



A NOVEL SELF TUNING CONTROLLER DESIGN FOR UPFC AND STATCOM TO MINIMISE INTER HARMONIC OSCILLATIONS

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Abstract

Power system planners have come to rely on FACTS devices to overcome several operational limitations in terms of thermal stability, voltage stability and other limitations offered by transmission lines. The FACTS devices are capable of controlling the power flow alternating voltage magnitude, phase angles, circuit resistance under capable of providing a holistic approach for multiple issues encountered during the transfer of power. One of the fore most concerns in guaranteeing the secure operation of power systems is the nearness of low frequency electromechanical oscillations ordinarily in the frequency range of 0.1-0.8 Hz. This work is one such endeavour to damp the low frequency oscillation. This research work aims to utilize the capabilities of FACTS devices to damp the low frequency oscillations. The idea is proposed in the form of an auxiliary self tuning control scheme for the FACTS device to assist the conventional PI controller to damp out power oscillations. Two FACTS devices in Static Compensator (STATCOM) and Unified

Power Flow Controller (UPFC) are used in this work to damp low frequency oscillations. The results are presented for damping of oscillations for a two area power system. Simulation results show the reliability of the proposed self-tuning controller in damping low frequency oscillations.

Keywords: FACTS, UPFC, STATCOM, Oscillations.

1 INTRODUCTION

Modern day power systems are a complex and complicated association of a huge number of associated controllers and generators and different types of loads. These loads can vary from simple resistive loads to the complex ones with electronic controllers with the addition of more controllers and loads the nonlinearity and the complexity of the power systems has increased many folds. Consequently these systems are now viewed as complex nonlinear dynamic systems the exhibit the wide variety of instability problems. One of the fore most concerns in ensuring the secure task of power systems is the presence of low frequency electromechanical oscillations typically in the range of 0.1-0.8 Hz. One way of ensuring the safe and reliable operation is to enhance the dynamic stability of the system and damp these oscillations. This research work is one such endeavour to damp the low frequency oscillation.

Oscillations that are limited to a single plant or a single generation are called as plant mode or local mode oscillations. The charts of these oscillations are well understood and normally they have frequencies in the range of 0.7 to 2.0 Hz. Those oscillations which are associated with groups of generation (or) groups of plants are called inter-area mode oscillations. These Oscillations whose charts are not that well understood the frequency in the range of 0.1 to 0.8 Hz. Damping these oscillations have become crucial to ensure the safe and reliable operation of the power systems. One family of device that has enhanced the safe and reliable operation of the network is FACTS. According to the definition provided by the IEEE New technology[1] The flexible alternate current transmission system is based on power electronic controllers are capable to improve power transfer capacity, stability and controllability of A.C transmission systems.

Several methods exist to damp the oscillations. The general

method is to induct power system stabilizer (PSS) on generators. This will improve the power system stability but there are limitations to determine the ideal values for PSS parameters. However, selecting in-adequate values cause in-stability on power system. Therefore selection of correct and adequate values is so important and vital. Numerous approaches have been suggested for to determine the correct value for PSS parameters as back as 1981 for oscillation damping in power systems like pole placement, artificial neural network and optimal control. Variable structure control and Adaptive control based on model control theory [713]. It is getting increasingly difficult to damping the inter harmonic oscillations through traditional methods because of variety of reasons. One important reason being the lack of adequate and accurate information to model all the components of the power system with increases inter connections, multiple ownership patterns, the presence of distributed generations and participation of many independent power producers have made it very difficult to obtain accurate and up to date information about overall system. In view of the rapid growth in demand, Indian system operators on the operating the power systems closer to their stability limits. In addition to this large regions have been connected by few lines resulting in slightly damped modes. This gives rise to significant challenges in handling small signal stability in the Indian grid. The Indian grid system has encountered several cases of oscillations ranging from local oscillations to inter area oscillations. In the western grid oscillations were observed in between Vindhyachal and Korba regions, on account of weak transmission in the Eastern and Western part of the grid. Also during large grid synchronizations these oscillations were encountered and were subsequently damped using TCSC (Thyristor Controlled Series Capacitor). In the year 2003 during the synchronization of Eastern and Western grid TCSC was used for damping low frequency oscillations. Similarly TCSC installed lines were used to damp out inter-area oscillations in the synchronization of Eastern region grid and Northern Eastern grid. Oscillations were also observed since December 2013 after the synchronization of NEW grid with the Southern region grid. The long inter regional lines that were present between the eastern region grid and western region grid necessitated the installation of the TCSC to suppress these oscillations during grid synchronization National

Load Dispatch Centers(NLDC) and Regional Load Dispatch Centers (RLDC) employed Synchro phasor measurement unit to monitor the oscillations in real time. The baseline oscillation mode in the Indian grid is depicted in the table 1 [14].

Table 1: Baseline oscillation mode in the Indian grid.

Serial no	Mode HZ	Region
1	0.2-0.25	Sudan grid and NEW grid
2	0.7-0.75	Eastern-north eastern and western region
3	0.6	Eastern-north eastern and western region
4	0.5	North eastern grid with rest of the grid

The primary objective of the proposed work is to design an adaptive control scheme over a PI control loop for FACTS devices. An auxiliary self-tuning control scheme has been designed for the FACTS device to assist the existing PI control to damp power oscillations. The ST controller assists with the pole shift controller and adaptive recursive least square identifier. Two FACTS devices in Static Compensator (STATCOM) and Unified Power Flow Controller (UPFC) are used in this work to damp low frequency oscillations. The self tuning controller applied in this work varies from the ANN and FUZZY logic control method. It is different from ANN, which needs off line training and is depending on assumptions indispensable for fuzzy techniques. Alternatively addresses these inadequacies by attaining the concepts of indirect adaptive theory. The indirect adaptive control technique comprises of a controller and identifier. The identifier operates on an identified plant model of a power system. It identifies the auto-regressive moving average (ARMA) parameters online and uses parameter appraisals to tune suitably the matching control parameters making it to yield achievable control performance. The adaptive controller and identifier mentioned operates sensibly severe disturbances as well as the ST controller recommended is composed of an adaptive constrained recursive least squares (CRLS) identifier on a pole shift (PS) controller. It is recommended to the use of self-tuning control to intensify the stability of a multi-machine power system using the UPFC and STATCOM, when facing particularly with insecurities in

parameters of transmission system.

2 MODELLING OF FACTS DEVICES

FACTS devices enhance the power flow transfer capability of the transmission system. Their ability to control the power rapidly enhances the stability margins of the system and also provides proper damping. The installation of FACTS devices helps to minimize the losses and also enable the power system to work within the thermal limits. In this section the injection models of UPFC and STATCOM devices used in this work are explained.

a. Modelling of STATCOM

Static synchronous compensator is a FACTS device which is usually connected as shunt to the network enabling generation on absorption of reactive power. STATCOM is capable of controlling all three principle parameters like voltage, impedance and phase angle. STATCOM can be considered to the voltage source converter based shunt FACTS device, which is capable of injecting controllable reactive power into the system. A functional model of STATCOM is shown in figure.1. In the VSC connects to any utility bus through a shunt transformer in reference to fig.1. V_{ac} is the bus voltage I_{ac} is the current injected by a STATCOM while the output voltage of VSC is denoted by V_{out} .

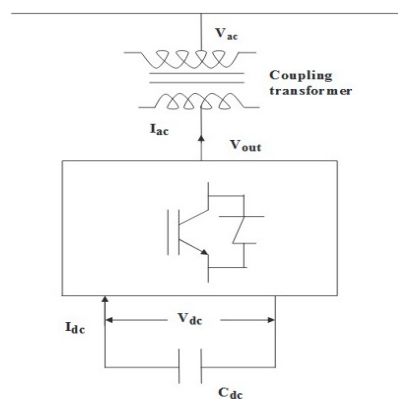


Figure 1: A Functional model of STATCOM

A three arm IGBT bridge is formed with an IGBT with back to back diode. The top three IGBTs are referred to as the positive groups, while the bottom three IGBTs are referred to as negative group. When these IGBTs conduct an inverter operation takes place while the diodes conduct a converter operation takes place. The concept of STATCOM power exchange is illustrated using the figure 2. STATCOM can be considered to be an adjustable voltage source behind a reactance in view of this there is no need to have capacitor banks and shunt reactors to have reactive power generation or absorption this factor accounts for the compact design of a STATCOM.

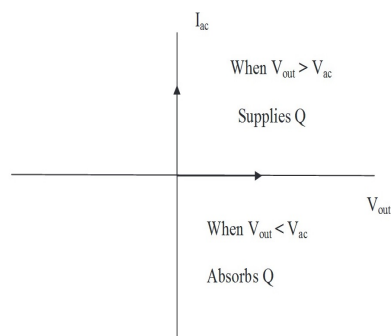


Figure 2: Power exchange while using a STATCOM

The STATCOM equivalent circuit as shown in the figure 3. From the equivalent circuit it is observed that by changing the amplitudes of the 3Φ output voltage of the converter, the exchange of reactive power is controlled between the AC system and the converter.

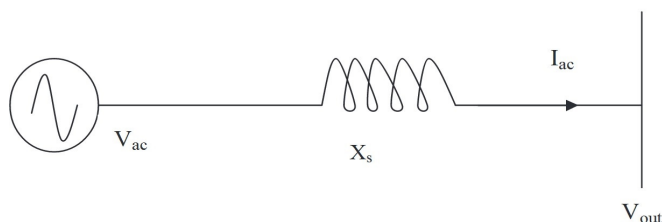


Figure 3: Equivalent circuit of STATCOM

In case the amplitude of V_{out} is higher than the amplitude of the bus voltage V_{ac} then there is flow of current through the reactance from the convertor to the AC system. In this case the convertor generates capacitive reactive power for the AC system. The other case if the amplitude V_{ac} is less than V_{out} there is a current flow from the AC system into the convertor. In this case the convertor absorbs inductive reactive power from the AC system. If the voltages are equal then the STATCOM is at floating state and reactive power exchange becomes zero. A small DC capacitor at DC side V_{sc} reactively limits the ability of STATCOM reactive power exchange with in a transmission system. The coupling transformer has two volts in its first role it connects the convertor to the high voltage power system and in its second role it prevents the short circuit in DC capacitor and rapid discharge this is brought about through the transformers inductance.

b. Modelling of UPFC

The unified power flow controllers are in a position to offer concurrent control of multiple power system parameters, including transmission phase angle and voltage impedance. This controller is capable of providing reactive shunt make up phase fitting series compensation and is also capable to multiple control objective maintenance. The UPFC can be formed by appliances such as a shunt connected transformer and a voltage source converter in a parallel branch along with the dc capacitor. The UPFC further incorporates a series injected transformer and voltage source converter. The common dc link capacitor is usually used to operate the two voltage source converters which are connected to as back to back, AC to DC voltage source converters.

Mainly the shunt converter is used to give demand of active power of series converter with common dc link. This converter-1 is also capable to delivers or absorbs the reactive power. This can be achieved on demand and hence it gives independent shunt reactive compensation for the line. The converter-2 performs the main working of UPFC by injecting controlled voltage phase angle and magnitude with the line in series. The back to back converters along with the transformers are depicted using the figure 4.

The figure 5 shows the equivalent UPFC circuit. The series converter can replace with controllable voltage source V_{se} and shunt converter to be replaced by a controllable current source, in the

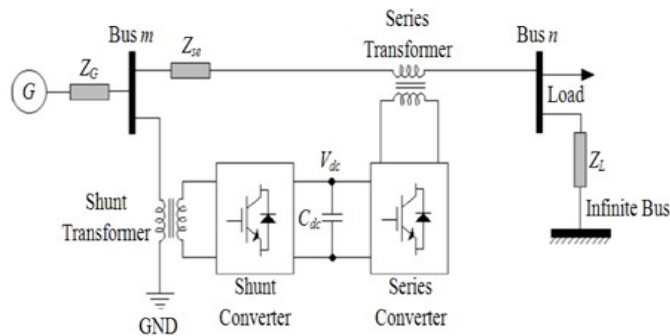


Figure 4: Structure of UPFC as connected in the network

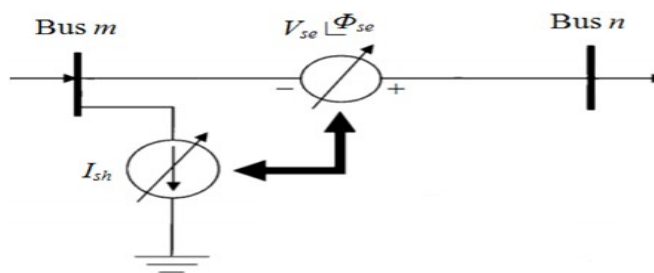


Figure 5: Equivalent circuit of UPFC

equivalent circuit. While the magnitude of the output voltage regulates the voltage, its angle Φ_s is used for phase regulation. UPFC controllable parameters include: magnitude of the voltage injected in the series with the transmission line, V_{se} with the ranges $[0, V_{se\max}]$, phase angle of the same voltage injected, Φ_s that is within the range $[1, 2\pi]$ and the shunt reactive current I_{sh} , with the ranges $[I_{sh\min}, I_{sh\max}]$. [15].

3 THE PROPOSED ST CONTROLLER

The algorithm assumes the process to be described by a discrete ARMA model of the form

$$A(z^{-1})y(t) = B(z^{-1})u(t) + e(t) \quad (1)$$

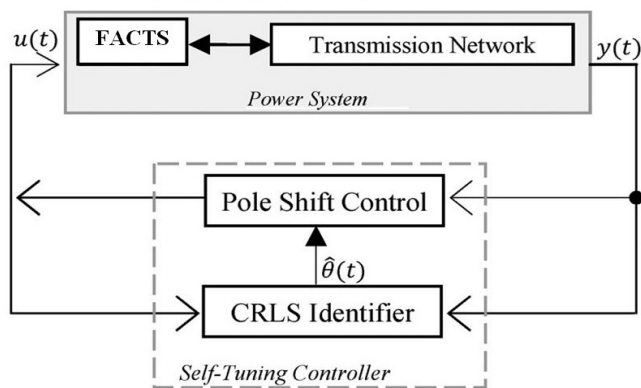


Figure 6: Proposed configuration to damp oscillations

Where polynomials $A(z^{-1})$ and $B(z^{-1})$ in backward shift operator z^{-1} are defined as

$$A(z^{-1}) = 1 + a_1 z^{-1} + a_2 z^{-2} + \dots + a_{n_a} z^{-n_a}$$

$$B(z^{-1}) = b_1 z^{-1} + b_2 z^{-2} + \dots + b_{n_b} z^{-n_b}$$

Where

n_b = order of the polynomial $A(z^{-1})$

n_a = order of the polynomial $B(z^{-1})$

and variables $e(t)$, $y(t)$ and $u(t)$ are white noise, the system output and system input respectively. Equation (1) can be rewritten for suitable identification as

$$y(t) = \tilde{\theta}^T(t) \varphi(t) + e(t) \quad (2)$$

$$y(t) = \hat{y}(t | \hat{\theta}, \varphi) + (t) \quad (3)$$

Where

$\hat{y}(t|\hat{\theta}, \varphi)$ = the prediction of $y(t)$

$\hat{\theta}^T(t)$ = estimated system parameter vector a

Measurement variable vector $\varphi(t)$ is given by

$$\hat{\theta}(t) = [a_1 \ a_2 \ a_3 \ \dots \ a_{na} \ b_1 \ b_2 \ b_3 \ \dots \ b_{nb}]^T \quad (4)$$

$$\varphi^T(t) = [-y(t-1) - y(t-2) \dots - y(t-2) \dots - y(t-n_a) \times u(t-1) \dots u(t-n_b)] \quad (5)$$

Where

$\varphi^T(t)$ = Stored data vector of system output of last n_a samples and system input of the last n_b samples.

The prediction error, $\varepsilon(t)$ is given by

$$\varepsilon(t) = y(t) - \hat{y}(t|\hat{\theta}, \varphi) = e(t) \quad (6)$$

The RLS criterion finds the most likelihood value of $\hat{\theta}(t)$ which minimizes prediction error estimation.

$$J(N) = \frac{1}{N} \sum_{k=1}^{k=N} [e(t)]^2 \quad (7)$$

The system parameter vector $\hat{\theta}(t)$ can be calculated by below recursive equations

$$\hat{\theta}(t) = \hat{\theta}(t-1) + K(t)[y(t) - \hat{\theta}^T(t-1)\varphi(t)]\beta(t) \quad (8)$$

(a)

where the weighing factor for the last identified parameters is equal to one and that for the prediction error is given by the modification coefficients (or gain matrix) $k(t)$

$$K(t) = \frac{P(t-1)\varphi(t)}{\rho(t) + \varphi^T(t)P(t-1)\varphi(t)} \quad (8b)$$

$$P(t) = \frac{1}{\rho(t)} P(t-1) \quad (8c)$$

where $\rho(t)$ is the time varying forgetting factor, is the covariance (of error in estimate) matrix, and $k(t)$ is the gain vector. The forgetting factor $\rho(t)$ is calculated as

$$\rho(t) = \rho_0 \rho(t-1) + (1 - \rho_0); \quad 0 < \rho_0 < 1. \quad (8d)$$

The RLS algorithm in every iteration uses a set of previous and present system measurements to find the system output (t) and also calculates the prediction error $\varepsilon(t)$. By using and the stored measured values in error covariance matrix $P(t-1)$, then estimates a set of modification coefficients $k(t)$. With $k(t)$ a new set of identified system parameters $\hat{\theta}(t)$ is measured as in (8a).

Eq.(8a) is modified by a constrained-RLS identification technique with the inclusion as constraint term.

$$\hat{\theta}(t) = \hat{\theta}(t-1) + K(t)[y(t) - \hat{\theta}^T(t-1)\varphi(t)]\beta(t) \quad (9)$$

Where $\beta(t)$ is calculated at each sampling instant as follows:

$$N_1 = \|\hat{\theta}(t)\|_2$$

$$N_2 = \|K(t)[y(t) - \hat{\theta}^T(t-1)\varphi(t)]\|_2$$

$\|\cdot\|_2$ denotes the corresponding vector normalization and positive constant β_0 which determines the parameter update rate. At fault inception (and after short duration) of power system, the N_2/N_1

ratio enhances faster as greater than β_0 . At time period $\beta(t)$ uses the value β_0/N_2 lesser the estimation rate and there by contributing to smoother action of controller. After removal of fault when the power system reaching to a stable operating point, the ratio N_2/N_1 gradually enhances to less than β_0 to get $\beta(t)=1$. For identification process both ST controller and third-order ARMA system model is used in proposed model. Inter-area mode of oscillations at the range of 0.1 to 0.8 Hz exhibits by two-area system is subject to a disturbance and to reduce this disturbance of oscillations a third-order model has been found in local mode as discussed in the introduction. Complex conjugate poles (oscillatory) and real poles (Non-oscillatory) instability of system so second order and fourth order models are not useful. Complex poles (two pairs) can only represent the oscillatory response, two or four real poles generally are not needed to show the non-oscillatory part of a single mode inter-area oscillation. 5th, 7th, 9th or higher odd numbered models could be used.

4 RESULTS AND DISCUSSION

Two area systems [16] are benchmark systems for study of inter-area oscillations, on each area it consists of two generators, connected through a 220 km tie line. Generally all generators are connected with DC exciter models and transient models. Figure.7 shows The test system on-line diagram. Because the FACTS devices are originated in transmission systems, local input signals like bus voltages or bus currents, power deviation δP are preferable always. In this paper, feedback signal is represented by δP . The important case choosing the feedback signal is done by the optimal sitting of the FACTS device.

The results of the system without controller, with PI controller and with self tuning controller of STATCOM and UPFC are shown using Table 2.0 and Table 3.0. From the tables it can be observed that there is significant reduction in settling time for both UPFC and STATCOM based controllers. The performance is better compared to a standalone PI controller as well. In all cases of analyze, the self-tuning controller is capable to reduce the power oscillations within few seconds from its activation and the damping ratio values

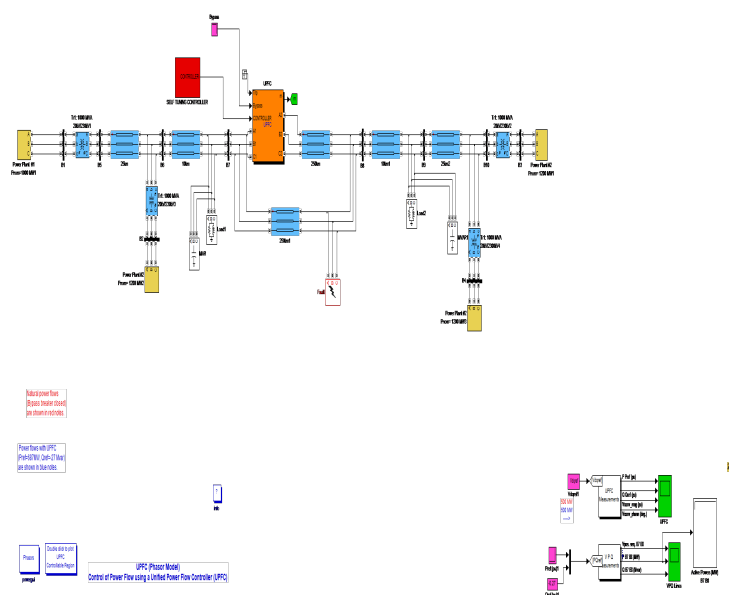


Figure 7: Line diagram of two area system

are acceptable instead of delay time resulting the signal conditioning at the first oscillation cycle. It can be seen that the damping times have improved from as given in Table 2.0 and Table 3.0 In order to further check controller ability to stabilize the system in the presence of a Single Phase fault a fault is applied at bus 8 in the system. It is observed that when the ST controller is operating the damping of the oscillation has been significantly improved. It can be inferred from the tables that the performance of the proposed controller is clearly visible for all three types of faults induced at to different buses namely bus 7 and bus 8. The average reduction in settling time for the STATCOM based controller is 16.34 % when compared to the scenario in which no damping controller is present.

On the other hand when the comparison is made in regard to PI controller the average reduction for all the fault cases is 2.81%

Table 2.0: Settling time for different faults using STATCOM-Self Tuning Controller

S.No	Fault	Settling Time (Seconds)		
		Without Controller	With PI Controller	With ST Controller
1	Normal Fault	0.864	0.657	0.64
2	Single Phase Fault at Bus 8	1.3	1.162	1.12
3	Two Phase Fault at Bus 8	1.34	1.15	1.11
4	Three Phase Fault at Bus 8	1.125	1.18	1.16
5	Single Phase Fault at Bus 7	1.425	1.2	1.19
6	Two Phase Fault at Bus 7	1.32	1.18	1.12
7	Three Phase Fault at Bus 7	1.5	1.25	1.22

When the comparison is made between STATCOM and UPFC, the UPFC based controller delivers a better performance across all the fault scenarios. The average reduction in settling time for the STATCOM based controller is 22.80 % when compared to the scenario in which no damping controller is present. On the other hand when the comparison is made in regard to PI controller the average reduction for all the fault cases is 11.76. It can be inferred from the results that the reduction achieved by UPFC is enhanced in comparison to STATCOM and PI. There is significant reduction of 11.76 % for UPFC when compared to a PI based compensator, this is close to 8% enhancement when compared with reduction percentage of STATCOM over PI.

In order to validate the performance of the proposed controller in terms of enhancement of damping ratio a 4 cycle single phase fault and a 4 Cycle three phase fault is applied between bus 8 and the ground. The results for this scenario are depicted using Table 3.0 and Table 4.0. The enhancement of damping ratio is compared in the absence of a controller and also in the presence of a conventional PI damping controller.

Figure (8) and Figure (9) clearly demonstrates the enhanced damping performance delivered by the proposed ST controllers.

Table 3.0: Settling time for different faults using UPSC-Self Tuning Controller

S.No	Fault	Settling Time (Seconds)		
		With Out Controller	With PI Controller	With ST Controller
1	Normal Fault	0.864	0.657	0.592
2	Single Phase Fault at Bus 8	1.3	1.162	1.043
3	Two Phase Fault at Bus 8	1.34	1.15	1.057
4	Three Phase Fault at Bus 8	1.125	1.18	1.02
5	Single Phase Fault at Bus 7	1.425	1.2	1.07
6	Two Phase Fault at Bus 7	1.32	1.18	0.99
7	Three Phase Fault at Bus 7	1.5	1.25	1.08

Table 4.0: Damping performance of the proposed approach using STATCOM for damping inter area oscillations

Fault	No Damping Controller		Damping using PI		Damping Using Proposed ST +UPFC	
	Freq. (Hz)	Damping ratio %	Freq. (Hz)	Damping ratio %	Freq. (Hz)	Damping ratio %
4 Cycle 3 Phase Ground to fault @ Bus 8	0.46	2.4	0.54	7.61	0.55	24.6
4 Cycle 1 Phase Ground to fault @ Bus 8	0.44	5.1	0.57	9.85	0.58	15.3

Here also both the FACTS based controllers outperform PI based damping control in delivering an enhanced damping ratio.

The UPFC based damping controller delivers an enhanced performance when compared to the STATCOM based controller. It can be inferred from table 6.0 that the enhancement of damping ratio for a UPFC base controller is 22.2% when compared to a no controller configuration in the case of a 4 Cycle 3 Phase to fault between bus 8 and ground. For the same scenario the damping

Table 5.0: Damping performance of the proposed approach using UPFC for damping inter area oscillations

Fault	No Damping Controller		Damping using PI		Damping Using Proposed ST +UPFC	
	Freq. (Hz)	Damping ratio %	Freq. (Hz)	Damping ratio %	Freq. (Hz)	Damping ratio %
4 Cycle 3 Phase Ground to fault @ Bus 8	0.46	2.4	0.54	7.61	0.55	24.6
4 Cycle 1 Phase Ground to fault @ Bus 8	0.44	5.1	0.57	9.85	0.58	15.3

■ 4 Cycle 3 Phase Ground to fault @ Bus 8

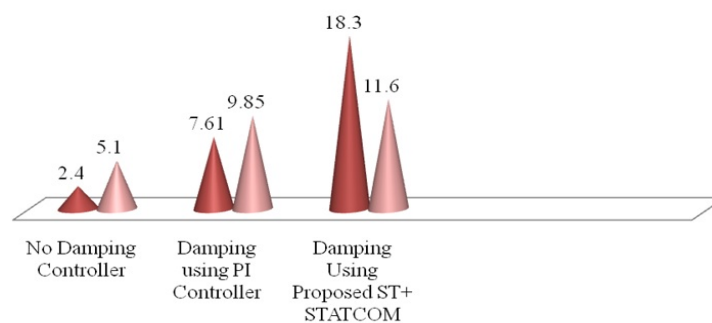


Figure 8: Damping performance measured in terms of damping ratio of the proposed approach using STATCOM for damping inter area oscillations

ratio provided by the STATCOM based controller is 15.9 % which is around 6 % lesser than the damping ratio provided UPFC based controller. The performance is visible for 4 Cycle 1 Phase fault between bus 8 and ground. The improvement is damping ratio is 10.2 for UPFC based control while the improvement is 6.06 % for a STATCOM based controller. This translates to 4 % improved enhancement for UPFC over STATCOM based damping controller.

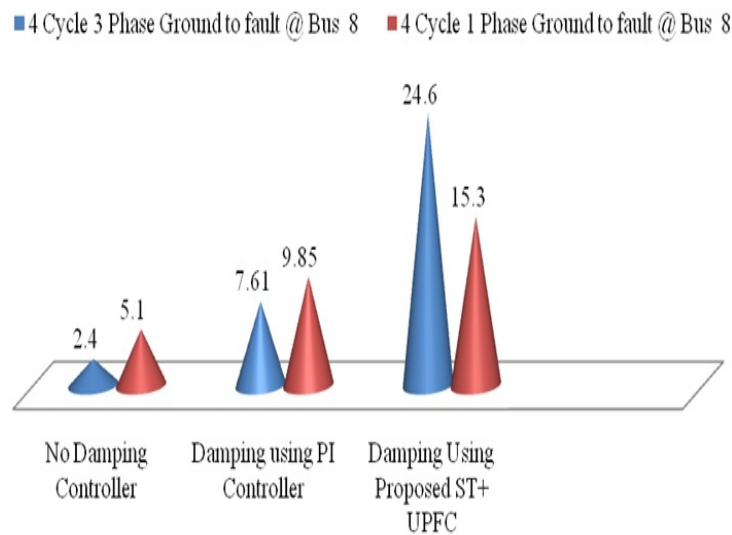


Figure 9: Damping performance measured in terms of damping ratio of the proposed approach using UPFC for damping inter area oscillations

Table 6.0: Percentage Increase in Damping Ratio for different FACTS devices using the proposed approach as compared to no controller configuration

	4 Cycle 3 Phase Ground to fault @ Bus 8	4 Cycle 1 Phase Ground to fault @ Bus 8
Damping Using Proposed ST+ UPFC	22.2	10.2
Damping Using Proposed ST+ STATCOM	15.9	6.06

5 CONCLUSION

Self tuning controller has applied to UPFC and STATCOM is presented in this paper. Simulation results shows that proposed method

automatically improves the damping characteristic in different mode of operating conditions. For avoiding interactions among the controllers the tuning is done in a coordinated way. Self-Tuning Regulator is a investigated controller and the system model parameters estimated by Recursive Least-Squares method. For transient stability improvement an open-loop controller is used and also power flow control by closed-loop PI-controller is presented. Different operating conditions of the four-machine system have been used to validate the proposed self-tuned controller. The obtained results proved that the proposed controller has successfully provided the good damping for inter harmonic oscillations for the multi machine power system.

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