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Power quality enhancement by using Z-DVR based series voltage compensation with black widow optimization technique

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ABSTRACT

In distribution system, voltage quality issues are the most concerning disturbances influencing the power quality (PQ). As a result, to alleviate this PQ concerns such as sag, swell, fluctuation, interruption, and harmonics on the sensitive load, the series voltage compensator dynamic voltage restorer (DVR) is utilized. Furthermore, a Z-source inverter (ZSI) based DVR is proposed in this paper to improve the power system's voltage restoration properties. To compensate the voltage concerns which is occurs in passive and transmission components, the 3-φ Z-DVR inverter with proportional integral derivative (PID) controller tuned by black widow optimization (BWO). By short circuiting the legs of inverter in the ZSI, prepare the possibility of buck and boost in voltage and utilize the LC impedance grid which incorporated power source to inverter circuit. In addition, to obtain the injecting voltage, PID control scheme for ZSI based DVR is proposed in this paper. The proposed modelling and simulation of DVR is implemented in MATLAB/Simulink tool and the outcomes are analyzed. Furthermore, reduction in voltage concerns, and total harmonics distribution (THD) with BWO tuned PID controller is superior which is 1.01% when compared with existing methods such as Harris Hawks optimization (HHO) based PID, genetic algorithm (GA) based PID controller.

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1. INTRODUCTION

Equipment makers, electric utilities, and customers are all concerned about power quality (PQ). Low PQ is recognized as an outcome of numerous PQ problems such as total harmonics, voltage swell, voltage sag, voltage interruption, and so on. Voltage flicker, sag, harmonics, swell, harmonic distortion, interruption, transient's impulse, and fluctuation are some of the difficulties that might occur in the distribution system. Harmonics, voltage interruption, sag, and swell are the most prevalent and severe PQ defects in power systems. Voltage quality is also the most vital aspect in PQ from the sensitive point of view. In today's low voltage power distribution systems, voltage imbalance is one of the most common PQ issues [1]. Moreover, in the power system, voltage sags are the recent failure data and most prevalent type of disturbance, which caused the customer's financial loss because of mis-operation of customer equipment consequent in stoppage of commercial/industrial activities/disruption. An estimate for the sag events responsible for tripping of these equipment can be made by combining the probabilistic assessment of voltage sags with the sensitivity information of electrical equipment over a specified period. Furthermore, at the power frequency, voltage sag is determined as a reduction of transient (0.5-1 min) in RMS voltage between 0.1 to 0.9 pu. In commercial businesses, buildings, and hospitals, voltage sag causes voltage-sensitive electrical-electronics loads to fail, resulting in severe process interruptions and significant data and/or economic losses. The amplitude, duration, and phase angle jump of a voltage sag are all determined. To alleviate voltage sag, the requirement for higher PQ has prompted end users to install power acquisition technology [2]–[5]. Also, to combat voltage swell as well as sag, conventional DC-DC converters is utilized as direct AC-AC converters. Although, they have certain limitations when it comes to asymmetrical sags.

To mitigate voltage swells, as well as voltage sags, several devices like flywheels, DSTATCOM, unified phase-shift (UPS), and tap changing transformers are employed. In recent years, different equipment such as dynamic voltage restorer (DVR), flexible AC transmission systems (FACTS), and other devices have been created to reduce the impacts of sag [6]. Among these, DVR is one of the most cost-effective and frequently used in dual-phase-shift (DPS). To creates or absorbs reactive power, DSTATCOM is a FACTS device with a shunt connection, also it is utilized to regulate voltage and hence enhance transient stability. By using reactive power shunt compensation, a D-STATCOM is commonly used to manage bus voltage. The D-STATCOM is a solid-state device with three-phase shunt coupled power electronics. It is integrated to the distribution systems near the load. The three-phase inverter, coupling transformer, and DC capacitor are made the DSTATCOM. Utilizing either line current or bus voltage, DSTACOM has the capability of compensation. DSTATCOM has two features for control modes: one that controls the load voltage and the other that injects reactive and harmonic components in the current mode [7]–[9]. However, for voltage disturbance compensation in distribution system, DVR is utilized to alleviate voltage issues like harmonics compensation, sag, swell, load unbalancing owing to uneven supply of voltage magnitude and perturbation conditions of voltage. DVR is an integrated series specialized power device in the distribution electric system with control and power unit that helps to prevent sensitive equipment damage and contributes to a continuous and reliable supply for customers [10], [11]. DVR, is a nonlinear technology, can cause the system to become unstable or oscillate. To investigate the reliability of an integrated system with power electronics equipment, a sufficient condition for integrated system reliability was provided, that can be obtained using the impedance characteristics of the system's equipment and the Nyquist criteria [12], [13].

The DVR is integrated to a series solid state device which infuses voltage into the system utilizing an injection transformer to adjust the voltage at the load's sensitive side. Voltage compensation such as voltage sag and voltage swell, is the main issue in the power system. On the consumer side, the voltage sags and swells create power by supplying low power from grid-connected systems, influencing power electronic devices and loads [14]. The DVR device compensates for voltage difficulties by maintaining a constant voltage and injecting the needed voltage level. A critical control strategy for preserving distribution system stability is also included with the DVR device [15]. Appropriate control is required to avoid voltage quality issues and maintain a steady condition in grid-based distribution systems.

Z-source dynamic voltage restorer (DVR) is an advanced power electronics device used to improve the quality of the electrical power supplied to sensitive loads. It provides a solution for mitigating voltage sags and swells, which are common power quality issues. The Z-source topology used in the DVR enables it to respond quickly to voltage fluctuations, which makes it highly effective in improving the voltage stability and reliability of the electrical power system. "If a voltage sag or dip occurs, the Z-source DVR quickly injects a compensating current to restore the voltage level".

The goal of this research is to solve voltage problems in grid-connected system with non-linear loads. The appropriate optimization with proportional integral derivative (PID) controller and Z-DVR device must be chosen to alleviate voltage difficulties in the system. The following are the paper's main contributions:

i) Grid system is connected with the non-linear loads by utilizing transformer. Z-DVR is chosen in this paper and integrated between the grid and the load to mitigate the voltage issues.
ii) Voltage issues such as sag, swell, interruption, fluctuations, and harmonics may be introduced into the interconnected system through voltage signals. The usage of a Z-DVR device can help to reduce the impact of voltage issues on the system's reliability. A black widow optimization (BWO) approach with PID controller is used to regulate the Z-DVR device, which allows the grid to minimize voltage faults and accurate for load demand.
iii) The controller provided constant electricity to adjust for load demand and absorb extra energy from the grid system, which had injected the necessary power to meet load demand and decrease voltage concerns. The recommended control strategy is developed and validated by including the load on the grid side. The performance of the proposed methodology is compared to that of existing methodologies such as genetic algorithm (GA) and Harris Hawks optimization (HHO).

The remaining section of this paper is organized as follows, in section 2, the review works towards voltage mitigation utilizing DVR are discussed. The proposed system architecture with descriptions is explained in section 3. Moreover, this section consists of the grid connected load in proposed design explanations, Z-DVR, and BWO approach with PID controller explanations are discussed. Additionally, the result and discussion of the proposed method and comparison with existing methods are determined in section 4. In section 5, the conclusion of the paper is given.

This section contains numerous types of methods to alleviate the voltage issues with the incorporation of the DVR devices by different researchers. In this section, the voltage problem mitigation-related works are reviewed. Yuan *et al*. [16] have presented the DVR technique for harmonic as well as sag compensation without the detection of harmonics. During both steady-state dips and transient grid voltage, a simple harmonic and sag compensation was retrieved by introducing DVR. Hence with the decreased load computation, PQ of load-side voltage was enhanced without detection block of voltage harmonics. The accuracy of the presented technique was superior in different conditions. Similarly, with synchronous reference frame (SRF) controller voltage problems were alleviated and designed in transmission lines by utilizing Z-DVR i.e., series voltage compensation technique by Kumar and Livinsa [17]. To protect the transmission line from severe damage, Z-source inverter (ZSI) based DVR with SRF controller was utilized for the regulation of DC-link voltage and the compensation of voltage sag. By employing a modified control scheme in DVR, the accuracy of the voltage sensitive loads was enhanced.

Furthermore, a selective detection of reliable peak and mitigation harmonic voltage with DVR was discussed by Jo *et al*. [18]. From supercapacitor bank to vital load, the compensator mitigates interruption or voltage sag within 2 ms delay also produced the rated voltage. In the heavy non-linear load, a new selective technique for alleviating of harmonic was presented for controlling voltage and attaining total harmonics distribution (THD) value of 5% during the compensation of sag. In addition, DVR was utilized for fast restarting and flexible method for induction motors (IMs) presented by Shao *et al*. [19]. The DVR was utilized to present a “flexible voltage” strategy to address the issue of residual voltage in IM resuming when the motor power was reapplied as well as interrupted. To restart the IM quickly with significantly decreased torque pulsation and current surges, a “flexible voltage” was employed. To minimizing the current inrush and time of IM restarting, the presented approach was superior. As well as to track the effective non-sinusoidal AC signal, the “flexible voltage” was decomposed into three parts of sinusoidal to attain zero-error by controlling the technique.

Likewise, to alleviate phasor jumps and voltage sags by utilizing DVR, a comparative analysis was discussed by Tu *et al*. [20]. For sensitive loads, the prevention of voltage quality was enhanced in both recovery stages and compensation of voltage, an analysis was demonstrated. To provide flexible voltage, the proposed technique was superior in overall control and logical operation. The performance of the presented approach was effective to validate the analysis. Also, in 3-φ distribution system for compensating voltage issues, the energy storage compressed air powered DVR was utilized by Sundarabalan *et al*. [21]. With high response time and zero emission of greenhouse gas, a compressed air energy storage method with third generation was modelled and designed. The variation of voltage due to various faults and modelling of sensitive loads was analyzed by connecting CAESPDVR with distribution system. In the distribution system, the mitigation of voltage swells and sags was effective by utilizing CAESPDVR with enhanced stability and decreased cost.

Similarly, Zhang *et al*. [22] have discussed DVR with single-phase analysis and modelling of impedance. By utilizing a suitable DVR with linear model, the single-phase impedance of DVR was determined-based 1-φ stability integrated DVR with reduced Nyquist criteria. In a wide frequency band, the analysis of reliability criteria and modelling of impedance was obtained. The author failed to determine the impedance model with influence of DC link capacitance. Moreover, the DVR’s performance was enhanced by Andrews and Joshi [23] utilizing the proportional-resonant (PR) controller. In the output voltage, a phase shift of proportional integral (PI) controller with reference voltage makes the unstable system. So, to decrease the steady state error, a proportional resonant (PR) controller was introduced in this paper. For alleviation of voltage swell as well as sag, the realization of DVR was analyzed and implemented.

Additionally, Khanh *et al*. [24] have presented the DVR to alleviating the voltage sags because of direct-on-line (DOL) starter in 3-φ asynchronous motors. For minimizing voltage sags, the reliable and accurate of the presented control method was superior with various configuration of DVR. The compensation of voltage sags was totally attained by the proposed strategy. In industrial distribution systems, optional application of energy storage of DVR with DSTATCOM extended for compensating other issues occurred in power system. Furthermore, for mitigating voltage swell as well as sag, a DVR with 1-φ AC/AC trans ZSI was discussed by Mousavi and Babaei [25]. For compensation, DVR was integrated proportional to the grid, So, large energy storage i.e., DC link was not required in this system. By controlling transformer’s turn ratio and duty cycle, the ZSI of DVR can mitigate the voltage swell as well as sag easily. To prevent current and voltage spikes on the switches, the trans ZSI converter was utilized rather than the snubber circuit for safe technique of commutation. The capability and the stability of the proposed methodology was implemented in EMTDC/PSCAD software to minimize the voltage issues.

Although the solutions for reducing voltage difficulties with integrated DVR devices have proven to be effective, they do not totally solve the problem. Hence, the authors integrated the BWO technique with a

PID controller to adjust for voltage quality difficulties. A suitable voltage issue mitigation technique should solve the majority of the difficulties identified in the exiting research. As a result, a unique control technique based on the Z-DVR device will be developed and employed with grid-connected non-linear loads to address voltage concerns such as sag, swell, interruption, THD, and fluctuations, and so on.

2. DESIGN OF PROPOSED METHODOLOGY

The flow of the proposed methodology work is given in Figure 1, which starts from the identification of the PQ, to enhance the quality of the power, the appropriate device DVR is used and then PID controller with BWOA is designed and analysis, finally results and THD comparison are proposed. A 3-φ and 3 winding transformers with a 1 MVA and a 50 Hz frequency range is connected between the 11 kV, 50 Hz 3-φ AC grid and the sensitive load in Figure 2. The controller block receives the actual voltage from the 3-φ AC grid as well as the reference voltage. The controller block which contains the PID controller, the gain parameters of the PID controller is tuned with the help of the BWO algorithm. Then utilizing the pulse width modulation (PWM) block that provide the pulse cycle to the inverters which is presented in the ZSI. After this, ZSI outcomes given to the DVR, finally, the DVR compensated the required voltage issues such as sag, fluctuation, swell, harmonics, and interruption.

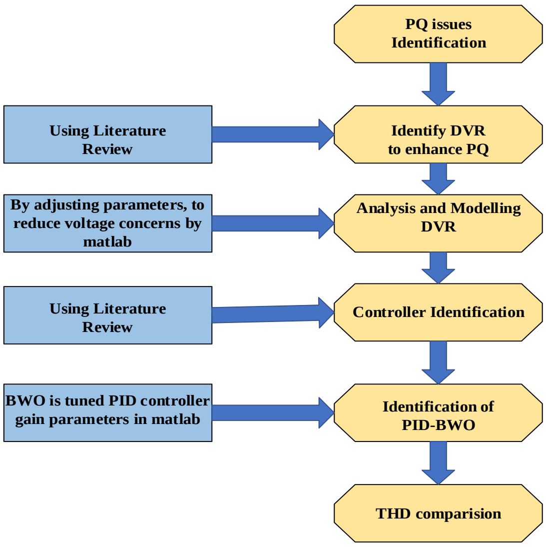

Figure 1. Flowchart of the proposed work

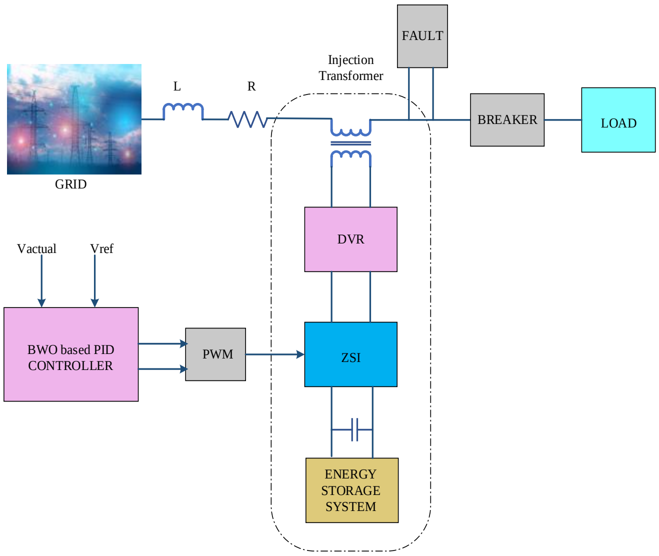

Figure 2. 3-φ AC grid and the sensitive load

2.1. Background of DVR

The DVR is a series compensator based on a power electronic converter that protects sensitive loads from source side and other external disturbances. In this DVR system, solid state-based power electronic switches are used in the inverter. DVR injects a set of 3-φ AC output voltages in synchronism and series with the distribution feeder voltages. The restorer's DC input terminal is integrated to a suitable energy storage device (ESD). The main components in DVR are ZSI, transformer, filter, and ESD.

i) Function transformer: The DVR is protected the critical loads which is integrated in series with injection transformer. The transformer's primary goal is to integrate the DVR to the distribution system, where the inverter produced the injected voltages are introduced.
ii) Function of filter: The filter's main purpose is to suppress the inverter's harmonic voltage by ignoring the switching harmonics, which are at a high frequency level or otherwise within allowed limits.
iii) ZSI: The buck-boost type of inverter with impedance networks (unique passive input circuits) which named as ZSI that raise the DC input voltage by shooting through the inverter bridge.
iv) ESD: During the compensation, the real power needs of the DVR is provided by the ESD and also stores the energy in DC form. Several types of ESDs are available including lead acid battery, flywheels, supercapacitor, and SMES and the inverter receives DC supply from these ESDs.

2.2. Fundamental functioning of DVR

The fundamental working of the DVR is intending to achieve the load voltage range to its required level by injecting the appropriate series voltage to the grid. Figure 3 demonstrated the equivalent circuit of the Z-DVR where load bus's Z impedances z_{th}^* relies upon the fault level. The DVR injects the series voltage v_{DVR}^* over the injection transformer at the time of the v_{th}^* drop of system voltage and maintained the v_l^* which is the required voltage magnitude. The DVR's series injected voltage is written as:

$$v_{DVR}^* = v_l^* + z_{th}^* i_l^* - v_{th}^* \tag{1}$$

where v_{th}^*: when fault condition, voltage of system; i_l^*: required current of load; z_{th}^*: required impedance of load; and v_l^*: magnitude of required voltage load.

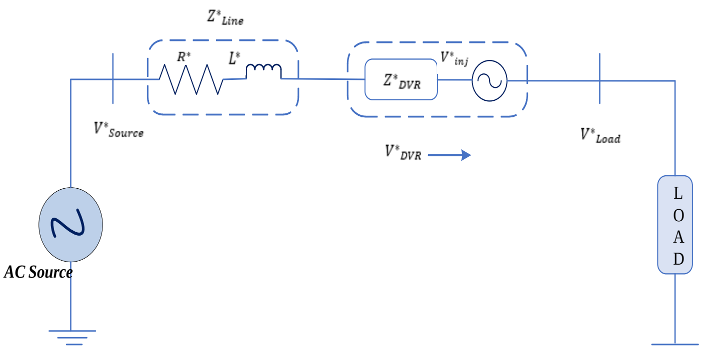

Figure 3. Equivalent circuit

2.3. Process of ZSI

Both voltage-source inverter (VSI) and current-source inverter (CSI) are the type of inverter topology utilized in traditional DVR. The DVR based on VSI is the buck type inverter and provides the buck type output voltage which means achieved the constricting the maximum voltage. The problems acquired in the energy storage devices (ESD) during the diminishing DC link voltage with VSI topology alone in DVR system. In that same way, the drawbacks of the utilization of the CSI alone in DVR is its normally a boost converter. In addition, additional circuitry has to be utilized to achieved the necessary voltage and also vast voltage level is needed for applications. Nevertheless, this raised the complicacy of the circuit and decreased the dependability as well as efficacy.

An alternative method to the conventional inverter topologies, ZSI has been utilized with many intrinsic benefits. In conventional VSI and CSI, additional zero vector and the shoot through switching state are prohibited but available in ZSI. The electromagnetic interference (EMI) noise is heavily affected the VSI and CSI but less affected in ZSI. For the duration of the process of load compensation, ZSI voltage type topology is proposed in this paper along with utilization of buck boost property of the inverter and SD can be used. To defend the source from the feasible current flow, a series diode is integrated in the middle of the source and the impedance network.

At the end of the source side, the incorporation of two inductors and capacitors are connected which is called as impedance network. For the impedance source inverter (ISI), the filtering element is the incorporated network circuit which is the ES and the second order filter is provided by the ISI. The voltage and current ripples are more efficaciously dormant by this method. Contrasting with the conventional inverter, the capacitor and inductor necessarily should be smaller.

The impedance source network (ISN) decreases their inductor to two capacitors in equidistant during the inductors are small and zero approach and turns out conventional voltage source. Contrast with conventional VSI, the ISN should need smaller size and less capacitance with the inductor feed the more ES and filtering. In accordance with, the ISN decreases their capacitors to two inductors in equidistant during the capacitors are small and zero approach and turns out conventional voltage source. Consequently, the CSI's inductor needs and material size in the worst case.

Figure 4 demonstrated the Simulink structure of the Z-DVR. The controller gate pulse is given to the inverter of the ZSI in front of the DVR. Various control techniques are proposed for the traditional ZSI, in this paper, PWM control technique based PID with BWO algorithm is utilized to operate the Z-DVR. For the conventional ZSI, many control strategies are proposed, nevertheless in this research, a PWM control technique based PID with BWO algorithm is used to operate the Z-DVR.

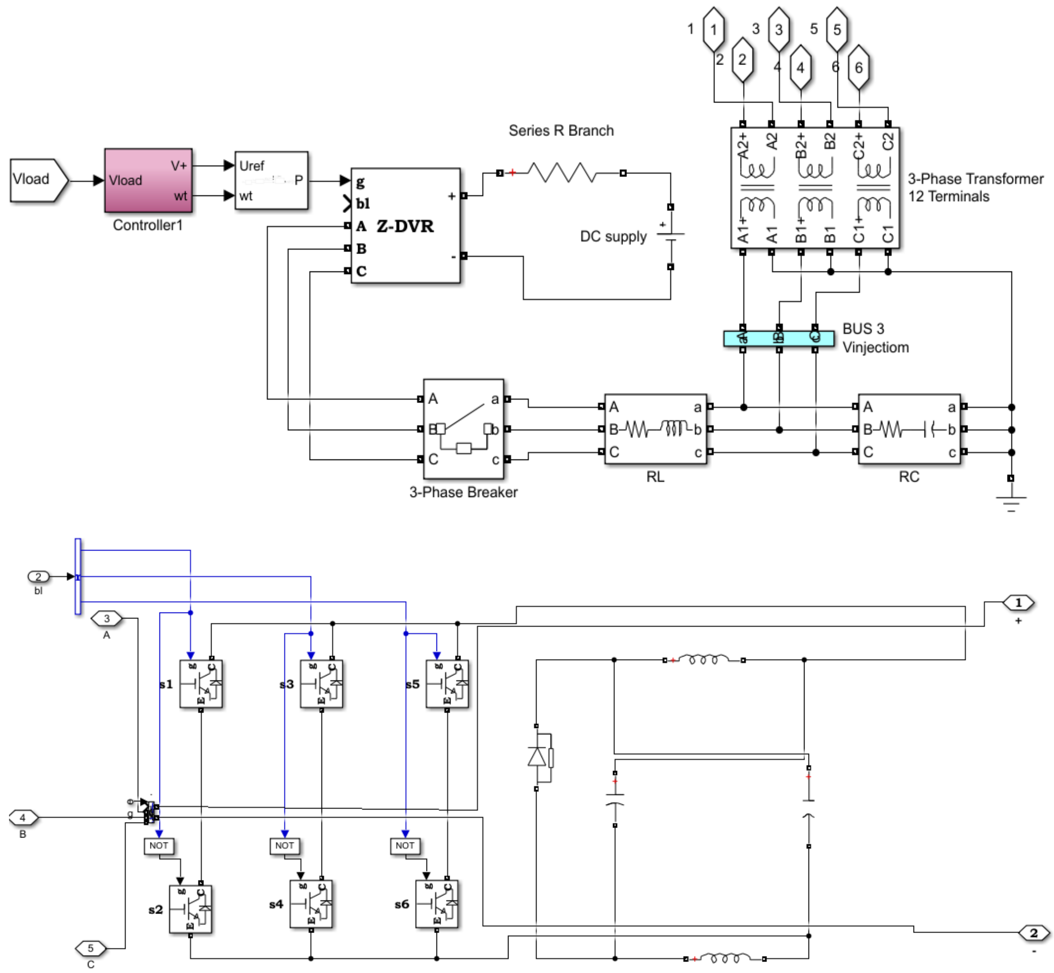

Figure 4. Structure of the Z-DVR

2.4. Optimization process of BWO

Black widow optimization (BWO) is a metaheuristic optimization algorithm inspired by the hunting behavior of black widow spiders. Figure 5 demonstrated the life cycle of the BWO. The optimization process of BWO can be divided into the following steps:

i) Initialization: The algorithm begins by initializing the population of black widow agents, each representing a potential solution to the optimization problem.
ii) Prey capture phase: During this phase, the black widow agents search for potential prey in the search space. This is done by evaluating the fitness of each agent's solution and selecting the best ones to serve as potential prey.
iii) Cannibalistic phase: Once the prey has been identified, the black widow agents engage in a cannibalistic phase where they compete with each other to capture the prey. This competition is modeled using a selection operator that favors agents with better fitness.
iv) Mating phase: After the cannibalistic phase, the top-performing agents are selected to mate and produce new solutions. This is done by applying crossover and mutation operators to the selected agents' solutions.
v) Population update: The new offspring solutions are then inserted into the population, and the least fit agents are removed to maintain a constant population size.
vi) Termination: The algorithm terminates when a stopping criterion is met, such as a maximum number of iterations or a satisfactory level of solution quality. Throughout the optimization process, BWO maintains a diverse population of solutions by using a niche formation mechanism that encourages exploration of different regions of the search space. This allows the algorithm to avoid getting stuck in local optima and to converge to high-quality solutions.

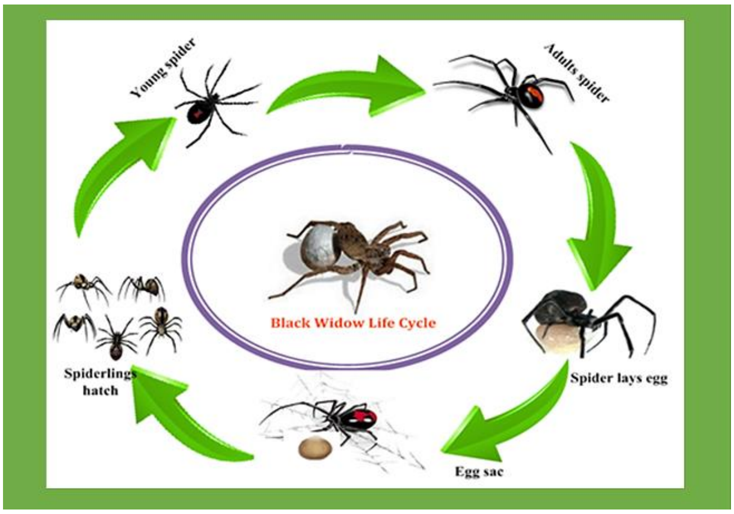

Figure 5. Lifecycle of the black widow spider

2.4.1. Process of initialization

For the current problem, the suitable structure of the solution is formed by the value of the variable of the issue to solve an optimization issue. The structure is known as the chromosome and particle positions as per the GA and PSO algorithms. In the BWO algorithm, it is denoted as the widow. From the black widow spider, the potential solution for all issues is assumed at BWO. With the black widow spider, the probable solution for the issues has been deal and issues of the variable values are exhibited. The array is defined as:

$$widow^* = [X_1, X_{2,} \ldots . X_{m_{Var}}] \tag{2}$$

where m_{Var}: The dimensional value in the optimization problem; and $X_1, X_{2,} \ldots . X_{m_{Var}}$: The floating numbers. The fitness function of the widow is defined as (3).

$$fitness = f(widow^*) \tag{3}$$

At partition over the message receiving, the widow refers to the propagation of every node. By spider first population, the optimization algorithm starts with the candidate widow matrix size $m_{pop} * m_{Var}$ is generated. For implementing the procreating through mating, the parents are chosen randomly and the male black widow is eating by a female black widow.

2.4.2. Process of procreate

The procreate process in black widow optimization (BWO) involves the creation of new solutions through the combination of existing solutions. This process is similar to the reproduction of individuals in natural selection, where genetic material is combined to produce offspring with new characteristics. In BWO, the procreate process involves selecting two or more solutions from the current population and combining them to create a new solution. The combination is typically done by selecting parts of each solution and combining them in some way. This can be done using various techniques such as crossover, mutation, and selection.

Crossover involves selecting parts of two parent solutions and combining them to create a new solution. This can be done in various ways, such as selecting a random subset of each parent and combining them, or selecting alternating parts of each parent and combining them. Mutation involves making random changes to a solution to create a new solution. This can be done by changing a single part of the solution or making multiple changes. Selection involves selecting the best solutions from the new offspring solutions and adding them to the population. This is done to ensure that the new solutions are of high quality and improve the overall performance of the population. The procreate process is typically repeated multiple times in BWO to create a new generation of solutions. This process is often combined with other optimization techniques such as local search and elitism to further improve the performance of the population. this algorithm is reproducing the array with alpha which contains the offspring produces (4) and (5).

$$y_1^* = \alpha^* \times x_1^* + (1-\alpha^*) \times x_2^* \tag{4}$$

$$y_2^* = \alpha^* \times x_2^* + (1-\alpha^*) \times x_1^* \tag{5}$$

Here, x_1^* and x_2^* are denotes the parent spider and y_1^* and y_2^* denotes the baby spider which is called offspring. In randomly chosen numbers, the process is repeated for the $m_{Var/2}$ times, for the best individuals that are newly generating the population, to the array by fitness value, the children and parents are added based on cannibalism rating.

2.4.3. Process of cannibalism

In BWO, the population of candidate solutions is divided into two groups: the "prey" and the "spiders." The spiders represent the stronger solutions, while the prey represent the weaker ones. During each iteration of the algorithm, the spiders hunt the prey, and the weakest prey are eliminated from the population. Cannibalism in BWO refers to the fact that the spiders can also eat each other if necessary. Specifically, if a spider is weaker than one of the prey, it will be eliminated from the population, just like the weaker prey. This creates a competitive environment in which the spiders must constantly adapt and improve in order to survive. Overall, the process of cannibalism in BWO is an important aspect of the algorithm's ability to find high-quality solutions to optimization problems. By constantly eliminating weaker solutions, the algorithm is able to converge towards a set of strong, high-quality solutions.

2.4.4. Process of mutation

In BWO, mutation is a process by which new candidate solutions are generated by making small random changes to existing solutions. The process of mutation in BWO works as follows:

i) Randomly select a spider from the population of candidate solutions.
ii) Make a small random change to the spider's position in the solution space. This can be done using various techniques, such as adding a small amount of random noise to the spider's position or randomly selecting a new position in the solution space within a certain range of the spider's current position.
iii) Evaluate the fitness of the mutated spider. This involves calculating the objective function value for the new solution, which represents how well it performs in terms of the optimization problem being solved.
iv) Replace the original spider with the mutated spider if the fitness of the mutated spider is better.
v) Repeat the process with another spider until a certain stopping criterion is met.

2.4.5. Convergence

Convergence in black widow optimization (BWO) refers to the point at which the algorithm has found a set of high-quality solutions that are close to optimal, and further iterations of the algorithm are unlikely to improve the solutions significantly. In BWO, convergence is typically determined based on a combination of factors, such as the number of iterations that have been performed, the number of solutions that have been evaluated, and the rate at which the algorithm is improving the solutions. One common way to measure convergence in BWO is to monitor the best solution found so far over the course of the algorithm's iterations. If the algorithm is consistently finding better solutions over a certain number of iterations, but then stops making significant improvements, this may be an indication that the algorithm has converged.

2.4.6. The setting of parameters

In BWO, the setting of parameters is an important aspect that can significantly impact the performance of the algorithm. Here are some of the key parameters in BWO and their typical values:

i) A larger population size can help to explore the search space more thoroughly, but can also increase the computational cost. A typical value for the population size in BWO is between 10 and 50.
ii) A typical value for the number of iterations in BWO is between 100 and 1000.
iii) A typical value for the web length in BWO is between 0.1 and 1.
iv) A higher probability of mutation can help to explore the search space more thoroughly, but can also increase the risk of losing good solutions. A typical value for the probability of mutation in BWO is between 0.05 and 0.1.
v) A higher value of alpha can lead to more rapid convergence, but can also increase the risk of getting trapped in local optima. A typical value for the alpha parameter in BWO is between 1 and 3.

The optimal values for these parameters can vary depending on the specific problem being solved, and may need to be tuned through experimentation. Figure 6 illustrated the flowchart of the BWO. The BWO algorithm is utilized to determine the optimal values of the PID (K_p, K_i, and K_d) parameters.

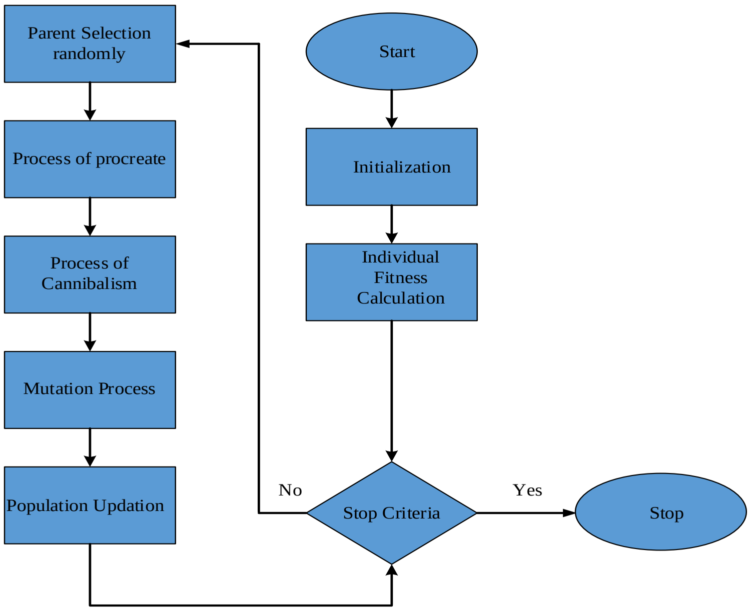

Figure 6. Flowchart of BWO

2.4.7. PID controller process for Z-DVR

The Z-DVR uses a proportional integral derivative (PID) controller to regulate the output voltage and maintain it at a constant level during disturbances. Here is the general process for the PID controller in the Z-DVR:

i) Measurement of output voltage: the output voltage of the Z-DVR is continuously measured using voltage sensors.
ii) Error calculation: the error between the desired output voltage and the actual measured output voltage is calculated by the PID controller. The error signal is used to determine the required correction to maintain the output voltage at the desired level.
iii) Proportional control: the proportional term of the PID controller is responsible for providing a correction to the output voltage proportional to the error. The proportional gain parameter (K_p) is used to determine the magnitude of this correction.
iv) Integral control: the integral term of the PID controller is responsible for correcting any steady-state error in the output voltage. The integral gain parameter (K_i) is used to determine the magnitude of this correction.

v) Derivative control: the derivative term of the PID controller is responsible for providing a correction based on the rate of change of the error. This correction helps to improve the response time of the system and reduce overshoot. The derivative gain parameter (K_d) is used to determine the magnitude of this correction.
vi) Summation of control signals: the output signals from the proportional, integral, and derivative control terms are summed to produce the total control signal.
vii) Adjustment of compensation voltage: the compensation voltage generated by the Z-DVR is adjusted based on the total control signal. This adjustment helps to maintain the output voltage at the desired level during disturbances.
viii) Repeat the process: the PID controller continuously measures the output voltage and adjusts the compensation voltage to maintain the desired level of output voltage during disturbances. The PID gain parameters may be adjusted using the black widow optimization (BWO) algorithm to optimize the performance of the controller.

In Figure 7 illustrated the schematic diagram of the proposed PID controller with BWO algorithm.

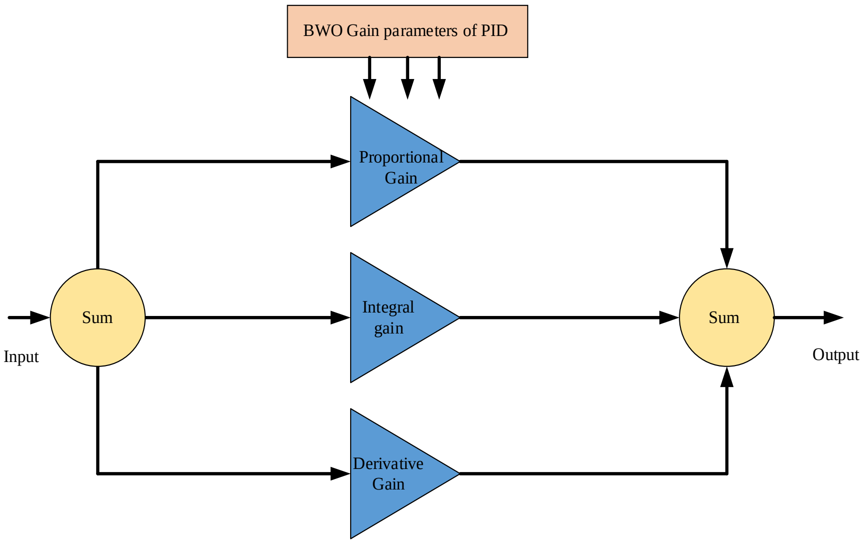

Figure 7. Schematic diagram of PID controller with BWO

3. SIMULATION

3.1. Simulation and modelling

In the Table 1, the parameters utilized for simulation are listed. The proposed simulation diagram is depicted in Figure 8. Under 3-φ faults, the proposed technique is estimated as well as analyzed. Voltage issues like swell, fluctuation, sag, interruptions, and THD is determined by the proposed approach. In this simulation diagram, 3-φ supply is given as input source, and 3-φ transformer is utilized to step-up/step-down the voltage and current. In between the source and the 3-φ parallel RLC load, the Z-DVR is integrated to compensate the voltage quality issues. For introducing faults like voltage swell, fluctuation, sag, interruption, and harmonics in the source side, fault device is connected, also breaker is employed to protect the circuit/system from vital conditions. For mitigating voltage issues, the Z-DVR is utilized to compensating voltage as well as to meet the load demand.

Table 1. System parameters utilized for simulation

Sl. No	Specification	Rate	Sl. No	Specification	Rate
1	Fault resistance	0.03 Ω	8	DC supply	500 V
2	Frequency	50 Hz	9	Resistance	0.1 Ω
3	Nominal power	1000 kW	10	PID controller	K_p=40
4	Breaker resistance	100 Ω			K_i=154
5	Snubber resistance	1 MΩ			K_d=10
6	Nominal phase voltage	400 V	11	Carrier frequency	2250 Hz
7	Active power	4.42 kW	12	Ground resistance	0.001 Ω

To carry out the implementation with the appropriate control methology, the ZSI based DVR is utilized in this section. For voltage sag and fluctuation compensation under RLC load condition, a Z-DVR with optimized BWO-PID controller is presented. To the distribution system, a 3-φ breaker is utilized to control the RLC load connection. In the source voltage, the voltage sag as well fluctuation is occurred because of the sudden change of heavy load. The simulation outcome of Z-DVR with RLC load is illustrated in Figure 9.

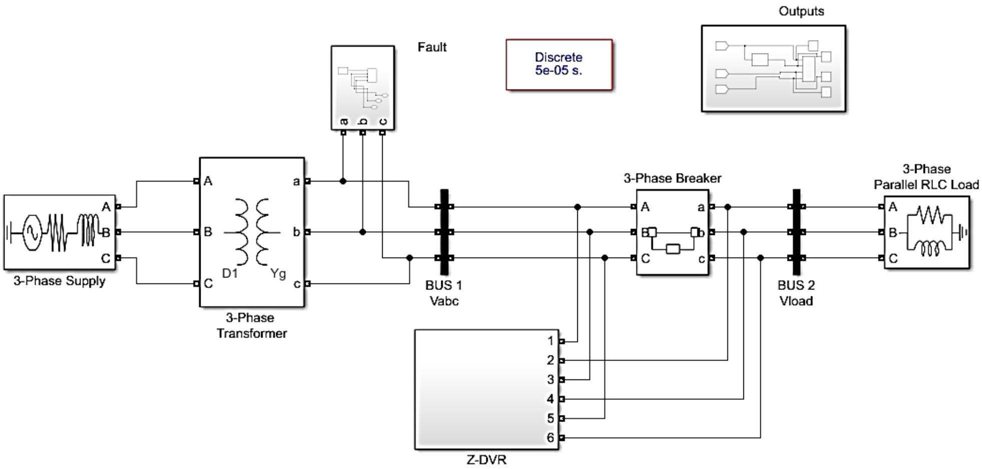

Figure 8. Proposed methodology's Simulink diagram

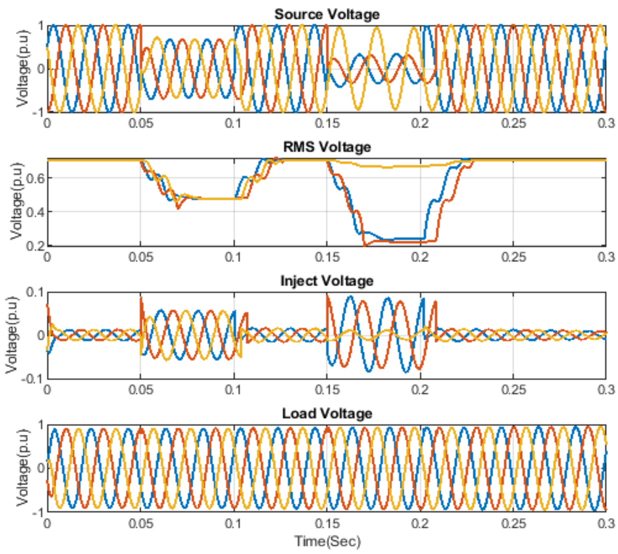

Figure 9. Implementation outcome of source voltage, RMS voltage, injected voltage, and load voltage

A voltage sag as well as fluctuation occurs in the distribution system as a result of sudden load variation. From t=0.05 s to t=0.1 s, a magnitude of 3-φ voltage sag of the normal voltage is occurred, additionally from 0.15–0.2 s, a 3-φ voltage fluctuation is also occurred in the same transmission line. Initially, the square root of the mean i.e., RMS value of voltage is analyzed for both voltage sag as well as fluctuation for determining the instantaneous values of voltage. Then, to compensate the voltage problems in the distribution system, transformer inject the required voltage to meet the demand of the load. In the distribution system, Z-DVR is integrated to mitigate the voltage issues. During typical load conditions, the Z-DVR does not give any voltage to the system, although it provides the appropriate voltage in fault condition with the necessary polarity and magnitude to maintain the system at the defined load voltage level. Due to the sudden modification of heavy load, the voltage swells as well as interruptions is also appeared in the source voltage and the outcome of Z-DVR implementation with RLC load is depicted in Figure 10.

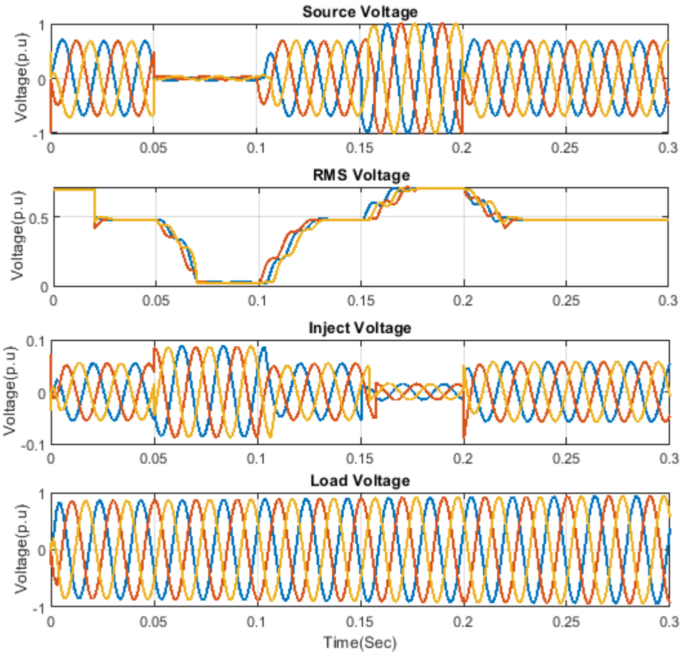

Figure 10. Simulation outcome for source voltage, RMS voltage, injected voltage, and load voltage

In the distribution system, voltage interruptions as well as voltage swell is appeared due the abrupted variation of load. From t=0.05 s to t=0.1 s, a magnitude of 3-φ voltage interruptions of the normal voltage are occurred, additionally from 0.15–0.2 s, a magnitude of 3-φ voltage swell is also occurred in the same transmission line. For determining the instantaneous values of voltage in both voltage interruptions as well as swell, the square root of the mean i.e., RMS value of voltage is determined. Also, in the distribution system the voltage problems are compensated by introducing the required voltage utilizing transformer to meet the load demand. To mitigate the voltage issues in the distribution system, a Z-DVR is interconnected with optimized BWO-PID controller. The Z-DVR does not provide any voltage to the system under normal load conditions, however in a fault state it injects the voltage with the required polarity and magnitude to keep the system at the desirable load voltage level. During voltage interruptions and swell, the ZSI based DVR determines the maximum capability of voltage injection to compensate the voltage interruptions as well as swell in the transmission line to meet the demand of the load.

3.2. Result and analysis

3.2.1. Case 1: Compensation of voltage sags

In order to ensure stable and consistent system operation, it is necessary to address the issue of voltage sag. This can be achieved by implementing a Z-DVR system that incorporates an optimized BWO-PID controller to compensate for the sag and provide the necessary voltage to meet the load demand. Figure 11 provides an analysis of the voltage levels at the source, injection, and load under sag conditions. The analysis begins with an examination of the source voltage, followed by the injection voltage, and finally the compensated voltage sag signals.

The source voltage is created by a fault in the time duration between 0.1 to 0.2 s. The voltage of the three-phase source side is 1 pu and after 0.1 s it decreased and attain the voltage level 0.68 pu, then again it rained to reach 1 pu after 0.2 s. The injected voltage is given by the Z-DVR, the value of the injected voltage is 0.06 pu in between the 0.1 to 0.2 s. Then the voltage is compensated by the injected voltage which is generated by the Z-DVR within the time interval 0.1 to 0.2 s. Thus, the voltage sag is minimized by utilizing the optimized Z-DVR-based BWO-PID controller to meet the required demand of the load.

The RMS of the sag signal with the source signal is demonstrated in Figure 12. The sag signal is compensated in between 0.1 to 0.2 s, for the proposed technique mitigated sag signal is settled at 0.68 pu. In voltage sag, the RMS i.e., the square root of the mean is analyzed for identifying the instantaneous values. The RMS of the sag signal is settled at 0.4805 pu that remains constant until the sag signal is cleared. In between 0.1 to 0.2 s, RMS value of sag signal is visualized clearly.

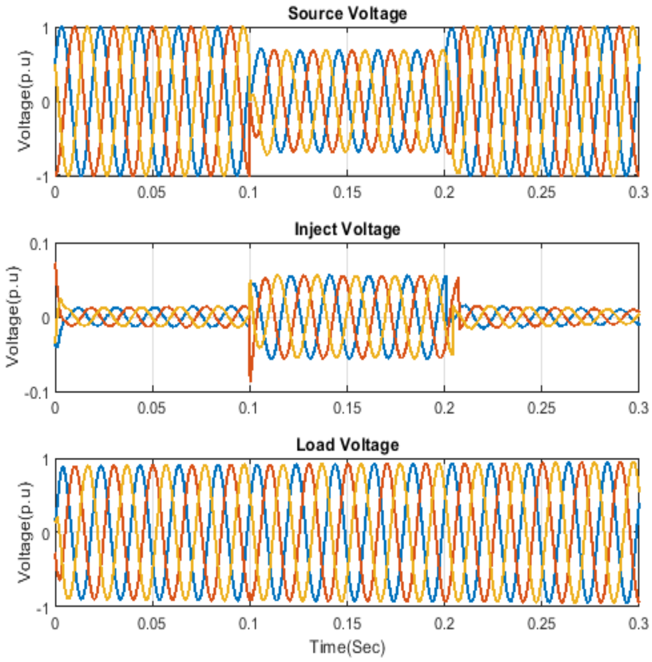

Figure 11. Compensated voltage sag signal with Z-DVR

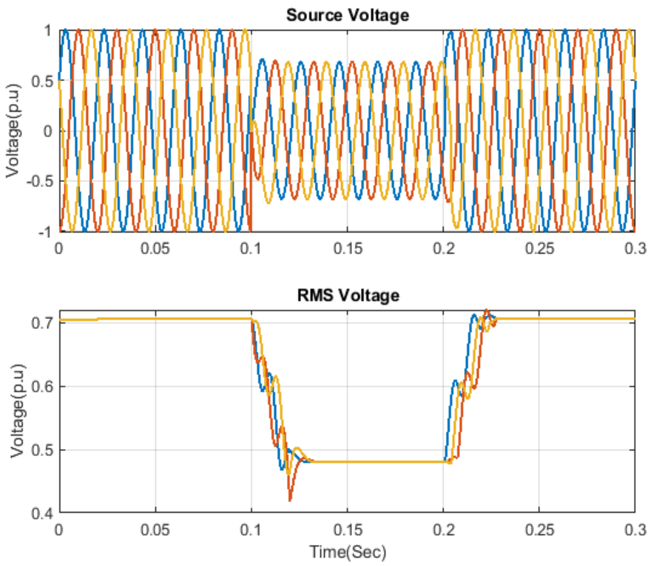

Figure 12. Sag signal with RMS voltage

3.2.2. Case 2: Compensation of voltage swells

The effectiveness of the suggested approach is evaluated based on the swell situation. By combining the fault and the source, the system is subjected to the swell condition. Various sources are examined and their performances are analyzed in the assessment of the swell condition. Figure 13 depicts the assessment of the voltage swell signal that has been alleviated using Z-DVR. In which the swell signal is overshot from 0.1 to 0.2 s which is fault created in time interval. In addition, the Z-DVR is utilized to compensate the swell signal by the injected voltage, and finally, the compensated load voltage is reached at 1 pu.

In Figure 14, the RMS of the swell signal with the source voltage is demonstrated. The swell signal is compensated in between 0.1 to 0.2 s, for the proposed technique mitigated swell signal is reduced at certain time interval. In voltage swell, the RMS i.e., square root of the mean is analyzed for determining the instantaneous values. The RMS of the swell signal is settled at 0.705 pu which remains constant until the swell signal is minimized. In between 0.1 to 0.2 s, RMS value of swell signal is visualized clearly.

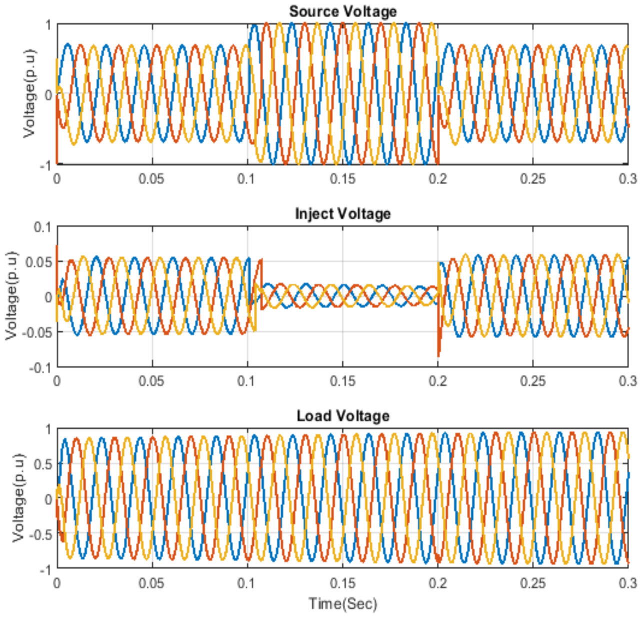

Figure 13. Compensated voltage swell signal with Z-DVR

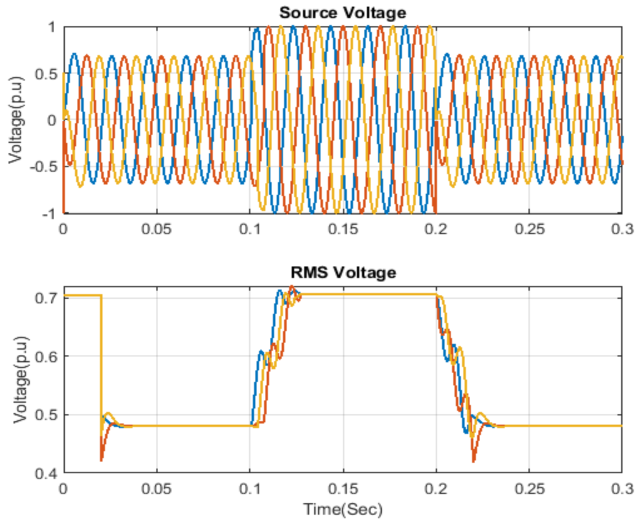

Figure 14. Swell signal with RMS voltage

3.2.3. Case 3: Compensation of voltage fluctuations

The performance of system is evaluated under fluctuation conditions, the fluctuation is created in the source with the fault. Figure 15 analysis the voltage fluctuation condition source voltage, injection voltage and load voltage. In source voltage, from the voltage of three phase, one of the phases i.e., blue phase is fluctuated in between the time interval 0.1 to 0.2 s. Then the injected voltage is used to compensate by the Z-DVR which is 0.05 pu from 0.1 to 0.2 s after 0.2 s. This injected voltage is utilized to compensate the voltage of load side. However, load voltage reaches a steady voltage.

Figure 16 illustrates the RMS of the fluctuation signal with the source signal. The proposed approach compensates the fluctuation signal from 0.1 to 0.2 s, also in fluctuation of voltage, the RMS is utilized to evaluating the instantaneous values. From that RMS voltage of blue phase oscillates from 0.1 to 0.2 s, whereas it contains some harmonics and settled at 0.507 pu which remains constant until the mitigation of fluctuation signal after 0.2 s, it steadily increases, red phase varies from 0.1 to 0.2 s and it attains 0.657 pu that is constant till the alleviation of voltage fluctuation as well as it contains some harmonics, and yellow phase overshot at 0.71 pu which remains constant while some harmonics are presented to oscillate the voltage signal, from that blue phase fluctuates higher than the other two phases in between 0.1 to 0.2 s.

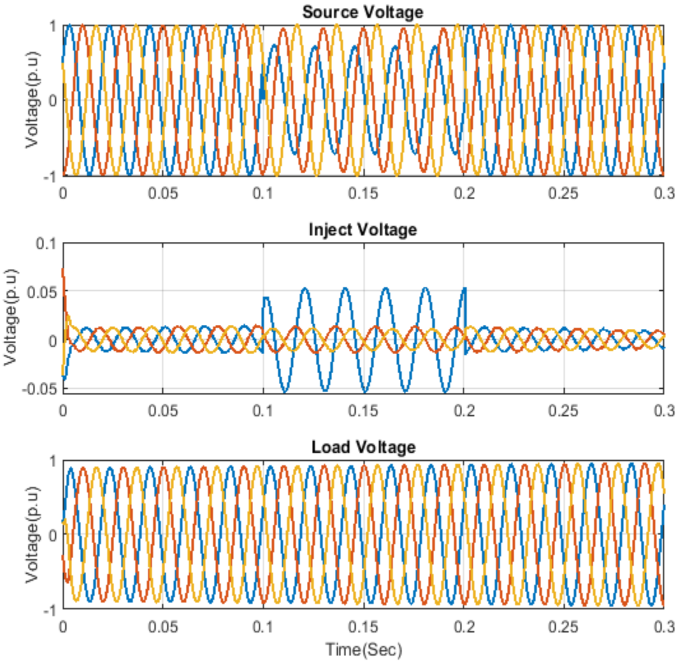

Figure 15. Compensated voltage fluctuation signal with Z-DVR

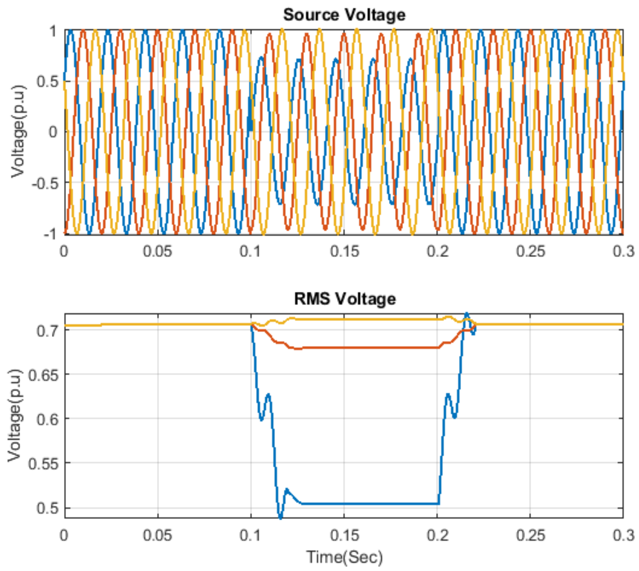

Figure 16. Fluctuated signal with RMS voltage

3.2.4. Case 4: Compensation of voltage interruptions

Figure 17 provides a visualization of the source voltage, the injected voltage, and the compensated load voltage. At the time interval of 0.1 to 0.2 s, a fault occurs, causing an interruption in the source signal. During this period, the three-phase voltage is interrupted on the source side and the interrupted voltage signals are transmitted. To restore the voltage signal, Z-DVR is employed to inject voltage signals between 0.1 and 0.2 s. This enables the source voltage to be compensated by the injection voltage from Z-DVR, meeting the load demand within the time interval of 0.1 to 0.2 s.

In Figure 18, the RMS of the interruption signal with the source voltage is illustrated. The interruption signal is compensated in between 0.1 to 0.2 s, for the proposed technique mitigated interruption signal is minimized at certain time interval. Hence in voltage interruption, the RMS i.e., square root of the mean is analyzed for establishing the instantaneous values. The RMS of the interrupted signal is settled at 0.001 pu that remains constant until the interrupted signal is minimized. In between 0.1 to 0.2 s, RMS value of interrupted signal is visualized in Figure 18.

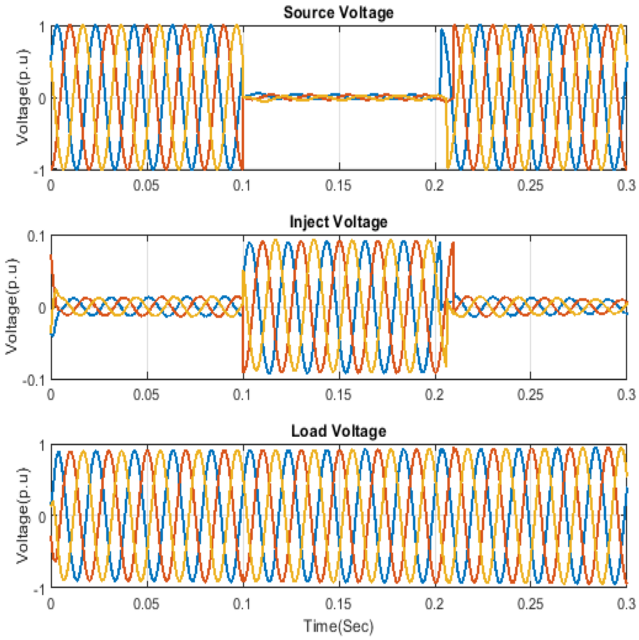

Figure 17. Compensated voltage interruption signal with Z-DVR

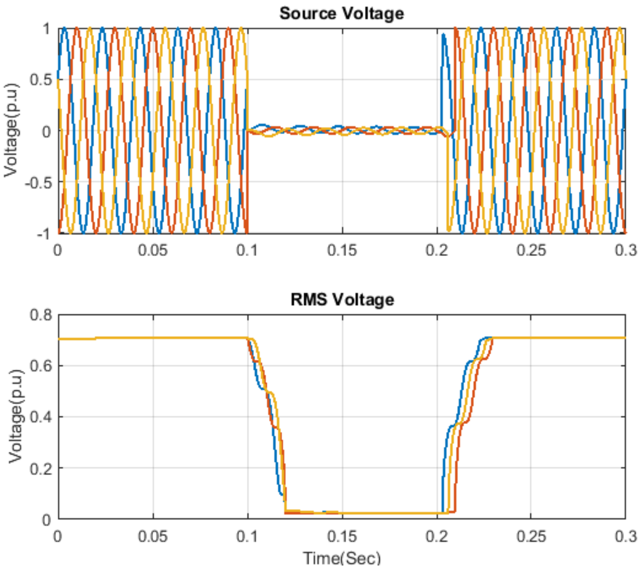

Figure 18. Interrupted signal with RMS voltage

3.2.5. Estimation of total harmonics

The THD of the proposed technique with control techniques is demonstrates in Figure 19. In this Figure the mitigation of harmonic is 1.01% with respect to the frequency in Hz. Moreover, it is clearly estimated that the proposed Z-DVR with optimized BWO-PID controller approach is superior than the HHO-PID, GA-PID, and MRSF controller which are the existing techniques utilized to compared the proposed approach's outcome. The mitigated voltage quality issues are effective by utilizing the proposed methodology i.e., Z-DVR-based optimized BWO-PID controller techniques. The Table 2 illustrates the comparative analysis of THD percentage with conventional techniques. The percentage of THD for MRSF controller is 2.99%, GA-based PID controller is 1.18%, and HHO-based PID controller is 1.06% which is clearly clarify the proposed technique is more accurate than the existing techniques. Table 2 demonstrates the THD comparison with traditional methods. The proposed Z-DVR with BWO based PID controller significantly mitigates voltage problems as compared to traditional controllers such as HHO based PID controller, GA based PID controller, and MRSF controller, as shown in this result section.

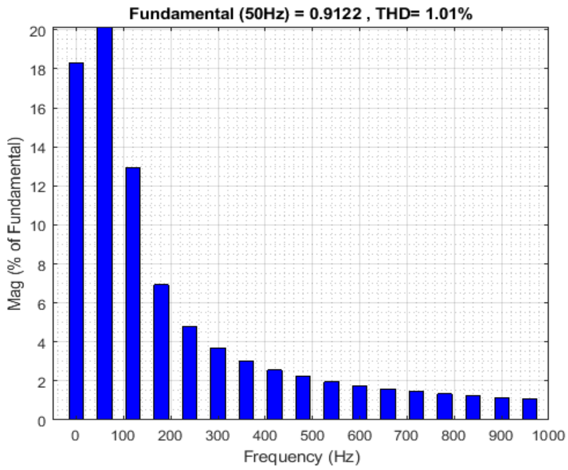

Figure 19. Harmonics estimation

Table 2. THD comparison with convolution method

Techniques	% of THD
Proposed	1.01%
HHO-PID	1.06%
GA-PID	1.18%
MRSF	2.99%

4. CONCLUSION

In the distribution system, an effective custom power device namely DVR for mitigating the voltage issues such as fluctuation, sag, interruption, swell, and harmonics. Moreover, in order to maintain a steady and balanced load voltage at nominal value, the proposed DVR injects the desired voltage component to dynamically correct any deviation in supply voltage in case of external disturbances. For providing appropriate compensation in load side, ZSI based DVR combined with PID controller which is regulate by the BWO algorithm is modelled and the same is installed in the distribution system in this paper. The Z-DVR integrated with proposed controller simulation is done in MATLAB/Simulink 2020 Ra version platform. The performance of the ZSI-DVR with PID controller simulation outcomes and THD comparison demonstrated that the proposed controller is superiors compared to other conventional controllers such as HHO-PID, GA-PID, and MRSF controller.

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