S. Chandrashekhar Reddy[1], P.V.N.Prasad[2], A.Jaya Laxmi[3]

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Hybrid Approach for Voltage Sag Mitigation in Distribution System by Optimal Location and Size of Distributed Generation

Voltage sag is one of the severe forms of power quality problems in distribution network. It should be mitigated as soon as possible for preventing the load from getting damaged. In the paper, a hybrid approach for voltage sag mitigation in distribution system is proposed. Mitigation is performed by optimally installing DG units in the network. In the hybrid approach, we use two well known Artificial Intelligence techniques (AIs) which are Genetic Algorithm (GA) and artificial neural network (ANN). The proposed approach consists of 3 stage operation. First, a training dataset for ANN with 2 cases is developed using GA. In second stage, ANN is trained and tested with generated training dataset. At end of this stage, ANN is able to provide the optimal locations and sizes for the cases of single DG connection or double DG connection. In third stage, again GA is employed but this time; it is used to optimize the real and reactive powers to be generated by connected DGs. The performance of the proposed approach is tested on IEEE 30 bus system using MATLAB platform. It is showed that the proposed approach is able to mitigate the voltage sag in bus voltages along with the benefits of reducing total power loss and voltage profile improvement in all buses.

Keywords: Voltage sag, Distribution system, Distributed Generator (DG), Genetic Algorithm (GA), Neural network (NN), Newton-Raphson Method

1. Introduction

In power distribution system, voltage sag is the most severe power quality problem which shares around 70% of total power quality problems possible [1]. It can destroy the most important power electronic devices such as computers, industrial control systems, adjustable-speed drives [2], programmable logic controllers (PLC) and robotics [3] thus lead to economical losses [4]. Voltage sag occurrence is referred when the voltage amplitude is decreased up to 10 to 90% of its peak value for the duration of half cycle to one minute [5][6]. This non desirable characteristic of voltage can be noticed when lightning strikes, equipment failures, power line contacts, faults, short circuits, sudden load changes, transformer energizations and large motor start ups are appeared [7] [8].

There are different ways such as dynamic voltage restorer (DVR) [9], flexible AC transmission systems (FACTS), artificial intelligence techniques and distribution generator (DG) installations used to mitigate voltage sags in power systems. DG is a small-scale power generation situated near the load centers in order to reduce the total cost of service and total power losses [10]. Some other benefits of DG units in distribution level are peak load sharing, enhanced system security and reliability, improved voltage stability, grid strengthening, reduction in the on-peak operating costs etc [11]. The main motive of applying DGs is to increase rational use of energy, deregulation or competition policy, diversification of energy sources, availability of modular generating plant, ease of finding locations for smaller generators, shorter construction time and lower capital costs for smaller plants, and proximity of the generation plant to heavy loads, which reduces the transmission costs [12].

Energy sources such as gas turbines, micro turbines, IC engines, wind electric conversion systems (WECS), geothermal systems, solar-thermal-electric systems, photovoltaic systems (PV) and fuel cells are promising DGs in distribution system [13][18].

[*] Corresponding author: S.Chandrashekhar Reddy, Assoc.Professor , Department of Electrical & Electronics Engineering, Christu Jyothi Institute of Technology & Science, Jangaon ,Warangal-506167 ,A.P-India
E.Mail: chanduredy6@yahoo.com

Generally, DG units are integrated in the existing distribution system and studies have been done for finding the best location and size of DGs to produce utmost benefits [14][20]. The main goals that are considered while identifying the optimal DG location and size are the minimization of transmission loss, maximization of supply reliability, maximization of profit of the distribution companies etc [15]. Due to substantial costs, the DGs should be allocated properly with optimal size for enhancing the system performance in order to minimize the system loss as well as to improve the voltage profile while maintaining the system stability [16][19]. The effect of placing DG on network indices will differ based on its type and location and load at the connection point [17].

In this paper, voltage sag mitigation of distribution system is performed by optimally choosing DG unit's locations and sizes. The optimization of DG unit installation is achieved by hybrid approach involving GA and ANN. This hybrid approach consists of 3 stages. First, training dataset for ANN is computed by GA, secondly ANN is trained based on the generated training dataset and in last stage GA is again executed to optimize the generating real and reactive powers of connected DGs. The detailed description of the proposed approach is shown in Section 2. In Section 3, the performance of the proposed approach is validated using implementation results and discussions.

2. Proposed hybrid approach for voltage sag mitigation in distribution system

Voltage sag occurrence is referred, whenever the normal RMS voltage is subjected to a decrease between 10% and 90% at power frequency, for durations of 0.5 cycles to 1 minute. This is the most frequent power quality issue present in the distribution system. Faults on parallel feeders, large motor's startups and heavy load connections are most responsible for voltage sags in the distribution system. Consequences of voltage sag are malfunction of microprocessors-based control systems, unnecessary tripping of relays and inefficient motor running. It is needed to reduce the damage of equipments in distribution system due to voltage sag. Here, hybrid technique is involved for voltage sag mitigation by optimally placing Distributed Generator (DGs) with their optimal capacity. The hybrid technique consists of two artificial intelligent techniques, named Genetic Algorithm (GA) and Artificial Neural Network (ANN). The main objective is to mitigate the voltage sag in distribution network, which occurs due to the sudden increase in load. It leads to congestion in different buses and disturbs its voltage profile. By locating the optimal places for DGs and their capacity based on load requirement, voltage sag mitigation is possible. A new approach is proposed using hybrid technique for locating DGs with their corresponding capacities. It consists of three stages:

(i) Generating training dataset for ANN using GA

(ii) ANN is trained and tested to identify optimal placement of DGs

(iii) Computing optimal power to be generated by DGs.

Initial step for identification of optimal locations of DGs is computation of power flow between the buses. Power flow between the buses is calculated using Newton-Raphson method. It is the commonly used method for load flow calculation because it has the advantage of lesser number of iterations, when compared to other methods. The real power flow P_i and reactive power flow Q_i in the buses mainly depends on voltage and angle values and they are computed using Eq. (1) and Eq. (2).

$$P_i = \sum_{k=1}^{N} V_i \times V_k \left(G_{ik} \times \cos\theta_{ik} + B_{ik} \times \sin\theta_{ik} \right) \tag{1}$$

$$Q_i = \sum_{k=1}^{N} V_i \times V_k \left(G_{ik} \times \sin\theta_{ik} - B_{ik} \times \cos\theta_{ik} \right) \tag{2}$$

where, N is the total number of buses, V_i & V_k are the voltage at i^{th} bus and k^{th} bus respectively, θ_{ik} is the angle between i^{th} bus and k^{th} bus and G_{ik} & B_{ik} are the values of conductance and susceptance respectively. After calculating the real and reactive power flow between the buses, the total power losses in the system can be computed using Eq. (3).

$$P_{loss} = \sum_{i,j=1}^{N} \mathrm{Re}\,al\left[Conj\left(\left(V_m(i)\right)\times\left(V_m(j)\right)\right)\times Y_{ij}\times B\right] \tag{3}$$

where, V_m is the voltage magnitude, Y_{ij} *i*s the Y-bus matrix and B is the base MVA. The Y-bus matrix mainly depends on the values of resistance and reactance. After computing the total power loss in the system, the suitable locations needed to be identified for fixing the DGs is obtained using GA and NN and the amount of power to be generated by DG is computed by GA. The detailed explanation of three stages proposed approach is as follows :

2.1. First Stage: Generating training dataset for ANN using GA

Genetic algorithm is the well known optimization algorithm realized from human evolution. It is applied in most real life applications and well used in different power system applications like power quality problems. Here, it is employed for generating 2 case training dataset for ANN which provides the possible optimal locations for DGs to be connected in distribution system. GA mainly consists of five sub-stages: initialization, parent selection, crossover, mutation and termination.

2.1.1. Initialization

In initialization stage, chromosomes are randomly initialized. Let the size of population be $P = \{X_i = X_1, X_2, \ldots , X_N\}$, where X_i is the i^{th} chromosome of size N. For case 1, single DG connection in distribution system is considered; Each X has three genes, location of the DG, real and reactive powers to be generated by DG.

2.1.2. Parent selection

Parent selection means, selecting best fitness valued chromosomes for crossover. Fitness function used for selecting best one is total power loss equation (3). According to their best fitness value (low total power loss), chromosomes are selected. Then selected ones are called as parents and forwarded to crossover operation.

2.1.3. Crossover

Crossover means exchanging the genes from one chromosome to other. After crossover, we have generated offspring from parents. There are so many crossover operations available such as one-point, two-point and three-point crossovers. It depends on crossover rate and can be provided by user.

2.1.4. Mutation

Mutation is randomly changing some value in offspring at the same position. It is needed to help the offspring solutions to get away from local optima. There are so many mutation operations available such as Gaussian, uniform, non-uniform, boundary, flip bit, bit string mutation. It depends on mutation rate and can be given the user.

2.1.5. Termination

The process up to 4 stages is repeated until it reaches the maximum number of iterations. At the end of termination, it will provide the best chromosomes obtained so far from N chromosomes i.e., for single DG connection, we get optimal location of DG and its corresponding real and reactive to be generated. This means we are generating best training data set for ANN.

The algorithm is again employed to generate training dataset for increased total number of DGs to be connected i.e., two, so the output genes become six. From this GA, generated training dataset of optimized inputs and outputs are available for ANN i.e., for given number of DGs to be connected in distribution system, their optimal location with active and reactive powers are predicted with reduced total power loss. After generating training dataset, the next step is to train the ANN.

2.2. Second Stage: ANN is trained and tested to identify optimal placement of DGs

Artificial Neural Network is the analogy for human brain and is adaptive when properly trained. Providing optimal locations of DGs in distribution system to the given number of DGs to be connected using ANN is possible only when it is properly trained. For training ANN, we have the training dataset generated by GA. Here, ANN is used to select the best location for DG which can mitigate the voltage sag in bus voltages. The proposed ANN for voltage sag mitigation in distribution system is shown in Fig.1.

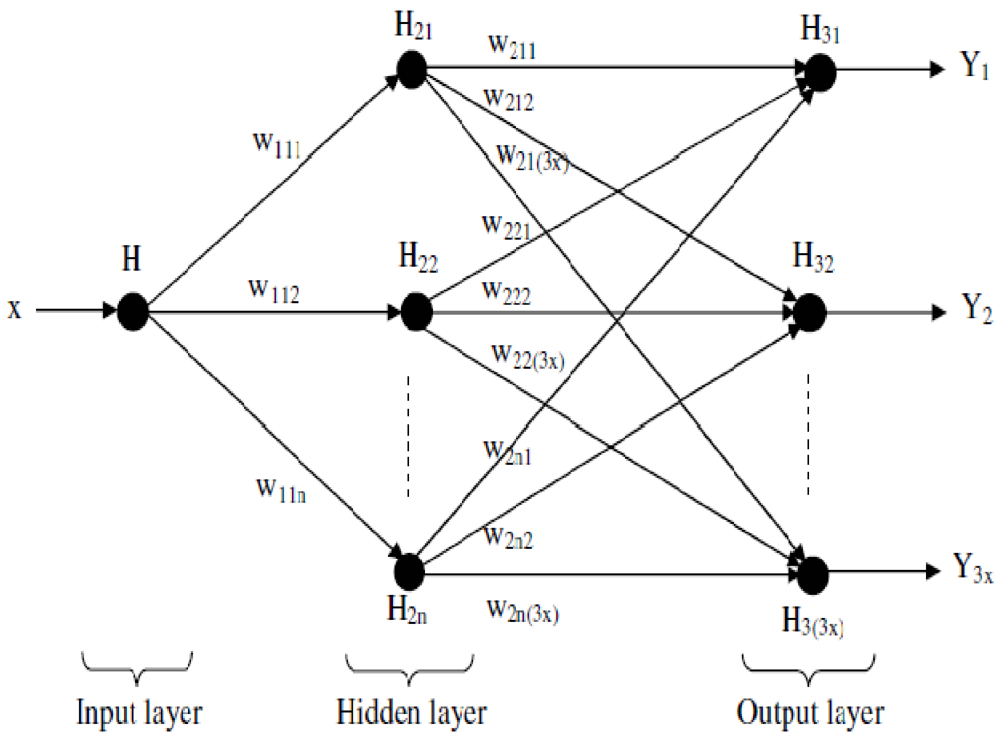

Figure 1: Proposed ANN for predicting optimal locations of DGs

As shown in Fig.1, proposed ANN structure consists of three layers, namely input layer, hidden layer and output layer. Here input layer consists of x nodes, hidden layer consist of n nodes and output layer consists of $3x$ nodes. Here, the network is trained using Back Propagation (BP) algorithm.

BP algorithm is clearly explained as follows.

Step 1: Initialize the input weights of each neuron in ANN,

Step 2: Apply x input to the network and calculate output of the network. Y_1, $Y_2 \ldots\ldots Y_{3x}$ are the outputs of the network and are illustrated in Eq. (4), Eq. (5) and Eq. (6),

Step 4: Compute the BP error,

Step 5: Adjust the weights of all neurons according to the BP error obtained.

Step 6: Repeat the steps 2 and 3 until, BP error is reduced to minimum value.

$$Y_1 = \sum_{r=1}^{n} W_{2r1} Y_1(r) \tag{4}$$

$$Y_2 = \sum_{r=1}^{n} W_{2r2} Y_2(r) \tag{5}$$

$$Y_{(3x)} = \sum_{r=1}^{n} W_{2r(3x)} Y_{(3x)}(r) \tag{6}$$

where,

$$Y(r) = \frac{1}{1 + \exp(-W_{11r} \cdot x)} \tag{7}$$

After training process, it is tested with different testing dataset to provide the optimal locations of DGs in distribution system. After testing, ANN is ready to provide optimal locations of DGs and their real and reactive powers for the given number of DGs to be connected. The next process is to identify the power to be generated by the connected DGs to reduce the total power loss in the system and improve the voltage profile of buses.

2.3. Third Stage: Computing optimal power generation using GA

Outputs of the ANN are optimal location of DGs and their corresponding real and reactive powers. In this stage, optimal real power and reactive powers to be generated by optimally placed DG are computed using GA. We know that, GA consists of mainly five stages. In initialization process, real and reactive powers are taken as genes for a single chromosome. N chromosomes are randomly initialized. Then, total power losses are computed for N chromosomes and are ranked according to their low total power losses. Next crossover operation is performed on selected parents to produce offspring with the crossover rate. Proceeding to crossover operation, mutation operation is performed on the offspring to avoid the problem of local optimum. After mutation, a new generation of population is obtained and above process from parent selection to mutation is repeated until the termination condition is reached. Here, the termination condition is maximum iterations or lowest total power loss in the distribution system. At the end, it provides the optimal capacity of each optimally located DG so that it mitigates the voltage sag in distribution system along with less total power losses and bus voltage profile improvement. Flow chart of GA for providing optimal real and reactive powers to be generated by connected DGs is illustrated in Fig 2.

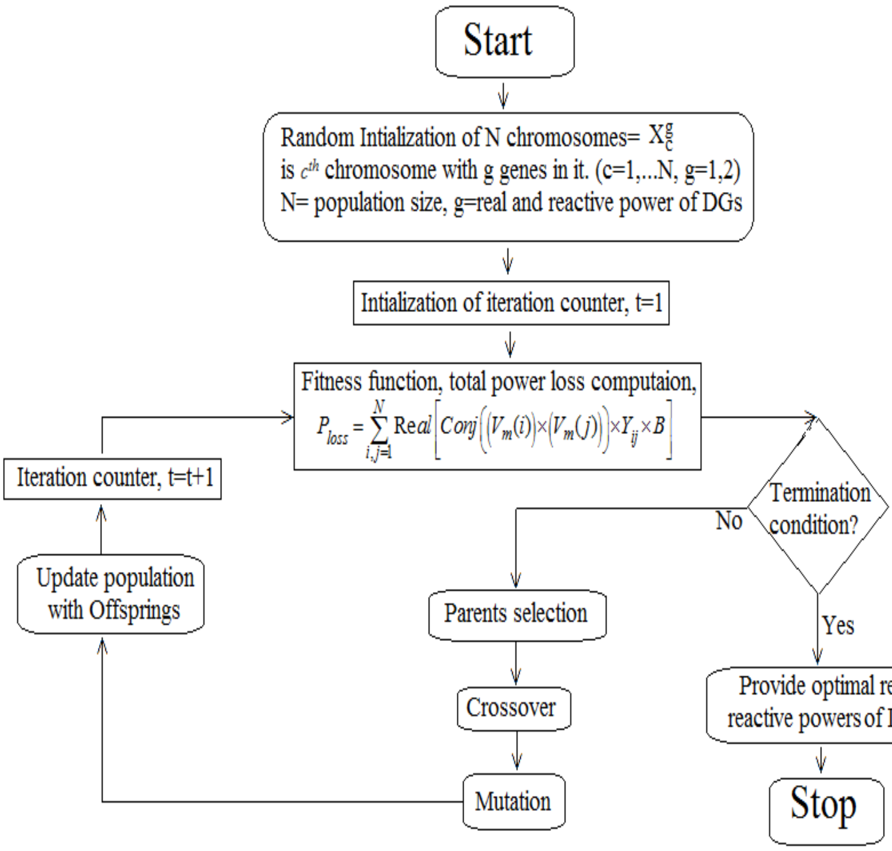

Figure 2: Flow chart of GA for providing DGs optimal real and reactive powers

3. Results and Discussion

The performance of the proposed approach is tested on IEEE 30 bus system using MATLAB 7.11. Initially, GA and ANN are used to compute optimal locations of DGs. After optimally locating DGs, again GA alone is employed to optimize the real and reactive powers to be generated by connected DGs. The purpose of doing so is to mitigate the voltage sag in all buses of distribution system which caused due to the sudden load increment. The line diagram of IEEE 30 bus system is shown in Fig 3.

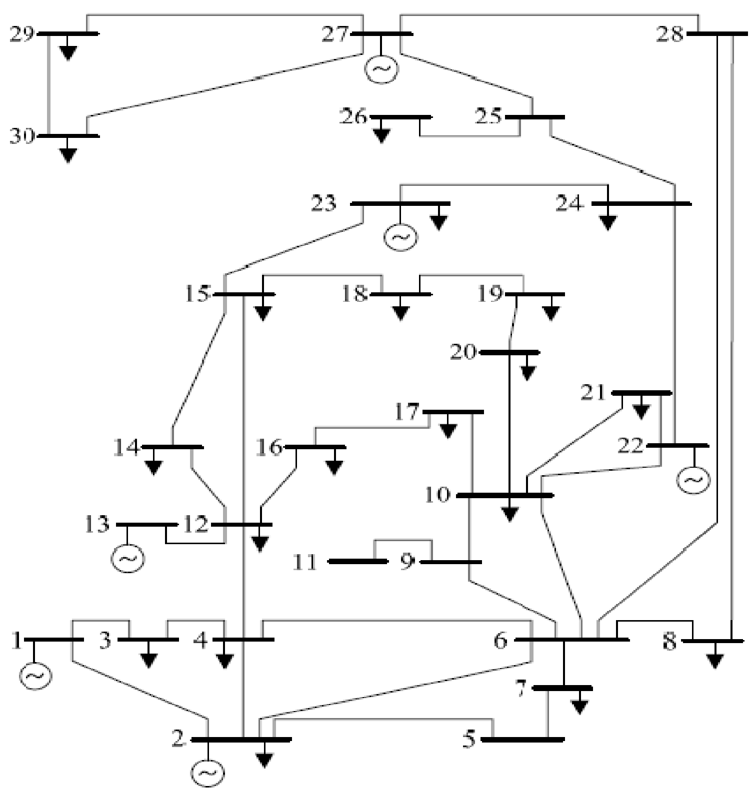

Figure 3: IEEE 30 Bus test system

As shown in Fig 3, bus 1 is considered as the slack bus and the base MVA of the system is 100 MVA. Buses 2, 13, 22, 23 and 27 are generator buses and remaining all other buses are load buses. The performance of the proposed approach is evaluated by injecting voltage sag condition in the distribution system. The total load of the system is 283.4 MW and the load is suddenly increased to 293.4 MW. Whenever the load exceeds in the distribution system, it causes a sudden decrease in the magnitude of voltages at all buses. Hence it can be said that bus voltages are affected with the appearance of voltage sag. The voltage sag can be mitigated by locating the optimal location of DG with optimal size in the distribution system and is computed by proposed hybrid approach. The load is suddenly increased by 10 MW at 0.06 sec and DGs are connected at 0.12 sec. For one DG connection in the distribution system, the proposed approach computed that the DG should be connected at 16^{th} bus. Similarly for two DGs connection, DGs should be connected at 5^{th} and 21^{st} buses. After optimally installing the DGs in bus system, it mitigated the voltage sag in all buses. This is evaluated by checking the performance of the some bus voltages. For the case of one DG connection at bus no.16, the performance of voltages of buses 4, 6, 7, 16, 26, 28 and 30 are shown in Fig. 4 to Fig. 10.

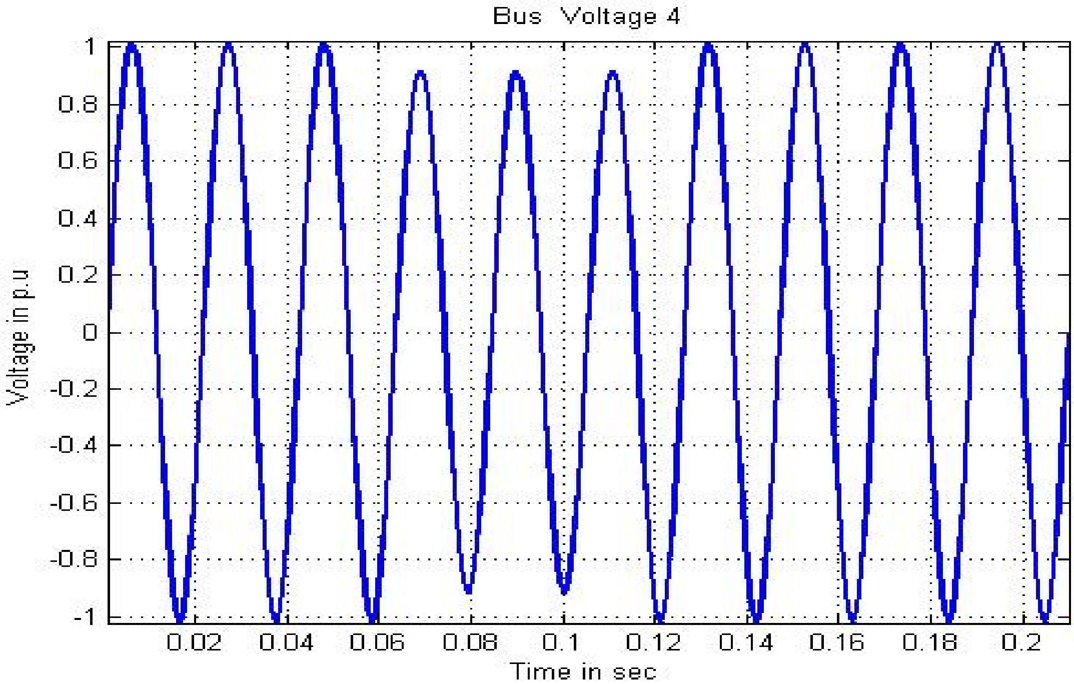

Figure 4: The performance of the 4th bus voltage for one DG connection

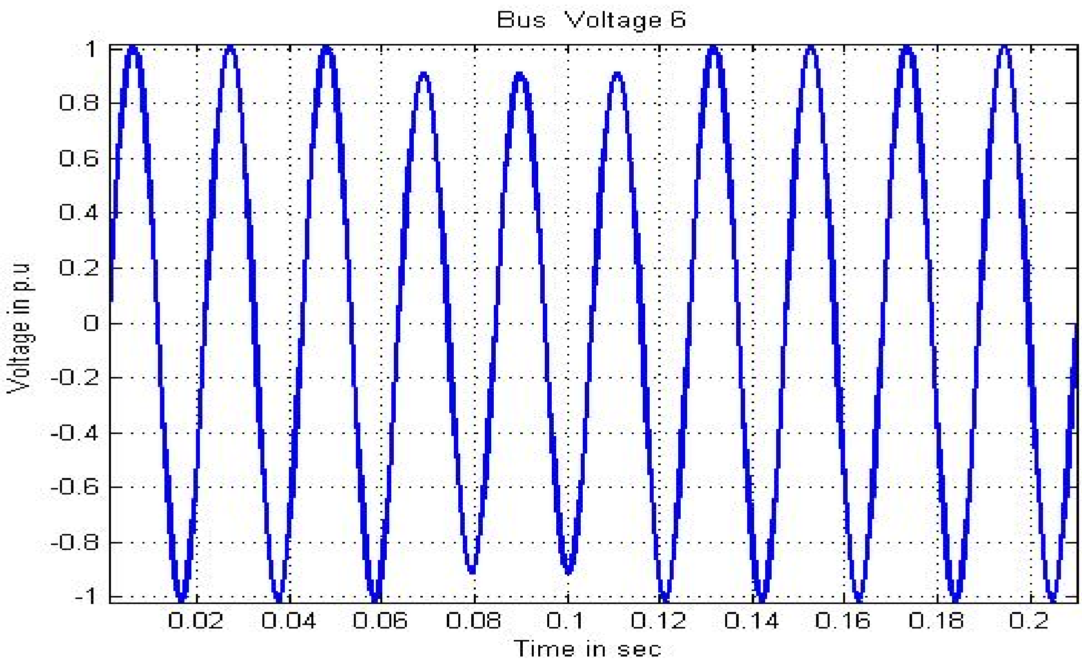

Figure 5: The performance of the 6th bus voltage for one DG connection

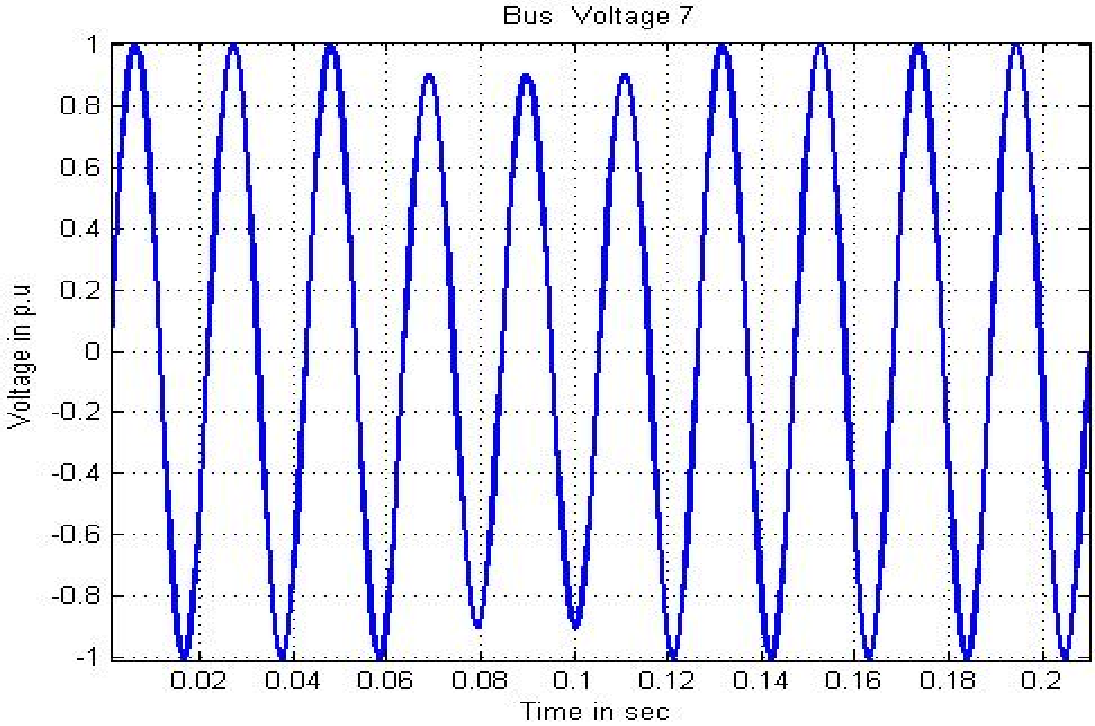

Figure 6: The performance of the 7th bus voltage for one DG connection

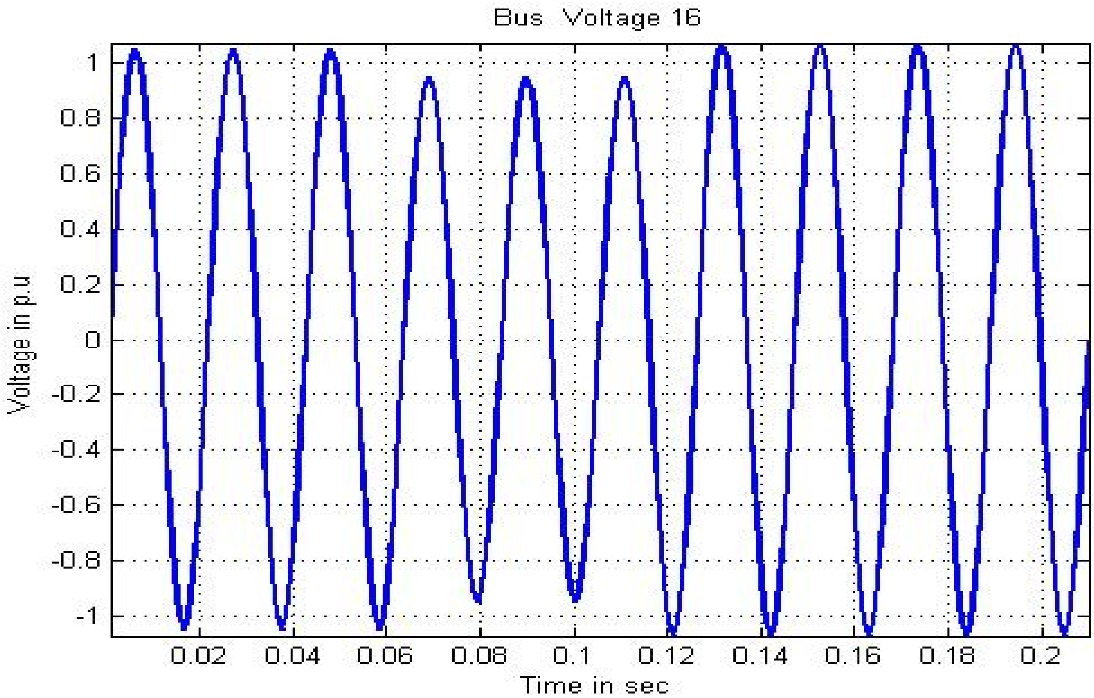

Figure 7: The performance of the 16th bus voltage for one DG connection

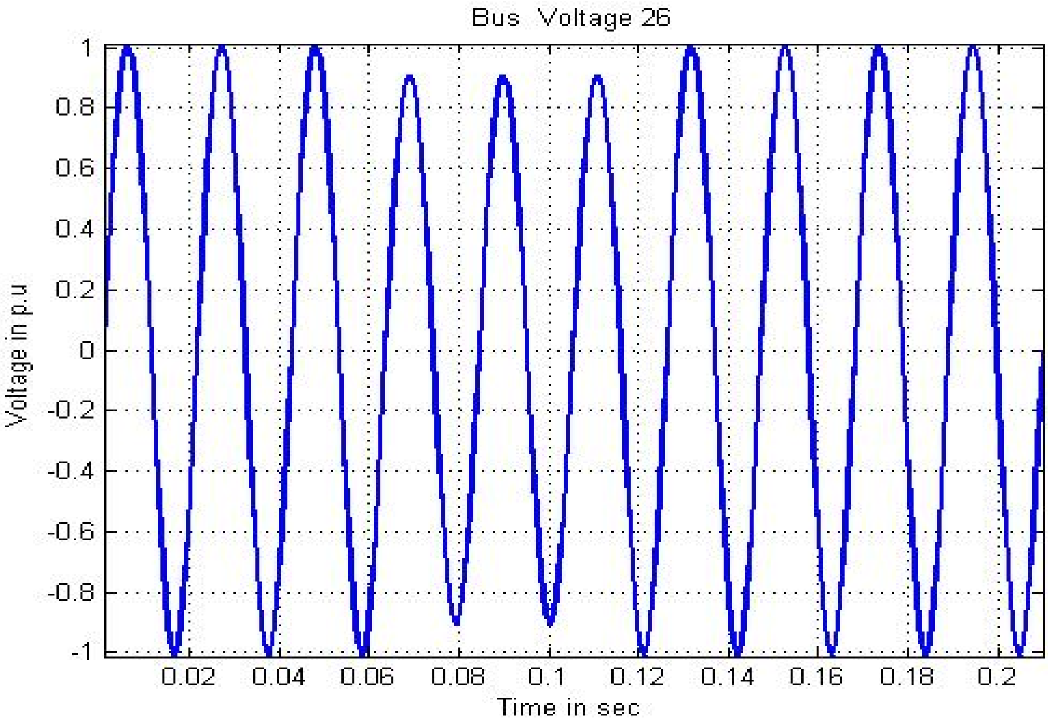

Figure 8: The performance of the 26th bus voltage for one DG connection

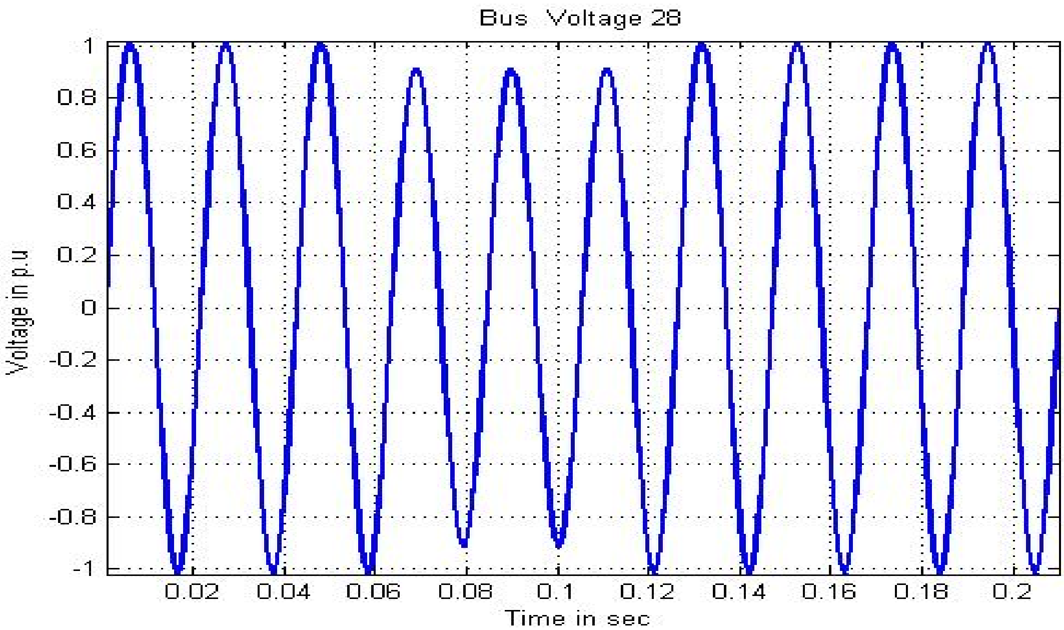

Figure 9: The performance of the 28th bus voltage for one DG connection

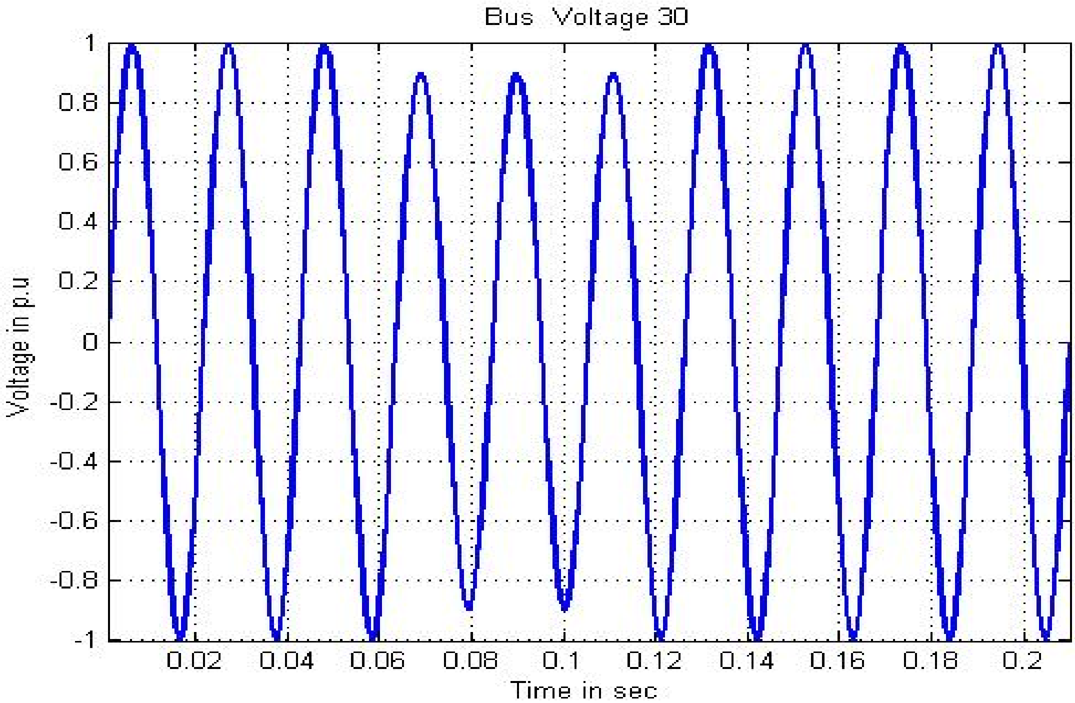

Figure 10: The performance of the 30th bus voltage for one DG connection

By inspecting Fig. 4 to Fig. 10, we can say that, at time t = 0.06 sec, voltage sag is appeared in seven buses with a duration of 3 cycles between t = 0.06 sec and t = 0.12 sec. The DG connected at 16th bus has a optimal power of 32.3662 MW. Similarly, for the case of two DGs connection at 5th and 21st buses with optimal capacities of 9.9012 MW and 9.6827 MW respectively, the performance of voltages of buses 3, 9, 14, 17, 20, 24 and 29 are shown from Fig. 11 to Fig. 17.

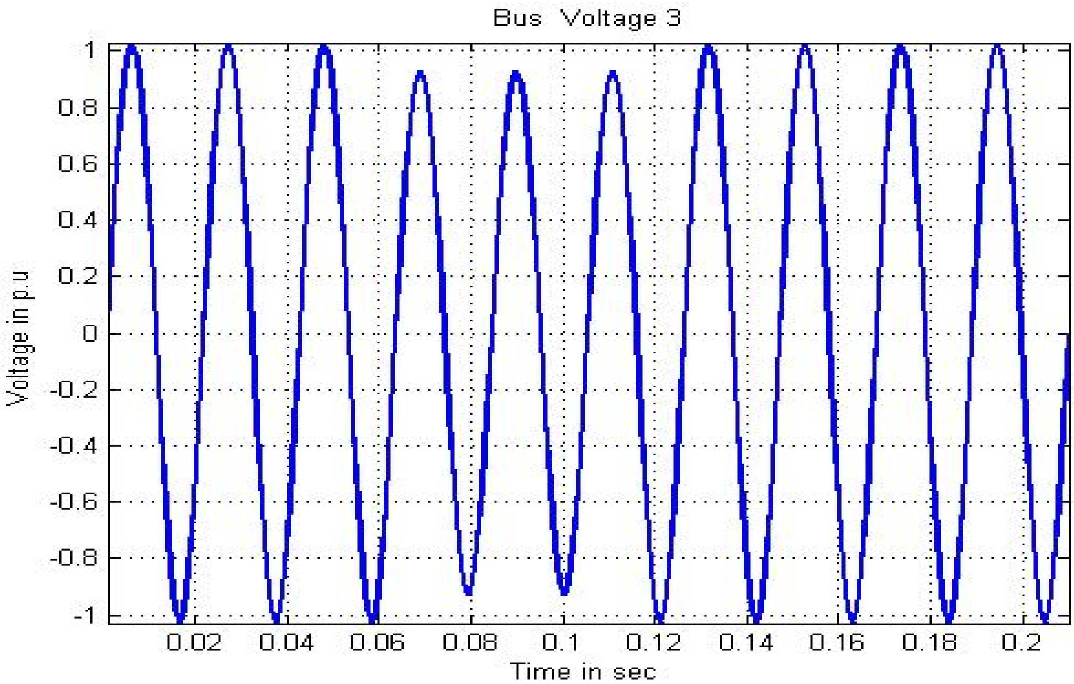

Figure 11: The performance of the 3rd bus voltage for 2 DG connection

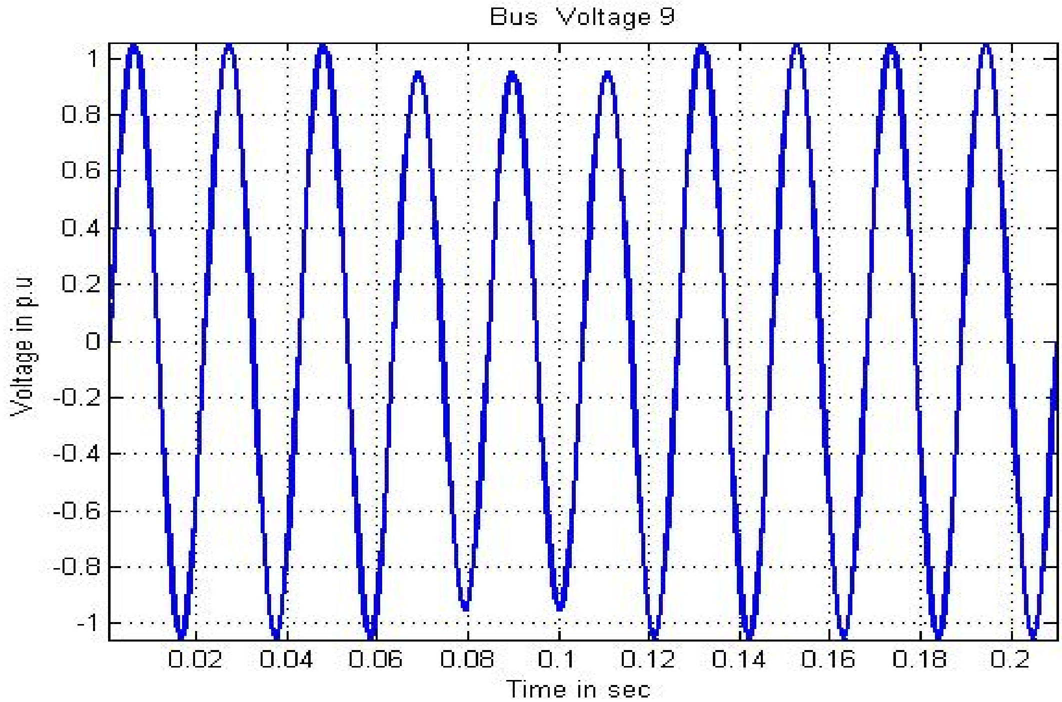

Figure 12: The performance of the 9th bus voltage for 2 DG connection

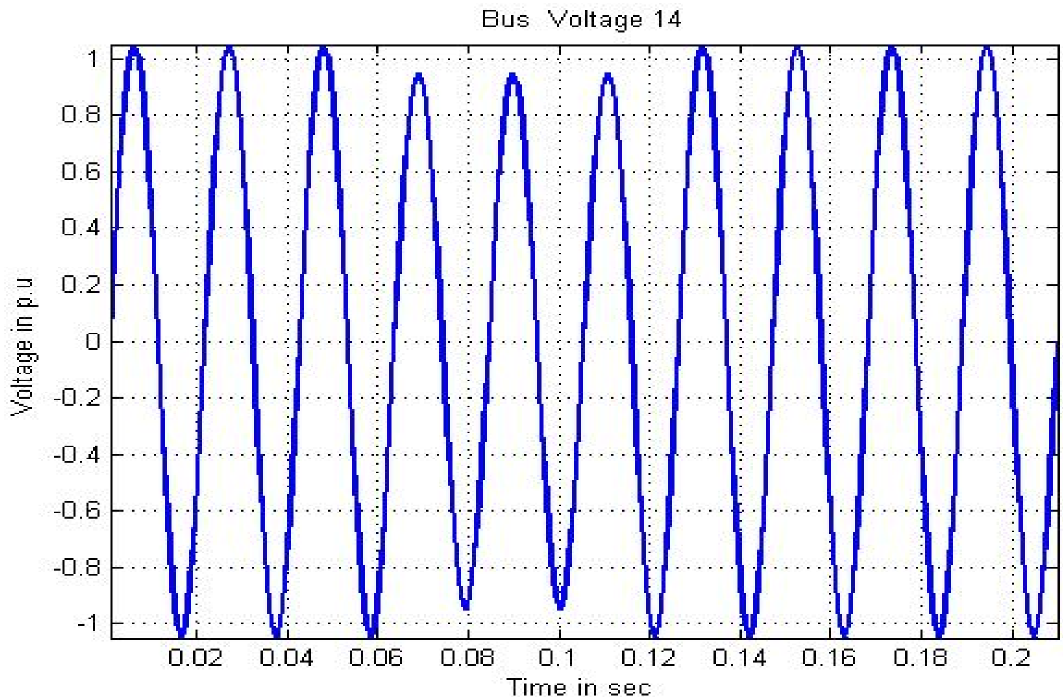

Figure 13: The performance of the 14th bus voltage for 2 DG connection

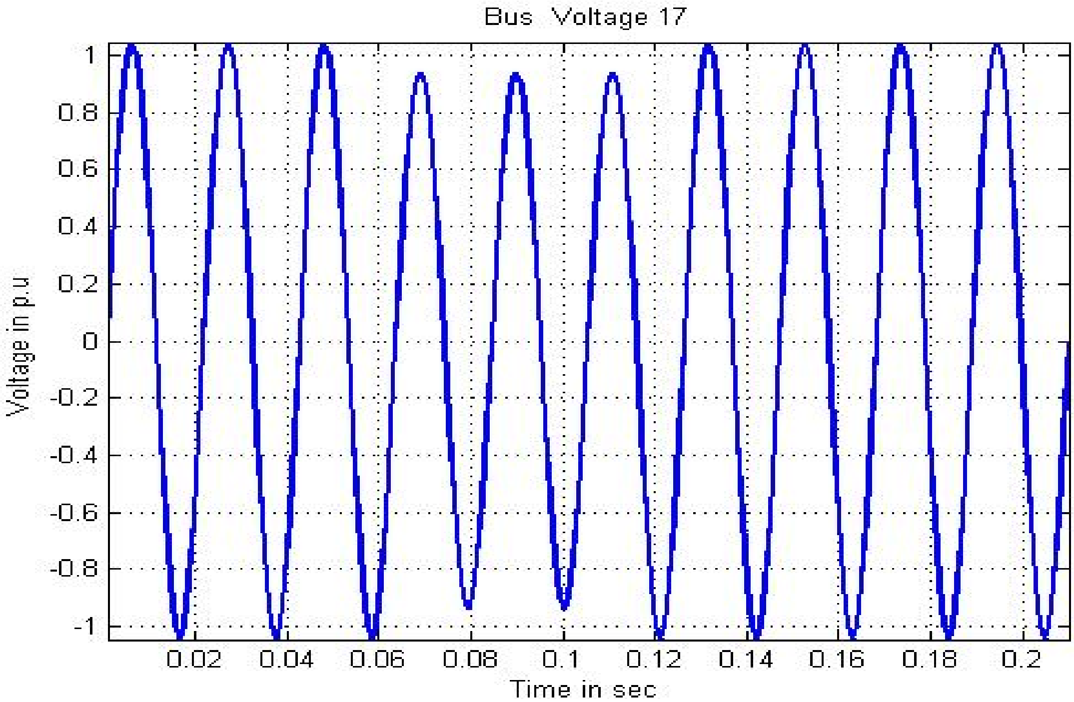

Figure 14: The performance of the 17th bus voltage for 2 DG connection

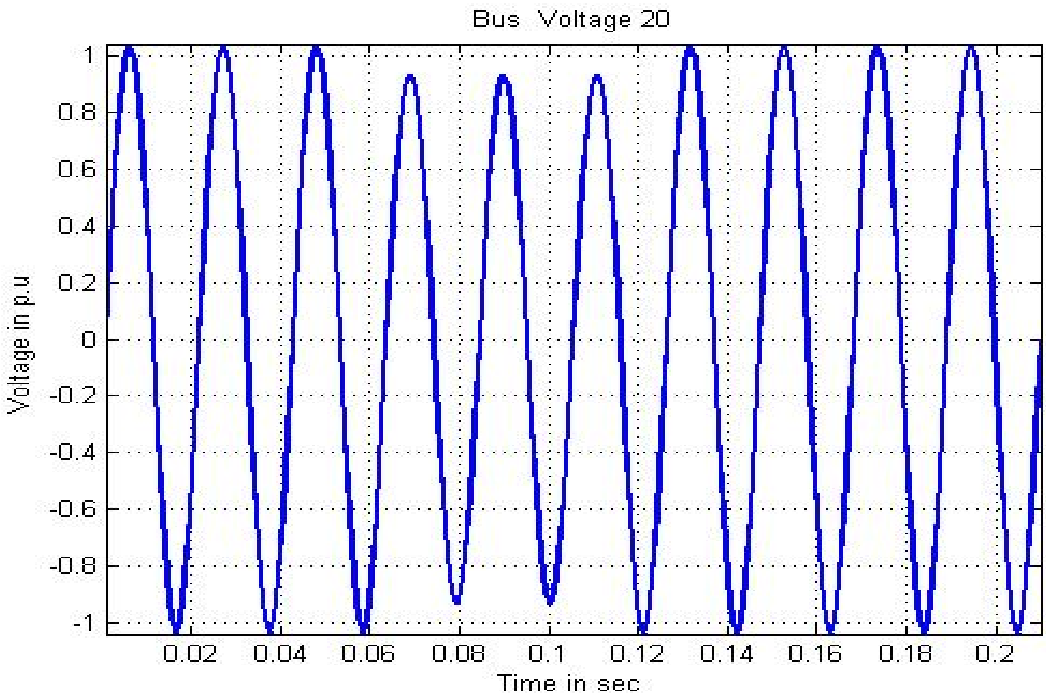

Figure 15: The performance of the 20th bus voltage for 2 DG connection

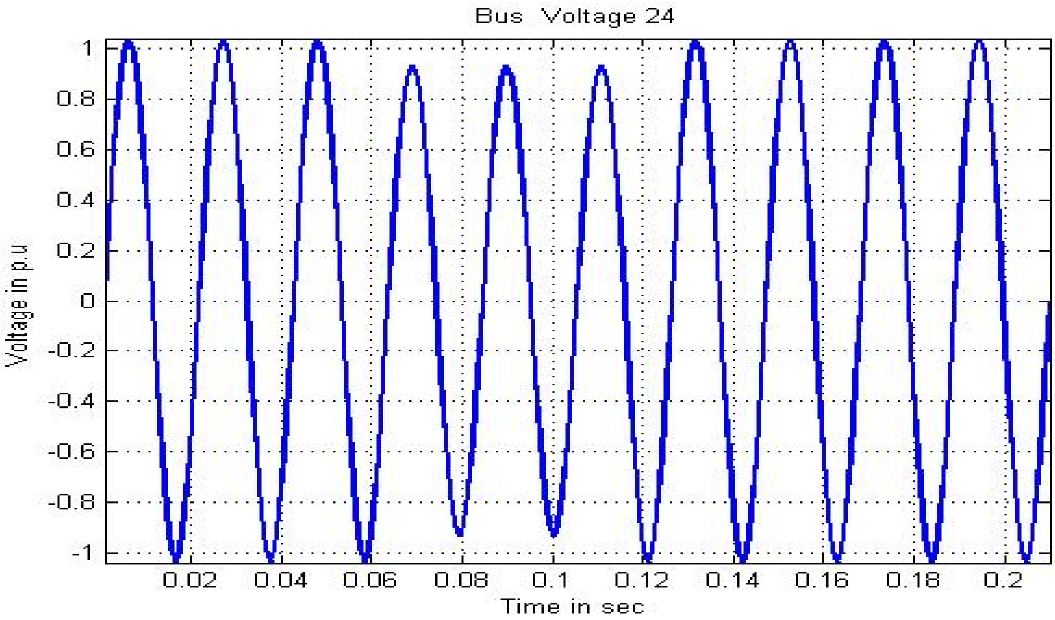

Figure 16: The performance of the 24th bus voltage for 2 DG connection

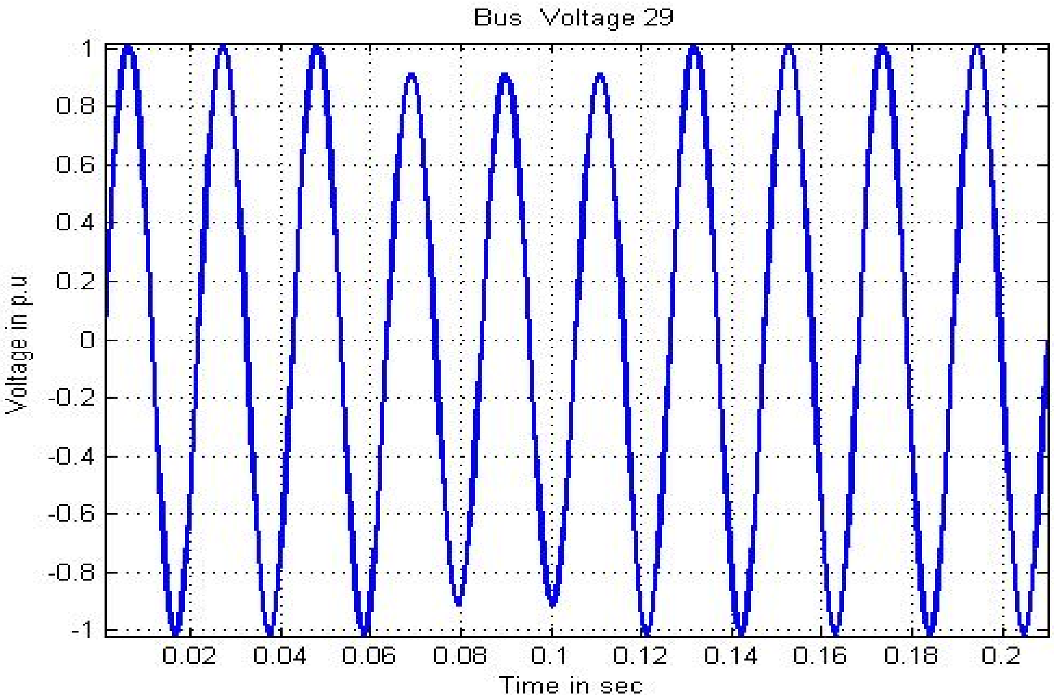

Figure 17: The performance of the 29th bus voltage for 2 DG connection

By inspecting Fig. 11 to Fig. 17, we can say that, the voltage sag appeared in seven buses with a duration of 3 cycles between t = 0.06 sec and t = 0.12 sec. Through the performance of the bus voltages for one DG or two DGs connection, it is showed that the sag appearance in the bus voltages is mitigated in a short duration of 0.06 seconds.

Along with, voltage sag mitigation, proposed method has minimized the total power losses in the distribution system and also improved the bus voltage profile. With the real and reactive powers generated by connected DGs are tabulated in Table 1 to show the effectiveness of the proposed approach for loss reduction.

Table 1: Total Power Loss for 2 cases of DG connection

No. of DGs	DG Bus No.	Active Power of DG (MW)	Reactive Power of DG (MVAR)	Total Power Loss (MW)	% Reduction of Power Loss
Zero	--	--	--	11.4250	--
One	16	32.3662	4.8681	9.4279	17.48%
Two	5	9.6597	4.1999	9.3118	18.50%
	21	9.4206	3.3716		

Under normal conditions, the power losses are 10.890 MW and with sudden load increment of 10 MW, it increased to 11.4250 MW. After the installation of 32.3662 MW single DG at 16^{th} bus, the total loss is reduced to 9.4279 MW (17.48% reduction). Similarly for double DG connection when DGs are connected at 5^{th} and 21^{st} buses with 9.6597 MW and 9.4206 MW of active powers respectively, the loss reduced to 9.3118 MW. By comparing total power losses of distribution system for all cases, it showed that the proposed approach can optimally site and optimally size the DGs such that total power losses will be considerably reduced. Similarly, checking for bus voltage profile improvement, after connecting DGs in 30 bus system for two cases, voltages of load buses are computed and tabulated in Table 2.

Table 2: Voltages of 30 bus system in Per Unit (P.U.) value

Bus No.	Normal condition	No DG (load increased)	One DG	Two DGs
3	1.0284	1.0276	1.0309	1.0290
4	1.0204	1.0196	1.0234	1.0211
5	1.0100	1.0100	1.0100	1.0100
7	1.0068	1.0064	1.0079	1.0071
8	1.0100	1.0100	1.0100	1.0100
9	1.0541	1.0535	1.0565	1.0562
10	1.0469	1.0461	1.0506	1.0509
11	1.0820	1.0820	1.0820	1.0820
12	1.0625	1.0621	1.0670	1.0639
14	1.0478	1.0473	1.0522	1.0500
15	1.0429	1.0420	1.0466	1.0461
16	1.0485	1.0472	1.0725	1.0504
17	1.0421	1.0411	1.0514	1.0454
18	1.0322	1.0305	1.0350	1.0348
19	1.0290	1.0268	1.0313	1.0313
20	1.0327	1.0302	1.0348	1.0348
21	1.0334	1.0324	1.0368	1.0410
24	1.0315	1.0298	1.0333	1.0354
25	1.0292	1.0254	1.0268	1.0288
26	1.0117	1.0079	1.0093	1.0113
28	1.0174	1.0162	1.0182	1.0174
29	1.0166	1.0093	1.0095	1.0113
30	1.0053	0.9997	0.9998	1.0017

The voltages of bus numbers 5, 8 and 11are same under all conditions and the voltage of each bus is improved after installing one DG / two DGs. The percentage improvement of voltage deviation for all busses are computed with respect to the slack bus voltage then all bus voltages are within tolerable limits as shown in Fig.18.

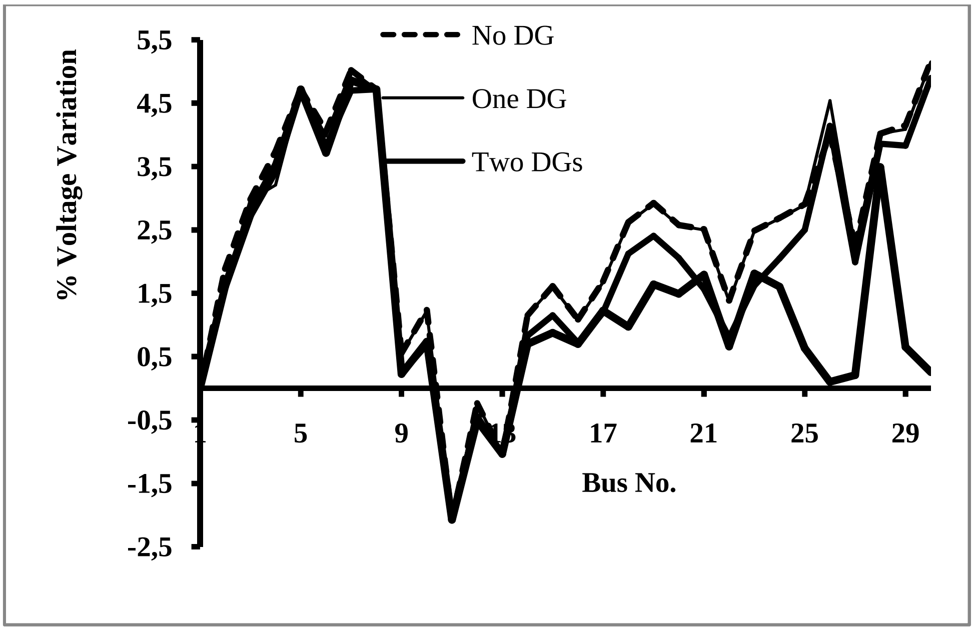

Figure 18: Percentage Variations of Bus Voltages Compared with Slack Bus Voltage

The inspection of Fig. 18 reveals that there is least variation of voltage of load buses in case of double DG connection, when there is a sudden rise in load. By comparing the percentage of bus voltage deviation for 4 cases, it showed that the proposed method can improve the voltage profile of load buses by installing DGs in the distribution system. Hence, through implementation results and discussions, we showed that the proposed method is capable of mitigating voltage sag in all buses along with reducing total power loss and improving bus voltage profile.

4. Conclusion

Voltage sag is the severe power quality problem in distribution network. It should be mitigated as soon as possible for preventing the load from getting damaged. In this paper, a hybrid approach based DG unit installation is used for voltage sag mitigation. First, a training dataset for ANN with 2 cases is developed using GA. Then, ANN is trained and able to give the optimal location and its size. Again, GA is used to optimize the generating real and reactive powers of the DGs to be connected. To validate the performance of the proposed approach, it is tested on IEEE 30 bus system using MATLAB platform. For first case of single DG connection, it located 16th bus as optimal choice with 32.3662 MW (+4.8681 MVAR) power which reduced the total power loss by 17.48% of the No DG connection. And, for the second case of two DGs connection, it located 5th and 21st as the optimal choices with 9.6597 MW (+4.1999 MVAR) and 9.4206 MW (+3.3716 MVAR) respectively. It reduced the total power loss by 18.50%. Bus voltages have experienced voltage sag due to the sudden load increment, which was taken care of by optimally sitting the DGs in the network. It also mitigated the buses voltage sag which was appeared at 0.06 seconds in a short duration of 3 cycles. The voltage profile of the busses is also improved using the DGs. From the simulation results, it can be concluded that the proposed approach is able to mitigate the voltage sag by optimally installing the DGs in the distribution network.

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