

# CONTROL OF DYNAMIC VOLTAGE RESTORER BY CHAOTIC ACCELERATED PARTICLE SWARM OPTIMIZATION TO IMPROVE POWER QUALITY INDICES

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**Abstract:** – *Dynamic voltage restorer (DVR) is the mostly used custom power device for improving power quality indices. The main function of DVR is to mitigate the problems of voltage sag and voltage swells. In this paper, DVR is used to control voltage sag as its main objective and to reduce total harmonic distortion (THD) as the second objective. DVR is controlled by proportional-integral (PI) controller. To obtain the optimal values for the coefficients of the PI controller a new control strategy called chaotic accelerated particle swarm optimization (CAPSO) algorithm which is an advanced version of PSO is used. An appropriate objective function for the optimization process is developed by the combination of fuzzy logic and neural network. The simulation results are obtained in MATLAB/SIMULINK software and a comparison is made between the results obtained from simulation of classic PI controller, standard PSO and CAPSO*

**Key Words:** dynamic voltage restorer (DVR), particle swarm optimization (PSO), chaotic accelerated PSO (CAPSO), voltage sag, total harmonic distortion (THD).

## 1 .INTRODUCTION

In recent years due to the increase of sensitive loads the demand for stable and qualitative electric power supply has been increased cumulatively. But, at the same time due to the rapid growth of industrial loads, power electronic devices, computer processors lead to the increase in non linear loads which added to the increase in power quality problems. So the main aim of the power system is to supply stable and high quality electric energy to the customer's one of the important reasons for the increase in demand for the stable electric power supply is its economic advantages. Due to the stable electric supply, efficiency and equipment lifetime increases leading to increase in reliability factor and better product quality is

obtained. On the other hand, due to interruption or deviation in delivered power quality leads to increase in repair of equipment and interruption in production. Thus in industrial environment stable power supply not only influence the asset savings but also increase the manufacture opportunities [1].

Power quality problems can be defined as any power problem that results in failure or mal operation of electric equipment. The minor causes for the power quality problems are power factor decrement, corona and skin effect losses, and transmission and distribution losses. Some of the major causes are asymmetric and symmetric faults, magnetic inrush currents. Due to these power quality problems harmful defects such as supply interruptions, voltage sags/dips, voltage swells, voltage transients, flickers and harmonic distortions occur. The most common disturbances in power system is voltage sags and swells. According to IEEE standard, a sudden decrease in voltage in the range of 10-90% for 0.5 cycles up to 1 min is termed as voltage sag [2]. The presence of dc voltage or current in the ac power system is termed as dc offset. Due to this, magnetic saturation occurs in transformer leads to increased heating losses and reduction in reliability. All these lead to harmonics.

The devices that are installed, maintained and controlled at the customer premises to improve power quality are customer power devices. These devices are based on solid state power electronic components. Some of the most commonly used custom power devices are uninterruptible power supplies (UPS), DVR and active power filters (APF). Among these devices the most reliable device for voltage abnormalities is the DVR. The main requirement in the utilization of DVR is its control system to achieve faster response to the variations of load voltages. The main purpose of control system is to generate pulses for the operation of VSC during system disturbance such that required voltage is injected by the

DVR to maintain a constant voltage magnitude across the load terminals [3]. Many researches have done on performance analysis and control of the DVR. Initially, an ordinary PI controller is used for the control of DVR [4] but the classic pi controller has poor operation in steady states. Several researches are carried out such as predictive control [5], robust control [6] and sliding mode control [7]. At present many researches are carried based on intelligent control techniques to control DVR operation. Firstly, fuzzy logic controller is used to control DVR in [8]. Design of fuzzy logic controller is very easier than previously stated methods because exact mathematical model is not required. Later on emotional controllers [9], hebb-learning controller in [10] are used to control DVR.

Most of the aforementioned researches even though shown good performance in steady and transient states, owing to complexity and non-linearity of power system, the controller design has become a challenging task. Also these approaches reduce voltage sag but do not consider voltage THD. So in [12] bi-objective PSO is used to vary the coefficients of the PI controller. In this paper a new control technique called CAPSO, a bi-objective optimization technique is developed to reduce voltage sag and voltage THD. The results are obtained in MATLAB software and are compared with other controllers to evaluate the performance of the proposed model.

## 2. DVR STRUCTURE AND FUNCTIONALITY

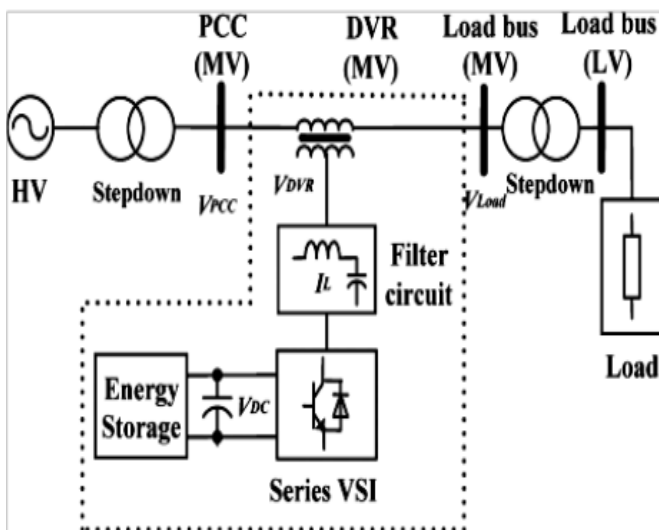


Fig -1: DVR unit structure

DVR is the mostly used series connected custom power device to attain voltage stability. To achieve this is voltage is injected into the line through two modes of operation: standby mode and injection mode [13]. During normal operation DVR works in standby mode supplying voltage

needed to overcome the transmission and distribution losses. It operates in injection mode when voltage sag occurs during disturbances. The schematic diagram of DVR unit connected to distribution system is shown in Fig.1 depicts the main components of DVR.

1. Voltage source inverter: the inverter is operated based on the pulses generated by the control technique i.e., pulse width modulation (PWM) technique. The input terminals of inverter are connected to energy storage equipment and output terminals are connected across injecting transformer through low pass filters. Insulated gate bipolar transistor (IGBT) switches are used for inverter operation. Diode is connected across IGBT to provide self commutation.
2. Injecting transformer: the secondary of the transformer is connected in series with the distribution system and the load, to couple the DVR with power system. Its primary is connected across the inverter. The secondary winding connections of this transformer are wound based on the winding type of step down transformer near to the load.
3. Energy storage experiment: on occurrence of voltage sags to provide necessary voltage and active power these are connected across VSI. Some of the energy storing devices are lead acid batteries, capacitor banks and flywheels.
4. Passive filters: in this context low pass filters are used to eliminate the harmonics generated in the VSI during D.C to A.C conversion. These filters are made by the combination of resistors, capacitors and inductors and the value of these parameters are tuned based on trial and error.

## 3. MULTI-OBJECTIVE OPTIMISATION USING FUZZY MEMBERSHIP FUNCTION

At first, each objective is described in the form of a fuzzy membership function. Then these membership functions are combined giving suitable weighting coefficients to form a satisfactory fuzzy objective function [10].

### 3.1. Membership function of voltage sag

Voltage sag is the difference between the reference bus voltage and real bus voltage. The voltage sag is calculated using the expression

$$D = \max |v_b - v_1| \quad (1)$$

Where  $v_b$  is the reference bus voltage and  $v_1$  is the load bus voltage. According to IEEE-519 standard, bus voltage can vary between 0.95 p.u and 1.05 p.u. So, in this paper we assign  $D_{\min}=0$  and  $D_{\max}=0.05$ . The membership function is specified in (2) and pictorially represented in Fig. 2

$$\mu_D = \begin{cases} \frac{D_{max}-D}{D_{max}-D_{min}} & \text{for } D_{min} \leq D \leq D_{max} \\ 1 & \text{for } D \leq D_{min} \\ 0 & \text{for } D \geq D_{max} \end{cases} \quad (2)$$

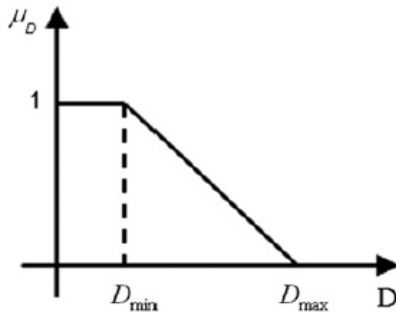


Fig -2: Voltage sag membership function

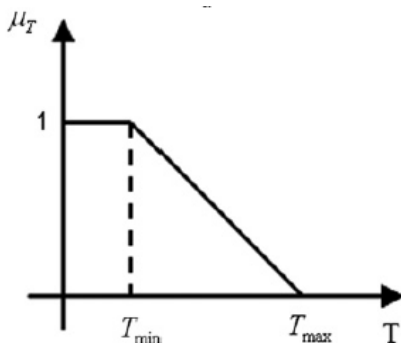


Fig -3: Voltage THD membership function

### 3.2. Membership function of voltage THD

Voltage harmonics causes serious effects on sensitive load. So considering harmonic reduction as a second objective along with the voltage sag reduction minimizes the power quality problems on sensitive loads. Supply voltage harmonics are analyzed by voltage THD factor and its membership function is specified in (3) and pictorially represented in Fig.3

$$\mu_T = \begin{cases} \frac{T_{max}-T}{T_{max}-T_{min}} & \text{for } T_{min} \leq T \leq T_{max} \\ 1 & \text{for } T \leq T_{min} \\ 0 & \text{for } T \geq T_{max} \end{cases} \quad (3)$$

According to IEEE-519 standard, bus voltage can vary between 0.95 p.u and 1.05 p.u. so, we assign  $T_{min}=0$  and  $T_{max}=0.05$

### 3.3 Bi-objective function

The objective function is a linear combination of the membership functions of voltage sag and voltage THD as specified in (4).

$$F = -(w_1\mu_T + w_2\mu_D) \quad (4)$$

Where  $\mu_D$  is the voltage sag membership function and  $\mu_T$  is the voltage THD membership function. Coefficients  $w_1$  and  $w_2$  are weighting factors. The values of these factors are determined by the power system experts. For optimization of the problem appropriate membership functions and weighting factors corresponding to each object has to be chosen. The value of weights are chosen such that their sum must be equal to 1 and they must be chosen between [0, 1]. These weights represent the priority of the chosen objectives.

The objective function obtained through fuzzification of objectives is fed to feed forward neural network. A feed forward neural network works as compensation signal generator. Feed forward neural networks are designed for each, voltage sag of d and q reference frames and THD of sensitive load voltage. Each network is designed with three layers. The input layer with single neuron, the hidden layer with 21 neurons and the output layer with 1 neuron. Activation functions chosen are tan sigmoidal for input and hidden layers and pure linear for the output layer. The training algorithm used is Levenberg Marquardt back propagation (LMBP). The architecture of neural network is shown in Fig.4. where  $x(1)$  and  $Y(1)$  are input and output of neural network which are voltage sag of d and q reference frames and THD of sensitive load voltage for three different neural networks.

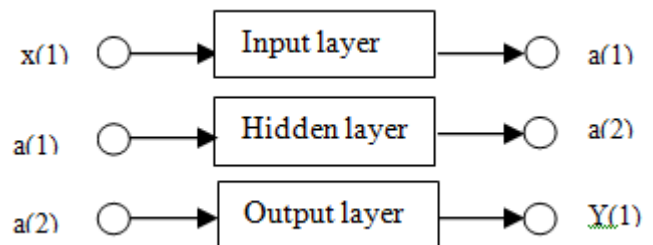


Fig -4: Architecture of neural network

## 4. CONTROL STRATEGY

### 4.1 Standard PSO algorithm

Eberhart and Kennedy developed the PSO algorithm for the first time in 1995[14] inspired by the social behavior of animals searching for food such as flock of birds or a school of fishes. Initial population is generated based on the experts view. All particles move randomly in an n-dimensional space and the position of each particle is defined by various components. Each particle has two ways to move. One towards the position of the current global best ( $G_{best}$ ) and the other towards its own best location i.e., individual best ( $P_{best}$ ). For each particle with position vector  $X_i$  and velocity vector  $V_i$  in an N-dimensional space are determined by (5) and (6) respectively.

$$X_i^0 = [P_{i,1}^0, P_{i,2}^0, \dots, P_{i,n}^0] \tag{5}$$

$$V_i^0 = [v_{i,1}^0, v_{i,2}^0, \dots, v_{i,n}^0] \tag{6}$$

After each iteration the position of each particle is compared with its previous positions and best position is determined as  $P_{best}$ . Let at Kth iteration individual best is  $X_{p_{best},i}^k$ .  $X_{G_{best},i}^k$  is the best position reached by the whole group until Kth iteration. After each iteration, the velocity and position of each particle is generated by using the formula (7) and (8) respectively.

$$V_i^{k+1} = \omega V_i^k + \alpha_1 R_1 (X_{p_{best},i}^k - X_i^k) + \alpha_2 R_2 (X_{G_{best},i}^k - X_i^k) \tag{7}$$

$$X_i^{k+1} = X_i^k + V_i^{k+1} \tag{8}$$

Where  $\alpha_1$  and  $\alpha_2$  are known as learning co-efficient. In this paper, we assign  $\alpha_1=2$  and  $\alpha_2=0$  at the beginning of search process. As search process proceeds,  $\alpha_1$  decreases linearly and  $\alpha_2$  increases linearly. By the end of search process they reach 0 and 2 respectively. Inertia constant  $\omega$  takes the value in the range [0, 1]. In this paper it is set to 1 at the beginning because increase of mass stabilizes the movement of particles. During the search its value decreases linearly and reaches to zero by the end of search process.

#### 4.2 Accelerated PSO

There are various types of PSO algorithms, of all those accelerated PSO shows some more advantages in convergence for global search than other algorithms. Accelerated PSO (APSO) was developed by Yang for the first time in 2008. Both the global best and the individual best are used by the standard PSO but the APSO uses global best only. The primary reason to use individual best is to increase the diversity in the search solutions but in APSO this is achieved by using the randomness property [15]. Therefore without using individual best a simplified version with only the best group experience is proposed to accelerated the convergence of the algorithm and the velocity vector is generated by using the formula

$$V_i^{t+1} = V_i^t + \alpha(\varepsilon - 0.5) + \beta(G_{best} - X_i) \tag{9}$$

Where  $\varepsilon$  is the random variable and  $\beta$  is the acceleration constant.  $\beta$  takes value in the range [0,1] and for most of the applications it is between 0.2 and 0.7.

#### 4.3 Chaotic APSO

From (9) it is clear that the main parameters of the APSO are learning coefficients because they characterize the variation of the global best. So the value of learning coefficients is very crucial in determining the speed of convergence. For example if  $\beta$  assigned to a lower value it leads to slower convergence rate. On the other hand if it is high, it leads to a false global best. So learning coefficient

values effect the convergence. In this paper chaos generator is used to determine the inertia coefficient ( $\omega$ ) in (7). In order to achieve this, chaos generator is multiplied with the previous value of inertia constant. The updated inertia coefficient can be calculated using (10) and (11).

$$f_k = \mu f_{k-1} (1 - f_k) \tag{10}$$

$$\omega_{new} = f_k \omega \tag{11}$$

Here  $\mu$  is the swing range control parameter of chaos generator. Its takes values in the interval [0, 4]. Due to the sensitivity of the chaos generator to initial values the values mentioned in (12) cannot be assigned. Here we assign  $\mu = 4$  and  $f_0 = 0.1$

$$f_0 \neq \{0, 0.25, 0.5, 0.75, 1\} \tag{12}$$

### 5. PROPOSED METHOD

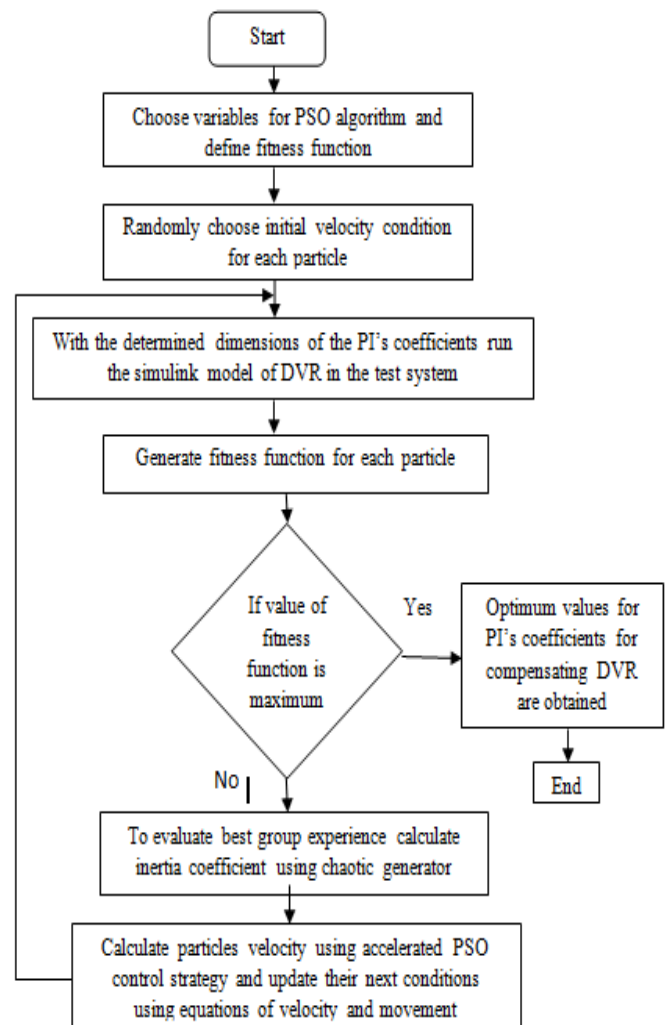


Fig -5: General optimization procedure for optimum PI coefficients determination

The main goal of this project is to select optimum values for the PI's parameters. The optimization algorithm tries

to search appropriate values for PI's parameters. Here we choose CAPSO algorithm as the optimization algorithm. As power system is complex in nature especially during fault conditions a large population size has to be taken. But, a large population size decreases convergence rate of algorithm on the other hand a small population size leads to get stuck in local minima. So, the effect of population size on standard PSO is very high. So to increase the convergence rate acceleration factor is introduced and chaos theory creates more diversity. Hence by using just two terms best group experience and inertia, the speed of convergence towards better solution is achieved. Therefore in this approach of algorithm, a combination of chaos theory and APSO is used. The general optimization for optimum PI coefficients is shown in the form of flow chart in Fig.5.

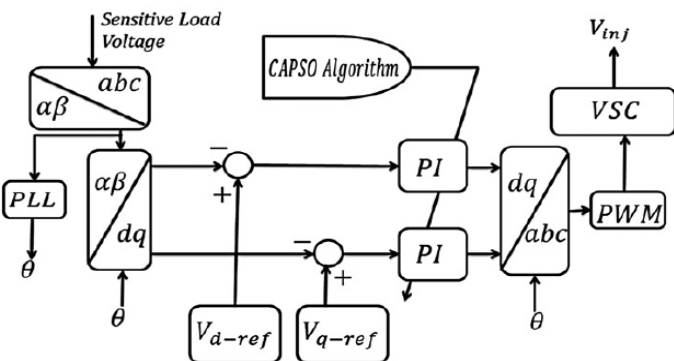


Fig -6: DVR control structure

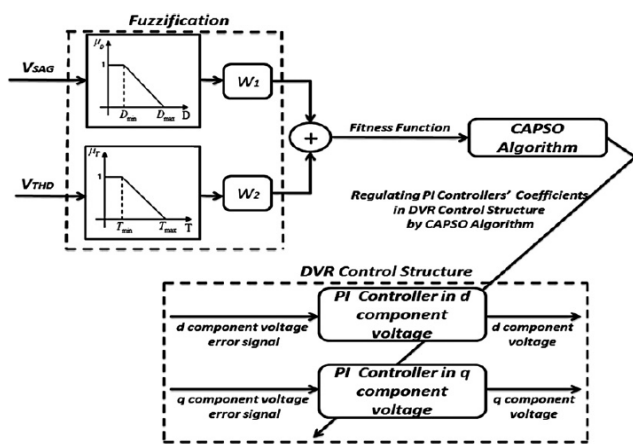


Fig -7: Proposed control structure

According to this flow chart the values of voltage sag and voltage THD are obtained from MATLAB/SIMULINK software. These values are given to fuzzy membership functions defined in (2) and (3) and these membership functions are placed in objective function in (4). For every particle in the search process this procedure is repeated for each iteration in optimization algorithm. The DVR

control structure and proposed control strategy is shown in Figs 6 and 7 respectively.

When DVR is connected to the supply line the phase angle of the reference signal is synchronized with the supply voltage phase angle. By using feedback synchronizing control loop the deviation of line voltage with the reference voltage is continuously monitored. Through parks transformation three phase (abc) signal is converted to dq rotating reference frame. Angular position of rotating reference frame is calculated by phase locked loop (PLL). PLL synchronizes the variable frequency three phase sinusoidal signals.

By connecting sensitive load voltage to parks transformation block we calculate  $V_d$  and  $V_q$ . Under balanced conditions  $V_d=1$  and  $V_q=0$  and during fault conditions these values changes. Now the generated dq voltages are compared with the reference dq voltages and the error is feed to the PI controller located in both d and q voltage components. The dq output voltages of PI controller are converted back to three phase voltage by parks transformation as shown in Fig 6. With the help of PWM technique pulses are generated and are applied to voltage source converter to produce voltage that has to be injected into the distribution system.

6. SIMULATION RESULTS

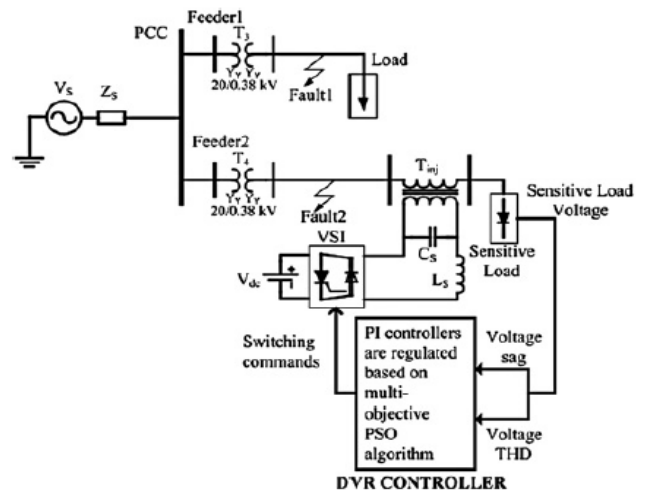


Fig -8: Distribution network with DVR and its proposed controller

A two bus power distribution system with one bus containing sensitive load is considered for the purpose of case study. The DVR with proposed controller is connected to the distribution network as shown in Fig. 8 and its parameter ratings are shown in appendix A. In the view to simulate more critical conditions two faults are simulated. The first fault is near the non sensitive load and the second one is on the source side of the series injection transformer. The first fault is an asymmetric two phase fault and occurs in the A, B phases and second fault is a

symmetric three phase fault in A, B, C phases. Parameters of both the faults are shown in table 1.

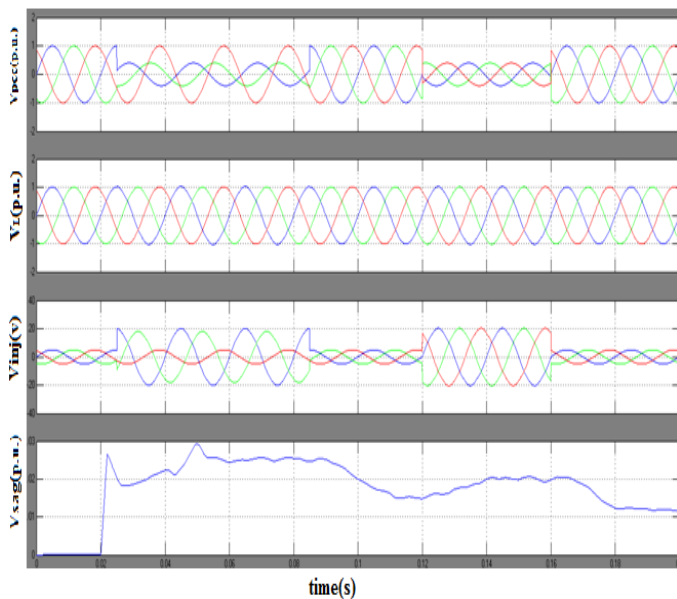
**Table -1:** Fault parameters

| scenarios | Fault points | Fault periods    | Fault resistance | Earth resistance |
|-----------|--------------|------------------|------------------|------------------|
| 1         | A,B          | [0.025<br>0.085] | 4.6              | 0.1              |
| 2         | A,B,C        | [0.12<br>0.16]   | 4.6              | 0.1              |

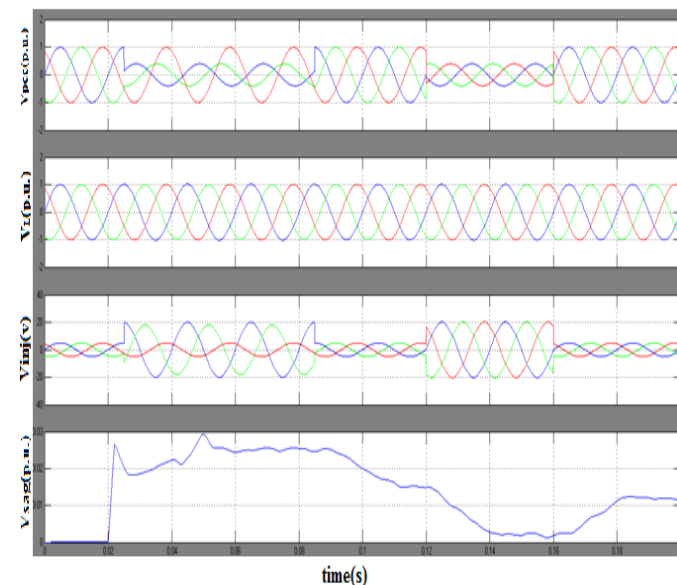
Initially DVR is controlled with classical PI controller and then the optimal values of PI controller are solved using single objective PSO in MATLAB/SIMULINK environment. The number of dimensions is two for each PI controller.

These dimensions represent the two coefficients i.e., proportional and integral gains of the PI controllers. A PSO algorithm with maximum 100 iterations and particle size 20 is taken. The voltage sag waveforms when DVR controlled with classic PI control and PI controlled with single objective PSO is shown in Fig. 9 and Fig. 10. Voltages at point of common coupling (PCC), across sensitive load terminals, injected voltage by DVR and sensitive load voltage deviations are observed in each of the figures. Their harmonic order spectrum are shown in Fig.13 and Fig.14 respectively.

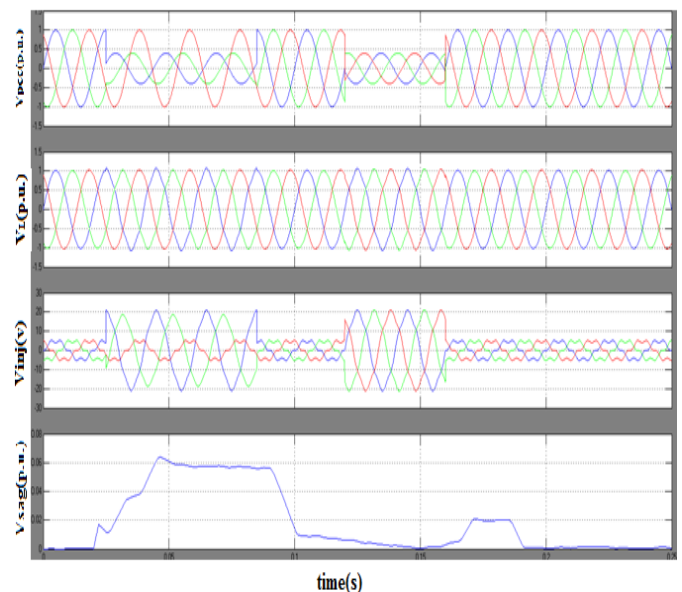
Though there is a noticeable change in there voltage sag values but THD index can be improved further. So in this paper we consider bi-objective optimization algorithm with voltage THD as its second objective. With the same number of iterations and particles considering the same case study we simulate results for DVR control with bi-objective standard PSO and DVR controlled with bi-objective CAPSO algorithm. There voltage sag waveforms are shown in figs. 11 and 12 respectively. Voltages at point of common coupling (PCC), across sensitive load terminals, injected voltage by DVR and sensitive load voltage deviations are observed in each of the figures. Their harmonic order spectrum are shown in Fig.15 and Fig.16 respectively. These clearly show an improvement in the THD signal and deviation signal of line voltage caused by system faults than the aforementioned algorithms.



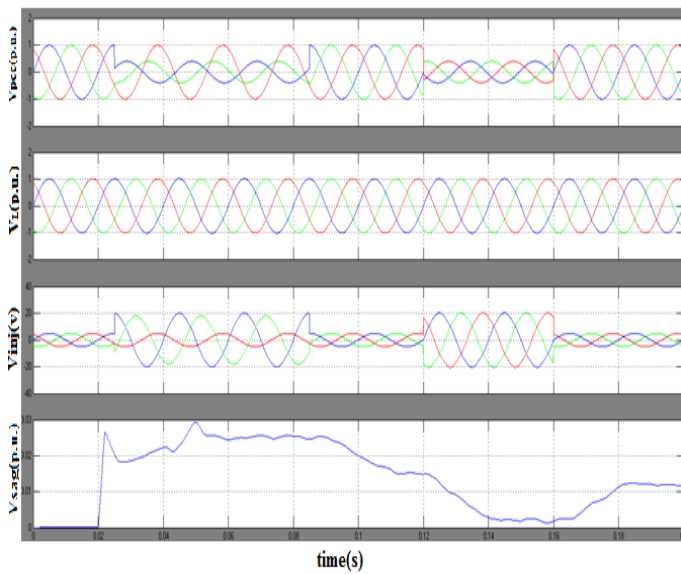
**Fig -9:** DVR control with classic PI



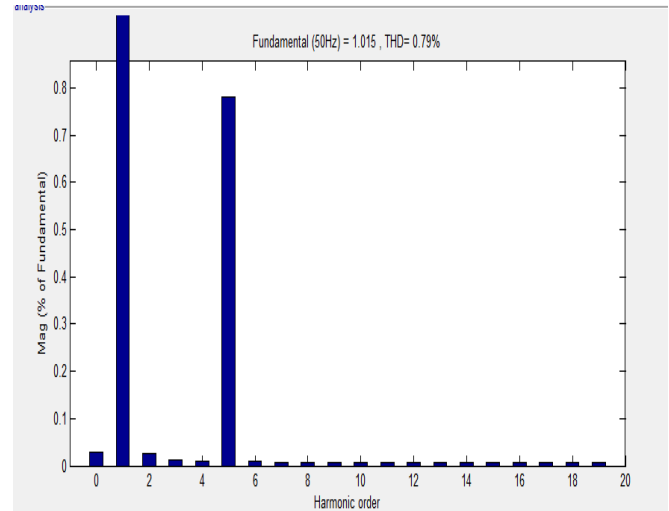
**Fig -10:** DVR control with PI controller regulated with single-objective PSO



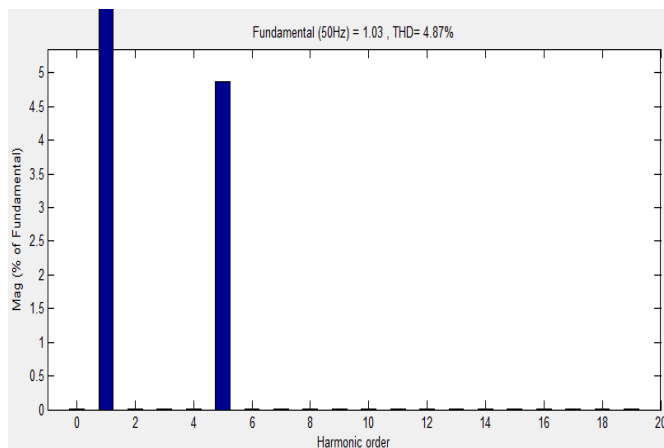
**Fig -11:** DVR control with PI controller regulated with multi-objective standard PSO



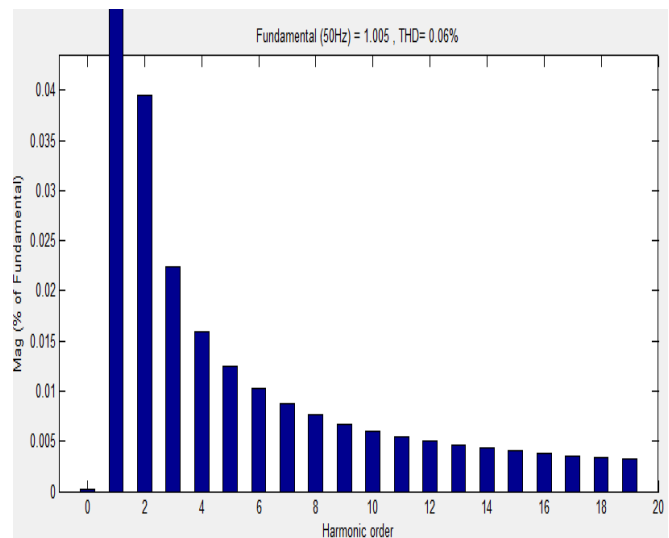
**Fig -12:** DVR control with PI controller regulated with multi objective CAPSO



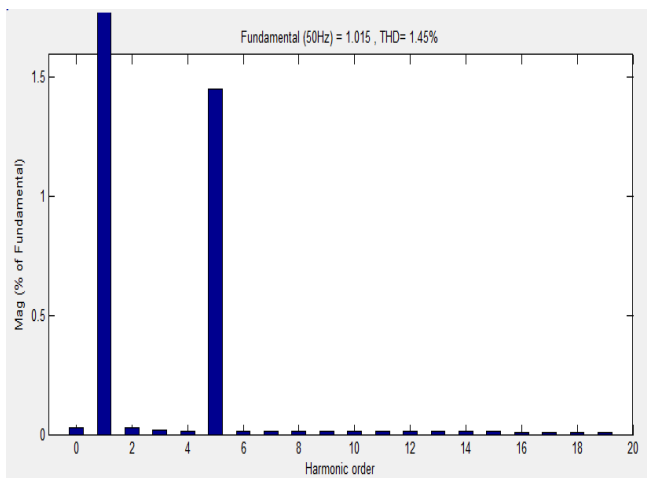
**Fig -15:** DVR control with PI controller regulated with bi-objective PSO



**Fig -13:** DVR control with PI controller



**Fig -16:** DVR control with PI controller regulated with multi objective CAPSO



**Fig -14:** DVR control with single objective PSO

## 7. CONCLUSIONS

According to the results obtained it is clearly shown that the CAPSO algorithm outperforms than other control techniques. In this paper, a new modification to PSO algorithm is presented in order to improve its performance. For PI controller better set of coefficients are achieved using this algorithm. Based on the combination of fuzzification and ANN a bi-objective optimization algorithm is developed in order to improve voltage sag and THD indices. The obtained simulation results reveals that the bi-objective algorithm has better performance than single objective algorithm. Hence by using CAPSO algorithm to control DVR a stable voltage with low THD can be provided for customers.

**Appendix A**

|  |   |
|--|---|
| System frequency $F_n$                         | 50 Hz   |
| Power supply voltage $V_s$                     | 22.5 kV   |
| Active power for sensitive load P              | 20 kW   |
| Reactive power for sensitive load              | $Q_l = 4$ kVAR<br>$Q_c = 1$ kVAR                                  |
| Active power for non-sensitive load P          | 25 kW   |
| Reactive power for non-sensitive load $Q_l$    | 4 kVAR  |
| Distribution transformer rated power and ratio | $P_n = 32$ kW,<br>20000/380                                       |
| Distribution transformer impedances            | $R_l = 0.0003$ pu,<br>$X_l = 0.001$ pu,<br>$R_m = X_m = 500$ pu   |
| Series transformer rated power and ratio       | $P_n = 15$ kW,<br>100/1000  |
| Series transformer impedances                  | $R_l = 0.00001$ pu,<br>$X_l = 0.0003$ pu,<br>$R_m = X_m = 500$ pu |
| DVR switching frequency $F_s$                  | 10 kHz  |
| DC voltage source $V_{DC}$                     | 200 V   |

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