Optimal Placement of Custom Power Devices in Power System Network to Mitigate Voltage Sag under Faults

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ABSTRACT

Voltage sag has been considered to be a serious power quality problem faced by many utilities. Placement of custom power devices may prove to be an effective remedy for solving power quality problems. In this paper, an Artificial Neural Network (ANN) based approach for optimal placement of Distribution Static Synchronous Compensator (DSTATCOM), Dynamic Voltage Restorer (DVR) and Unified Power Quality Conditioner (UPQC) in a power system network has been considered to mitigate voltage sag under faults. Voltage sag under different type of short circuits has been estimated using MATLAB/SIMULINK software. Optimal location of custom power devices has been obtained using a feed forward neural network trained by post-fault voltage magnitude of three phases at different buses. A comparative performance of DSTATCOM, DVR and UPQC in voltage sag mitigation has been studied to select most effective controller out of three controllers for the system. Case studies have been performed on IEEE 14-bus system. The effectiveness of proposed approach of placement of custom power devices has been established on the test system considered.

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1. INTRODUCTION

Voltage sag (also known as voltage dip) has been defined as reduction in the root mean square (RMS) voltage in the range of 0.1 to 0.9 per unit (p.u.) for duration greater than half a cycle and less than one minute [1]. The voltage sag may be caused by faults, increased load demand and transitional events such as large motor switching [2],[3].Occurrence of voltage sag may result in loss of production in automated processes, since a voltage sag can trip a motor or cause its controller to malfunction. Voltage sag can also force a computer system or data processing system to crash. Voltage sag may cause adverse effects on the performance of sensitive loads. According to a study in United States (U.S.), the total damage by voltage sag may amount to 400 Billion Dollars [4].

With the advancement in power electronics, new controllers known as Flexible AC Transmission System (FACTS) have been developed [5]. These controllers have been proved to be quite effective in power flow control, reactive power compensation and enhancement of stability margin in alternating current (AC) networks [6]. Power electronics based controllers used in distribution systems are known as custom power devices [7]. Most promising custom power devices include Distribution Static Synchronous Compensator (DSTATCOM), Dynamic Voltage Restorer (DVR) and Unified Power Quality Conditioner (UPQC). These controllers have been proved to be quite helpful in solving power quality problems [7]. However, due to high cost, and for effective control, these are to be optimally placed in an interconnected distribution network.

Placement of DVR to mitigate voltage sag caused by source side imbalance and harmonics has been considered in [8]. A phase advance compensation strategy to inject optimum amount of energy from DVR to correct voltage sag has been considered in [9]. Design of a 12-pulse DSTATCOM with feed forward compensation scheme has been proposed in [10] to mitigate voltage sag and improve power factor. Placement of DSTATCOM for mitigation of voltage sag and voltage flicker using Kalman filter and its derivatives has been considered in [11]. Phase adjustment in voltage injected by DVR has been proposed in [12] to mitigate voltage sag and swell. An optimum UPQC with minimum Volt Ampere (VA) requirement which aims at the integration of series active and shunt active power filters has been considered for mitigation of unbalanced voltage sag [13]. Placement of DSTATCOM and DVR has been considered in [14] to mitigate voltage sag and swell. Placement of DVR in a small radial distribution system has been considered in [15] to mitigate voltage sag. In phase voltage injection by DVR was considered in this work. A novel sag detection method for the line-interactive DVR has been presented in [16]. Placement of UPQC with minimum active power injection has been considered in [17]. Left shunt configuration UPQC has been considered in [18] for voltage sag mitigation. Sag in supply voltage has been created by injecting a negative voltage in the circuit. In [19], voltage sag and swell mitigation, load balancing, power factor correction and harmonic reduction have been considered using UPFC. The synchronous reference theory has been used to get reference signals for series and shunt active power filters of UPFC. A novel compensation and control strategy for Series Power Quality Regulator (SPQR) for voltage sag/swell and steady-state voltage variation reduction has been proposed in [20]. Two topologies for DVR based on direct converters without direct current (DC) link have been presented in [21]. These topologies are effective in control of voltage disturbances such as sag/swell.

The works presented in [8]-[21] have considered placement of custom power devices in small radial distribution systems. Very limited attempt seems to be made in optimal placement of custom power devices in interconnected power systems. Placement of Static VAR Compensator (SVC), Static Compensator (STATCOM) and DVR for voltage sag mitigation in a predominantly meshed sub-transmission network and a predominantly radial distribution network has been considered in [22]. However, placement of Flexible AC Transmission System (FACTS) controllers have been considered at an arbitrarily selected bus and no specific criterion has been suggested to determine optimal location of such controllers. Optimal placement of FACTS devices based on Nichiang Genetic Algorithm (NGA) has been suggested in [23] to minimize financial losses in the network due to voltage sag. Optimal placement of FACTS controllers using genetic algorithm (GA) based optimization has been suggested in [24] to mitigate voltage sag in a meshed distribution system. An ANN based approach for optimal placement of DSTATCOM to mitigate voltage sag in a meshed interconnected power system has been suggested in [25].

In this paper, optimal placement of DSTATCOM, DVR and UPQC has been considered in an interconnected power system, and their relative performance in voltage sag mitigation has been studied. Since most of the sags in the power system are caused by short-circuit faults in transmission and distribution network, fault simulations/studies have been historically the most popular tool for voltage sag estimation [2]. Classical symmetrical component analysis, phase variable approaches, and complete time domain simulations are among widely used methods for fault simulation in power system [26]. In the present work, time domain simulations have been done using MATLAB/SIMULINK software [27] and voltage sags have been estimated under different type of faults without any controller in the systems, and with placement of DSTATCOM, DVR and UPQC, respectively in the system. Case studies have been performed on IEEE 14-bus system [28].

2. CUSTOM POWER DEVICES MODEL

In the present work three types of custom power devices have been considered. The proposed models of these devices are presented below.

2.1. DSTATCOM model

In the present work, the DSTATCOM has been represented as three independently controllable single phase current sources injecting reactive current in the three phases at the point of coupling (the load bus at which DSTATCOM is placed). The DSTATCOM model has been shown in Figure 1 [25]. The control scheme consists of three control switches which can be set on/off as per compensation requirement. The amount of reactive compensation provided by DSTATCOM can be adjusted to mitigate voltage sag at load buses. The three switches remain open during pre-fault condition and are closed upon occurrence of faults. This permits injection of independently controllable reactive currents under fault, to the three phases of DSTATCOM bus.

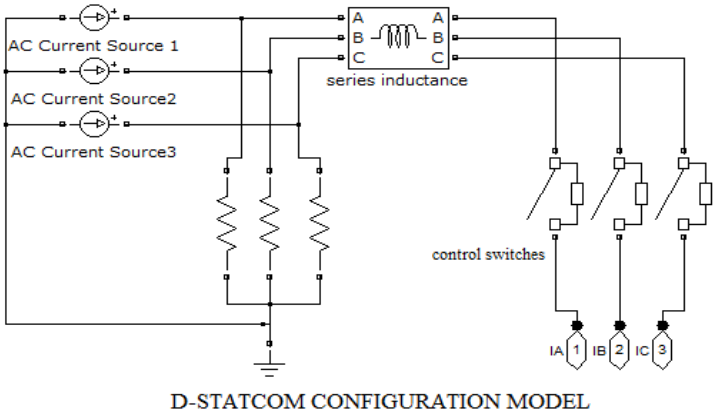


Figure 1. DSTATCOM model

2.2. DVR model

In the present work, the DVR has been represented as three independently controllable single phase voltage sources injecting complex voltages in series with the line in the three phases. The magnitude and angle of injected voltages may be controlled to mitigate voltage sag at load buses. The proposed DVR model has been shown in Figure 2. The control scheme consists of six control switches which can be set on/off as per compensation requirement. During pre-fault condition, the three control switches connected in series with the controllable single phase voltage sources are open and the other three control switches in parallel with controllable voltage sources, are closed. As the fault takes place, the three switches connected in series with independently controllable voltage sources are closed, and the remaining three switches are made open. This permits injection of controllable complex voltages under faults in the three phases of the line.

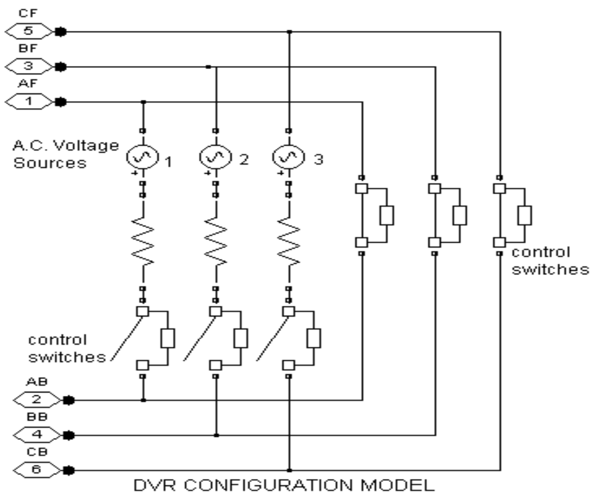


Figure 2. DVR model

2.3. UPQC model

In the present work, UPQC has been considered as combination of DSTATCOM and DVR models suggested in sections 2.1 and 2.2, respectively.

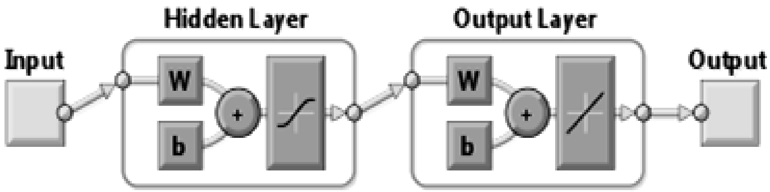
3. RESEARCH METHOD

In this work, feed forward Artificial Neural Network with back propagation algorithm has been used to find optimal location for DSTATCOM placement. The architecture of this network has been shown in Figure 3.

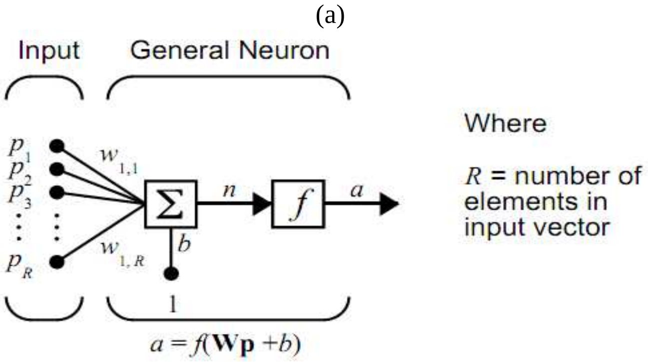
In Figure 3, the input data p(1), p(2), ……….p(R) flow through the synapses weights $w_{i,j}$. These weights amplify or attenuate the input signals before being added at the node represented by a circle. The summed data flows to the output through an activation function f. The neurons are interconnected creating different layers. An elementary neuron with R inputs has been shown in Figure 3. Each input is weighted with an appropriate weight w. The sum of the weighted inputs and the bias, b forms the input to the transfer function f.

Once the network weights and biases are initialized, the network is ready for training. The training process requires a set of examples of proper network behavior—network inputs, p and target outputs, t. During training the weights and biases of the network are iteratively adjusted to minimize the network performance function. The default performance function for feed forward networks is Mean Square Error (M.S.E.) — the average squared error between the network outputs and the target outputs. The gradient is determined using a technique called back-propagation, which involves performing computations backward through the network.

In the proposed neural network architecture there are 20 hidden layers and 14 output layers. This network can be trained to give a desired pattern at the output, when the corresponding input data set is applied. The training process is carried out with a large number of input and output target data. The simulation model of the power system network under study is developed using MATLAB/SIMULINK software [27]. This model is used to find the three phase per unit (p.u.) voltages of all the buses of the network under different type of short-circuits viz. single line to ground (L-G), line to line (L-L), double line to ground (L-L-G) and three phase (L-L-L or L-L-L-G) faults. Post-fault voltages have been used to train a feed forward neural network with back-propagation algorithm. The training process is carried out with large number of input and output target data. The pre-fault p.u. voltages of the different buses have been considered as output target data. The Mean Square Error (average squared deviation of different bus voltages from the target value) is calculated for different buses. The bus having highest Mean Square Error (M.S.E.) is considered as the optimal bus for the placement of DSTATCOM. The placement of DVR is considered in each of the lines connected to the optimal bus. The line where placement of DVR results in the maximum mitigation of voltage sag is considered as the optimal line for the placement of DVR. The UPFC placement is considered in optimal line towards optimal bus. Post-fault three phase voltages of all the load buses are plotted versus time for the four cases – (i) without any controller (ii) with placement of DSTATCOM at the optimal bus (iii) with the placement of DVR in the optimal line and (iv) with the placement of UPQC in optimal line towards optimal bus. The relative performance of DVR, DSTATCOM and UPQC in voltage sag mitigation is studied to decide most suitable controller out of the three controllers considered.



(a)



(b)

Figure 3. Artificial Neural Network architecture

4. RESULTS AND ANALYSIS

Case studies were performed on IEEE 14-bus system [28] having 14 buses and 20 lines. The system consists of 5 synchronous machines three of which are synchronous condensers. There are 11 loads in the system having a net real and reactive power demand of 259 MW and 81.3 MVAR, respectively. The single-line-diagram of the system has been shown in Figure 4.

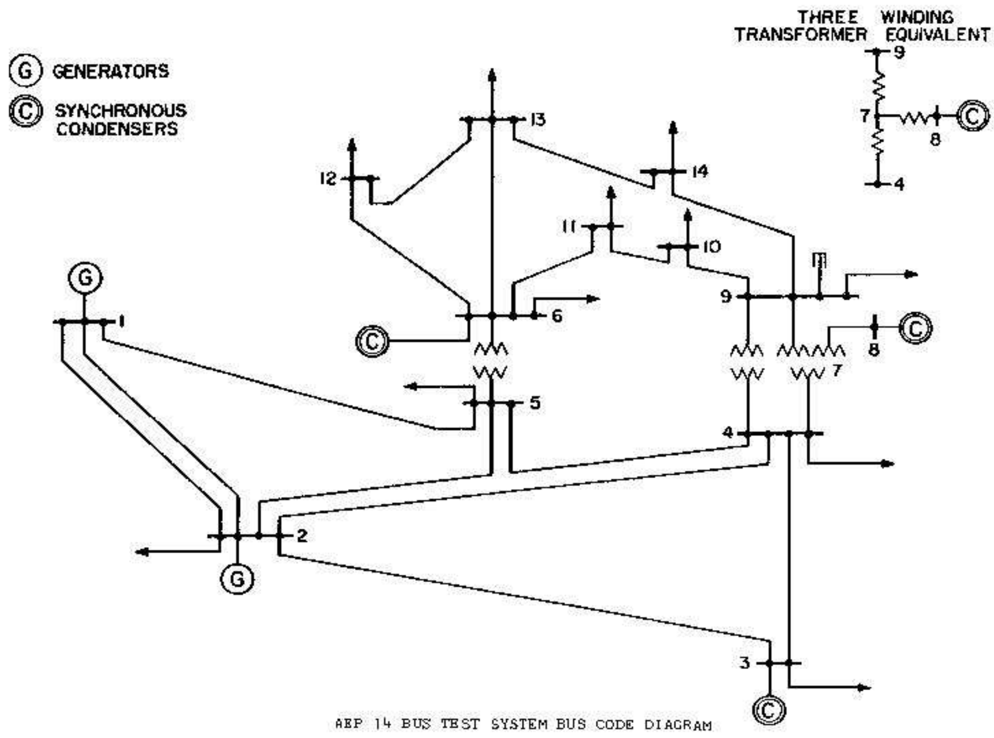


Figure 4. Single-line-diagram of IEEE 14-bus system

The simulation model of IEEE 14-bus system was developed using MATLAB/SIMULINK software [27]. The simulation block diagram of the system has been shown in Figure 5. This plant model has been used to find three phase bus voltages under different type of faults, and for the database collection to train the artificial neural network. The voltage database was prepared by creating L-G, L-L, L-L-G and L-L-L-G fault at different buses during the period 33.33 milliseconds to 83.33 milliseconds. The normal per unit (p.u.) voltages of different buses (taken as 1.0 p.u. in this work) were considered as output target data. Some data were used to test the network and Mean Square Errors (the average squared deviation of post-fault bus voltage from its pre-fault value) were calculated for all the buses. The ANN training performance has been shown in Figure 6. It is observed from Figure 6 that bus-5 has the highest value of Mean Square Error. Hence, bus-5 was considered as the optimal location for the placement of DSTATCOM. Placement of DVR was considered in each of the lines connected to bus-5 viz. line 5-1, line 5-2, line 5-4 and line 5-6, respectively, and post-fault three phase voltages of buses were calculated. It was observed that placement of DVR in line 5-4 was more effective in voltage sag mitigation compared to DVR placement in line 5-1, line 5-2 and line 5-6, respectively. Therefore, line 5-4 was selected as the optimal line for the placement of DVR controller. UPFC placement was considered in optimal line 5-4 towards optimal bus-5. In order to study impact of DSTATCOM, DVR and UPQC in voltage sag mitigation, the DSTATCOM model presented in section-2.1, the DVR model presented in section-2.2 and UPFC model presented in section-2.3 were considered and their SIMULINK model were developed. Post-fault three phase p.u. voltages of all the buses for all type of faults considered viz. L-G, L-L, L-L-G and L-L-L-G faults, were obtained without any controller, with placement of DSTATCOM at bus-5, with placement of DVR in line 5-4 and with placement of UPQC in line 5-4 towards bus-5, using the software package MATLAB/SIMULINK [27]. Post-fault three phase bus voltages at bus-2 and at bus-5 with L-G fault at bus-4 have been shown in Figure 7. Post-fault three phase voltages at bus-6 and at bus-14 with L-L fault at bus-4 have been shown in Figure 8. Post-fault three phase voltages at bus-5 and at bus-13 with L-L-G fault at bus-9 have been shown in Figure 9. Post-fault three phase bus voltages at bus-2 and at bus-3 with L-L-L-G fault at bus-9 have been shown in Figure 10. It is observed from figures 7, 8, 9 and 10 that placement of custom power devices results in significant reduction of voltage sag under all type of short circuits considered. It is also observed from figures 7, 8, 9 and 10 that out of three controllers considered in this work, UPQC is most effective in voltage sag mitigation.

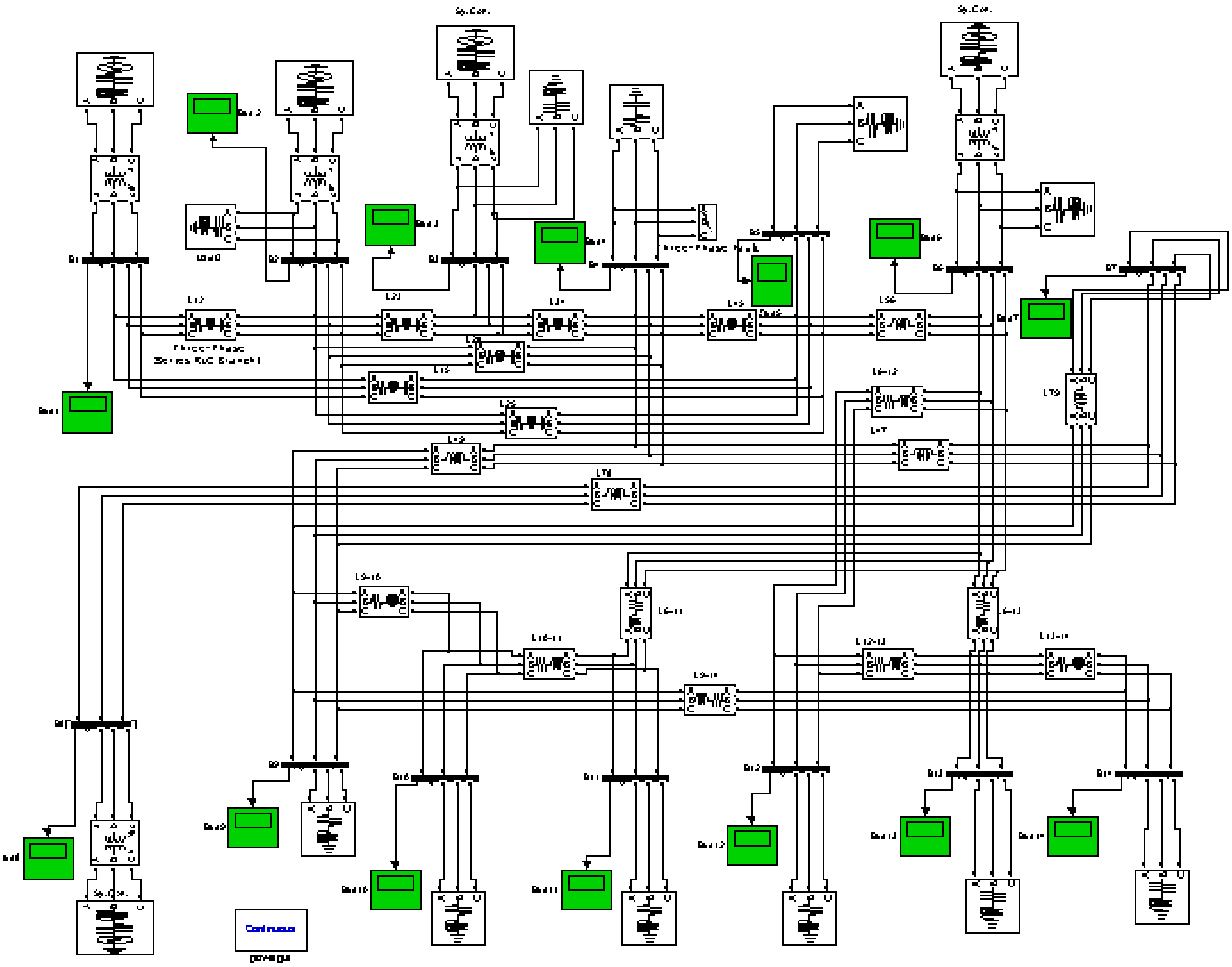


Figure 5. IEEE 14-bus system (MATLAB/SIMULINK) model

Bus No.	M.S.E.
1.	1.15e-04
2.	0.0022
3.	0.0438
4.	0.0035
5.	**0.0682**
6.	0.0030
7.	0.0048
8.	0.0117
9.	0.0057
10.	0.0070
11.	0.0049
12.	0.0092
13.	0.0034
14.	0.0091

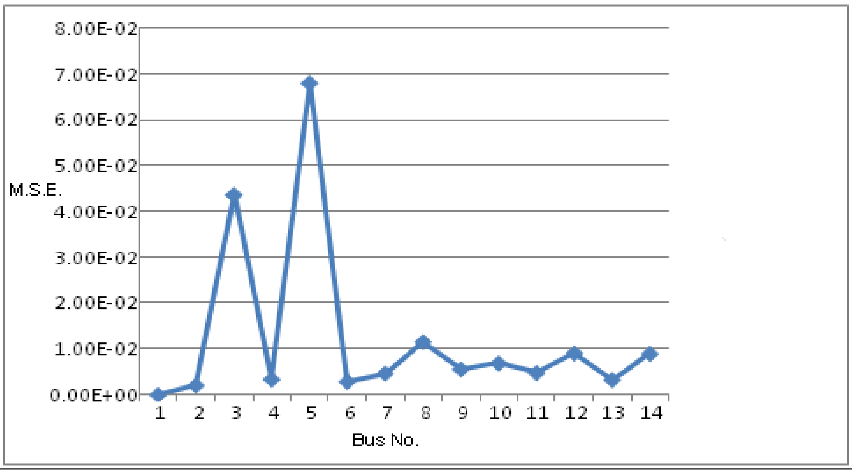


Figure 6. ANN training performance of different buses (14-bus system)

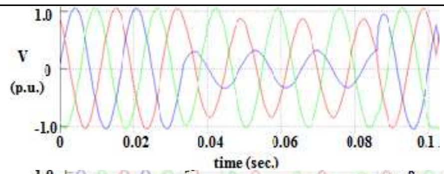
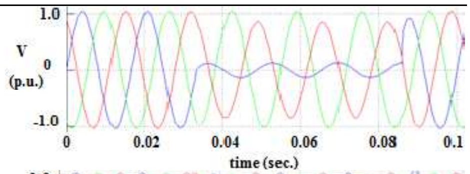
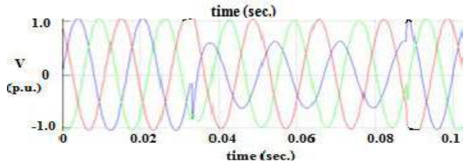
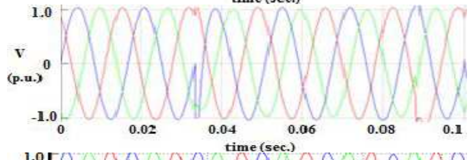
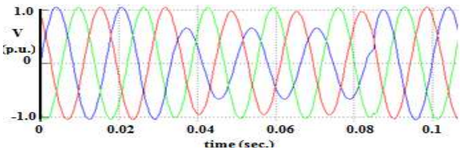
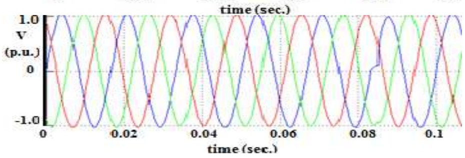
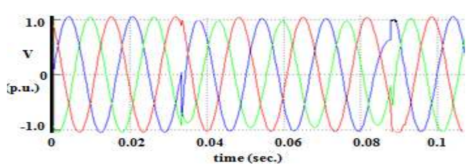
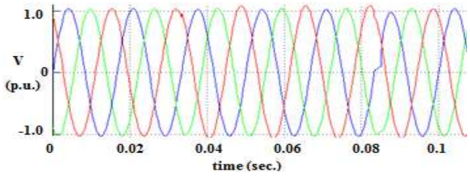
Bus number	bus-2	bus-5
Without controller		
With DSTATCOM at bus-5		
With DVR in line 5-4		
With UPQC in line 5-4 towards bus-5		

Figure 7. Three phase voltages at bus-2 and at bus-5 with L-G fault at bus-4

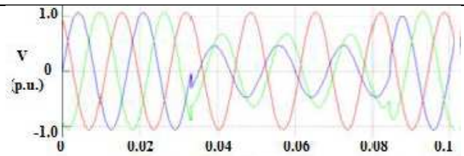
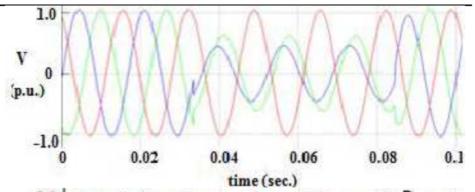
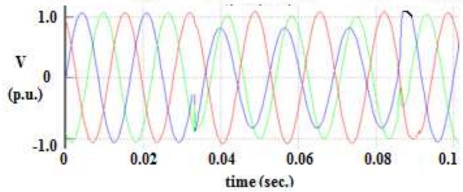
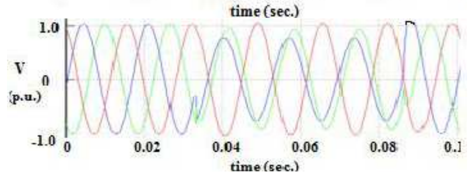
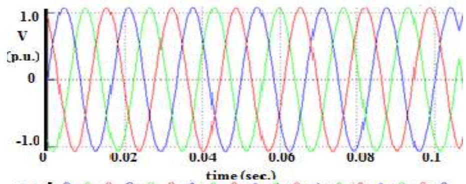
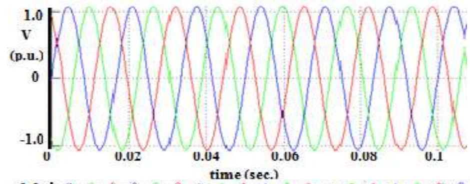
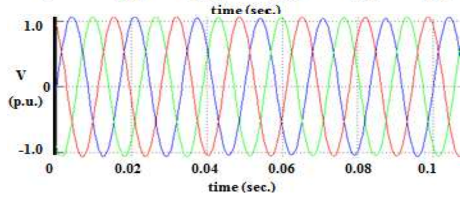
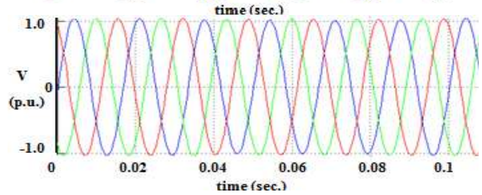
Bus number	bus-6	bus-14
Without controller		
With DSTATCOM at bus-5		
With DVR in line 5-4		
With UPQC in line 5-4 towards bus-5		

Figure 8. Three phase voltages at bus-6 and at bus-14 with L-L fault at bus-4

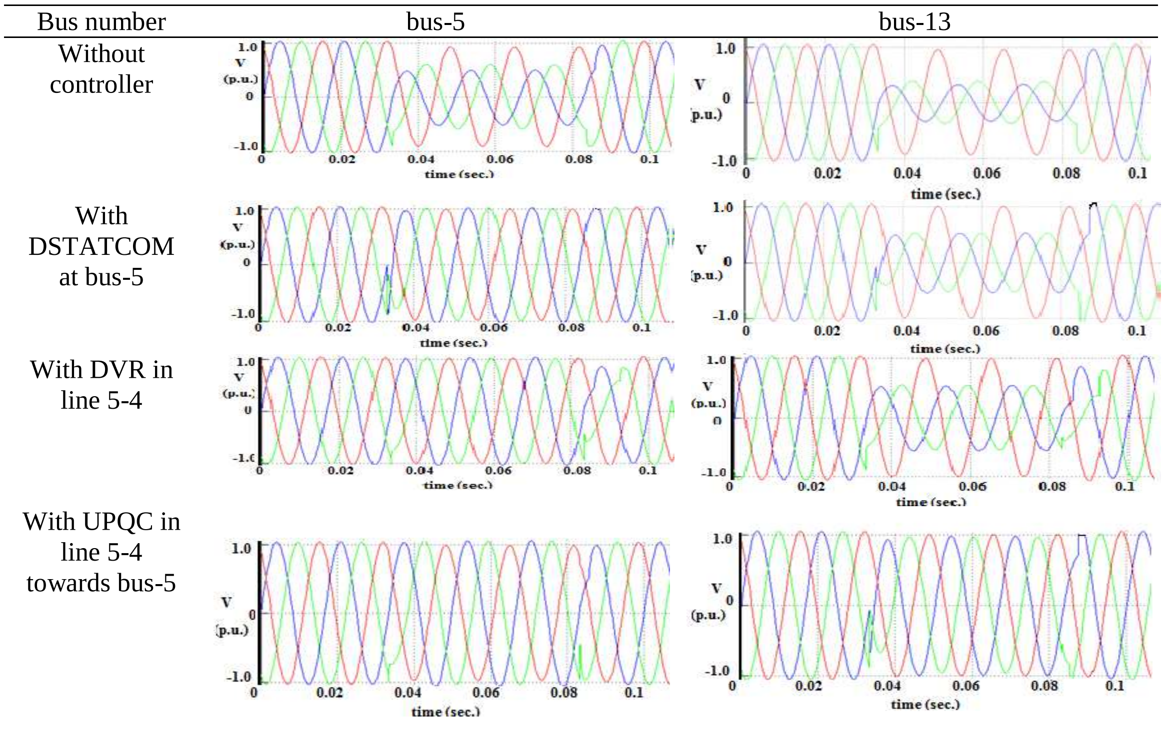


Figure 9. Three phase voltages at bus-5 and at bus-13 with L-L-G fault at bus-9

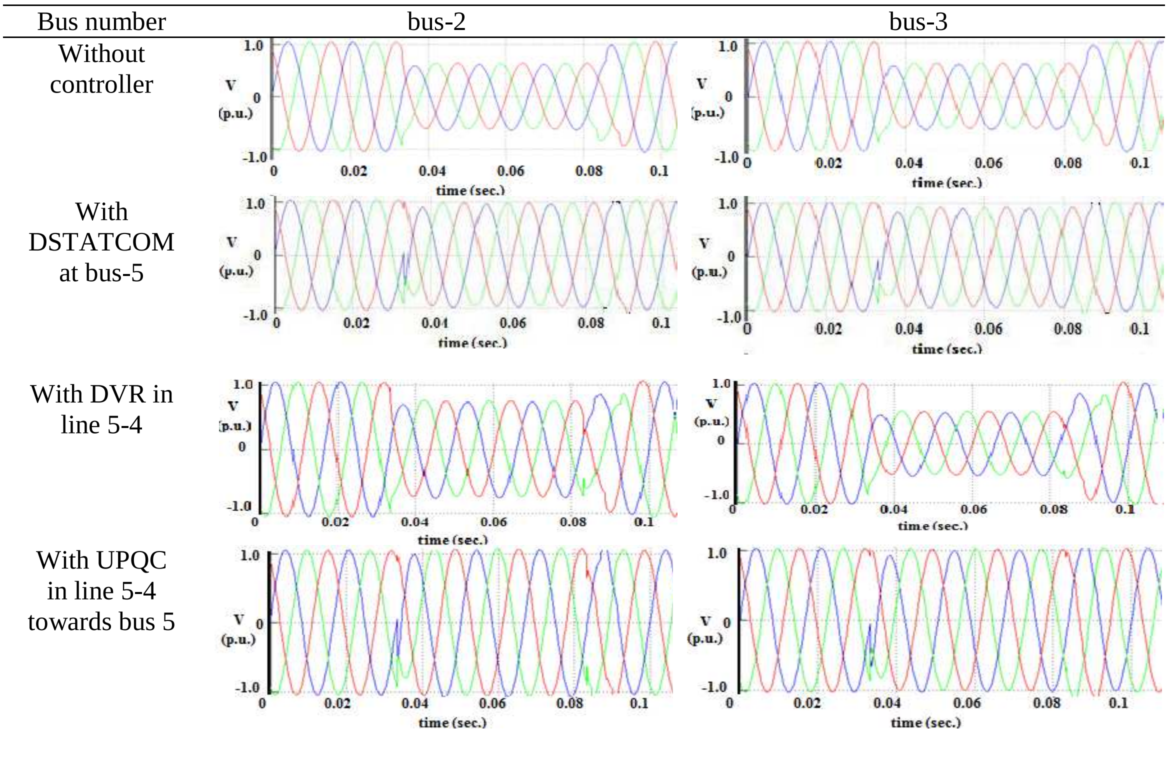


Figure 10. Three phase voltages at bus-2 and at bus-3 with L- L-L-G fault at bus-9

5. CONCLUSION

In this paper, an ANN based approach has been considered for optimal placement of DSTATCOM, DVR and UPQC controller to mitigate voltage sag in an interconnected power system. Case studies have been performed on IEEE 14-bus system with the help of MATLAB/SIMULINK software. The time domain simulations of post-fault voltages have been obtained without any controller and, with DSTATCOM placed at the optimal bus, with DVR placed in the optimal line and with UPQC placed in optimal line towards optimal bus. The simulation results obtained on the test system establish the effectiveness of proposed approach of placement of custom power devices in voltage sag mitigation. The placement of UPQC seems to be more effective in voltage sag mitigation compared to placement of DSTATCOM and DVR controllers.

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