PRODUCTION ENGINEERING ARCHIVES

Reparation of voltage disturbance using PR controller-based DVR in Modern power systems

D. Danalakshmi¹, S. Prathiba², M. Ettappan³, D. Mohan Krishna⁴

¹ Department of Electrical and Electronics Engineering, GMR Institute of Technology, GMR Nagar, Rajam, India,

² Department of Electrical and Electronics Engineering, Chennai Loyola-ICAM College of Engineering & Technology (LICET), Loyola Campus, Nungambakkam, Chennai-600034, India,

³ Department of Electrical and Electronics Engineering, Chennai Institute of Technology, Chennai, Tamil Nadu, India,

⁴ Department of Electrical and Electronics Engineering, GMR Institute of Technology, Rajam, India

Corresponding author e-mail: danalakshmi.d@gmr.it.edu.in

Article history

Received 03.01.2021

Accepted 24.02.2021

Available online 31.03.2021

Keywords

Smart Grid

power quality

PI and PR controller

Self Balanced Differential Evolution

Dynamic Voltage Restorer

Total Harmonic Distortion

Abstract

The Smart Grid environment gives more benefits for the consumers, whereas the power quality is one of the challenging factors in the smart grid environment. To protect the system equipment and increase the reliability, different filter technologies are used. Even though, consumers' expectations towards the power quality are not fulfilled. To overcome these drawbacks and enhance the system reliability, a new Custom Power Devices (CPD) are introduced in the system. Among different CPDs, the Dynamic Voltage Restorer (DVR) is one of the voltage compensating devices that is used to improve the power quality during distortions. When the distortions such as voltage swell and sag occur in the distribution system, the control strategy in the DVR plays a significant role. In this article, the DVR performance using Proportional Integral (PI), Proportional Resonant (PR) controllers are analyzed. A robust optimization algorithm called Self Balanced Differential Evolution (SBDE) is used to find the optimal gain values of the controllers in order to reach the target of global minimum error and obtain fast response. Then, a comparative analysis is performed between different controllers and verified that the performance of PR controller is superior than the other controllers. It has been found that the proposed PR controller strategy reduces the Total Harmonic Distortion (THD) values for all types of faults. The proposed SBDE optimized DVR with PR controller reduces the THD value less than 4% under voltage distortion condition. The DVR topology is validated in MATLAB/SIMULINK in order to detect the disturbance and inject the voltage to compensate the load voltage.

DOI: 10.30657/pea.2021.27.3

JEL: L23, M11

1. Introduction

Electric grid is designed for one way communication, and limited in choice with few consumers. To overcome the drawback of one-way communication, and the issues in the demand side, a smart grid is designed and developed. A smart grid is an electric grid that provides information and communication technology to collect data and information about the behavior of suppliers and consumers in an automated fashion. The basic differences between the smart grid over the traditional grid is shown in Table 1. Hence, Smart Grid is a generic tag for the application of computer, intelligence and networking capabilities to prevailing electricity distribution systems. Customer participation and real-time pricing are the characteristics of a smart grid. It improves the existing electrical characteristics

and resources like reliability, efficiency, generation and distribution. The necessity of the smart grid is to increase the effectiveness as well as automatic control towards distribution (Janjic et al., 2011). Though there are more challenges in the implementation of the smart grid such as capital cost, regulatory barriers and resistance to manage the demand, some benefits are also attained such as improvement of power quality, good communication and power reliability. Power quality issue is one among the vital aspects in designing the smart grid, since it affects the consumer load directly in the power sector. The other reason is the introduction of renewable power sources. Due to intermittency and variability of the introduction of renewable power sources, the smart grid creates a great impact on voltage variation (Danalakshmi et al., 2020). The smart grid comprises of several components, such as smart

meter, phasor measurement unit that helps to give the magnitude of the power quantity at the instant of time. Smart meters are helping indirectly to manage the voltage and power factor. The smart meter is an advanced electric meter that provides more information about the power provided for the domestic purpose. Other devices, such as transformer are used to step-up or step-down voltages.

Table 1. Comparison of the smart grid over the traditional grid

Sl. No.	Area	Traditional grid	Smart grid
1	Communication	Half duplex	Full duplex
2	Type	Electromechanical	Digital
3.	Power	Centralized	Centralized & distributed
4.	Monitoring & Controlling	Manual restoration	Self-healing
5.	Market	Choice of a few consumers	Choice of many consumers

Due to different faults at the distribution side, the voltage level of the utility system becomes poor. This scenario will affect the power quality on the consumer side. The quality of power can be enhanced with the help of DVR. DVR uses Stationary Reference Frame, theory-based controllers, for maintaining voltage. Stationary Reference Frame control, also called as $\alpha\beta$ -control that regulates the control signals in stationary two-phase frame. In this paper, the analyses of THD using PI, PID and PR controllers are also discussed, and the effectiveness of PR based DVR controller are highlighted. The significant contributions in this research article are listed below:

The contributions of this work are as follows:

1. The proposed model reduces the distortion in the voltage during sag or swell conditions and thereby reduces the THD value.
2. DVR model is analyzed using MATLAB/SIMULINK platform for different scenarios
3. THD values are computed for different scenarios and it is found that THD value is less than 5% using proposed model.
4. Different controllers are integrated with DVR model to analyse the results in different scenario.
5. SBDE algorithm is used to tune the optimal gain values for the controller to obtain steady state output voltages. The controller gain in this proposed method is tuned using a robust SBDE algorithm for different operating conditions. Optimal controller gain using meta heuristic technique is obtained and the dynamic response is verified. The control strategy uses the error driven controllers to achieve the maintenance of load voltage.
6. PR based DVR controller is proposed as a compensating device in utility system to control the dq- axis series injected voltage of the DVR that subsequently maintain the voltage across sensitive load in unclear and unstable conditions.

In the future, the modern power system should have the PR based DVR controller to maintain constant load voltage during a fault condition. The fault lines are identified using sensor and controlling action are manipulated, and information is provided to load controller to inject PR based DVR in the line.

2. Related work

The disturbances in power quality affect the performance of electrical devices, which may lead to serious damage of the electrical devices. Here, the double loop controllers are used to detect the disturbance and to mitigate the same. The control and grid synchronization techniques along with voltage detection are used with DVR to provide good quality power under disturbance condition. In the paper (Tien et al., 2018), PR and sequence-decoupled resonant (SDR) controller are integrated as double loop controller in stationary frame. The variables used in the model is injection current and voltage in stationary frame in order to provide the appropriate voltage during disturbances.

In order to regulate the voltage during disturbances, the Sliding mode controller (SMC) is used in the DVR model. Particle Swarm Optimization (PSO) algorithm is used to find the optimal gain values in SMC in order to minimize the Integral Square Error (ISE). PSO optimized SMC are compared with different controllers and found that the THD value in the load voltage is less (Jeyaraj et al. 2020).

A novel under damped adaptive reaching law is used in the sliding mode control of DVR. Results have been developed with different illustrations under different disturbances. This method works well towards mitigating the disturbance, but the only drawback in this model is that it is applied to the second order non linear system (Pandey et al., 2017).

Grasshopper Optimization Algorithm(GOA) is used in the DVR model in order to tune the parameters of the PID controllers. GOA optimized DVR model is used to mitigate the voltage swell and sag in the system and results are compared with other optimization algorithms, such as cuckoo search, Grey wolf and Flower pollination to achieve minimum error. GOA optimized DVR model showed superior performance compared with conventional active disturbance rejection controller, which was verified in MATLAB/SIMULINK platform (omar et al., 2019).

Energy storage system integrated with DVR along with fuzzy logic controller was used to increase the capability of low voltage of the system. Zero active power tracking technique was used in the DVR model and showed the superior results during disturbances compared to other techniques (Yan et al., 2019).

DVR is used to improve the power quality in the sensitive load with appropriate control circuit. Voltage source with 3rd harmonics and 5th harmonics are introduced through programming and applied to the system. DVR based control strategy eliminates the harmonic content in the system and provides the smooth output across the load. Approximately, the THD value is reduced to 4% and also maintains the steady state voltage for different scenarios. The authors have suggested using the soft computing techniques in the DVR based

control strategy model (Danbunrungrakul et al. 2017; Zhang and Mu, 2019). Table 2 shows the different DVR approaches used in the references.

Table 2. A Comparison of Various DVR based approaches

Ref	Control Strategy Model	Applications
(Tien et al., 2018)	DVR with PR and SDR controller are integrated as double loop controller	To inject the voltage or current in order to provide the appropriate voltage
(Jeyaraj et al., 2020)	DVR with PSO optimized sliding mode controller	To find the optimal gain values to minimize the error
(Pandey et al., 2017)	DVR with adaptive reaching law	To mitigate the voltage disturbance
(Omar et al., 2019)	DVR with GOA based PID controller	To maintain the steady state voltage during voltage sag and swell condition
(Yan et al., 2018)	DVR with Energy Storage System	To resume the low voltage ride through for a renewable energy systems
(Danbunrungrakul et al. 2017)	DVR with zero real power tracking system	To maintain the steady state voltage during voltage sag and swell condition
(Zhang and Mu 2019)	DVR	To eliminate the harmonics in the voltage with reduced THD

3. Types of faults and Customized Electric Equipments (CPD)

The cause of poor power quality mainly depends upon the fault in power system equipment and the unexpected load variation. The unexpected load variation can be dealt with alternator, whereas the fault in the power system equipment is an unavoidable one. Faults in power system equipment decrease the reliability and efficiency of the system. Electrical faults generally caused by a failure of consumer equipment such as transformers, machines, due to environmental impacts such as lightning and others. These faults cause interruption of the equipment operation. Fault analysis is required in a power system to design the size of the conductors and ratings of the equipment. All the equipment should be deliberated in such a manner that they can withstand fault current, which usually flows in large quantity. The fault current can be found in case of balanced/unbalanced faults. The conductors can be designed in such a manner that they can withstand such a colossal current. In the power system, there are two types of faults, i.e. symmetrical and unsymmetrical faults.

The different types of fault and percentage occurrence of fault are shown in Table 3. It is found that LG fault is most frequently occurring fault, and it plays a major role in THD analysis.

During fault conditions, some fluctuations occur in load voltage by which the load voltages do not maintain constant values. The voltage fluctuation leads to poor power quality

which directly affects the consumer loads. To overcome this drawback and maintain the constant load voltage under fault conditions, an advanced power electronic controller has been developed. The evolution of electronic power controllers such as CPD and FACTS device are important in maintaining reliability and power quality (Hingorani, 1995).

Table 3. Different types of fault and their percentage

S. No.	Type of Fault		% occurrence of fault
1.	Symmetrical fault	Line to line to line to ground (L-L-L-G)	2 - 5%
		Line to line to line (L-L-L)	
2.	Un-symmetrical fault	Line to ground (L-G),	60 - 70%
		Line to line (L-L)	5 - 10%
		Double line to ground (L-L-G)	15 - 20 %

The FACTS devices are mainly used to enhance the power quality and reliability at the transmission line, whereas CPD is used to improve power quality at the consumer side. Several methods exist towards enhancing the quality of power which are active and passive filters. It consists of inductor and capacitor component. Nevertheless, the stability of the system is poor while using the filter circuit.

CPD are of two types, namely compensating type and network reconfiguring type (Jothibas and Mishra, 2014). DVR comes under the compensating device which is mainly used for voltage maintenance. DVR is more imperative in the industry side to mitigate the voltage correlated issues and protect the sensitive loads.

4. A Modern Electric Transmission and Distribution System

The modern power system consists of new devices such as FACTS and customized electrical equipments at the transmission and distribution infrastructure (Rauf and Khadkikar, 2014). Though the advanced controllers are in use, if there is no proper information to the modern devices, they do not respond immediately for the dynamic loading condition. Hence, it is necessary to deploy smart measuring and monitoring devices with electronic power controllers. In this proposed system, it is assumed that the controllers fetch information about the power system quantities through the Internet of Things (IoT). The IoT consists of various components such as sensors and actuators. The sensors, such as voltage sensor and current sensors measure the voltage and current quantity. If any abnormal conditions occur, the actuator gives a signal to the customized electrical equipments through proper computation and communication platforms which improve the power quality issues accordingly. IoT technology is used in several power system operations such as smart building, industrial automation, smart metering, automatic lighting system in public places (Dhowmya et al., 2021).

In the power sector, IoT devices are widely used because of the flexibility in usage of the devices. The Modern power system can be incorporated with new technologies, i.e. software

and hardware which provide the maximum benefits to the consumers. It is roughly divided into three categories which are listed below.

1. Advanced components and equipments.
2. Communication control and measurements.
3. Support tools-improved decision.

Fig. 1(a) shows the modern power system with IoT based power system components. The power flow control and protection from overloads are the significant functions of the transmission and distribution of power system. Power electronic devices are used in both transmission and distribution system, but their deployment is limited to particular applications due to maintenance and relatively expensive. From Fig. 1(a), it is inferred that customized electric equipment plays a vital role in the modern power system. By using sensors, voltage is monitored and collected from both the transmission and distribution side. The collected data are manipulated, and appropriate controlling actions are taken in the load side. If any voltage sag and swell happens in load side, the fluctuations will spoil the quality of power in particular affected line. The controlling signal is given to the affected region, and the DVR is injected in the corresponding line. To improve the power

quality and system reliability, DVR is connected at load side where the distortion arises. At the same instant, the voltage is maintained constant by using a DVR.

4.1. Block Diagram of DVR

In the load side, the DVR is connected in-series, supplies the essential frequency and voltage which is called a static compensator used to balance the voltage distortion. DVR is used towards controlling the fault current, harmonics and transients. Fig. 1(b) represents the various blocks in DVR along with the explanation as followed.

In the proposed method, the controlling technique in the injection transformer determines the sample voltage that is to be injected. The Injection transformer is used to restrict the distortion and the energy to be transferred at the secondary side (Zhang and Mu, 2019). Between the Voltage Source Converter (VSC) and distribution, the transformer uses the DVR to transfer the required voltage. The power circuit of DVR and distribution network are connected at High voltage (HV) and Low voltage (LV) side respectively.

Fig. 1a. Modern power system with IoT based technology by incorporating the CPD

A VSC is a power converter, and it can produce the required level of AC voltage (Pandey et al., 2017). The persistence of a capacitor is to reduce the harmonic ripple. A harmonic filter is used for harmonic reduction. It has a little assessment of approximately 2 % of the load power connected to the transformer winding. In DVR, VSC provides the necessary utility voltage. The positive and negative gate pulse is given to the upper and lower switches of the inverter using a PWM control technique (Saeed et al., 2014). The voltage generation is controlled by Synchronous Reference Frame (SRF) method. This SRF method is excellent, but requires a PLL technique to work in an unclear and unstable load environment. The benefit of SRF method compared to other control strategies is achieved

by allowing the transition of space coordinates independent of time. This control strategy part is required in order to provide smooth controlling action over the voltage signal and thereby maintain the stability of the system. The PR controller is implemented in a synchronous d, q reference frame (SRF-PR) that has deadbeat response for current reference tracking. It ensures decoupling between the d and q axis. It also maintains the controller ability of tracking without error in the absence of positive sequence current reference of fundamental frequency. Furthermore, the controller ensures the full decoupling between the currents of axes d and q (Busada et al., 2019).

The different types of controllers are available such as PI and PID controllers. In this work, a PR controller is proposed to reduce the THD further, and the results are compared with other controllers (Surendran et al., 2014). The control technique mainly depends on the load type. Here, the loads are very much sensitive to both voltage magnitude and phase angle. The occurrence of faults in the system leads to error in the voltage phase angle measurement. Phase-Locked Loop (PLL) is adopted for tracking voltage sequence. Fig. 1(b) shows the block diagram of system under study. The capacitor acts as a storage unit which is used to give supply to the DVR with the required real power. VSC is used for the conversion process from DC to AC in order to inject the transformer with desired voltage and frequency. Transformer is used to transform the

voltage from VSC to distribution side. Filter is used to remove the harmonic content of the voltage from VSC. Controllers play a major role for controlling the voltage across the load. To reduce or remove the error between actual and estimated angles, different controllers like PI, PID and PR are used. Comprehensive analysis were presented to assess the performance of each controller in obtaining good quality of power.

DVR is placed near the sensitive load to protect from disturbances. The acceptable voltage variation is $\pm 5\%$ from the nominal value. The load voltage is given by

$$V_L = V_S + V_{DVR}$$

Where V_S and V_{DVR} are the source and DVR voltages

$$S_L = V_L I_L = P_L - jQ_L = (P_S - jQ_S) + (P_{DVR} - jQ_{DVR})$$

Where S_L is apparent power at load, P_L and Q_L are the real and reactive power consumptions by load.

Fig. 1b. Block diagram of system representation

4.2. Proposed control scheme

The proposed control scheme is represented in Fig. 2 which consists of five steps as follows:

1. Detect the system voltage disturbance
2. Compare the load voltage with reference voltage
3. Synchronize the controller with supply voltage
4. Introduce the controller scheme
5. Voltage source converter are driven by giving appropriate gate signal.

Step 1: Type of fault plays a major role in detecting time and depth of voltage disturbance. Various methods are available to detect the faults. The reference and load voltages are transformed from abc to $dq0$ using parks transformation as in Eq.1

$$\begin{bmatrix} V_d \\ V_q \\ V_0 \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \cos(\theta) & \cos(\theta - \frac{2\pi}{3}) & \cos(\theta + \frac{2\pi}{3}) \\ -\sin(\theta) & -\sin(\theta - \frac{\pi}{3}) & -\sin(\theta + \frac{\pi}{3}) \\ 0.5 & 0.5 & 0.5 \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \quad (1)$$

Step 2: The reference and load voltages in $dq0$ frame are compared to obtain the error signal. The error signal is used to

detect the change in supply state which is obtained using the Eq. 2.

$$e_t = \sqrt{(V_{ref,0} - V_{L,0})^2 + (V_{ref,d} - V_{L,d})^2 + (V_{ref,q} - V_{L,q})^2} \quad (2)$$

Step 3: PLL are used as a tool for the synchronization of controller output signal with reference input signal in phase and frequency

Step 4: SBDE algorithm is used to find the optimal controller gain values. The prime objective of the controller is to minimize the error signal. For this, a novel SBDE algorithm is used to find the optimal gain values of different controllers (Danalakshmi et al., 2018).

Step 5: Last step is the conversion of voltage from $dq0$ to abc frame as given by Eq.3. Thereby, the gate signals are given to drive the VSC and hence compensates the voltage variations in load

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} \sin(\theta) & \cos(\theta) & 1 \\ \sin(\theta - \frac{2\pi}{3}) & \cos(\theta - \frac{2\pi}{3}) & 1 \\ \sin(\theta + \frac{2\pi}{3}) & \cos(\theta + \frac{2\pi}{3}) & 1 \end{bmatrix} \begin{bmatrix} V_d \\ V_q \\ V_0 \end{bmatrix} \quad (3)$$

Fig. 2. Proposed DVR control scheme

4.3. Different types of controller

The controller plays a vital role in DVR which regulates the voltage at the load end when it forced for the unbalanced condition due to distortion. The different types of controller are given as follows.

4.3.1. Proportional Integral controller

This controller combines the proportional and integral controller by feedback mechanism. The controller calculates the error by comparing the set value with the measured value then according to the tuning parameters value, K_p , K_i and τ_I it calculates the controller output to maintain the process variable. The output of the PI controller is given by Eq. 4,

$$u(t) = u_{bias} + K_p e(t) + \frac{K_i}{\tau_I} \int_0^t e(t) dt \quad (4)$$

where,

$u(t)$ – controller output

u_{bias} – Value of $u(t)$ when the controller is first switched to automatic from manual mode

K_p and K_i – proportional gain and integral gain

τ_I – Integral time constant

$e(t)$ - Set Point (target value) – Process Variable (measured value)

Usually, the K_p , K_i and τ_I values are taken between 0 to 8, 0 to 1 and 0 to 50 seconds respectively.

The main advantages of this controller are good damping, zero offsets and no steady-state error. As the integrator involves, it increases the system type, reduces the steady-state error and improves accuracy. The major drawbacks of the controller are stability and slow response.

4.3.2. Proportional Integral Derivative controller

PID controller is one of the feedback controllers that combine three terms, namely proportional, integral and derivative control to control process variables. The output of controller is summing up of proportional, integral and derivative responses. The controller calculates the error by comparing the set values with the measured value and then according to the tuning parameters K_p , K_i , K_d , τ_I and τ_D . Then, it calculates the controller output to maintain the process variable. The controller output is given in Eq. 5,

$$u(t) = u_{bias} + K_p e(t) + \frac{K_i}{\tau_I} \int_0^t e(t) dt + K_d \tau_D \frac{de(t)}{dt} \quad (5)$$

where,

$u(t)$ – controller output

u_{bias} – value of $u(t)$ when the controller is first switched to automatic from manual mode

K_c – controller gain

τ_I & τ_D – constants at integral time and derivative time

$e(t)$ – set point (target value) – process variable (measured value)

K_p , K_i , K_d , τ_I and τ_D are the tuning parameters of the PID controller.

Usually, the K_d , τ_I and τ_D values are taken between 0 to 1, 0 to 50 seconds and 1 to 75 seconds

This controller eliminates the overshoot and the oscillations of the system output. A P-controller has the advantage of reducing the rise time but never eliminates the steady-state error. A PI-controller has the benefit of eliminating steady-state error. The PD controller increases the system stability and reduces the overshoot. All design provisions can be reached with the PID controller.

4.3.3. Proportional integral resonant controller (PR-controller)

PR controller is used to improve the performance of the VSC under unbalanced condition. PR is featured with the control of tracking the AC and DC quantities parallelly. PR controller provides zero error steadily in DC sample quantities and also to compensate for a harmonic disturbance. From control system theory, the connections between PI and PR compensator in series and parallel effectually provide ripple-free DC link voltage. The controller parameters should be tuned to obtain excellent designing in the control system (Surendran et al., 2014). PI compensator is used for controlling the DC component, and PR compensator is used to control the pulsating component. While reforming the phase- and amplitude-frequencies response, the DC and harmonic frequency components gain infinitely by converging DC tracking and harmonic disturbance errors to zero. Commonly used PR controller is represented by the following transfer function given in Eq. 6 (Jothibas and Mishra, 2014).

$$G_{PR}(s) = K_P + K_R \frac{s}{s^2 + w_e^2} \quad (6)$$

where w_e represents the AC reference angular frequency. The problem associated with PR type of controller is the inability to compensate the DC disturbance introduced in the control loop by non-linear loads. To avoid this problem, the PR controller is introduced as shown in Eq.7 with K_R between 0 to 1 and $w_e^2=1$

$$G_{PIR}(s) = K_P + K_I \frac{1}{s} + K_R \frac{s}{s^2 + w_e^2} \quad (7)$$

The PR Controller-based DVR is introduced in modern power system, and thereby quality service will be provided to the consumer.

5. Formulation of optimization problem

Fitness Function:

To perform the fine tuning of controller gain, the fitness function named as Integral time square error (ITSE) is defined by Eq. 8 and Eq. 9 which represents the objective of optimization problem (Danalakshmi et al., 2018).

$$ITSE = \int_0^\infty e_t dt \quad (8)$$

$$F(x) = \min(ITSE) \quad (9)$$

where e_t indicates the difference in error signal between the reference value and actual value of load voltage in dq0 reference. The fitness function has to be satisfied with following constraints.

Constraints:

1. The voltage level of feeder should operate between the operating limits from 0.9 to 1.05

$$0.9 \leq V_L \leq 1.05$$
2. The maximum value of THD of the feeder is limited as per IEEE standard 519 (Busada et al., 2019; Surendran et al., 2014).

In this proposed method, DVR can be controlled by PI, PID and PR Controller. The tuning parameters such as gain parameters of various controllers are tuned by optimization algorithm (Danalakshmi et al., 2018).

THD is the measure of distortion in the system, and it is the fraction of total powers from the harmonic components with fundamental frequency as shown in Eq. 10. The THD is measured by applying an input to the system as a sine wave, and obtain the total energy at the system output as harmonics of input frequency under fault conditions (Busada et al., 2019; Surendran et al., 2014).

$$T.H.D = \frac{\sqrt{\sum_{h \min}^{h \max} V_h^2}}{V_1} \quad (10)$$

where, V_h is the harmonic component h (rms value) of the quantity V . T.H.D value is limited as per Eq.11(Surendran et al., 2014).

$$T.H.D \leq T.H.D_{max} \quad (11)$$

5.1. Self Balanced Differential Evolution:

SBDE algorithm is one of the robust global searching techniques (Danalakshmi et al., 2018). The following steps are used in the SBDE algorithm. *Step 1:* The first and foremost step is the initialization of candidate population within the chosen limits. It can be written as Eq.12

$$y_{A,B}^G = y_A^l + \text{Rand}(y_B^l - y_B^u) \quad (12)$$

$A = 1, 2, \dots, n_p$, where n_p is population size

$B = 1, 2, \dots, D$, where D is the problem dimension

Parameters such as candidate size, iteration count, problem size, scaling value and crossover rate are initialized and solution are stored for every population vector.

Step 2: The second process in DE is the mutation process. The mutant vector is created using random vectors which are generated from the previous step. It can be written as mentioned in Eq. 13.

$$V_A^G = C \times y_{r1}^G + F \times (y_{r2}^G - y_{r3}^G), i = 1, 2, \dots, N_p \quad (13)$$

where F is the mutation scaling factor and C is the cognitive learning factor. The two factors such as C and F give faster convergence and explore the search space.

Step 3: The crossover is the third step which generates a trail vector using parent and mutant vectors in a probabilistic concept as in Eq. 14. Take crossover rate (CR) between 0 and 1.

$$u_i^G = \begin{cases} y_A^G, & \text{if random } B \leq CR \\ y_{A,B}^G & \text{otherwise} \end{cases} \quad (14)$$

Step 4: Selection process is the final stage of this algorithm in which the vector provides minimum fitness value and is selected using the Eq. 15.

$$y_{A,B}^{G+1} = \begin{cases} u_i^G & \text{if } f(u_i^G) \leq f(y_A^G) \\ y_{A,B}^G & \text{otherwise} \end{cases} \quad (15)$$

In this paper, SBDE is used for minimizing the error value (Danalakshmi et al., 2018). In SBDE, the search space are exploited or explored by introducing two new powerful factors such as cognitive learning factor and scaling factor as compared to conventional differential evolution.

Fig. 3. SBDE - controller block diagram

The main contribution in this paper is by applying the SBDE algorithm to find the optimized configuration of gain values of controllers. Fig. 3 shows the proposed SBDE-controller design model which is used to identify the optimized parameter values in the controller with ITSE as an objective function. ITSE is taken from the Matlab simulink model and deployed as a target objective in the SBDE algorithm. It generates a new

population and provides optimal tuning value using matlab.m file coding. It tunes the controller parameters iteratively to achieve the objective or unless stopping criteria is reached.

5.2. Implementation of SBDE algorithm:

SBDE is used to find the optimal gain value of the controller to get the acceptable voltage profile in order to ensure good power quality during disturbances. Comparison of dq0 of load voltage and reference voltage generates the error signal which is given as an input to the controller. The controller gain is tuned by optimization algorithm in order to minimize the error signal during fault condition and thereby makes the system to be stable during disturbance. The output from the controller is transformed into an *abc* reference frame. This signal is forwarded to the PWM generator which makes VSC to turn on after the completion of optimization loop and optimal solution. Then, the storage element will inject the voltage to the boosting transformer for better power quality in terms of bus voltage stabilization. During healthy conditions, the VSC is off since the error signal is zero and the storage element will not inject any voltage to the boosting transformer. The implementation of this process to determine the controller gain value and get global minimum solution is shown in Fig. 4.

Fig. 4. Proposed implementation of SBDE procedure for determining controller parameter

Algorithm: The parameter values to obtain the gain values of controllers are as follows:

Initialization

- The controller parameters are K_p, K_i, K_d, K_r
- The maximum no. of iterations, $i = 50$
- The scaling factor, $F = 0.5$
- The crossover rate = 0.4
- Number of control variables = 4
- Problem dimension = 55

Perform the objective function from ITSE for each pop vector.

Find the optimal solution of controller gain values with minimized objective function

while ($I < \text{Max. iterations}$)

Update the cognitive learning factor and scaling factor as given by Eq. 13

for ($j < \text{problem dimension}$)

Update new candidate population after performing mutation and crossover

$j = j + 1$

end for loop

update the new solution and check for reaching maximum iteration, i

$i = i + 1$

end

6. Results and Discussions

A Simulink diagram is developed with 415V source voltage, 50Hz at constant sensitive load with DVR circuit that compensates the voltage sag and swell as shown in Fig 5. Various fault conditions such as LL, LG, LLG, LLL and LLLG were created at a different period to analyze the performance of DVR for the abnormal condition. In this research, the voltage sag is produced with t between 0.06s and 0.13s and voltage swell with t between 0.27s and 0.47s. Different controllers such as PI, PID and PR are used to reduce the THD value and maintain constant voltage under fault at sensitive load. The load voltages and THD values at different fault conditions are calculated with DVR and without DVR.

Case 1: By using PI

In case 1, the sag and swell are created at the system and the load voltages are measured. The voltage disturbances have taken place with t from 0.06s and 0.13s and with time t from 0.27s and 0.47s. Then, the distorted voltage is detected and the appropriate voltage is injected through DVR. The reference and load voltage are compared and error signal is generated. Based on the error signal, SBDE algorithm is used to minimize the error signal and thereby optimal gain values are found as K_p, K_i and τ_i are 7.61, 0.32 and 10 seconds respectively. Then, the voltage is transferred from *dq0* to *abc* frame. Fig. 5a shows the load voltage without connecting DVR, and 5b shows the load voltage with the connection of DVR. From Fig 5a, it is found that there is a lower voltage during sag and high voltage during the swell condition. The occurrence of switching frequency and some fluctuations appeared in the voltage waveform at 0.06 to 0.13 seconds and at 0.27 to 0.47 seconds.

Fig. 5. Simulink model of three-phase DVR

The addition of an active filter will reduce the distortion if the switching frequency is less than 1 kHz (Busada et al., 2019). It is identified that above 1 kHz frequency, the distortion suddenly rises because of the drop in compensation effect. It occurs because of the phase difference in the main inverter output voltage and the command value.

The constant voltage is maintained during the remaining period. The load voltage having DVR is given in Fig 5b, and it is found that constant load voltage is maintained and extra voltage has been added or immersed when voltage swell and sag occur. During sag condition, DVR injects the voltage, thereby prevents from distortion.

Fig. 5a. load voltage without using DVR

Fig. 5b. load voltage by using DVR

Fig. 6 shows the THD under different fault conditions with various harmonic sequence of the basic frequency (50Hz). The THD values are high at LG fault compared with other types of fault. Furthermore, the THD values are low at LL fault compared with other types of fault.

(a) LL Fault by using a PI controller

(b) LG Fault by using PI controller

(c) LLG Fault by using PI controller

(d) LLL Fault by using a PI controller

(e) LLLG Fault by using PI controller

Fig. 6. THD under different faults by using PI**Case 2: By using PID**

In PI controller, the main problem is that it reacts slower during the the dynamic loading condition. In order to solve the issue, the PID controller has been developed. The voltage disturbances have taken place with t from 0.06s and 0.13s and with time t from 0.27s and 0.47s. Then the distorted voltage is detected and the required voltage is injected through DVR. The reference and load voltage are compared and error signal is generated. Based on the error signal, SBDE algorithm is used to minimize the error signal and thereby optimal gain values are found as K_p , K_i and K_d are 7.98, 0.1417 and 0.2562 seconds respectively. Then, the voltage is transferred from dq0 to abc frame. The Voltage compensation and THD values are calculated for the PID Controller based DVR. In Fig. 7a, the load voltage at sag and swell condition is illustrated. The voltage is decreased at sag condition and increased during swell condition. This uneven voltage may affect the load and leads to damage the electrical appliances. Therefore, in the proposed method, the DVR is inserted with a PID controller to compensate the sag and swell. To get the minimum THD and to eliminate the sag and swell in single line to ground, the optimal values of K_p , K_i and K_d are 7.98, 0.1417 and 0.2562 which are found using optimization algorithm. In Fig. 7b the sag and swell voltages are compensated by PID based DVR. Fig. 8 shows the THD values of the system after connecting the DVR and it has been noted that the THD values are controlled when compared with the PI controller based DVR system. However, still, the THD values calculated by PID are not satisfied because it contains a higher value of first harmonics which give poor sinusoidal waveform at the load end.

Fig. 7a. load voltage without using DVR **Fig. 7b.** load voltage by using DVR

(a) LL Fault by using PID controller

(b) LG Fault by using PID controller

(c) LLG Fault by using PID controller

(d) LLL Fault by using PID controller

(e) LLLG Fault by using PID controller

Fig. 8. THD under different faults by using PID**Case 3: By using PR**

To overcome the problems faced in PI and PID controllers, a new PR controller for DVR is proposed in the paper. The PR controller supplies infinity and high gain at DC as well as during some specific frequencies in the preferred harmonic disturbances. Fig. 9a shows the voltage swell and sag without DVR where the voltage waveform is not uniform. The voltage disturbances are created between time t with 0.06s to 0.13s and 0.27s to 0.47s. Error signal is obtained by comparing the load voltage and reference voltage and this error signal is given as an input to the optimization algorithm and optimal gain values are found $K_p=7.83$, $K_r=0.3$ and $w_e^2=1$. This optimal gain values are set for the PR controller in order to reduce the error signal. The voltage swell and sag are reduced by PR based DVR. Fig. 10 shows the THD values of the system for different fault condition when PR based DVR is connected as a compensating device. By this, it can be noticed that the THD values are less, while PR based DVR is connected with the system. The maximum THD values are estimated at LG fault, and this fault is higher in PI-based DVR. The minimum THD values are attained at LL fault, and it is very low THD when compared with PI, PID controller based DVR.

Fig. 9a. Load voltage without using DVR **Fig. 9b.** Load voltage by using DVR

(a) LL Fault by using PR controller

(b) LG Fault by using PR controller

(c) LLLG Fault by using PR controller

(d) LLL Fault by using PR controller

(e) LLLG Fault by using PR controller

Fig. 10. THD under different faults by using PR**Case 4: Without using a controller**

In this case, different faults are created without using the controller. Fig. 11 illustrates the THD of the load condition for different faults with various harmonic orders.

(e) LLLG Fault without using a controller

Fig. 11. THD under different faults without using a controller.**Table 4.** Different types of controllers and their THD

Type of fault	THD (%)			
	Without controller	PI	PID	PR
LL	20.60	3.91	3.09	1.83
LG	37.98	11.51	9.52	4.01
LLG	35.72	10.84	8.83	3.74
LLL	40.64	3.93	3.69	3.47
LLLG	15.04	3.98	3.45	2.55

(a) LL Fault without using a controller

(b) LG Fault without using a controller

(c) LLG Fault without using a controller

(d) LLL Fault without using a controller

The different types of controllers and their THD values are shown in Table 4. It shows that the THD value of the system with and without a controller. It is found that without a DVR controller, load voltage does not remain constant during a fault condition and also THD value is high. By using different controllers, THD values of the system are less for each fault and it is shown in Table 4. Among these controllers, it is found that by using PR controller, the voltage across the load is constant and also lower THD value under different fault condition.

In order to justify the performance of proposed algorithm and strategy, a comparative analysis of the controllers during single line to ground fault have been taken and they are shown in Table 5. Fig. 12 represents the convergence characteristics of fitness function using this algorithm in order to obtain the gain value of PR controllers.

Fig. 12. Convergence characteristics of fitness function

From the results shown in Table 5, it can be identified that the proposed algorithm gives the optimal gain values of the PR controller to achieve minimum error compared to other controllers. The ITSE using PR controller is 0.063 which is lesser than the ITSE obtained by other controllers. In the aspect of computation time, the proposed scheme requires less computation time of 0.527s to obtain the optimal gain values of PR controllers. The steady state error is also less smaller when compared to other controllers. In the other controllers, there is a phase difference between the output and reference voltage which makes the system unstable. Stability analysis and results shows that the PR controller eliminates the phase shift and reduces the steady state error with minimum time.

Table 5. Comparative analysis of different controllers during LG fault using optimization technique

Type of controller	Kp	Ki	Kd	KR	ITSE	Settling time (sec)
PI	7.61	0.3262	-	-	0.5884	1.26
PID	7.982	0.1417	0.2562	-	0.095	0.8
PR	7.83	-	-	0.3	0.063	0.527

In the future, the modern power system should have the PR based DVR controller to maintain constant load voltage during a fault condition. The fault lines are identified using sensors and controlling action are manipulated, and information is provided to the load controller to inject PR based DVR in the line. Thereby, the reparation of voltage is done in the affected line of the modern power system.

7. Conclusion

This paper explains the comparative assessment of PI, PID and PR categories of controllers towards improving the quality of power and mitigate the voltage distortions. The performance of DVR is inspected with various fault conditions. The simulated results under various control strategies of THD using different controllers are illustrated. Among these controllers, it is found that by using the PR controller, the voltage across the load is constant and also the THD value is less than 4% under different fault condition. Further, the optimization algorithm fine tunes the controller gain values to get obtain a minimum ITSE value of 0.063 with settling time of 0.527 secs for LG fault. Thus, the DVR with PR controller dispenses the best solution for power quality and voltage maintenance under fault conditions.

Appendix

Three-phase voltage: 415V with 50 Hz, RL filter is 0.002Ω and 1mH; switching frequency is 1 kHz with injection ratio as 1:1

Declarations

Competing interests

The authors declare that they have no competing interests.

Availability of data and materials

All the data is given in the paper are properly cited wherever necessary.

Funding

The authors declare that the research is not funded by any Government/ Private institution/agency.

Acknowledgement

The authors heartfully thank the editor and reviewers for their constructive comments.

Reference

- Janjic, A., Stajic, Z., Radovic, I., 2011. Power quality requirements for the smart grid design, International journal of circuits, systems and signal processing, 5(6), 643-651.
- Danalakshmi, D.; Gopi, R.; Hariharasudan, A.; Otolu, I.; Bilan, Y., 2020. Reactive power optimization and price management in microgrid enabled with blockchain. Energies, 13, 23, 6179, DOI: 10.3390/en13236179
- Tien, D. V., Gono, R., Leonowicz, Z., 2018. A multifunctional dynamic voltage restorer for power quality improvement, Energies, 11(6), 1351.
- Jeyaraj, K., Durairaj, D., Velusamy, A.I.S., 2020. Development and performance analysis of PSO-optimized sliding mode controller-based dynamic voltage restorer for power quality enhancement. International Transactions on Electrical Energy Systems, 30(3), e12243.
- Pandey, A., Agrawal, R., Mandloi, R. S., Sarkar, B., 2017. Sliding mode control of dynamic voltage restorer by using a new adaptive reaching law, Journal of The Institution of Engineers (India): Series B, 98(6), 579-589.
- Omar, A.I., Aleem, S.H.A., El-Zahab, E.E., Algablawy, M., Ali, Z.M., 2019. An improved approach for robust control of dynamic voltage restorer and power quality enhancement using grasshopper optimization algorithm, ISA transactions, 95, 110-129.
- Yan, L., Chen, X., Zhou, X., Sun, H., Jiang, L., 2018. Perturbation compensation-based non-linear adaptive control of ESS-DVR for the LVRT capability improvement of wind farms, IET Renewable Power Generation, 12(13), 1500-1507.
- Danbumrungrakul, M., Saengsuwan, T., Srithorn, P., 2017. Evaluation of DVR capability enhancement-zero active power tracking technique, IEEE Access, 5, 10285-10295.
- Zhang, F., Mu, L., 2019. New protection scheme for internal fault of multi-microgrid, Protection and Control of Modern Power Systems, 4(1), 14.
- Hingorani, N.G., 1995. Introducing custom power, IEEE spectrum, 32(6), 41-48.
- Jothibasu, S., Mishra, M.K., 2014. A control scheme for storageless DVR based on characterization of voltage sags, IEEE transactions on power delivery, 29(5), 2261-2269.
- Rauf AM, Khadkikar, V., 2014. An enhanced voltage sag compensation scheme for dynamic voltage restorer, IEEE transactions on industrial electronics, 62(5), 2683-92.
- Dhowmya, Bhatt, Danalakshmi, D, Hariharasudan, A., Lisn M., Grabowska, M., 2021. Forecasting of Energy Demands for Smart Home Applications, Energies 14(4), 1045, DOI: 10.3390/en14041045
- Pandey, A, Agrawal, R, Mandloi, R.S., Sarkar, B., 2017. Sliding mode control of dynamic voltage restorer by using a new adaptive reaching law, Journal of The Institution of Engineers (India): Series B, 98(6), 579-89.
- Saeed, A.M., Abdel Aleem, S.H., Ibrahim, A.M., El-Zahab, E.E., 2014. Power quality improvement and sag voltage correction by dynamic voltage restorer, Int Rev Autom Control, 7(4), 386-93.
- Busada, C.A., Jorge, S.G., Solsona, J.A., 2019. A Synchronous Reference Frame PI Current Controller With Dead Beat Response, IEEE Transactions on Power Electronics, 35(3), 3097-105.
- Surendran, V., Srikanth, V., TG SJ., 2014. Performance improvement of dynamic voltage restorer using proportional-resonant controller, In2014 Power and Energy Systems: Towards Sustainable Energy, 1-5. IEEE.
- Danalakshmi, D., Kannan, S., Kesavan, V.T., 2018. Reactive power pricing using cloud service considering wind energy, Cluster Computing, 21(1), 767-777.

在现代电力系统中使用基于PR控制器的DVR修复电压干扰

關鍵詞

智能电网，电能质量，PI和PR控制器，自平衡差分演化，动态电压恢复器，总谐波失真。

摘要

智能电网环境为消费者带来了更多利益，而电能质量是智能电网环境中具有挑战性的因素之一。为了保护系统设备并提高可靠性，使用了不同的滤波技术。即使没有满足消费者对电能质量的期望。为了克服这些缺点并增强系统可靠性，系统中引入了新的定制电源设备（CPD）。在不同的CPD中，动态电压恢复器（DVR）是一种电压补偿设备，用于改善失真期间的电能质量。当配电系统中发生诸如电压骤升和骤降之类的失真时，DVR中的控制策略将发挥重要作用。在本文中，分析了使用比例积分（PI），比例谐振（PR）控制器的DVR性能。为了达到全局最小误差的目标并获得快速响应，使用一种称为自平衡差分进化（SBDE）的鲁棒优化算法来找到控制器的最佳增益值。然后，在不同的控制器之间进行了比较分析，并验证了PR控制器的性能优于其他控制器。已经发现，所提出的PR控制器策略降低了所有类型故障的总谐波失真（THD）值。带有PR控制器的SBDE优化DVR在电压失真情况下将THD值降低了不到4%。DVR拓扑在MATLAB / SIMULINK中经过验证，以便检测干扰并注入电压以补偿负载电压。