Artificial-neural-network based unified power flow controller for mitigation of power oscillations

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ABSTRACT

The series and shunt control scheme of unified power flow controller (UPFC) impacts the performance and stability of the power system during power swing. UPFC is the most versatile and voltage source converter device as it can control the real and reactive power of the transmission system simultaneously or selectively. When any system is subjected to any disturbance or fault, there are many challenges in damping power oscillation using conventional methods. This paper presents the neural network-based controller that replaces the proportional-integral (PI) controller to minimize the power oscillations. The performance of the artificial neural network (ANN) controller is evaluated on IEEE 9 bus system and compared with a conventional PI controller.

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1. INTRODUCTION

The unified power flow controller (UPFC) concept is introduced by Gyugyi [1]. Among the different flexible AC transmission system (FACTS) devices UPFC is a multifunctional device [2]. As illustrated in Figure 1, the UPFC is consist of two voltage source converters, namely vehicle stability control$_1$ (VSC_1) and vehicle stability control$_2$ (VSC_2). The VSC_1 is in series with a transmission line through a series transformer (T_r) called a series converter. It injects voltage to the transmission line with variable phase angle and magnitude controlled by the series controller. The VSC_2 is connected in parallel with a transmission line through a shunt transformer (T_s) called shunt converter. It exchanges the real power required by the series converter and is controlled by the shunt controller. The primary task of UPFC is to control transmission lines power flow control [3], [4]. Apart from this, it is also used for enhanceing the power transfer capability [5], transient stability [6], [7], voltage profile improvement [8] and oscillation damping [9].

Different control strategies are used to control series & shunt converters are reported [10]-[26]. In terms of power system stability, the conventional proportional-integral (PI) and proportional integral derivative (PID) regulators used for UPFC suffers from inadequacies [10]. A self-tuned PI controller to enhance transient stability [11] and a multivariable PI controller [12] for power flow and voltage control is applied using UPFC.

Khodaparast and Khederzadeh, proposed the series control design for UPFC using PI controller [13]. The performance of the series controller's current regulator during power swing is investigated. They presented two remedial actions for the concentric power swing blocker. A fuzzy logic controller [14] is used for inter area and local mode oscillations using UPFC.

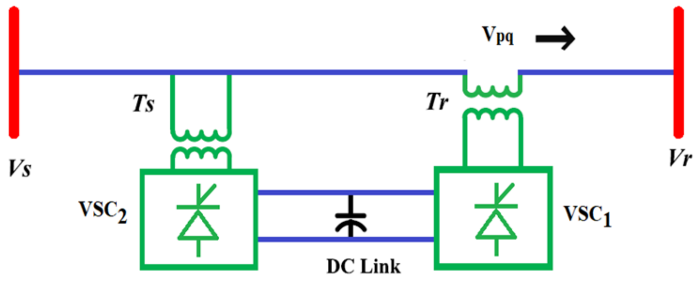


Figure 1. Basic structure of UPFC

Mishra has presented neural network-based adaptive UPFC. A radial biased function neural network (RBFNN) [10], [15] controller of UPFC is used to enhance transient stability. In [16] linearized Phillips–Heffron model is used with UPFC to minimize the power system oscillation. Hybrid controllers such as fuzzy-neural network [17], adaptive neurofuzzy inference control system [18], and genetic algorithm with gravitational search algorithm [19] are used for UPFC. Particle swarm optimization (PSO) [20]-[23] based controller used for UPFC.

The literature reveals, the controller design of UPFC plays an significant role in the syatem stability and mitigation of power swings [13], [24]. It reported limited work on the controller design of UPFC on power system oscillations during fault conditions. The contribution of this paper is i) series and shunt controller design using ANN controller to minimize the power swings. ii) Study of power swing and short-circuit conditions. iii) PI controller is compared with ANN controller to study the performance of UPFC.

2. UPFC CONTROLLER

2.1. Series controller

The series controller of UPFC, [13] is illustrated in Figure 2. The desired reference value of voltages, active and reactive power is set. The phase lock loop block provides the reference angle from the system sending voltage. The d-q variables of current and voltage are computed by the measurement system. Current regulation is done by two PI controllers.

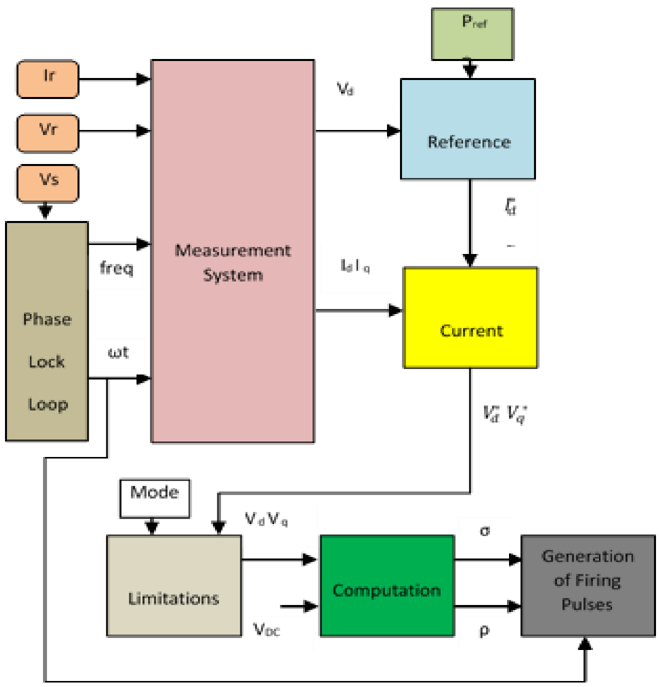


Figure 2. Series controller of UPFC

During the transient period, the current regulator plays a significant role. The detailed current regulation is shown in Figure 3 and done by two PI controllers. During power swings, the measured d-q component of currents (I_d, I_q) values are compared with the reference value (I_d^*, I_q^*). The variation in these signals causes the parameter of V_d^* and V_q^* intern varies the series voltage (V_{se}).

Figure 3. Current regulator by PI controller

The series injected voltage is given by (1).

$$|V_s(t)| = |V_s|_{Max} \quad (1)$$

Using P and Q reference value the value of I_d^* and I_q^* are [13],

$$I_d^*(t) = \frac{P_{\text{ref}} \cdot V_d(t) + Q_{\text{ref}} \cdot V_q(t)}{V_d^2 + V_q^2} \quad (2)$$

$$I_q^*(t) = \frac{P_{\text{ref}} \cdot V_q(t) - Q_{\text{ref}} \cdot V_d(t)}{V_d^2 + V_q^2} \quad (3)$$

where P_{ref} and Q_{ref} are reference values of UPFC, V_d and V_q are d-q components of voltage. The d-q components of measured current can be written as [13],

$$I_d^*(t) = |I(t)|\text{Cos}(\angle I(t) - \delta_1(t)) = \frac{P(t) \cdot V_d(t) + Q(t) \cdot V_q(t)}{V_d^2 + V_q^2} \quad (4)$$

$$I_q^*(t) = |I(t)|\text{Sin}(\angle I(t) - \delta_1(t)) = \frac{P(t) \cdot V_q(t) - Q(t) \cdot V_d(t)}{V_d^2 + V_q^2} \quad (5)$$

The PI controller of the current regulator is replaced by ANN controller is shown in Figure 4. Each ANN controller is having two-layered feed forward neurons with a single input, ten hidden layers and one output. The error signal obtained from d-q component with their reference value is applied as an input. The Levenberg-marquardt algorithm is used to train the neural network.

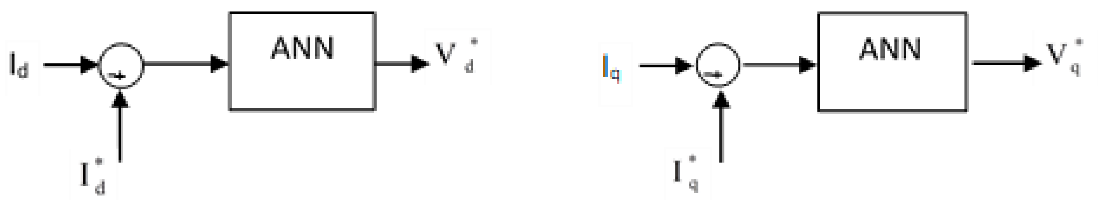


Figure 4. Current regulator by ANN controller

2.2. Shunt controller

The structure of the UPFC [25] shunt controller is shown Figure 5. The shunt converter's task is to supply of real power required by the series converter. The shunt current is drawn from the transmission line by the shunt converter. In shunt controller q component of current (I_q) from measurement and feedback signal from direct current (DC) capacitor voltage are used to control the necessary voltage of DC capacitor.

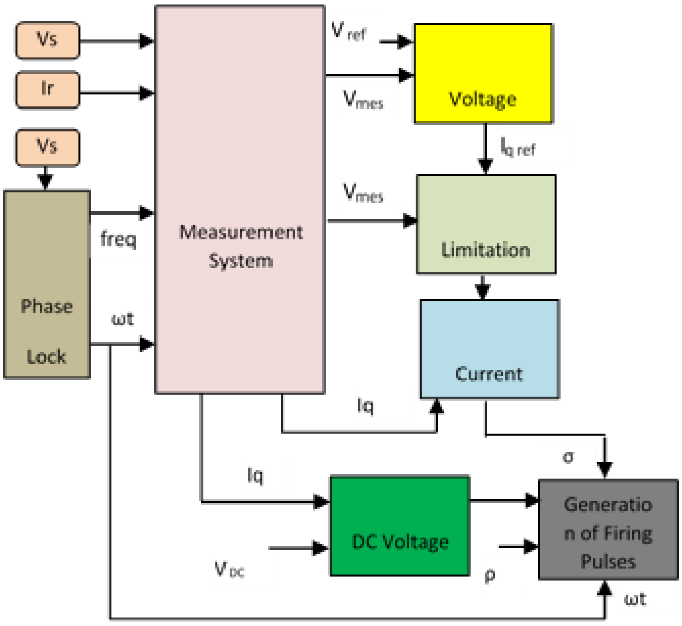


Figure 5. Shunt controller of UPFC

3. RESULTS AND DISCUSSION

To validate the performance of UPFC and coordination of series and shunt controller three machines, nine bus system (IEEE 9 bus) is considered, as shown in Figure 6. UPFC is connected at transmission lines 4-6 and simulated using power flow control mode. Power swing and fault conditions are discussed in this section.

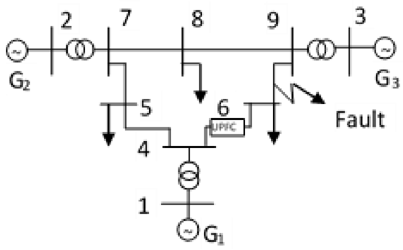


Figure 6. Three machine test bus system (IEEE 9 bus)

3.1. Case 1: Power swings

In this case real power (P) in the transmission line, 4-6 at t=5.25 Sec. is increased from 0.75 to 0.8 p.u. while reactive power (Q) remains constant. As a result of the power swings, the system response using PI controller is shown in Figure 7. The PI controller mitigates the real power swings at t=8.2 Sec. and reactive power swings at 9 Sec. respectively.

Figure 8 shows the system response using the ANN controller. Using ANN controller real and reactive power swings are suffered at t=5.1Sec. for case 1. It is observed that using ANN controller for reactive power response is slightly out of response with reference value is because of tolerance of feed-forward neural networks but ANN controller minimized the reactive power swings compared to PI controller. when comparing the PI and ANN controller, it is observed that the ANN controller takes the least time response to reduce the power swings.

3.2. Case 2: Fault condition

When three phases to ground fault is applied at bus 6 following three conditions are to be considered,

$0 \leq t \leq 5$ Pre fault condition.
$5 \leq t \leq 5.0167$ During fault conditions (line 6-4).
$t > 5.0167$ Post fault condition.

Considering the above conditions, the behavior of three machine bus test system with UPFC is examined. Figures 9 and 10 shows the power oscillations of P and Q with reference to P_{ref} and Q_{ref} using PI and ANN controller respectively. When the fault is applied at bus 6 the power oscillations oscillate, i.e. it deviates from the nominal value. Hence, there is a need to recover the system into a stable state as early as possible. With ANN controller recovers quickly from deviated value to its nominal value and regains synchronism at 5.5Sec. from the fault occurred. While PI controller regains synchronism at 6.5 Sec.

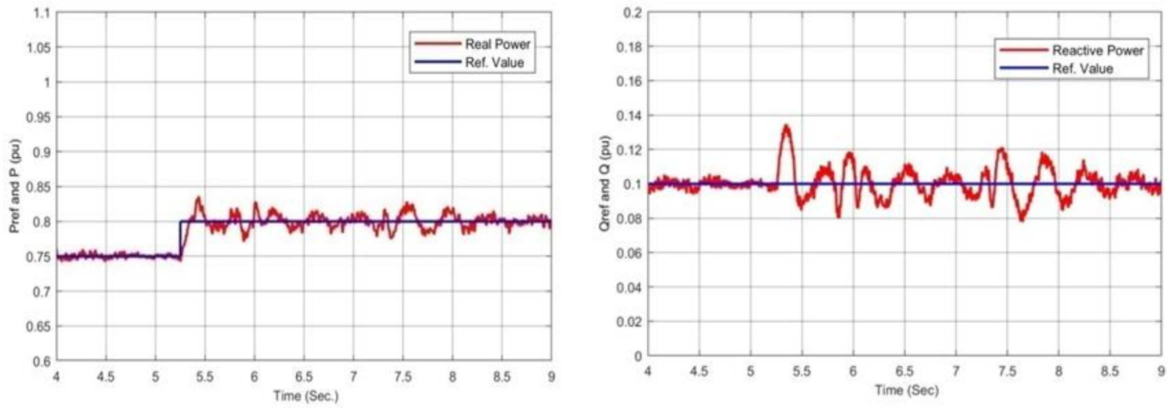


Figure 7. P and Q using swings PI controller for case 1

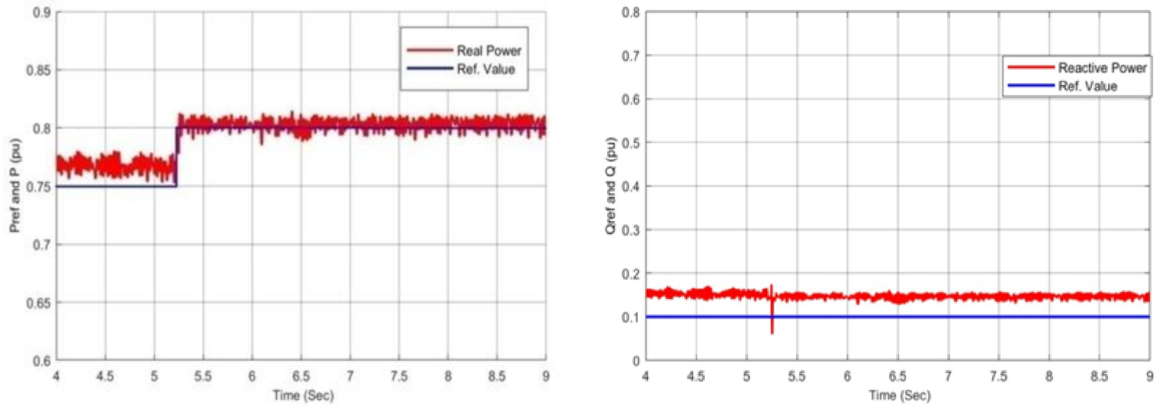


Figure 8. P and Q using swings ANN controller for case 1

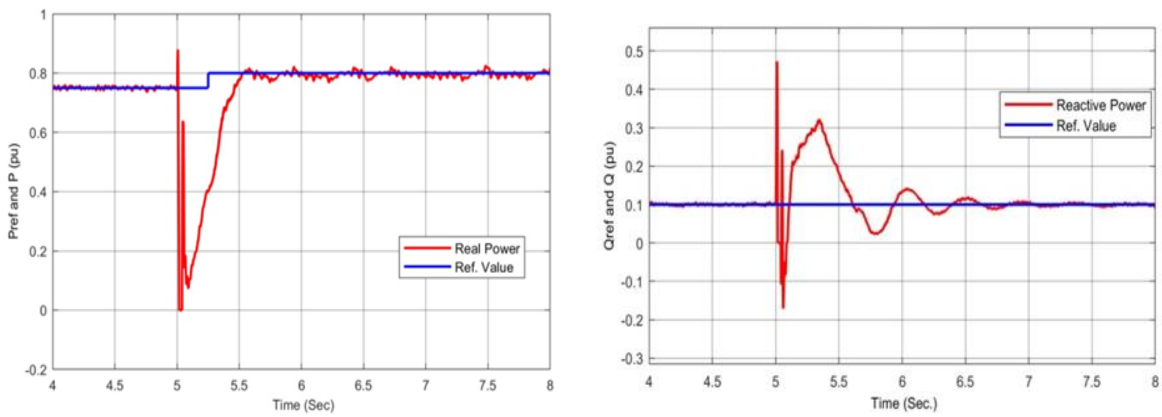


Figure 9. P and Q swings using PI controller for case 2

Figures 11 and 12 shows the voltage profile of DC bus (UPFC) using a PI controller and ANN controller for cases 1 and 2 respectively. In Figures 11 and 12, it is observed that for both cases, the voltage profile of DC bus using ANN controller is better compared to PI controller. In case 1 using PI controller voltage spikes are more compared to ANN controller. In case 2 DC voltage is settled at 6.5 Sec. using PI controller, whereas the ANN controller has settled at 5.3 Sec.

Figures 13 and 14 present the measured voltage shunt converter using PI and ANN controller for cases 1 and 2, respectively. Entire simulation, the shunt converter reference voltage (V_{ref}) is kept at 1 p.u. The reference voltage and measured voltage with the ANN controller of UPFC shows the better voltage profile and it follows reference compared PI controller. The voltage profile is enhanced with, ANN controller compared to the PI controller.

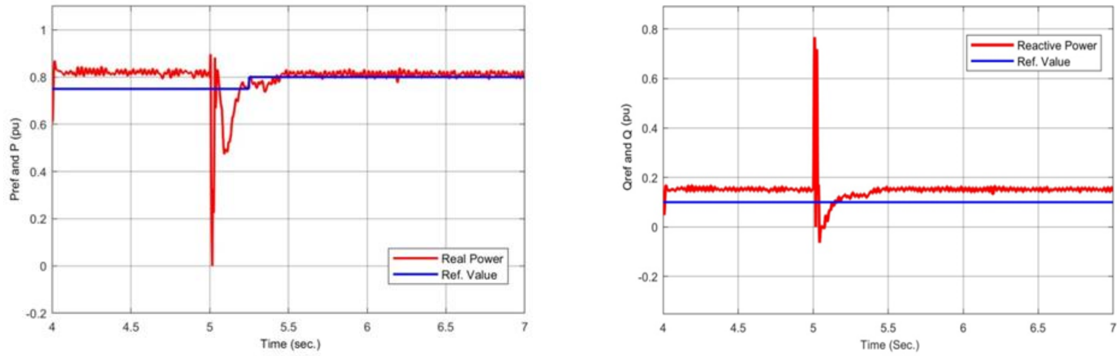
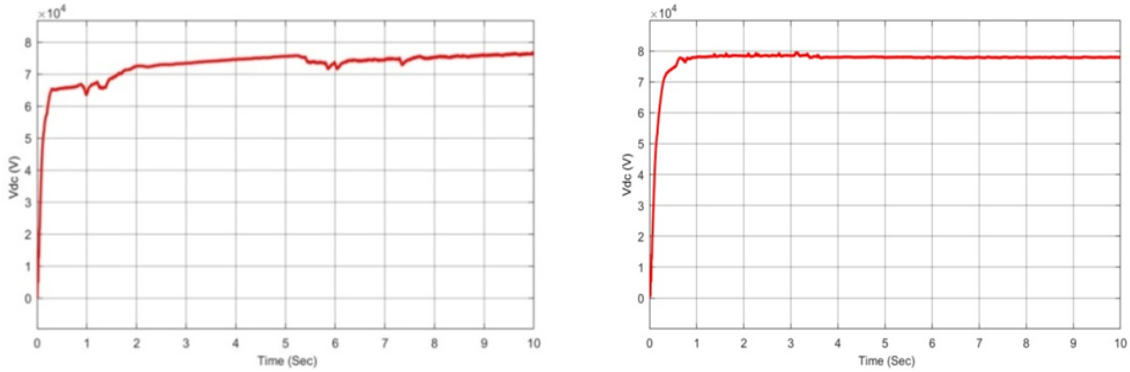
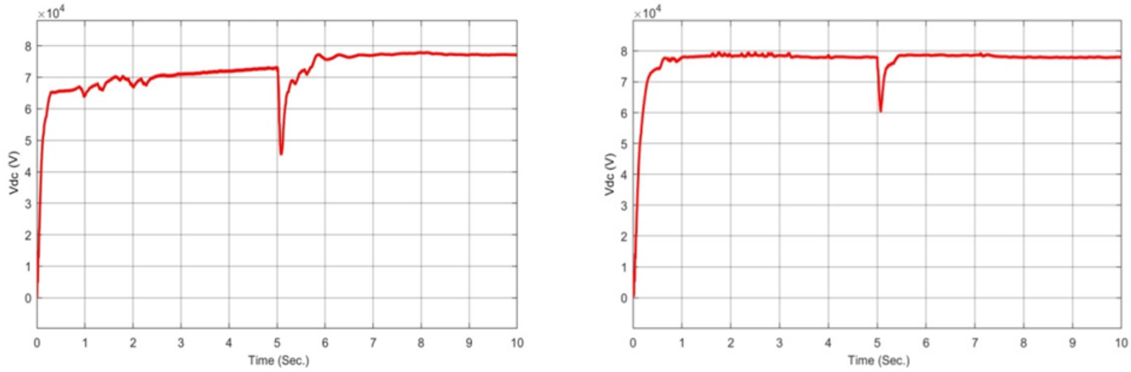


Figure 10. P and Q swings using ANN controller for case 2



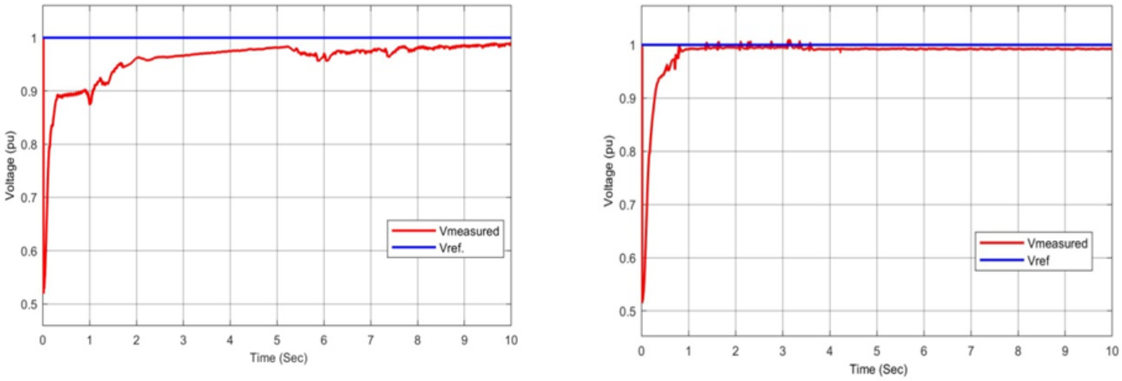
(a) (b)

Figure 11. Voltage profile of DC bus using: (a) PI controller and (b) ANN controller for case 1



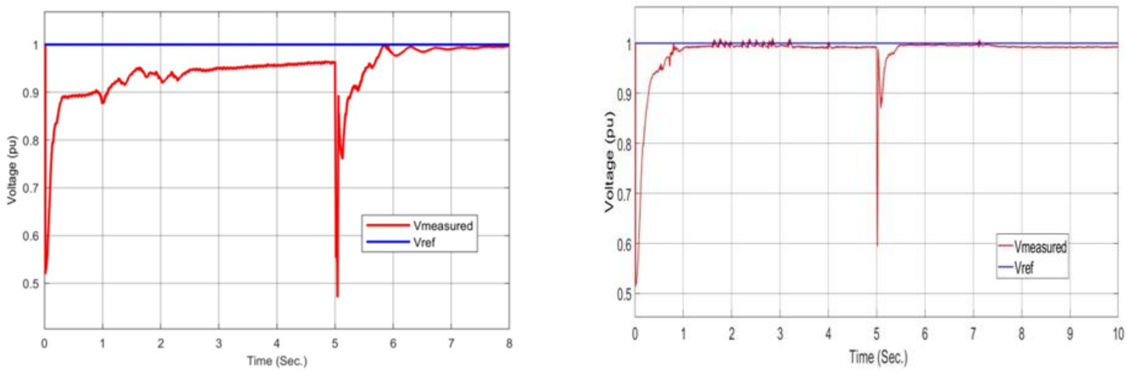
(a) (b)

Figure 12. Voltage profile of DC bus using: (a) PI controller and (b) ANN controller for case 2



(a) (b)

Figure 13. Shunt converter voltage of UPFC using: (a) PI controller and (b) ANN controller for case 1



(a) (b)

Figure 14. Shunt converter voltage of UPFC using: (a) PI controller and (b) ANN controller for case 2

3.3. Case 3: Change in fault location

In this case, the fault location is altered to verify the UPFC's performance. When three-phase to ground fault is applied to bus number 7, the same conditions as in case-2 are taken into account. When a fault is applied at 5 Sec. the power oscillations of P and Q using PI and ANN controllers are shown in Figures 15 and 16, respectively. Compare to ANN controller PI controller oscillations are more in case of real power. In reactive power oscillations, ANN controller shows better compared to PI controller.

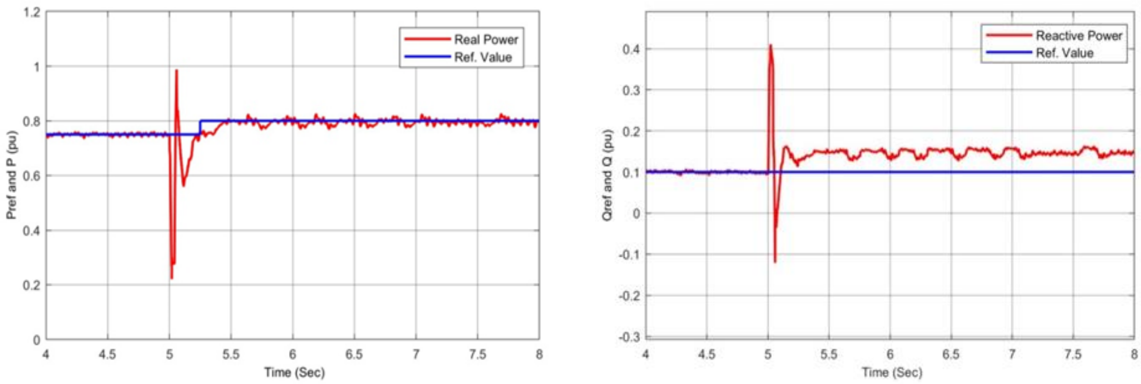


Figure 15. P and Q swings using PI controller for case 3

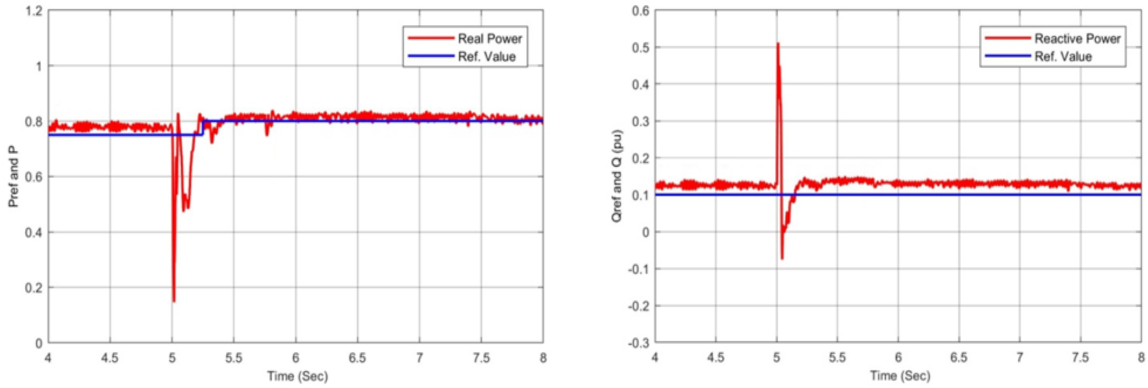


Figure 16. P and Q using swings ANN controller for case 3

4. CONCLUSION

The ANN-based series and shunt controller is designed to minimize the power swing and provide the enhancement of stability of the test system considered. This paper is focused on the design of the current regulator of the series controller of UPFC. Power swing and short circuit analysis is validating the performance of UPFC with the designed controller. The controller using ANN is found better compared to PI controller over different operating conditions shows the robustness of controller. The enhancement in shunt converter voltage profile is found and time response to mitigate the power swings is reduced using ANN controller compared to PI controller.

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