Journal of Architectural Design and Construction Technology
Volume 1 | Issue 1

Research Article Open Access

Optimal Fuzzy Control of Nonlinear Dynamical Systems Using Evolutionary Algorithms

Mohammad Dashti Javan[1], Seyed Ehsan Aghakouchaki Hosseini[2*] and Mohammad Bagher Menhaj[3]

[1]Amirkabir University of Technology (AUT), Electrical Engineering Department, Tehran, Iran
[2]University of Mohaghegh Ardabili (UMA), Civil Engineering Department, Ardabil, Iran
[3]Amirkabir University of Technology (AUT), Electrical Department, Tehran, Iran

***Corresponding author:** Seyed Ehsan Aghakouchaki Hosseini, University of Mohaghegh Ardabili (UMA), Civil Engineering Department, Ardabil, Iran. Email: hosseini_civil@hotmail.com*

Citation: Aghakouchaki Hosseini SE, Dashti Javan MD, Bagher Menhaj MD (2020) Optimal Fuzzy Control of Nonlinear Dynamical Systems Using Evolutionary Algorithms. J Arch Des Cons Tech 1(1):12-19.
https://doi.org/10.47890/JADCT/2020/SEAHosseini/10123452

Received Date: May 16, 2020; **Accepted Date:** May 21, 2020; **Published Date:** May 26, 2020

Abstract

Goal of this research is to produce a controlling voltage for Pulse Width Modulation (PWM) generator so that its Total Harmonic Distortion (THD) characteristic is reduced and Dynamic Voltage Restorer (DVR) compensates function of the system against error as well as turbulence in such a way that the end user has no trouble with supplied voltage. In this study, a DVR system has been utilized which is capable of counteracting adverse effects of changing voltage against sensitive loads. Continuous and stable supply of energy is the most important goal in serviceability of electrical networks. Turbulence in distribution networks causes disturbances in level and quality of the voltage. To eliminate destructive effects of these disturbances especially over sensitive users, one could use compensator devices. So, a PSO-Fuzzy controller has been employed to optimize SAG characteristics of voltage of the sensitive load. Simulation results obtained in this study, considering the complicated and nonlinear nature of DVR system, demonstrates efficiency of proposed PSO-Fuzzy controller in improving behavior of the dynamic voltage restorer introduced to the network for the purpose of eliminating destructive effects of imminent disturbances over sensitive users.

Key Words: Fuzzy Controller; Evolutionary Algorithms; Nonlinear Dynamical Systems;

Introduction

As there are a variety of equipment and abnormalities in the network when the power is generated, its quality will change, and hence electrical equipment and would not be energized uniformly and sufficiently [1]. On the other hand, voltage magnitude is among key factors affecting quality of electrical power which is directly related to the distribution system that is located at the end of power system, and hence directly connected to the customer [1, 2]. A number of devices for power quality improvement and system reliability have been introduced including, Flexible AC Transmission System (FACTS), Static Synchronous Compensator (STATCOM), Static Synchronous Series Compensator (SSSC), Interline Power Flow Controller (IPFC), and Unified Power Flow Controller (UPFC), among others [1]. However, recently for the purpose of power quality, Custom Power Devices which are used in the distribution system in contrast to devices that are designed for transmission system have been introduced. Some of these devices are Distribution Static Synchronous Compensator (DSTATCOM), Dynamic Voltage Regulator (DVR), Active Filter (AF), and Unified Power Quality Conditioner (UPQC) [1]. DVR is one of the most efficient custom power and distribution network devices that are connected in series and maintain the load voltage by injecting the three-phase output voltages during power system disturbance and by controlling the amplitude, phase and constant voltage frequency [1, 3]. The DVR system featuring fast response, lower cost and a smaller size [1, 4], protects sensitive loads from the impacts that voltage disturbances will produce at the point of common coupling (PCC) [5] and can compensate many dynamic power quality problems including voltage sag, voltage swell, voltage flicker, and harmonics, among others [6]. In general, DVR's function can be divided into two modes: standby mode and voltage injection mode. In the first case, weather a short circuit occurs or not, a small voltage is injected to cover the voltage drop caused by the transformer reactance losses. In the latter case, as soon as the voltage SAG is detected, the DVR injects the voltage into the desired load.

The DVR considered in this study consists of five major components including inverter, transformer, filter, power saver, PWM pulse generator as well as a regulator. A three-phase power supply system with associated transformers and a DVR system using power electronic equipment improves power quality. In this system, a 6-pulse inverter with insulated-gate bipolar transistor (IGBT) switches is responsible for generating the power. This signal is transmitted through a filter to a transformer with series connected coils, and would reach a sensitive load after changing its level. The goal is that the sensitive load receives the produced power with a good quality even if there is a fault in the network. This will be achieved by adjusting the fire angle of the IGBTs. The fire signal will be generated by a Pulse Width Modulation (PWM) pulse generator. In fact, the main operation of the controlling process will be done by the regulator block, which should provide the appropriate control voltage for the PWM input pulse to the G-base of the IGBT switches. Voltage of sensitive load is inserted to the regulator and, after a controlling process, the Vcontrol voltage is generated and will be sent to the PWM generator block as the regulator output. Park transform, also known as dq0 transform which is a mathematical transform for simplification of analyzing three-phase circuits is applied to the input voltage to the regulator. (Figure1) outlines schematic of a DVR system.

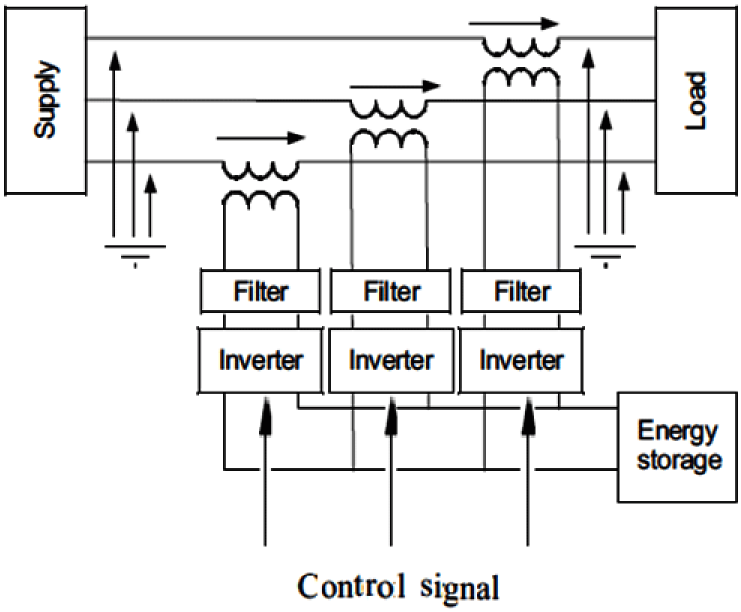

Figure 1: Schematic of Dynamic Voltage Regulator (DVR) System

To achieve a proper function, various control strategies including robust control [5], predictive control [6], sliding mode control [7], and adaptive PI controller based on human brain learning [8], have been proposed for controlling the commanded voltage.

Controller of a DVR is the only factor which determines its performance [5]. Hence, design of an efficient control strategy to control a DVR system with the final result of improved robustness, steady-state and transient performance is the focus of researchers [5]. In this research, the PWM pulse generator which produces the pulse signal will be controlled by a fuzzy controller in such a way that it can provide the appropriate PWM signal to fire the insulated-gate bipolar transistor (IGBT) switching equipment and the voltage loss due to the fault event can be injected into the circuit by the inverter so that the final user receives the correct, high-quality voltage. The fuzzy controller used in this study has been optimized through determining its parameters by Particle Swarm Optimization (PSO) algorithm as one of metaheuristic optimization techniques widely used in literature for optimization purposes.

In this study, the main goal is to produce a controlling voltage for the PWM pulse generator using the proposed PSO-based fuzzy logic controller (PSO-FLC) so that its Total Harmonic Distortion (THD) characteristic is reduced and DVR compensates function of the system against error as well as turbulence in such a way that the end user has no trouble with the supplied voltage.

Simulation of Dynamic Voltage Restorer (DVR) System

DVR system including inverter, transformer, filter, power saver, PWM pulse generator as well as a regulator was simulated with MATLAB software. In this system, a 6-pulse inverter with IGBT switches is responsible for generating power. This signal is transmitted through a filter to a transformer with series-connected coils, and reaches a sensitive load after changing its level. The objective is the sensitive load receives the generated power with a proper quality even when there exists a fault in the network. This will be achieved by adjusting the fire angle of the IGBTs. The fire signal will be generated by a PWM pulse generator. In fact, the main controlling process will be done by the regulator block, which should provide the appropriate control voltage for the input PWM pulse to the G-base of the IGBT switches. In this system, the yellow blocks are measurement units of three phases to measure the voltage values at different points. These values are employed inside the regulator to allow a closed loop control.

Simulation of Regulator and Normal Fuzzy Controller in MATLAB

The regulator plays the controlling role in the whole system to regulate the input PWM pulse to the inverter which based on IGBT switches. V2 voltage enters the regulator and after a controlling process, the produced Vcontrol goes to the PWM block as the regulator output.

The abc to dq0 block performs the Park transform operation. Park transform, also known as dq0 transform which is a mathematical transform for simplification of analyzing three-phase circuits is applied to the input voltage to the regulator. This transform is usually used to simplify the analysis of three-phase synchronous machines or control calculations of inverters. When the three-phase circuit is balanced, application of dq0 transform reduces the three alternating quantities to two DC ones. Calculations can be made on DC quantities and then the results of the three-phase AC can be obtained using inverse transform. The control loop here is in fact closed using the difference of values transformed by the Park transform and the desired values, hence leading to the Closed loop control. This signal enters the fuzzy controller and the Park-transformed control signal will exit the regulator to fire the IGBT. The fuzzy controller is implemented using the Fuzzy Toolbox in MATLAB software. Then, with respect to the considered membership functions, the if-then rules were written and applied to the fuzzy controller system. However, since response of the fuzzy system depends on the values of the membership functions and their shape, these functions need to be defined more precisely. Initial responses indicated the correctness of the implementation of the main system and the regulator, but these responses were not acceptable in view of controlling objective and need to be improved. In Fig. 2, the first graph is the three-phase input voltage generated by the Vps power source, the second is for the voltage delivered to the sensitive load Vsl, the third one corresponds to the voltage delivered to the normal load Vl, the fourth one is for the voltage injected to the inverter, Vinj, and the fifth graph is the current of sensitive load (lsl).

As can be seen in (Figure 2), the second graph, which is the voltage delivered to the sensitive load, has been compensated after occurring a fault in the power supply, but a symmetric three-phase voltage has not been provided for the sensitive load which indicates poor adjustment of fuzzy controller parameters. Thus, Particle Swarm Optimization (PSO) technique would be employed to determine the fuzzy controller parameters. After the primary fuzzy controller is implemented with the Min and Max operators and its associated rules for controlling the regulator part of the DVR system, in order to improve the response and find the fuzzy control parameters optimally, the fuzzy control system was coded in an M-file in MATLAB.

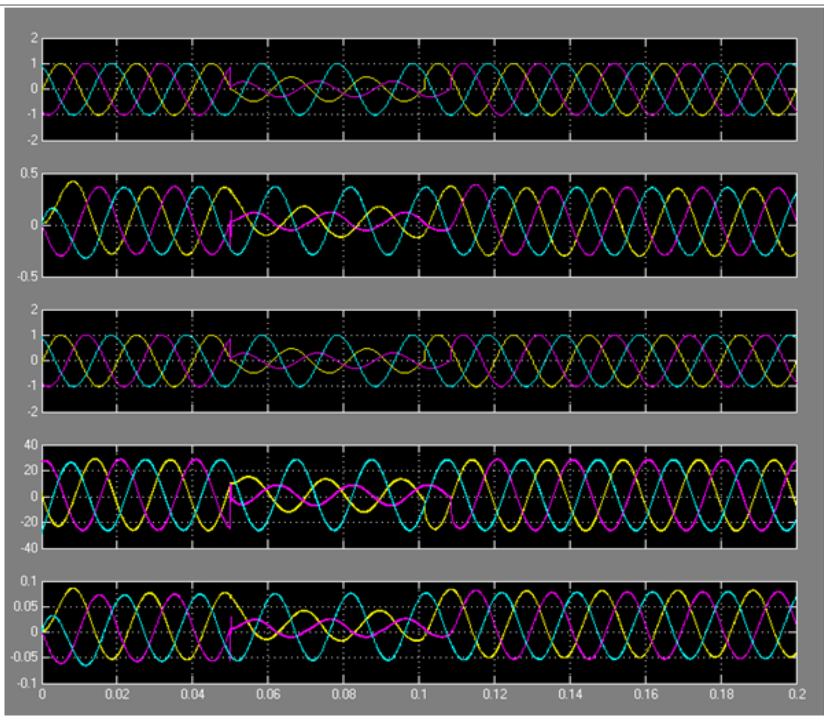

Figure 2: Graphs of Voltages Vps, Vsl, Vl, Vinj and Current lsl

Particle Swarm Optimization (PSO) Algorithm

The basis of this algorithm is that at first the population and particle swarm are randomly scattered in the search space. Each particle in the search space represents a possible answer and the particles will move toward the optimal response as time goes by and in this process will benefit from group search results as well as theirs. The purpose of this algorithm is efficient search of group of particles in the search space. The particles are directed to the best and most appropriate response. In this algorithm, the change of position of each particle is calculated from kinematic equations assuming constant velocity attributed to each particle. Velocity of each particle is affected by its velocity at the preceding moment, the degree of deviation from the best position obtained, and the distance to the best position found in the group. This algorithm was first applied by Kennedy and Eberhart [9]. In this algorithm, a mass of N particles moves in a D dimensional search space. Each particle modifies its motion according to its own experience as well as that of other particles in the previous steps and adjusts its position to achieve the best response. In order to show the kinematic equations governing the particle's behavior, we determine the position of the particle ith in a D dimensional space with the vector Xi = (x_{i1}, x_{i2}, ..., x_{iD}) and its velocity with the vector Vi = (v_{i1}, v_{i2}, ..., v_{iD}). As particles move in their own spaces, the best position each particle has ever reached is compared with its own current one, and the best position other particles in the whole group has achieved is considered as well, based on which the velocity vector required for the moving toward the optimal position in the next step is calculated. Personal best (Pbest), the best position that ith particle has ever reached and global best (Gbest), position of the best response of the whole group, are presented as below,

$$\mathrm{Pbest}_i = \left(\mathrm{Pbest}_{i1}, \mathrm{Pbest}_{i2}, \ldots, \mathrm{Pbest}_{iD}\right) \quad (1)$$

$$\mathrm{Gbest} = \left(\mathrm{Gbest}_1, \mathrm{Gbest}_2, \ldots, \mathrm{Gbest}_D\right) \quad (2)$$

Therefore, velocity of the ith particle in the next step is calculated through the following relation which is dependent on the velocity in the previous step, orientation towards the best response in the particles group and the past of the particle itself.

$$V_i^{(K+1)} = C_0 V_i^{(K)} + C_1 \times \mathrm{rand} \times \left(\mathrm{Pbest}_i - x_i^{(k)}\right) + C_2 \times \mathrm{rand} \times \left(\mathrm{Gbest} - x_i^{(k)}\right) \quad (3)$$

personal best (pbest) and the global best (gbest) and are selected in different methods in literature [10]. Depending on the velocity vector at the present moment and the previous position, the particle will move toward its destination as below,

$$X_i^{(k+1)} = V_i^{(K+1)} + X_i^{(k)} \quad (4)$$

Movement of particles in the search space would be possible by a proper definition of the concept of velocity as the controlling parameter in this algorithm. As can be seen, the particle's velocity in PSO algorithm will determine the direction of the motion towards the optimum position in each step.

Simulation of PSO-Fuzzy Controller

Parameters for membership functions determine the shape of the input and output membership functions and are very effective in response of the system under control. Using PSO algorithm, these parameters are considered as a swarm of particles and must be generated in such a way that minimizes the objective function. In this study, the objective function has been considered as the value of Total Harmonic Distortion (THD), to minimize the distortion in the sensitive load voltage. In fact, the purpose of the DVR system is to improve the voltage delivered to the sensitive load. For this purpose, optimum fuzzy controller should adjust the PWM pulse required to fire the IGBT power electronic equipment in such a way that sensitive load voltage does not detect voltage drop as well as phase cutoff.

First, the range of the input-output variables was specified and their membership functions were selected as Gaussian, after several examinations. To simulate the DVR system under the fuzzy controller, some faults and errors such as short circuit and dual phase were introduced to the power supply of DVR system which caused normal load voltage to drop while the sensitive load benefiting from DVR system, did not encounter such errors and received a correct and proper three-phase voltage. Indeed, the fuzzy controller optimized by PSO algorithm has been able to compensate the sensitive load voltage by generating the control voltage through the IGBT inverter set and filter. The PSO algorithm was implemented with 10 particles and at the beginning of the search process, values of acceleration coefficients C1 and C2 were adopted as 2 and 0, respectively. During the search process, C1 is decreased and C2 is increased both linearly, so that at the end they reach to 0 and 2, respectively. The constant C0, which represents effect of velocity in previous steps over current value was considered as 1 at the initiation of the algorithm implementation and reaches 0 at the end of the search with a linear behavior. Also, root-mean-square (RMS) of THD is calculated at each step of the algorithm and the particle values will be determined based on that. Particles move toward reduction of THD's RMS and their velocity and position are determined in this direction. The following block diagram of the system under control shown in (Figure 3). describes the relationship between different parts of the power system, power electronics and control system and illustrates what role each of the subsystems play.

Simulation Results

By introducing DVR system including power source, transformers, inverter, PWM pulse generator as well as regulator and controlling the system using fuzzy controller optimized by PSO algorithm, desired results were achieved. By adopting 10 particles for PSO algorithm and determining initial values for its constants,

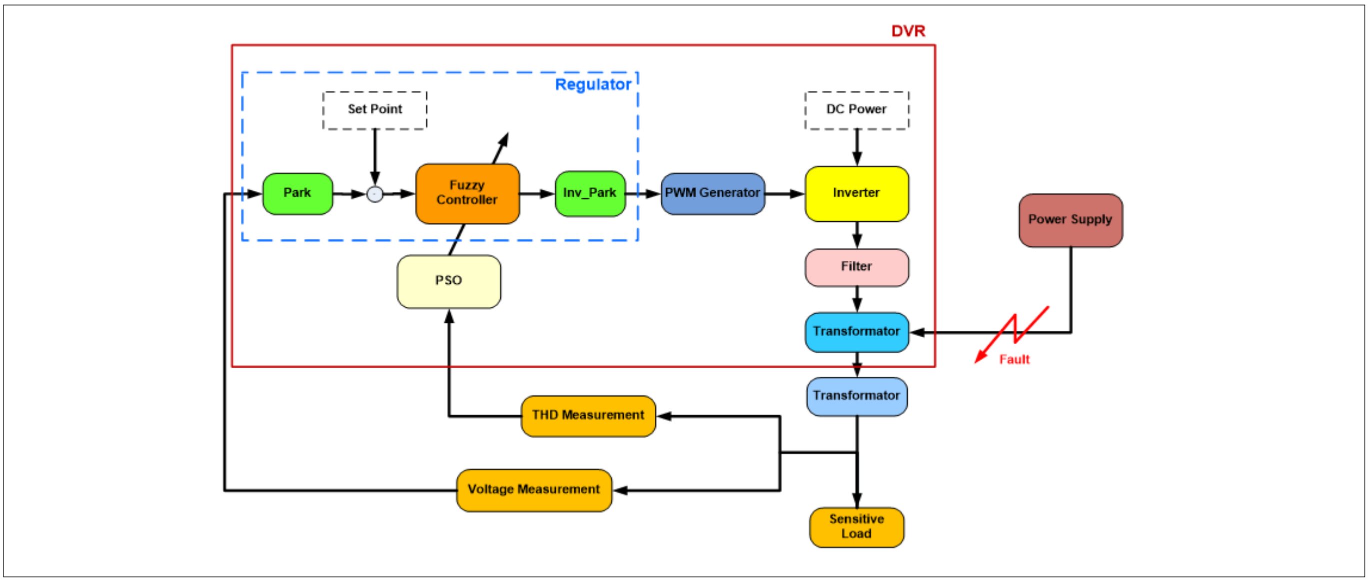

Figure 3: Schematic of Control System Using Proposed Approach

the fuzzy controller parameters, i.e. the membership functions parameters of the fuzzy control system were obtained as shown in Table I. The curves relating to if-then rules of fuzzy controller which illustrates the relationship between the input rules and each of outputs are shown in (Figure 4). The membership functions obtained from the parameters determined by PSO algorithm are as shown in (Figure 5 - 6) depicts membership functions for inputs with ranges [-1, 1] and [-0.1, 0.1] while (Figure 6) shows membership functions for outputs with ranges [-1, 3] and [-40, 40]. These parameters have obtained based on results presented in Table I which correspond to a search on the basis of 10 particles.

Voltages of three phases produced by the power source is as (Figure 7), which shows a drop for tow of phases at time 0.025s and only one phase supplies an appropriate voltage. Voltages of three phases delivered to the normal load for which the DVR system has not been considered is as depicted in (Figure 8), in which the voltage behavior just like that of source, faces a considerable turbulence in two of phases. In contrast, voltages of three phases given to the sensitive load for which the DVR system controlled with the PSO-fuzzy controller has been considered as per (Figure 9)is well-symmetric in all three phases with a negligible instantaneous fluctuation at the time 0.025s in two of the phases which is acceptable. Control voltages produced by the DVR system equipped with PSO-fuzzy controller is as illustrated in (Figure 10) which is not saturated and the injected voltages by the inverter benefiting from the PSO-fuzzy controller is as (Figure 11).

Table 1:

Input1_Parameters		**Input2_Parameters**	
0.084731159	-0.417089129	0.008473116	-0.04170891
-0.084731159	-0.196830482	-0.00847312	-0.01968305
0.084731159	0.020809973	0.008473116	0.002080997
0.084731159	0.218775852	0.008473116	0.021877585
0.084731159	0.413233862	0.008473116	0.041323386
Output1_Parameters		**Output2_Parameters**	
3.389246354	-16.68356518	0.169462318	-0.41043773
3.389246354	-10.30161429	-0.16946232	0.02999483
-3.389246354	-4.644962128	0.169462318	0.465174062
3.389246354	0.832398905		
3.389246354	6.151482133	0.169462318	0.86129223
3.389246354	11.35228066	0.169462318	1.249784593

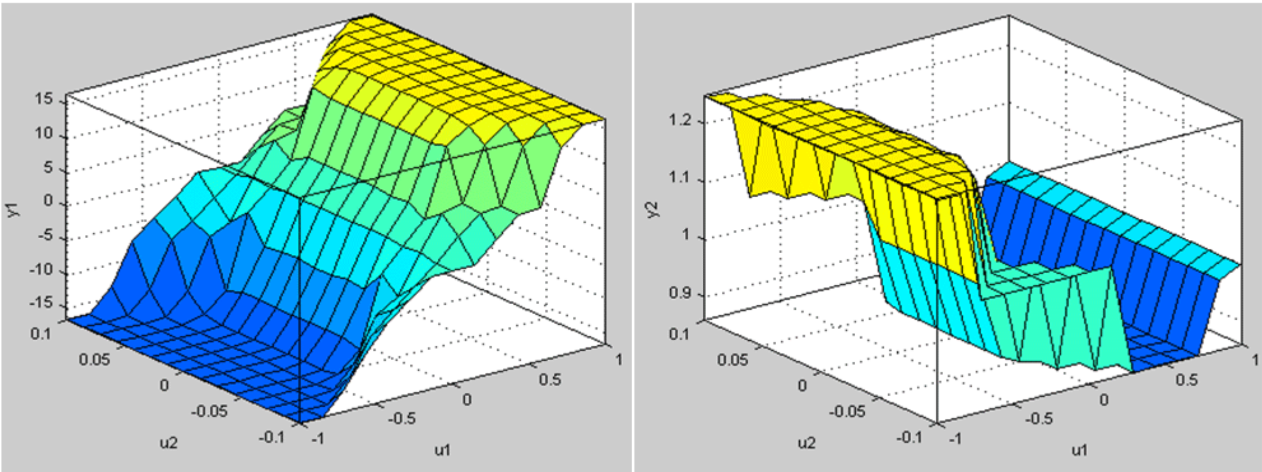

Figure 4: (a) and (b), relationships between if-then rules of fuzzy controller and outputs

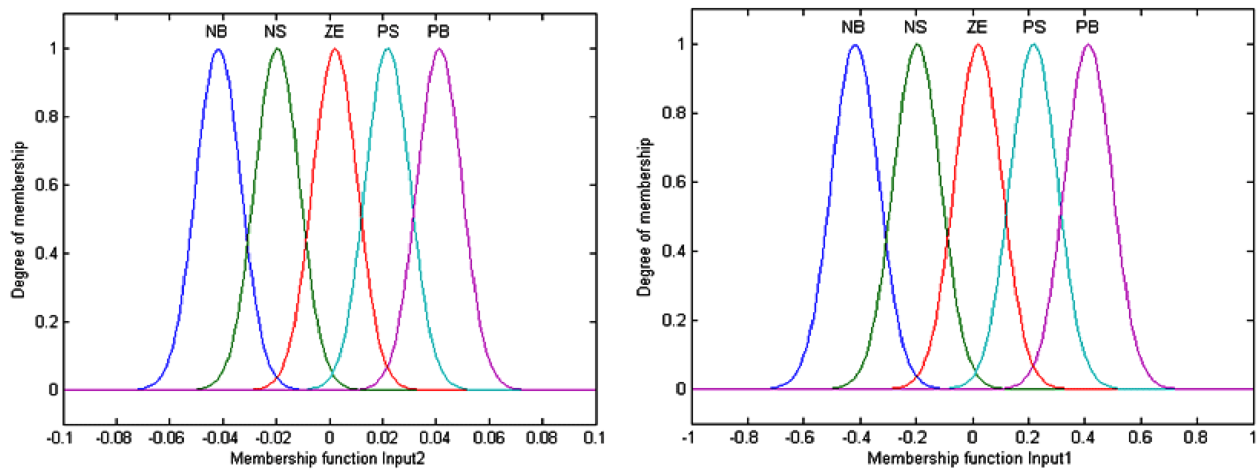

Figure 5: (a) Membership Functions for Input 1, (b) Membership Functions for Input 2

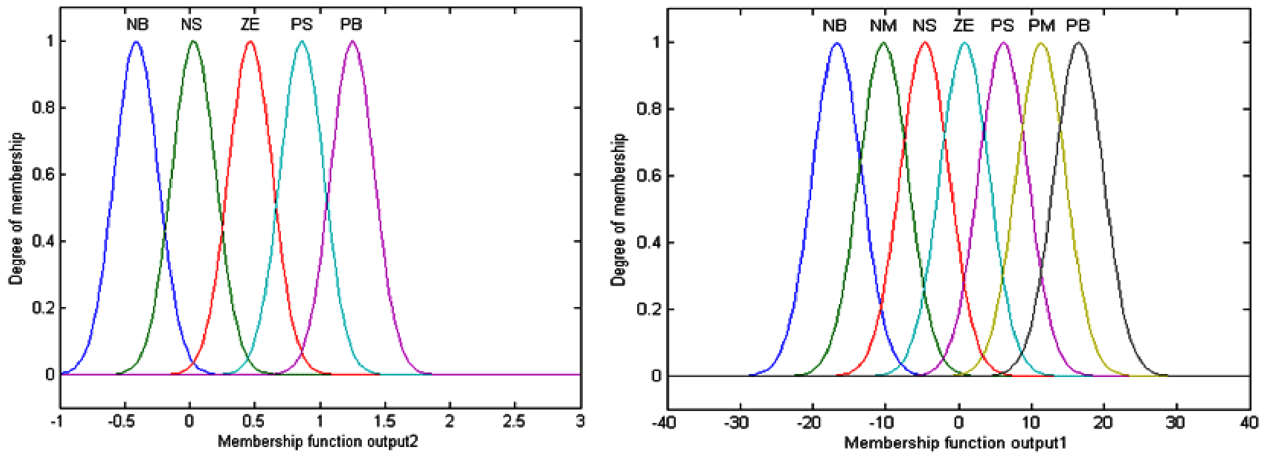

Figure 6: (a) Membership Functions for Output 1, (b) Membership Functions for Output 2

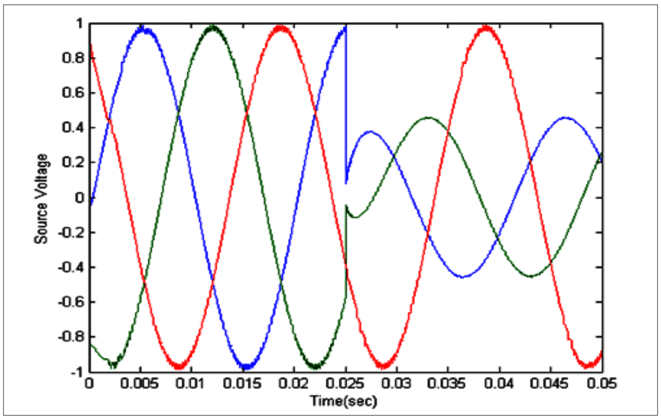

Figure 7: Voltages of Three Phases Produced by the Power Source

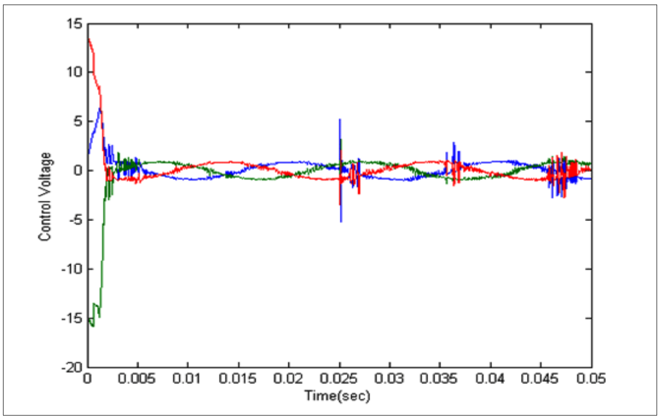

Figure 10: Control Voltages Produced by PSO-Fuzzy-Controlled DVR system

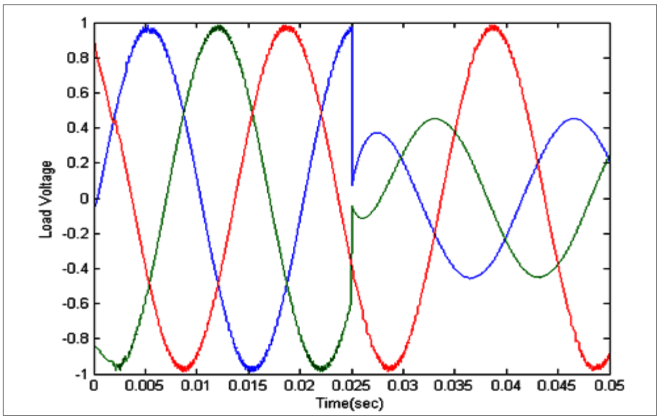

Figure 8: Voltages of Three Phases Delivered to the Normal Load Without DVR

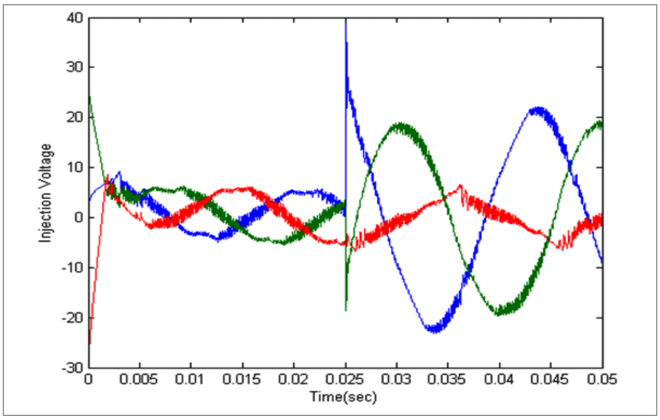

Figure 11: Injected Voltages by the PSO-Fuzzy-Controlled Inverter

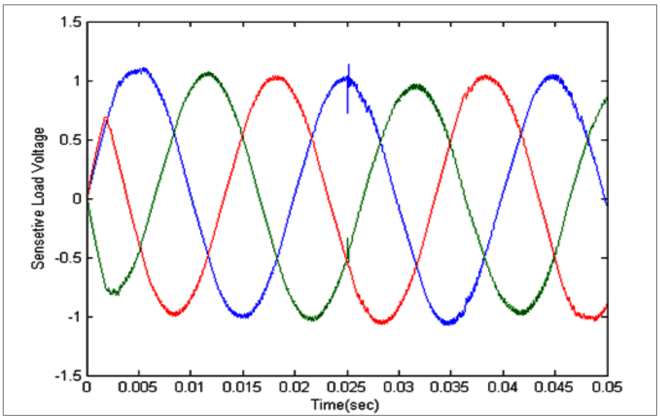

Figure 9: Voltages of three phases Given to the sensitive load with PSO-Fuzzy-Controlled DVR

Conclusion

In this research, a fuzzy controller optimized by Particle Swarm Optimization (PSO) technique was designed for Dynamic Voltage Regulator (DVR) system while fuzzy controller parameters were determined using this evolutionary algorithm. The optimized fuzzy controller generated the compensating voltage by the inverter containing insulated-gate bipolar transistor (IGBT) and injected it into the line so that sensitive loads available in the network receive a proper and error-free power. Using controlled DVR system, the network was able to supply a symmetrical three-phase voltage for sensitive loads. A PSO algorithm was coded and implemented in MATLAB to optimally adjust affecting parameters of fuzzy controller and employ an optimum DVR system for the purpose of eliminating turbulences occurring in the network. Simulation results obtained in this study, considering the complicated and nonlinear nature of DVR system, demonstrates efficiency of the proposed PSO-Fuzzy controller in improving behavior of the dynamic voltage restorer introduced to the network for the purpose of eliminating destructive effects of imminent disturbances over sensitive users. Fuzzy logic controller optimized by PSO algorithm could be able to efficiently optimize Sag characteristics of voltage of the sensitive load. Controlling voltage produced for Pulse Width Modulation (PWM) pulse generator reduced its Total Harmonic Distortion (THD) characteristics and DVR compensated function of the system against error as well as turbulence in such a way that the end user would not face any trouble with the supplied voltage.

References

1. Hazarika S, Roy SS, Baishya R and Dey S. Application of dynamic voltage restorer in electrical distribution system for voltage sag compensation. The International Journal of Engineering and Science (IJES), 2013;2(7):30-38.

2. Haque MH. Compensation of Distribution System Voltage Sag by DVR and DSTATCOM. IEEE Porto Power Tech Proceedings. 2002;1.

3. Ramachandaramurthy VK, Arulampalam A, Fitzer C, Zhan C, Barnes M, and Jenkins N. Supervisory control of dynamic voltage restorers. IEE Proceedings- Generation, Transmission and Distribution. 2004;151(4):509-516.

4. Wang B, Venkataramanan G, and Illindala M. Operation and Control of a Dynamic Voltage Restorer Using Transformer Coupled H-Bridge Converters. IEEE transactions on Power Electronics. 2006; 21:1053- 1061.

5. Li YW, Vilathgamuwa DM, Blaabjerg F, and Loh PC. A robust control scheme for medium-voltage-level DVR implementation. IEEETtransactions on Industrial Electronics. 2007;54(4):2249-2261.

6. Zhou H, Wei TZ, Zhao YL, and Qi ZP. Study on dynamic matrix predictive control of single-phase DVR. Proceedings of the Third International Conference on Electric Utility Deregulation and Restructuring and Power Technologies. 2010:2136-2140.

7. Kumar GVN, and Chowdary DD. DVR with sliding mode control to alleviate voltage sags on a distribution system for three phase short circuit fault. IEEE Region 10 and the Third International Conference on Industrial and Information Systems, Kharagpur India, 2008;1-4.

8. Shamsi-Nejad MA, Khalghani MR. DVR control using adaptive PI controller based on human brain learning. Proceedings of 17th Conference on Electrical Power Distribution. 2012;1-6.

9. Kennedy J and Eberhart R. Particle swarm optimization. Proceedings of ICNN'95 International Conference on Neural Networks. 1995;1942-1948.

10. HE Y, MA WJ and Zhang JP. The parameters selection of PSO algorithm influencing on performance of fault diagnosis. MATEC Web of Conferences. 2016;63:02019.