33.9%.

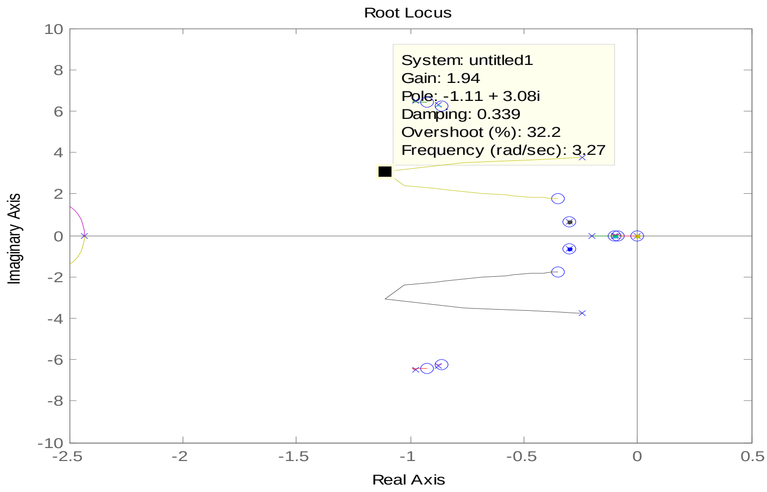

Figure 6: Root Locus of the Selected Eigenvalue

Results of Dynamic Simulation for Kundur two area system

Figures 7 and 8 shows the result of dynamic simulation with three phase fault on Bus 11 for 0.05 sec. The power flow on Bus 7 to Bus 8 and Bus 1 to Bus 5 were monitored. Bus 7 to Bus 8 is a tie line while Bus 1 to Bus 5 is a line localized in area 1.

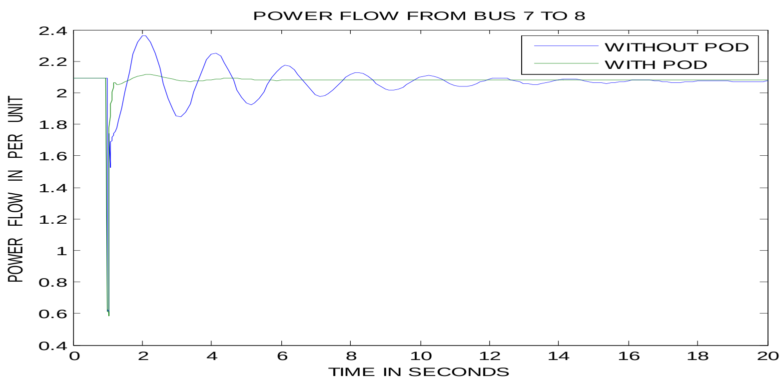

Figure 7: Power Flow from Bus 7 to Bus 8

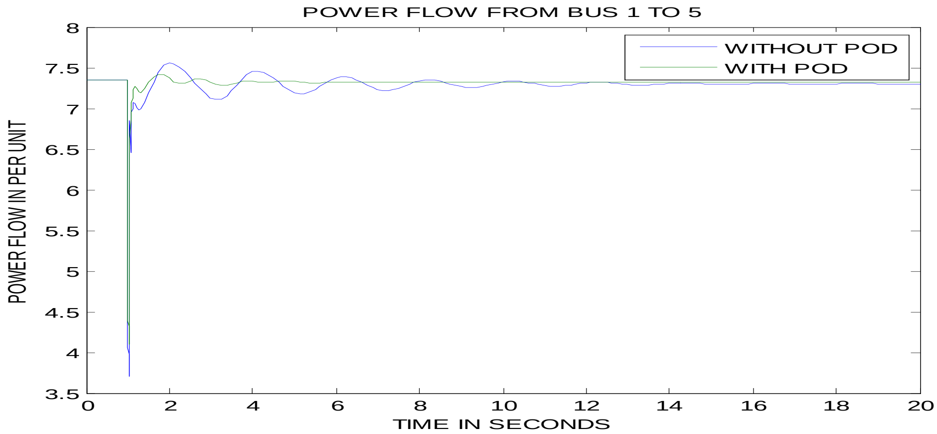

Figure 8: Power Flow from Bus 1 to Bus 5

Results of POD Design for the Nigerian System

The Nyquist plot for the Nigerian System is shown in Figure 9 and the root locus is shown in Figure 10.

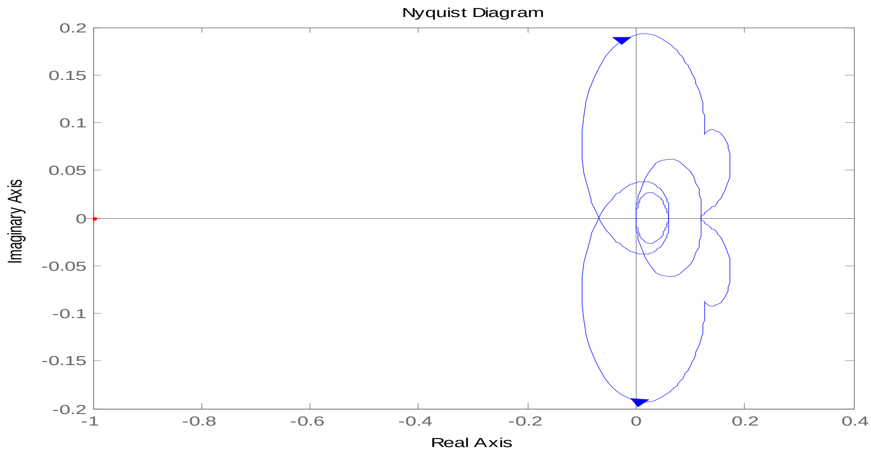

Figure 9: Nyquist Plot of the Open Loop Transfer Function

The Nyquist plot in Figure 8 shows that the system is stable under the present operating condition, but root locus in Figure 9 shows that the gain of the POD must not be allowed to reach 143 otherwise the locus will enter the right half plane and instability will set in with a damping of 1.03% and overshoot of 96.8 %. A gain of 22.6 will provide damping of 26.6 % and overshoot of 42 %

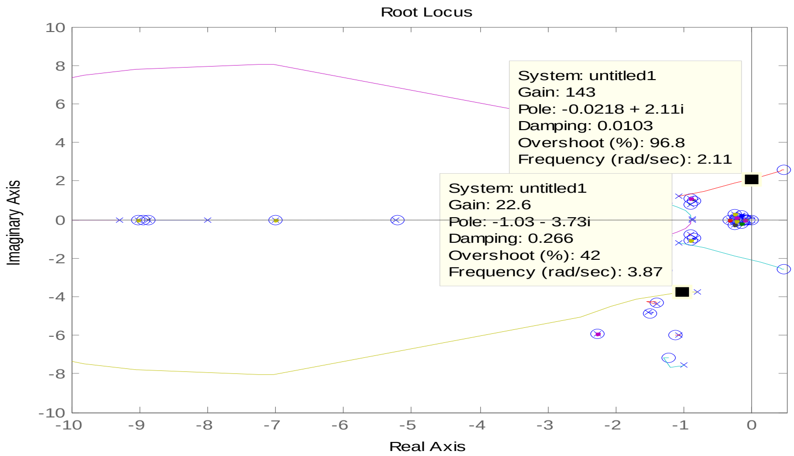

Figure 10: Root Locus of the Selected Eigenvalue

Results of Dynamic Simulation for Nigerian System

The Dynamic Simulation was performed with and without POD, the results obtained are shown in Figures 11 to 14. These results are the power flow on some critical lines, these lines are those in which the effect of local and inter area oscillation are most prominent.

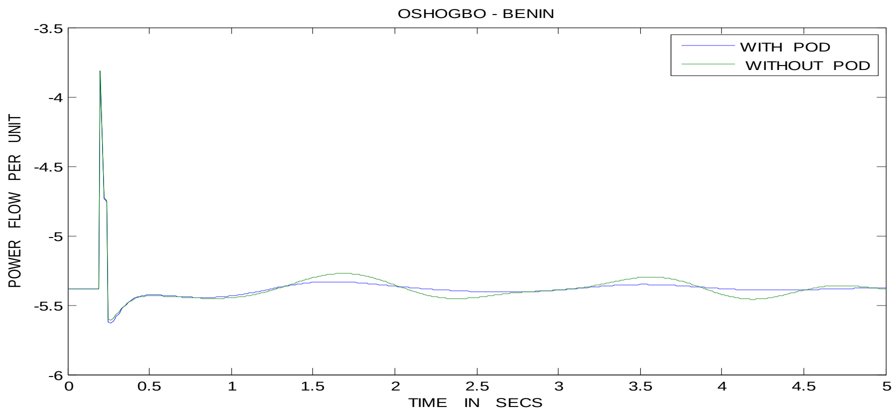

Figure 11: Power Flow on Oshogbo-Benin Line

The dynamic simulation graphs in Figures 11 and 14 reveals the effectiveness of this method in damping power oscillation in some of the power lines

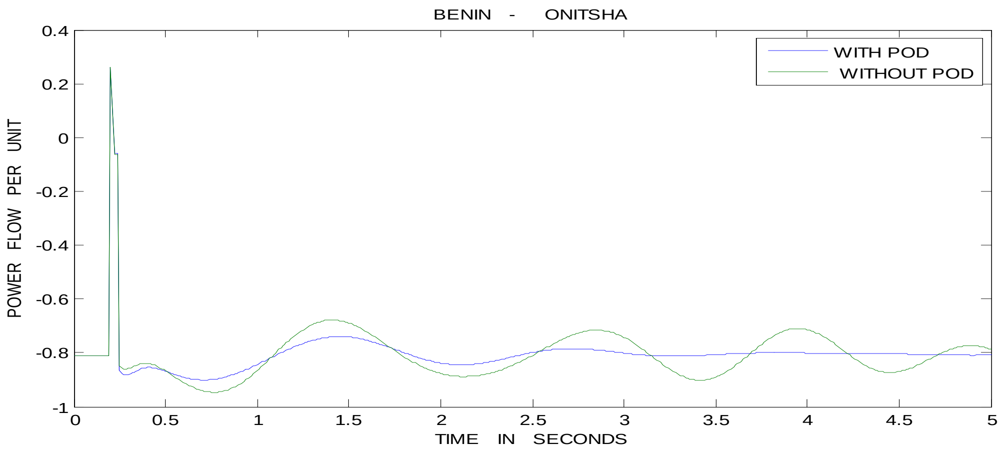

Figure 12: Power Flow on Benin-Onitsha Line

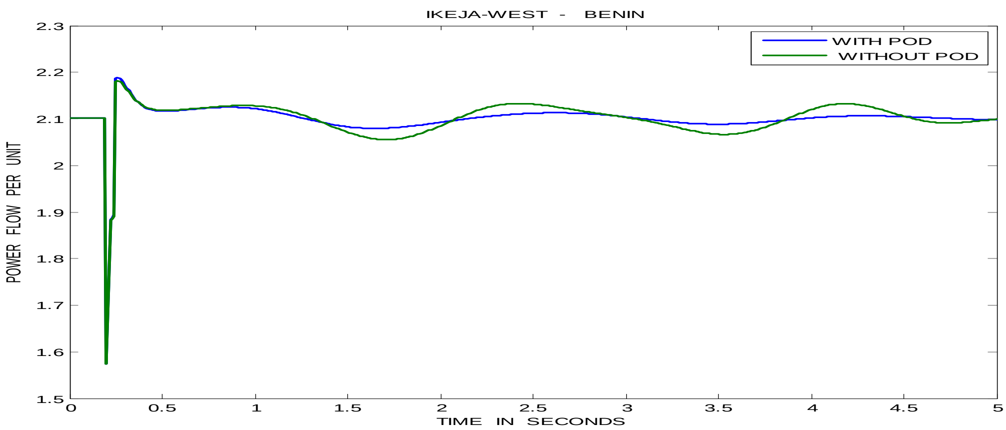

Figure 13: Power Flow on Ikeja West-Benin Line

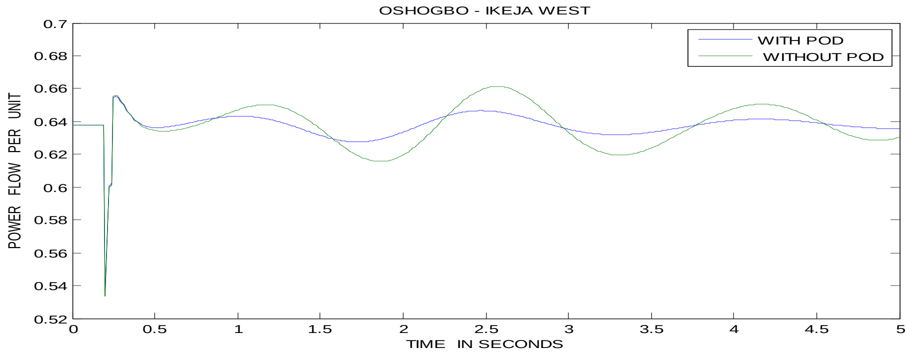

Figure 14: Power Flow on Oshogbo-Ikeja West Line

VII. CONCLUSION

In this work the Nigerian national grid is embedded with UPFC, the UPFC controller is equipped with Power Oscillation Damper this constitutes the main case study system. The methods of sensitivity analysis, root locus analysis and Nyquist analysis were deployed to determine the most effective parameters for the Power oscillation Damper for the two test cases.

The results obtained are clear indications of the effectiveness of this proposed method.

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