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Optimal placement of Dynamic Voltage Restorer in Radial Distribution System using Artificial Neural Network Approach

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Abstract - *Voltage sag is considered as one of the most severe and frequently occurring event in electric power system, and more prominent in distribution systems, especially in the radial unbalanced networks. Sensitive loads malfunction under these voltage fluctuations, due to a fault or overload. When uninterrupted operation of a load is desired, there is a necessity of a mechanism to dynamically compensate the voltage in the system. Dynamic voltage restorer (DVR) has been considered as an efficient device for such compensation, however, in a distributed network, an optimal placement of this device must be determined to maximize system performance. This paper focuses on a method based on Artificial Neural Network (ANN) to determine the optimal location of DVR in radial distribution systems. Working model of a DVR developed in MATLAB/SIMULINK simulation environment has been implemented to dynamically restore the node voltages back to the pre-fault conditions, whenever a fault occurs in the system. Optimal location for the placement of DVR has been found out using ANN based approach, with the target of minimizing the voltage deviation from the pre-fault voltages. Simulation results with DVR placed in the optimal location for IEEE 15-bus system and a 11-bus typical radial distribution system operating in Nepal, have been presented to verify the effectiveness of proposed scheme.*

Key Words: **Voltage Sag Mitigation, Distribution System, Dynamic Voltage Restorer (DVR), Optimal Placement, Artificial Neural Network (ANN)**

1. INTRODUCTION

Power quality has become an increasing concern to utilities and customers in today's time and the reason for demanding high quality uninterruptible power is the necessity of modern manufacturing and process equipment that operate at high efficiency, which requires stable and defect free power supply. Frequently occurring voltage sag is a prominent power quality disturbance in any distribution system— voltage sag happens when the RMS voltage decreases between 10 and 90 precents of nominal voltage for durations of one-half cycle to one minute [1]. Voltage sag may be caused due to faults, overloading of the electrical network, switching operations, high starting current drawn by heavy electric motor loads or the transfer of load from one power source to another. This results in failure of relays and contactors, tripping of contactors, dim light, fluctuating power, extinction of discharge lamps, malfunctioning of information technology equipment and electrical low-voltage devices [2].

Present methods used for the mitigation of voltage sag are new parallel feeders in the distribution system (distributed generation-DG), power electronic devices and uninterruptible power supplies (UPS).Though there are many different methods to mitigate voltage sag, the use of a Custom Power Devices (CPDs) is considered to be the most efficient method when it comes to voltage stability, reactive power compensation, power factor correction and harmonics level reduction. However, there are different types of CPDs, and the choice of these devices depends on the system operation and requirements. DVR, a series compensating device, is effective modern CPDs used in power distribution networks as it is cheaper, compact, and has a vibrant reaction to the disturbances with the ability to control active and reactive power flow. It is normally installed in the distribution system between the supply and the critical load feeder at the point of common coupling (PCC) which protects the end-consumer load from any unbalance of voltage supply even when the source side voltage is distorted. Effectiveness of voltage sag mitigation in distribution systems via DVR has been discussed comprehensively in [3]. In [4] authors have described DVR operating principles and voltage restoration methods at the PCC. Similarly, [5] discussed the performance of a DVR used for improving the voltage quality of distribution systems.

To optimize operation cost and for effective control, DVR must be optimally placed in distribution networks such that it is economically viable and meets required quality and reliability. The problem of optimally selecting the location of CPDs has been a wide area of research and several approaches like Particle Swarm Optimization (PSO), Genetic Algorithm (GA), Sensitive Index method, Artificial intelligence (AI) techniques, etc. have been implemented for determining optimal location of CPDs. Several research works have been carried out in the domain of optimal placement of CPD in distribution system. Distributed voltage sag mitigation by optimal placement of DVR using stochastic assessment has been studied in [6]. Authors in [7] have formulated a method for optimal placement of DVR in distribution systems using PSO algorithm. Similarly, paper [8] discusses the optimal location and sizing of DVR using optimization technique based on firefly algorithm. Similar works has been carried out in mesh distribution systems using sensitivity approach [9]. Use of ANN as an optimization tool has become very popular in finding solution to multi-objective optimization problem that would otherwise involve complex computations and measurements. In paper [10] optimal placement of CPDs in interconnected system has been carried out using ANN approach. Similar optimization approach has been used in paper [11] to find the optimal location of Distribution Static Compensator (DSTATCOM) in distribution system.

Several other works have been documented with ANN being used as a tool to determine optimal location of static compensation devices. However, very few studies have been performed for the optimal placement of DVR in radial distribution networks. Few works done in this front have presented CPDs as controllable voltage sources or current sources with control switches [10, 11].

This paper presents the ANN based approach for the optimal placement of DVR in radial distribution systems, with detailed modeling and control of DVR developed in MATLAB/SIMULINK simulation environment. The developed model and the results of operation of DVR at optimal location determined have been tested and validated using IEEE-15 bus radial distribution test system and a typical Nepalese radial distribution system. The simulations have been done using MATLAB/SIMULINK and voltage sags were studied under different type of faults. ANN has been created with network inputs and targets outputs and trained with Levenberg Marquardt algorithm and optimal location of DVR has been identified using the training performance. The speed and the parallelism of the calculations are the main advantages of these techniques. The developed DVR model is placed in the optimal location in order to mitigate voltage sag under faults.

In section 2, modelling and control of DVR is discussed, section 3 discusses the basic working of ANN and building and training of ANN for the optimization problem. Similarly, system description and methodology for optimal placement of DVR in IEEE-15 bus system and a 11-bus test system have been discussed in section 4. The results of simulation and discussion on the results are presented in section 5. Conclusions of the study and recommendations for future works have been presented in section 6.

2. DVR MODELLING AND CONTROL

DVR is a solid-state power electronic-based compensator which is connected in series to the utility's primary distribution system through an interfacing transformer which operates by injecting a voltage of the required magnitude and frequency in series with the incoming supply voltage so as to restore the load voltage to the pre sag state [12]. Its main components are energy storage unit, filter unit, inverter circuit, control unit and series injecting transformer. This process involves insertion of real/reactive power from DVR to distribution feeder for voltage compensation. DVR can operate in three modes, namely standby mode (during steady state), protection mode and injection mode (during sag). DVR can be represented as an equivalent circuit as shown in Fig- 1.

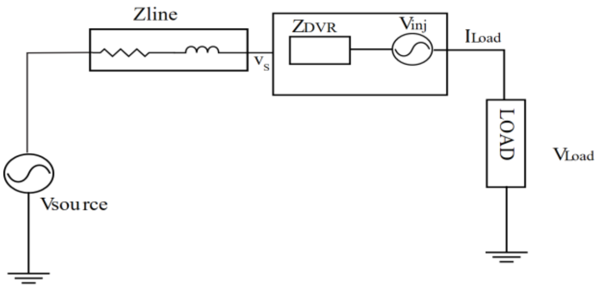

Fig -1: Equivalent circuit of DVR

The series injected voltage of the DVR can be written as:

$$V_{inj} = V_{load} - V_s$$

where V_{load} is the desired load voltage magnitude and V_s is the source voltage during the sag.

2.1 Control Strategy

The effectiveness of the DVR depends on the performance of the control technique. The basic functions of a controller in a DVR are the detection of voltage sag in the system during any faulted scenario, computation of the correcting voltage, generation of trigger pulses to the PWM based DC-AC inverter, correction of any deviation in the series voltage injection and termination of the trigger pulses when the event has passed [13].

A simple schematic diagram for the control of one of the phases of a three phase DVR is shown in Fig-2.

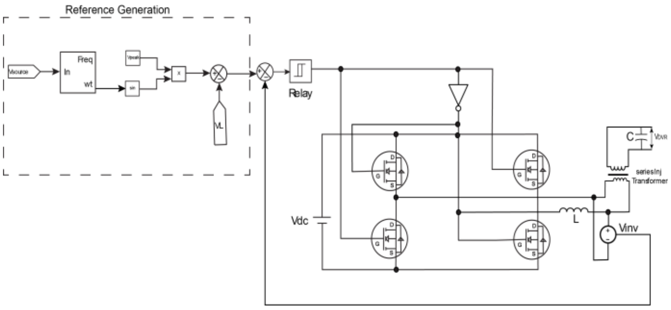

Fig -2: Control scheme for DVR

Based on the peak value of desired voltage at the load terminal and the phase of source voltage, a sine wave that represents the desired voltage across the load is generated and this instantaneous voltage is compared with the actual voltage that appears across the load. This difference gives the measure of amount of voltage to be injected by the compensator to bring back the load voltage to the desired value. For a voltage sag/swell, DVR should be able to maintain the phase of the injected voltage such that the total voltage across the load voltage does not change.

When a fault occurs at the load bus or on the line between the source and the load, the load voltage will undergo a sag and this sag in voltage gets reflected in the reference signal by an increase in the value previously zero to an amount by which the voltage has undergone sag. At the instant of fault initiation, the output voltage from the inverter is zero. The reference voltage is compared with inverter voltage and then the difference is fed to a relay. The relay output is used to switch the MOSFETs through gate pulses, such that the inverter injects the voltage to match the reference signal. DVR keeps injecting the voltage until the sag has been cleared. After the fault has been mitigated, the reference signal becomes zero as the voltage across the load is same as the desired voltage. The output of the DVR tracks the reference through a simple feedback control method.

The output voltage from the inverter is passed through a LC filter to obtain a smooth sinusoidal, injection voltage. This voltage is then injected through an injection transformer, connected in series with the line so that the injected voltage compensates the amount by which the load voltage has undergone sag.

3. ARTIFICIAL NEURAL NETWORK

ANN is a data processing system consisting of a large number of simple, highly interconnected processing elements (artificial neurons) in an architecture inspired by the structure of cerebral cortex of the brain. ANN is specified by a neuron model, architecture and a learning algorithm. Neuron model is the information processing unit of the neural network, architecture is a set of neurons and links connecting neurons and each link has a weight and a learning algorithm is used for training the network by modifying the weights in order to model a particular learning task correctly on training sets [14].

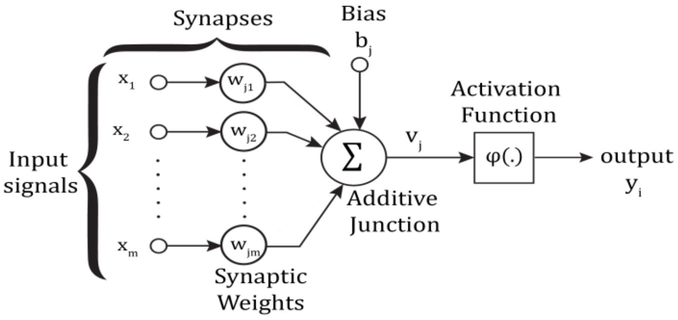

Fig -3: Artificial neurons

A simple artificial neuron model is shown in Fig-3. A neuron consists of a set of links associating the neuron inputs with weights, an adder function which computes the weighted sum of the inputs, activation function for regulating the amplitude of the neuron output and an external parameter known as bias. Several neurons can be situated in parallel, forming a layer, and several layers can be connected in cascade, forming a multilayer structure. ANN consists of artificial neurons and is organized in three interconnected layers: input, hidden, and output. After the initialization of network weights and biases, the network is ready for training.

3.1 Building and Training of ANN

Neural network fitting tool in neural network toolbox by MATLAB 2019a has been used to build the ANN which helps to select data, create, train and analyze a network and also evaluate its performance using mean square error (MSE) and regression analysis [15]. For the training of the neural network inputs and target outputs were determined and the units were arranged in a layered feed forward topology called Feed Forward Neural Network (FFNN). The FFNN has been created with input, output and hidden layer. The hidden layer uses tan sigmoid function and the output layer uses purelin function. Before training, the samples were categorized into training, testing and validation samples. This process has been shown in a simplified flowchart in Fig- 4.

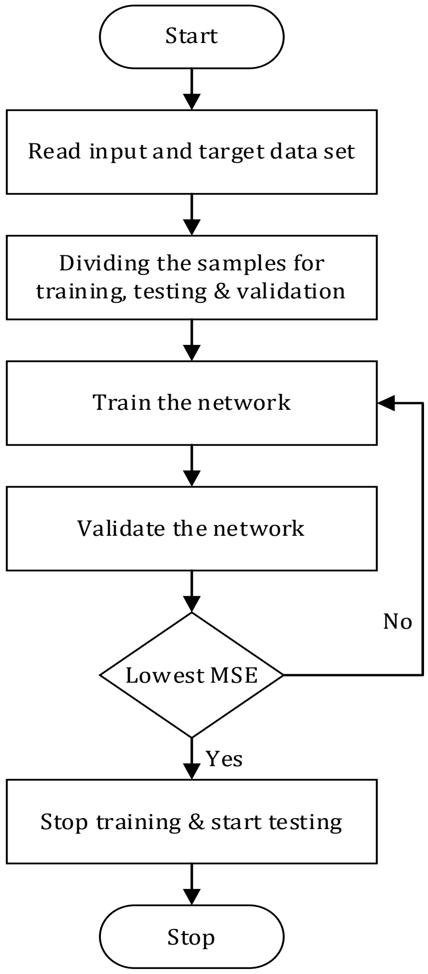

Fig -4: Flowchart for ANN implementation

In the present work, Levenberg Marquardt backpropagation (trainlm), network training function has been used which is considered to be fastest backpropagation algorithm. During training the network training function updates weights and biases of the network to minimize the network performance function. As the iteration process continues, the training and validation error usually decreases. The overtraining of the network is also not beneficial as it tends to increase the validation error. After some specific number of iteration, it would be convenient and time saving to stop the training.

4. OPTIMAL PLACEMENT OF DVR

4.1 Test System Description

Case study 1: IEEE 15 bus test system

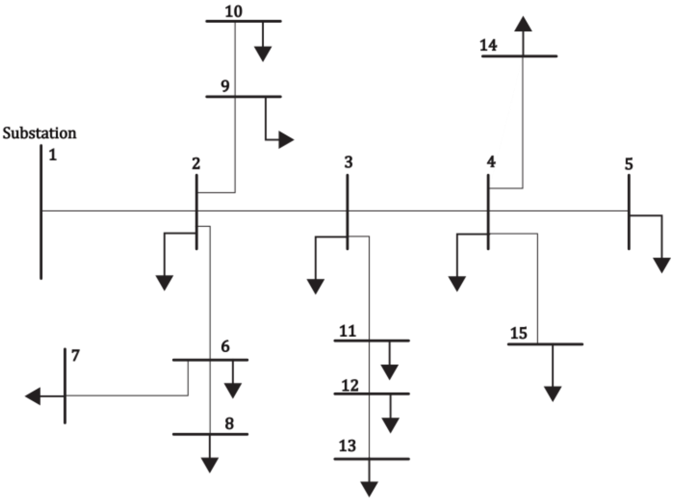

Fig -5: Single line diagram of 15 bus test system

A standard IEEE-15 bus test system, single line diagram of which is shown in Fig- 5, has been considered for analysis. It is composed of 15 buses including 1 generator bus and 14 load buses. All loads were treated as constant PQ loads. The total real and reactive power demand of the system are 1226.399 kW and 1251.1782 kVAR, respectively [16].

Case study 2: Nepalese Radial Distribution System

For second case study a typical Nepalese radial distribution feeder under operation is taken. The 'Sallaghari' feeder from 'Thimi' switching station has been considered for the analysis. The feeder is drawn from 11/0.4 KV Thimi switching station. As seen from the single line diagram of the feeder in Fig- 6, it consists of 11 buses composed of 1 generator bus and 10 load buses. All loads were treated as constant PQ loads. The net real and reactive power demand on the feeder is 1103 kW and 1116 kVAR respectively [17].

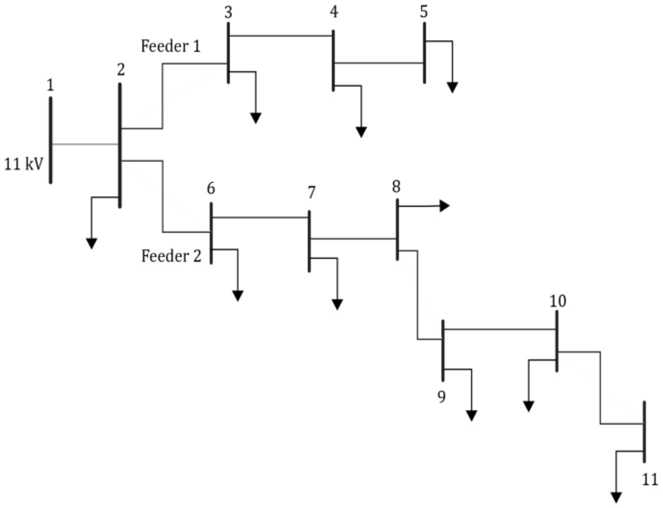

Fig -6: Single line diagram of Thimi-Sallaghari feeder

4.2 Methodology

The simulation model of both the test systems have been developed using MATLAB/SIMULINK software. The developed models have been analyzed by conducting short circuit studies on them and the time domain simulations have been done. The per unit (p.u.) three phase voltages of all the load buses of the network under different type of short circuits i.e single line to ground (L-G), line to line (L-L), double line to ground (L-L-G) and balanced three phase(L-L-L-G) faults for the duration of 0.1 second have been determined. The collected post fault- voltages were considered as input data and the nominal p.u. voltages of different buses were considered as output target data. Then the network weights and bias were initialized. The network has been trained using Levenberg-Marquardt algorithm. The training of the network results in error and output matrices. For all the load buses, average squared deviations of different bus voltages from the target value were calculated which provides the information about the most vulnerable bus of the system based on highest voltage deviation from the target. The bus having the highest deviation from the target has been considered as optimal location for the placement of DVR.

5. RESULTS AND DISCUSSION

5.1 Voltage Sag/Swell mitigation by DVR

The independent operation of the developed DVR model was observed by simulating a three phase fault for a period of 0.1seconds from t=0.2 to t=0.3s to create a voltage sag across the load and voltage swell was also simulated by injecting voltage externally from time t=0.4 to 0.5s. The p.u. load voltage, without the operation of DVR is as shown in Fig-7(a).

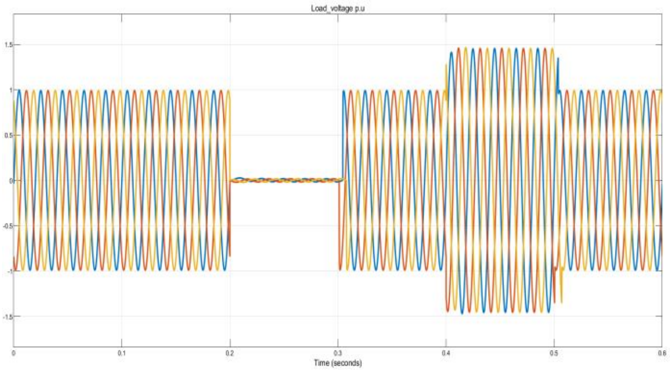

Fig -7(a): Load Voltage (without DVR)

After the occurrence of voltage sag and swell, DVR has been placed in series with a line feeding a load and the p.u. voltage across the load is studied. It can be clearly observed from Fig- 7(b) that when the source voltage has undergone sag from t=0.2 to 0.3 s and swell from t= 0.4 to 0.5 s, DVR has either injected or absorbed the power into the load to maintain a constant voltage across the load. DVR has injected voltage (power) into the load from t=0.2s to t=0.3s for voltage sag whereas, DVR has absorbed the excess voltage from t=0.4s to 0.5s for voltage swell. It is observed that, the voltage injected by DVR, during sag/swell varies to bring the load voltage back to 1 p.u. from any deviated values.

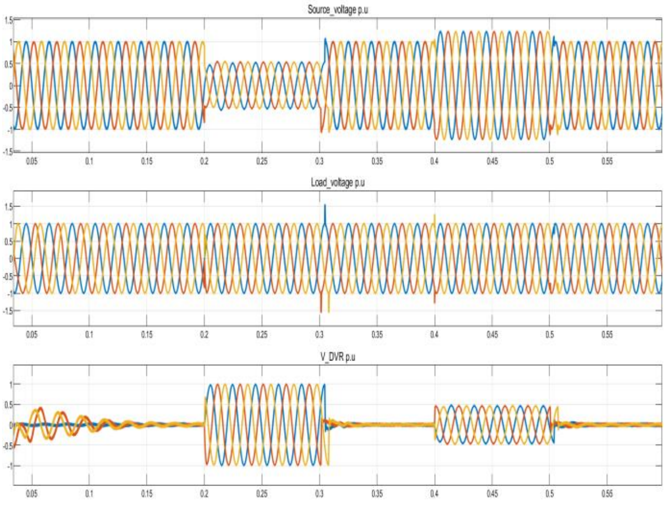

Fig -7(b): Bus voltage with DVR (i) Source voltage (ii) Load voltage (iii) DVR injected voltage

It has been shown that the developed DVR model mitigates voltage sags and swells occurring in the load, even when the source side voltage is distorted. This model is tested in different radial distribution systems, to effectively restore the voltages in the system buses under certain undesired events.

5.2 Determination of optimal location and placement of DVR

Case study 1: IEEE 15 bus test system

It was observed that bus-3 has the highest value of MSE. Placement of DVR was considered in each line connected to bus3 i.e. line 3-2, line 3-4 and line 3-11 and the post fault three phase voltages of buses were evaluated. It was observed that the placement of DVR in line 3-2 was more effective in voltage sag mitigation. Hence, line 3-2 has been considered as the optimal location for the placement of DVR.

Table -1: MSE at different buses for IEEE-15 bus system

Bus No.	MSE
2	0.005710681
3	***0.026843883***
4	0.004709069
5	0.00964141
6	0.011139057
7	0.016793617
8	0.006492284
9	0.01561628
10	0.006257219
11	0.009707834
12	0.016040048
13	0.008363755
14	0.005410275
15	0.010302398

For the validation of the result obtained for optimal location, DVR was placed in the line 3-2 and operated under different faulted scenario. A three-phase balanced fault was simulated in bus-2, for a period of 0.1s from t=0.2s to t=0.3s. When fault occurs in bus-2, the bus voltages in the other healthy buses also undergo sag. It can be seen from Fig- 8(a) that, all the buses that originate radially from bus -3, have felt the effect of the fault in bus-2 and a significant amount of voltage sag were observed in the buses going radially after bus-3 where the voltage has reduced to less than 0.4 p.u. This voltage level is not acceptable for the operation of loads in those buses and can cause severe malfunctioning of the loads.

With the placement of DVR at optimal location, simulations were carried out during the faulted scenario. The voltage profiles of the buses, going radially outwards from the line 3-2, where DVR was placed are shown in Fig- 8(b). It was clearly observed from Fig- 8(a) and 8(b) that, during a faulted scenario in the system, with optimal placement of DVR, we were able to restore the voltage of system buses to pre-fault condition.

In fact we can observe that pre-fault voltage of the buses going radially after bus 3 are in the range of 0.97 p.u in bus-3 and reducing upto 0.94p.u. in bus-5 and bus-14 as expected in a radial distribution system. However, with the placement of DVR in the optimal location, not only has the post fault voltage been restored back but also the pre-fault bus voltages without DVR have also been improved with bus 3 having its voltage at almost 1p.u. (pre-fault, and post-fault) and the voltage at other buses also seeing significant improvement in their voltage profile.

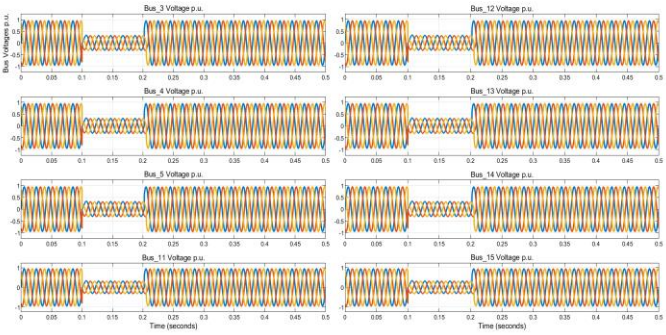

Fig -8(a): Bus voltages in p.u. with fault in bus 2 (without DVR)

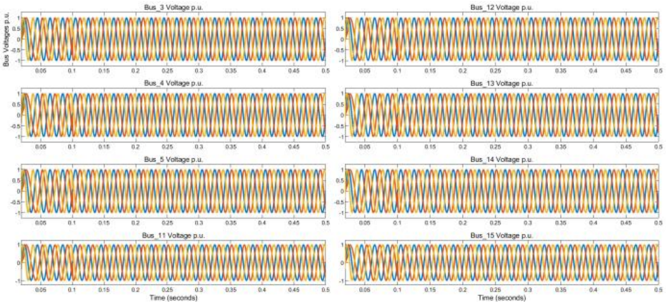

Fig -8(b): Bus voltages in p.u. with fault in bus 2 (with DVR in line 3-2)

Case Study 2: Nepalese radial distribution system

It was observed that bus-6 has the highest value of MSE.

Table -2: MSE at different buses for Nepalese 11 bus system

Bus	MSE
2	0.0612
3	0.0344
4	0.00792
5	0.01317
6	***0.0885***
7	0.01069
8	0.00414
9	0.00236
10	0.02102
11	0.02527

Placement of DVR were considered in each lines connected to bus6 i.e line 6-2 and line 6-7 respectively and post fault three phase voltages of buses were evaluated. It was observed that the placement of DVR in line 6-2 was more effective in voltage sag mitigation compared to DVR placement in line 6-7. Hence, line 6-2 has been considered as the optimal location for the placement of DVR.

For the validation of the results obtained for optimal location, DVR was placed in the line 6-2 and operated under different faulted scenario. A three-phase balanced fault was simulated in bus-4, for a period of 0.1s from t=0.2s to t=0.3s. When fault occurs in bus-4, the bus voltages in the other healthy buses also undergo sag. It can be seen from Fig- 9(a) that, all the buses originate radially from bus 6, have felt the effect of the fault in bus 4 and a significant amount of voltage sag were observed in the buses going radially after bus-6, where the voltage has reduced to around 0.6 p.u. which can be detrimental for any loads operating at those buses.

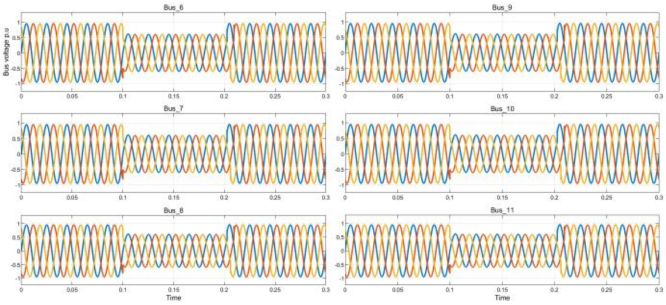

Fig -9(a): Bus voltages in p.u. with fault in bus 4 (without DVR)

With the placement of DVR in the optimum location, that is line 6-2, the simulations were carried out during the faulted scenario and the voltage profile in the buses going radially outward from line 6-2, is as shown in Fig- 9(b). It can be clearly observed from Fig- 9(a) and 9(b) that, during a faulted scenario in the system, with optimal placement of DVR, it is able to restore the voltage of system buses to pre-fault condition.

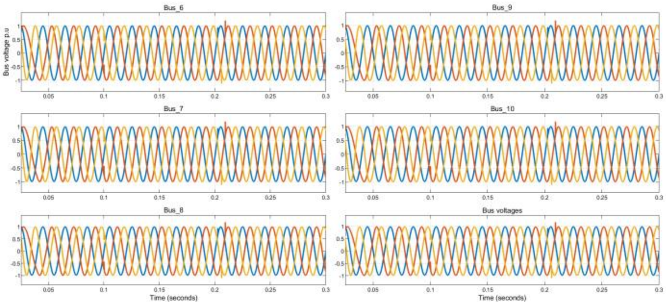

Fig -9(b): Bus voltages in p.u. with fault in bus 4 (with DVR in line 6-2)

It can also be observed that pre-fault voltages of the buses going radially after bus-6 are in the range of 0.96 p.u. in bus-6 and reducing upto 0.94p.u. in bus 11 as expected in a radial distribution system. However, with the placement of DVR in the optimal location, not only has the post fault voltage been restored back but also the pre-fault voltages without DVR have also been improved with bus-6 having its voltage at almost 1p.u. (pre-fault, and post-fault) and the voltage at other buses also seeing significant improvement in their voltage profile.

6. CONCLUSION

In this paper, a method based on ANN for determination of optimal location for the placement of DVR in radial distribution systems has been presented. The optimal location for placement determined by evaluating the Mean Squared Errors at each bus under all possible faulted scenarios was found out to be convenient and effective in mitigation of post-fault voltage sags seen at various buses of radial distribution systems. It has been shown through the results obtained by case studies done in standard IEEE-15 bus system and a typical Nepalese 11-bus radial distribution network, that a DVR placed at the optimal location not only restores the post-fault bus voltages back to rated voltage levels but also improves the overall voltage profile of the radial distribution systems. With the idea of decentralized voltage regulation and control being the main focus for distribution systems, especially with the advent of novel Smart Grid technology, ANN based approach for finding the optimal location for the placement of those decentralized regulators will have a much pronounced application. Use of ANN will be more relevant to solving the issues with voltage sag mitigation as practical implementation of AI into power system applications has come out as an effective way of solving complex problems by finding trends and patterns with various events occurring in power systems.

In more complex and interconnected distribution systems a large number of such DVRs need to placed and formulation of a more complex multi-objective optimization problem has to be carried out to perform decentralized voltage restoration, in such scenario training the ANN and control of DVR will have to be improvised based on the system and operational requirements.

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