Power Quality Enhancement in Grid-Connected Systems using Dynamic Voltage Restorer with Switched Inductor Cascade Boost Converter

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Abstract. The main objectives of the study are to improve power quality (PQ) in grid-connected systems and mitigate voltage disturbances by using a dynamic voltage restorer (DVR) powered by a Photovoltaic (PV) system. By integrating PV as the primary power input, the DVR supplies clean energy for voltage restoration, thereby enhancing system efficiency and reliability. This approach provides transition to sustainable energy practices by minimizing the dependency on traditional power grid during disturbances. These objectives were achieved by integrating a Switched Inductor Cascaded Boost Converter (SICBC) for efficient voltage boosting and employing a Pine Cone Optimized Proportional-Integral (PCO-PI) controller for precise output regulation. The SICBC provides provide high and stable voltage gain with improved conversion efficiency, essential for maintaining DVR performance at PV power fluctuations. The cascaded configuration mitigates stress on passive elements, contributing towards better thermal management and longer system life. By adopting the Pine Cone Optimization algorithm, the controller's parameters are fine-tuned to achieve optimal performance in terms of settling time, steady-state error and overshoot. The algorithm mimics the natural seed dispersal behavior of pine trees to explore and exploit the control parameter space effectively. The most important results are a recorded efficiency of 97.9% and a reduction in Total Harmonic Distortion (THD) to 2.56%, as demonstrated through MATLAB/Simulink-based simulations. Furthermore, the system demonstrated robust voltage compensation during both symmetric and asymmetric fault conditions. The obtained result reveals the proposed DVR-PV strategy substantially improves power stability and quality, reinforcing the practical viability of renewable-integrated compensators in modern electric grids.
Keywords: power quality, dynamic voltage restorer, controller, cascaded boost converter.

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Îmbunătățirea calității energiei electrice în sistemele conectate la rețea prin utilizarea unui regenerator dinamic de tensiune cu comutator convertor în cascadă cu inductor

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Abstract. Principalele obiective ale studiului sunt îmbunătățirea calității energiei electrice (PQ) în sistemele conectate la rețea și atenuarea perturbațiilor de tensiune prin utilizarea unui restaurator dinamic de tensiune (DVR) alimentat de un sistem fotovoltaic (PV). Prin integrarea PV ca sursă principală de alimentare, DVR-ul furnizează energie curată pentru restabilirea tensiunii, sporind astfel eficiența și fiabilitatea sistemului. Această abordare asigură tranziția către practici energetice durabile prin minimizarea dependenței de rețeaua electrică tradițională în timpul perturbațiilor. Aceste obiective au fost atinse prin integrarea unui convertor amplificator în cascadă cu inductanță comutată (SICBC) pentru o creștere eficientă a tensiunii și prin utilizarea unui controler proporțional-integral optimizat cu con de pin (PCO-PI) pentru o reglare precisă a ieșirii. SICBC oferă un câștig de tensiune ridicat și stabil, cu o eficiență de conversie îmbunătățită, esențialsssă pentru menținerea performanței DVR-ului la fluctuațiile de putere PV. Configurația în cascadă atenuează stresul asupra elementelor pasive, contribuind la o mai bună gestionare termică și la o durată de viață mai lungă a sistemului. Prin adoptarea algoritmului de optimizare Pine Cone, parametrii controlerului sunt reglați fin pentru a obține performanțe optime în ceea ce privește timpul de stabilizare, eroarea în stare staționară și depășirea valorii. Algoritmul imită comportamentul natural de dispersare a semințelor pinilor pentru a explora și exploata eficient spațiul parametrilor de control. Cele mai importante rezultate sunt o eficiență înregistrată de 97,9% și o reducere a distorsiunii armonice totale (THD)

la 2.56%, demonstrate prin simulări bazate pe MATLAB/Simulink. În plus, sistemul a demonstrat o compensare robustă a tensiunii atât în condiții de defect simetrice, cât și asimetrice. Rezultatele obținute arată că strategia DVR-PV propusă îmbunătățește substanțial stabilitatea și calitatea energiei, consolidând viabilitatea practică a compensatoarelor integrate din surse regenerabile în rețelele electrice moderne.

Cuvinte-cheie: calitatea energiei electrice, restabilitor dinamic de tensiune, controler, convertor de tensiune în cascadă.

Улучшение качества электроэнергии в системах, подключенных к сети при использовании динамического восстановителя напряжения с переключаемым каскадным повышающим преобразователем с индуктором

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Абстрактный. Основными целями исследования являются повышение качества электроэнергии в системах, подключенных к сети, и смягчение колебаний напряжения путем использования динамического восстановителя напряжения (ДВР), питаемого от фотоэлектрической (ФЭ) системы. Интегрируя ФЭ в качестве основного источника питания, ДВР поставляет энергию, получаемую из ВИЭ, для восстановления напряжения, тем самым повышая эффективность и надежность системы. Этот подход обеспечивает переход к устойчивым методам энергетики, минимизируя зависимость от традиционной электросети во время помех. Эти цели были достигнуты путем интеграции каскадного повышающего преобразователя с коммутируемым индуктором (КППСКИ) для эффективного повышения напряжения и использования оптимизированного пропорционально-интегрального регулятора PCO-PI для точного регулирования выходного сигнала. КППСКИ обеспечивает высокий и стабильный коэффициент усиления напряжения с улучшенной эффективностью преобразования, что необходимо для поддержания производительности ДВР при колебаниях мощности ФЭ. Каскадная конфигурация снижает нагрузку на пассивные элементы, способствуя лучшему тепловому регулированию и более длительному сроку службы системы. Благодаря использованию алгоритма оптимизации «Сосновая шишка» параметры контроллера точно настраиваются для достижения оптимальных характеристик с точки зрения времени установления, установившейся ошибки и перерегулирования. Алгоритм имитирует естественное распространение сосновых шишек, что позволяет эффективно исследовать и использовать пространство параметров управления. Наиболее важными результатами являются зарегистрированный КПД 97.9% и снижение коэффициента гармонических искажений (THD) до 2.56%, что было продемонстрировано с помощью моделирования в MATLAB/Simulink. Кроме того, система продемонстрировала надежную компенсацию напряжения как при симметричных, так и при асимметричных неисправностях. Полученные результаты показывают, что предлагаемая стратегия использования динамического восстановителя напряжения при работе с фотоэлектрической системой существенно повышает стабильность и качество электроэнергии, подтверждая практическую целесообразность использования компенсаторов с интегрированными возобновляемыми источниками энергии в современных электросетях.

Ключевые слова: качество электроэнергии, устройство динамической стабилизации напряжения, контроллер, каскадный повышающий преобразователь.

I. INTRODUCTION

In distributed systems, it is highly essential to improve PQ for achieving improved technical and economic development in power sectors with enhanced efficacy [1]. Significantly, consistent power delivery is the basic necessity for enhancing the cumulative functioning of the power system [2]. Therefore, power supply needs consistent supply without any disturbances to meet the requirements of the load [3]. Nevertheless, various aspects cause reduced PQ, thus, it is highly regarded crucial to remove these unwanted interruptions and disturbance in order to attain improved PQ [4-5]. The utilization of power converters and non-linear loads leads to disturbances in PQ, which includes voltage swells and sags, voltage deviations, disturbances and harmonics, which in turn causes intense effects on power distribution systems [6-7]. As these problems affects the power supply, rectifying these issues plays a major part. In addition to this, the consistent power delivery is also affected by these issues, which leads to equipment damage and economic losses [8-9]. PQ issues have significantly produced various losses including reduced efficiency, loss of equipment, high maintenance, disturbances and energy losses [10]. Henceforth, it highly essential to rectify these issues, despite this, removing and mitigating PQ issues possess certain difficulties and complicity. Therefore, several PQ mitigating devices with increased performance is considered. One among these devices are Flexible Alternating Current Transmission System (FACTS) which enables seamless connection between the source and the load [11]. FACTS is further classified into static Volt-Amps Reactive (VAR) Compensators (SVC) and Static Synchronous Compensators (STATCOM) [12] which are utilised for rectifying PQ problems [13-15]. Table 1 comprises of various PQ rectification approaches along with their advantages and disadvantages.

Table 1

Various PQ improvement approaches

PQ mitigation devices	**Purpose**	**Advantages**	**Disadvantages**
SVC [16]	Controls voltage and reactive power.	Improved Voltage stability Minimises transmission losses	Cannot handle complicated voltage sag conditions Reduced reactive power rectification
D-STATCOM [17]	Introduces reactive power to mitigate PQ issues	PQ improvement Increases PQ with reduced losses	Cannot handle voltage disturbances Highly complicated
Unified Power Quality Conditioner (UPQC) [18]	Corrects voltage and current related to PQ	Enhanced PQ rectification Mitigates sag, swell and harmonics	Increased implementation cost Highly complicated

Among various FACTS devices DVR plays an important part is critically identifying and mitigating PQ issues. DVR introduces specific phase angle and voltage in series with the disturbance line to produce load voltage [19]. Moreover, to provide consistent and sustainable power to achieve enhanced DVR performance. The standard indicators of the quality of electric power comprises the reduced THD and assures the high power factor, replicating effective exploitation of electric power. It maintains voltage stability by efficiently compensating voltage sag and swell.

RES based PV system plays a crucial role, however, the initial power output produced by PV is quite low, which makes it highly essential to utilize power converters.

The cascaded boost converter enhances the efficiency of the voltage gain, enabling higher output voltages. However, it increases the current stress on the switching devices [20]. The interleaved boost converter effectively power-up active switches and reduce switching losses. Nevertheless, it involves more components leads to high component cost [21].

Buck-boost converter is utilized for step-up applications. Yet, extended switch-on durations lead to increased current ripple and higher conduction losses [22]. The boost converters are coupled with the inductors and the transformers allows increased static gain. Though, it does not perform well under reduced duty cycles [23].

Table 2

Comparison of Existing Works with proposed converter.

Existing Converter	Efficiency
V. Seshagiri Rao *et al* [20]	**92.4%**
Balaji Chandrasekar *et al* [22]	**88.1%**
Proposed	**97.9%**

Therefore, to prevail over these limitations, this system utilizes SICBC which obtains improved power conversion efficiency Additionally, to further enhance the converter performance, optimized control approaches are considered.

Grey Wolf Optimization (GWO) is used for tuning the controller parameters. Nonetheless, it has slower convergence and gets trapped in local optimum [24]. Particle Swarm optimization

(PSO) minimizes the error at the controller. Conversely, it takes long processing time to achieve optimal solution [25]. Whale Optimization Algorithm (WOA) mimics the behaviour of hunting whales to solve the optimization problem. Nevertheless, they are still prone to higher computational complexity, and parameter sensitivity [26]. Therefore, here PCO-PI controller is used, which offers improved robustness, reduced losses with increased convergence. The overall proposed system utilizing DVR powered using PV system with enhanced converter and control topology ensures improved PQ enhancement with optimum disturbance mitigation. The major outline and contributions of the proposed system is listed below,

- To implement DVR which enables improved mitigation of PQ issues, providing stable and controlled power output.
- To provide consistent and sustainable power supply using PV system to meet the power requirement of the DVR system.
- To utilize SICBC for attaining maximum and boost output voltage levels from PV system with improved efficiency.
- To deploy a PCO-PI controller for attaining enhanced control performance with highly regulated output voltage.

II. PROPOSED METHODOLOGY

Fig. 1 illustrates the proposed PQ enhancement system using DVR, where DVR enhances the quality of power by continuously monitoring and compensating voltage fluctuations. For which, PI controller compares the actual load with reference load, later PWM generator produces required PWM pulses. The produced PWM pulses are then fed into the Voltage Source Inverter (VSI), which generates stable voltage. In addition to this, to offer consistent power supply to meet the power necessities of the load, a PV system is coupled to the developed DVR system.

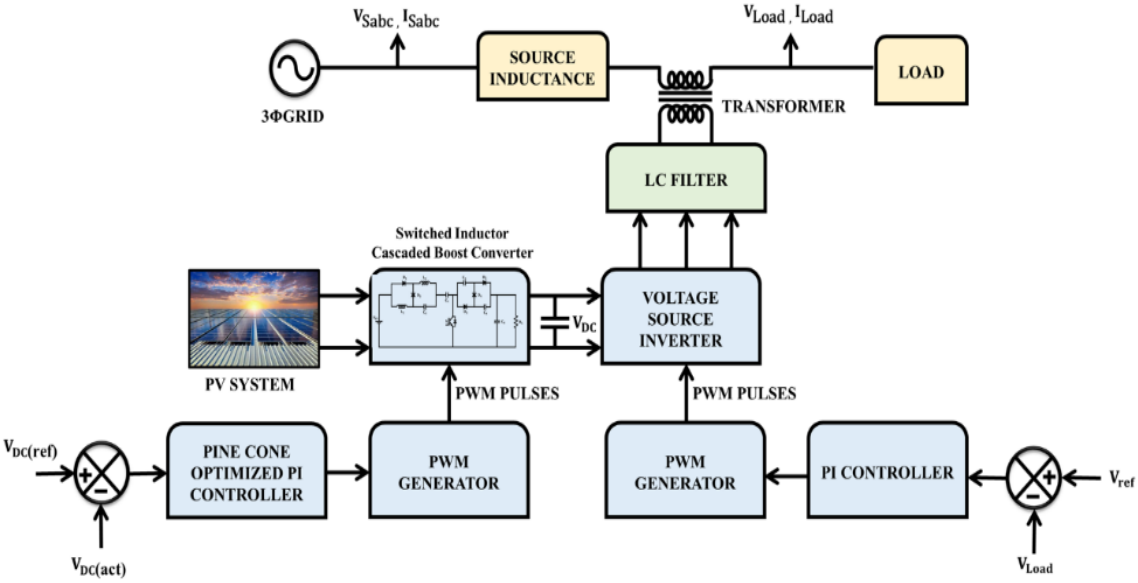


Fig. 1. Block diagram of developed system.

Initially, PV produces low output voltage and SICBC is deployed within PV system to boost the PV power production process. Additionally, PCO-PI controller is utilized for regulating the converter performance. This regulated output from PV is later fed into VSI for converting DC to AC power. Then, the inverter output is filter utilizing the LC filter for removing any further harmonics. Therefore, the proposed system as a whole offers highly improvised PQ by attaining effective compensation of voltage sag and swell with reduced THD, thus, assuring enhanced stability and reliability in grid-connected system.

A. Modelling of DVR

DVR is generally a voltage source converter that is attached in series with distribution system. DVR basically operates by introducing suitable voltage of required magnitude and waveform in series with the supply via the interjection transformer during voltage sag and swell conditions. Here, introduction of reactive and active power from DVR to distribution system is carried out.

DVR circuit diagram is revealed in Fig. 2 and their corresponding equation is represented using,

$$V_{DVR} = V_L + Z_{TH} I_L - V_{TH} \quad (1)$$

Where, V_L specifies magnitude of load voltage, Z_{TH} refers to system impedance, I_L denotes load current and V_{TH} indicates the system voltage respectively.

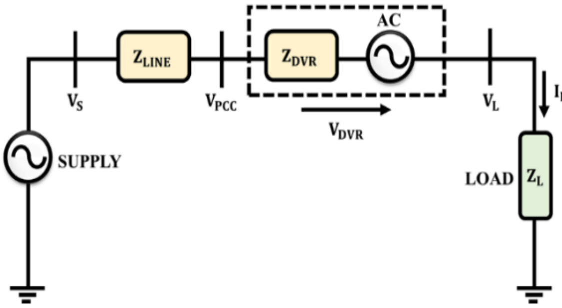


Fig. 2. Circuit Diagram of DVR.

The load current is attained using,

$$I_L = \frac{P_L + jQ_L}{V_L} \quad (2)$$

Here, V_L refers to the reference equation which is later expressed using,

$$V_{DVR}\angle \propto = V_L\angle 0 + Z_{TH} I_L \angle(\beta - \theta) + V_{TH}\angle\delta \quad (3)$$

Where, V_{DVR} angle is defined as $\propto$, Z_{TH} angle is given as β, V_{TH} is defined using δ angle and θ implies the power angle respectively.

$$\theta = tan^{-1}\frac{Q_L}{P_L} \quad (4)$$

and the complicated power introduction of DVR is represented as,

$$S_{DVR} = V_{DVR} I_L^* \quad (5)$$

To further provide consistent and sustainable power supply to meet the power demands of the load, RES based PV system is deployed, which provides continuous and clean energy source.

B. Modelling of SICBC

The SICBC enhances the voltage output from PV systems [27] by enhancing the voltage conversion gain.

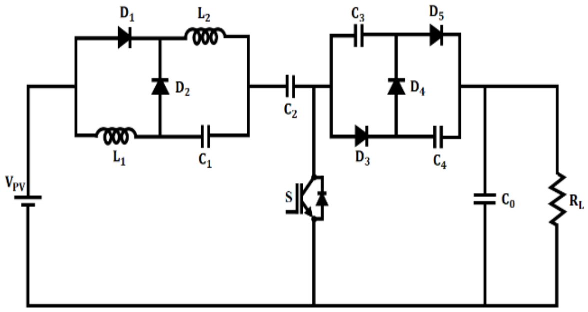


Fig. 3. Equivalent circuit of SICBC.

The control of a developed converter has 2 stages, as seen in Fig. 3.

Stage 1

When switch S is active as in Fig. 6, this stage is started. It is assumed that V_{C2} is equivalent to the voltage at input side. In addition, the half of output voltage is equivalent to $V_{C3} = V_{C4}$. Consequently, current flowing via inductor improves linearly, as depicted in Fig. 5.

$$V_{L1} = V_{PV} + V_{C1} + V_{C2} \quad (8)$$

$$V_{C2}(t_0) = \frac{1}{2}V_{C1}(t_0) = V_{PV} \quad (9)$$

$$V_{L1} = 4V_{PV} \quad (10)$$

$$\Delta I_{L1} = \frac{4V_{PV}}{L_1}(t_1 - t_0) = \frac{4DV_{PV}}{L_1 f_s} \quad (11)$$

$$V_{L2} = V_{PV} + V_{C2} = 2V_{PV} \quad (12)$$

$$\Delta I_{L2} = \frac{2V_{PV}}{L_2}(t_1 - t_0) = \frac{2DV_{PV}}{L_2 f_s} \quad (13)$$

$$\Delta I_{L1} = 2\Delta I_{L2} \quad (14)$$

$$t_1 - t_0 = DT \quad (15)$$

$$C_3 = C_4 \;\; V_{D3} = V_O - V_{C4} = \frac{V_O}{2} \quad (16)$$

$$V_{D5} = V_O - V_{C3} = \frac{V_O}{2} \quad (17)$$

$$C_3 = C_4 \;\; V_{O(max)} \times I_O = V_{in} \times I_{in(max)} = \frac{V_{O(max)} \times I_O}{V_{in}} \quad (18)$$

$$V_{C3} + V_{C4} = V_O \quad (19)$$

If $C_3 = C_4$, their voltage is partial the output voltage. Fig. 4 illustrates the developed converter's switching waveform.

Stage 2

When S is inactive, this stage is initiated. Here, D_2 is active whereas the diode D_1 is reversed-biased.

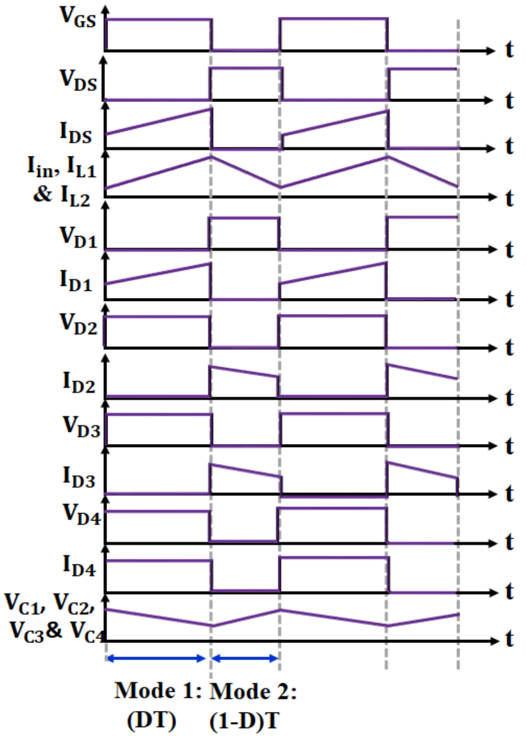


Fig. 4. Switching waveform of developed converter.

As a consequence, essential path to pass energy stowed in L_1 and L_2 to capacitors C_1, C_2 and the output is offered by diodes D_2, D_3 and D_5. Energy stowed in C_3 and C_4 is moved to load, while D_3 and D_5 are active whereas D_4 is reverse-biased.

$$V_{L1} = V_{PV} + V_{C1} + V_{C2} + V_{C4} - V_O = 4V_{PV} - \frac{V_O}{2} \tag{20}$$

$$\Delta I_{L1} = \left(4V_{PV} - \frac{V_O}{2}\right) \times \frac{(t_2 - t_1)}{L_1} = \left(4V_{PV} - \frac{V_O}{2}\right)\frac{(1-D)}{L_1 f_s} \tag{21}$$

$$4V_{PV} DT = \left(\frac{V_O}{2} - 4V_{PV}\right)(1-D)T \tag{22}$$

$$V_{L2} = -V_{C1} = -2V_{PV} \tag{23}$$

$$\Delta I_{L2} = \frac{-2V_{PV}(1-D)}{L_2 f} \tag{24}$$

$$V_{L3} = -V_{C2} = -V_{PV} \tag{25}$$

The capacitors C_3 and C_4 are linked in parallel, then

$$V_{C3} = V_{C4} \tag{26}$$

As voltage difference among capacitors C_1 and C_2 is identical to input voltage, then

$$V_{C1} = \frac{V_{PV}}{1-D} \tag{27}$$

Volt-second balance expression for inductor L_1 is,

$$(V_{PV} + V_{C1} + V_{C2})DT = -\left(V_{PV} + V_{C1} + V_{C2} - \frac{V_O}{2}\right)(1-D)T \tag{28}$$

The voltage gain is,

$$\frac{V_O}{V_{PV}} = \frac{4}{(1-D)^2} \tag{29}$$

Output voltage of proposed converter is managed by PI controller and its parameters are fine-tuned with the aid of PCO algorithm.

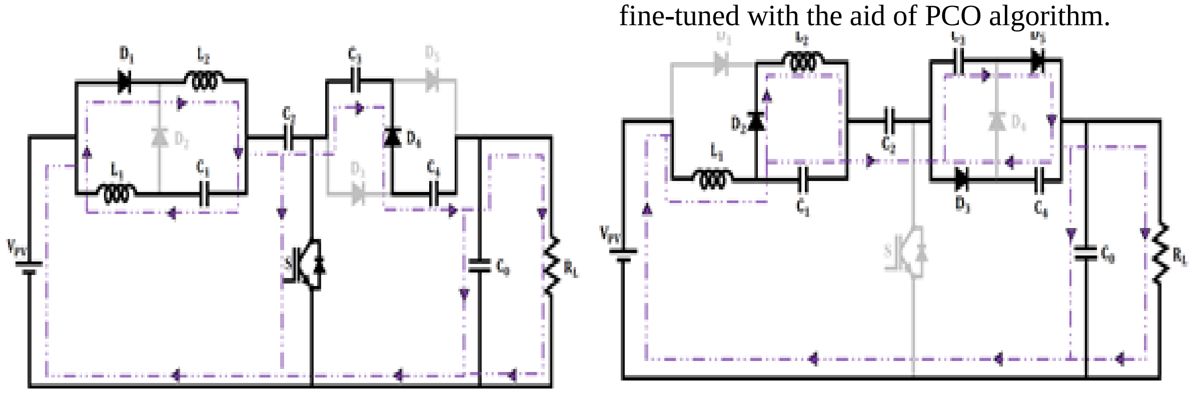


Fig. 5. Stages of developed converter.

C. Modelling of PCO-PI controller

PI controller is deployed to attain improved converter performance by adjusting the converter output. PI controller is composed of proportional gain (K_p) and integral time (T_i) and basic structure of PI controller is presented in Fig. 6.

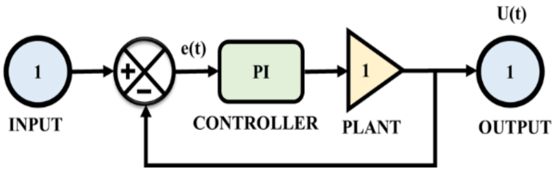


Fig. 6. Basic structure of PI controller.

$$U(t) = K_p . e(t) + K_i . \int_0^t e(t) dt \tag{30}$$

Where, $e(t)$ indicates distinction among reference and the actual output, and K_i refers to the integral value. The transfer function is,

$$G_{PI}(s) = \frac{U(s)}{E(s)} = K_p + \frac{K_i}{s} \tag{31}$$

Where, the complex frequency variable is indicated by s. This transfer function governs how the controller processes the error to regulate the output of converter. Despite this by further tuning these two constants, the performance of PI controller is enhanced. For which, here, PCOA is utilised.

The PCOA solutions are updated when the optimum solution is found. Therefore, this population and evolutionary based approach is utilized for solving the optimization problems. Firstly, PCOA consists of 2 populations namely pine trees and their corresponding cones.

The criteria for this optimization comprises reducing overshoot, settling time and steady-state error. The assumptions includes the system is initially stable with linear characteristics, the voltage deviation is measurable and utilized as a feedback, cones are randomly initialized around tree positions, cone dispersal follows probalistic pollination behaviour to explore local and global optima and the structure of PI control is unchanged and only gains are optimized to assure voltage regulation under disturbances. In PCOA initialization process consist of a tree at the centre for each segment and several cones are produced around each tree, which is given by,

$$LbS = lb + (i-1) \times \frac{ub - lb}{N_{tree}} \tag{32}$$

$$UbS = ub + (i-1) \times \frac{ub - lb}{N_{tree}} \tag{33}$$

Where, lb and ub represents the lower and upper bound, LbS and UbS are lower and upper bound of segments. Population of pine cone is produced as,

$$CX_{j,i} = LbS_i + \overrightarrow{rand}_{1\times dim} \times (rand \times UbS_1 - rand \times LbS_i) \tag{34}$$

Where, CX is pine cone's position, $\overrightarrow{rand}_{1\times dim}$ refers to random vector with normal distribution among 0 and 1, $rand$ defines the random number ranging between 0 and 1, pine tree and cone index is indicated as i and j. After initialization process, the position of each tree is similar to the finest cone.

Exploitation Phase:

While the pine cones grow mature significantly their weights increase which in turn causes these pine cones to go down from tree, which causes dispersal of cone to restricted region. For attaining this objective function equation (34) is used,

$$CX_{j,i}^{new} = \begin{cases} TX_i + w_1 \times R_1 \times \left(R_2 \times \left(Ub_s^i - Lb_s^i - TX_i \right) \right), \\ if\ Controlparameter = 0 \\ CX_{j,i} + w_1 \times R_1 \times (R_2 \times \left(Ub_s^i - Lb_s^i - T\ pop_{a\,ll,r1} \right) \\ -Tbest_{x,i},\ otherwise \end{cases} \tag{35}$$

Where, $CX_{j,i}^{new}$ represents pine cone's new position, $CX_{j,i}$ implies pine cone's updated position, TX_i indicates the tree position, Ub_s^i and Lb_s^i are the upper and super-cube's lower bound, $T\ pop_{a\,ll,r1}$ refers to the randomly chosen solution in memory of PCOA, $Tbest_{x,i}$ indicates i^{th} top solution of PCOA, w_1 denotes adaptive weight, $r1$ is random integer amid 1 and PCOA's memory size, R_1 and R_2 implies the random number between 0 and 1.

In PCOA, to attain enhanced balance between exploration and exploitation phase is utilized which is given as,

$$LbS = Lb + (i-1) \times \frac{ub - Lb}{N_{tree}} \tag{36}$$

$$UbS = Ub + (i-1) \times \frac{Ub - Lb}{N_{tree}} \tag{37}$$

$$Lb = lb + Radius_{lb} \times W \tag{38}$$

$$Ub = ub - Radius_{ub} \times W \quad (39)$$

$$W = \frac{\min FES}{FES_{max}}, 0.5 \quad (40)$$

$$Radius_{lb} = X_{best} - lb \quad (41)$$

$$Radius_{ub} = ub - X_{best} \quad (42)$$

Where, $Radius_{lb}$ and $Radius_{ub}$ determines the shrinking radius, adaptive weight W gets decreased from 1 to 0.5, X_{best} indicates present finest position, FES represents present generation and FES_{max} implies maximum number of generations. Fig. 7 depicts flowchart of PCOA.

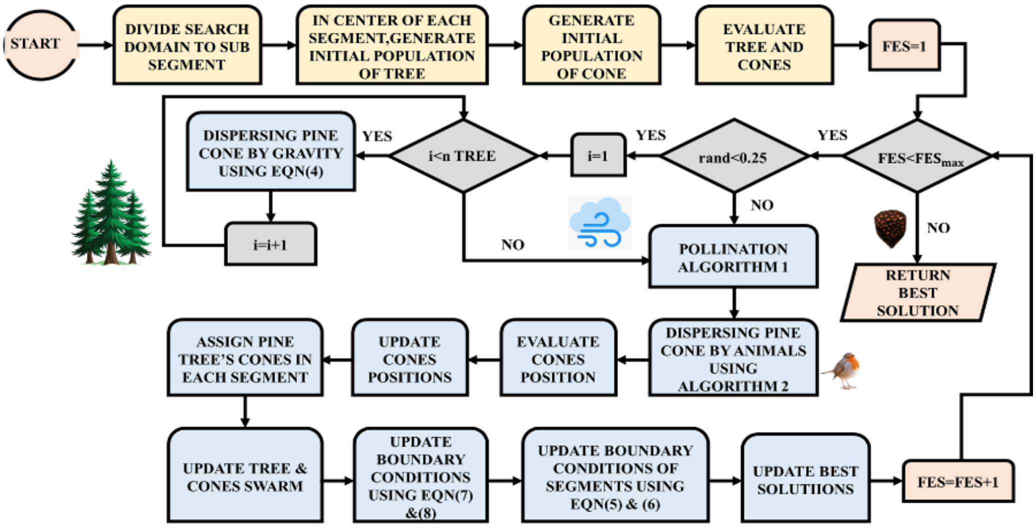


Fig. 7. PCOA Flowchart.

Exploitation Phase:

Hence PCOA replicates two different methods to attain this process, which is expressed using,

$$CX_{j,i}^{new} = CX_{j,i} + 0.5 \times \varnothing_{r1} \times \left(Tbest_j - CX_{r1,i}\right) + 0.5 \times \varnothing_{r3} \times \left(Tbest_j - CX_{r3,i}\right) \quad (43)$$

Here, $\varnothing$ represents the possibilities of successful pollination of pine cones, which is determined using,

$$\varnothing_i = 1 - e^{-\gamma * \sum_{j=1}^{n} a_{i,j}} \quad (44)$$

$$a_{i,j} = \frac{\frac{\beta}{d_{i,j}^{\alpha}} - \frac{\alpha}{d_{i,j}^{\beta}}}{\beta - \alpha} \quad (45)$$

Where, $a_{i,j}$ denotes impact of ith cone on j^{th} cone, $d_{i,j}$ is Euclidian Distance among i^{th} and j^{th} cone, $\propto, \beta$ and γ refers to the constant which defines the pollination process. Therefore, the entire system utilizing the proposed topologies enables enhanced PQ mitigation and improvement.

III. RESULTS AND DISCUSSION

The developed research is validated using MATLAB/Simulink tool. And the depicted results are discussed in detail and elaborated in this section along with their comparative analysis. Table 1 indicates the specification of parameters for developed research.

Fig. 8 represents the waveform of AC source in voltage swell condition. It is observed that source voltage is acquired with voltage swell, which arises in $0.2 - 0.4s$ with an amplitude of $475V$. Likewise, in the source current, voltage swell occurs is less than time period of $0.1s$ and then sustained at $40A$ with aid of control approach.

Characteristics of solar panel is indicated in Fig.9. An input voltage is maintained at $60V$ in the entire system. Also, an input current is changed in the beginning and settled at $20A$ with small distortions. Subsequently, an output voltage is slowly improved and settled at $801V$. Likewise, an output current is changed randomly and sustained at $11A$ with little fluctuations in the entire system.

Fig. 10 displays the waveform of actual and reference voltage. Before DVR injection, an actual voltage is sustained a reduced stable value with fluctuations. Then, the reference voltage is sustained a constant value with no oscillations.

Waveform of load is indicated in Fig. 11. Voltage of load is varied in an initial time and sustained at $400V$ with no oscillations. Consequently, the current of load is arbitrarily varied due to voltage swell and with the aid of $30A$ with no oscillations.

Table 3

Specification of parameters

Parameter	Specification
PV system	
Total Power	10000 W
Panel's peak power	250 W
Open circuit Voltage	$22.6V$
Short circuit Voltage	$12V$
Maximum Peak Current	$8.35A$
Maximum Peak Voltage	$29.95V$
No of cells in series connection,	2
No of cells in parallel connection,	16
Switched inductor cascaded boost converter	
L_1, L_2	$4.7\,mH$
C_1, C_2, C_3, C_4	$22\,\mu F$
C_0	$2200\mu F$
Switching Frequency	$10\,kHz$

Case 1: Voltage Swell Condition with Step Magnitude +0.2

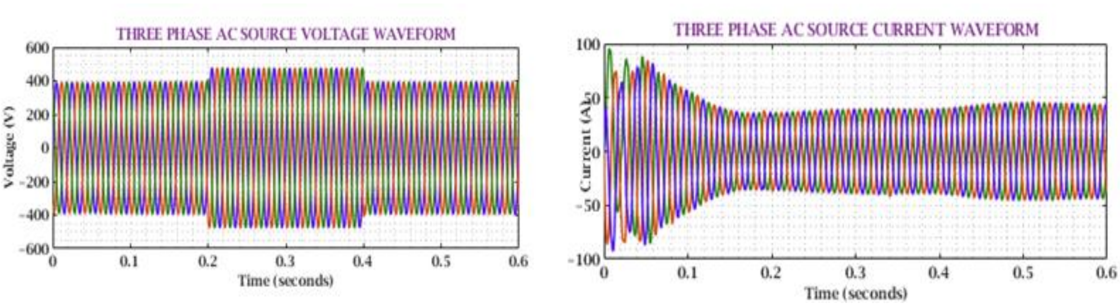


Fig. 8. Waveform of AC source current and voltage.

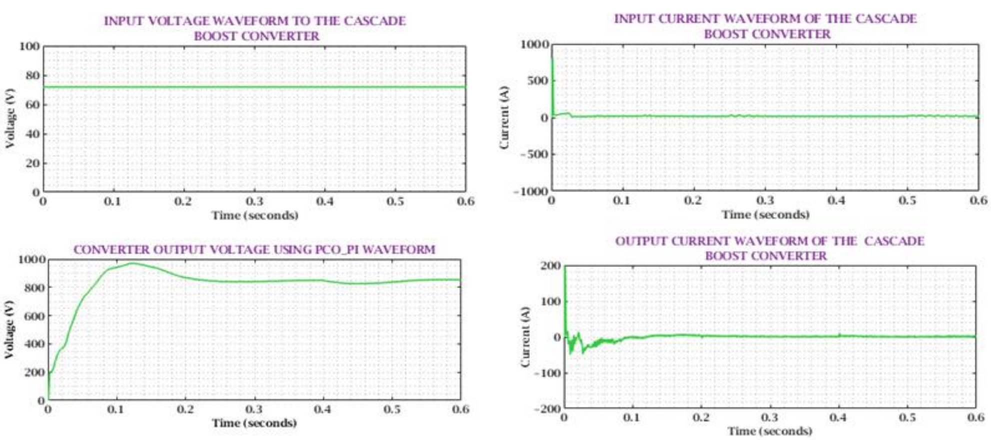


Fig. 9. Characteristics of solar panel.

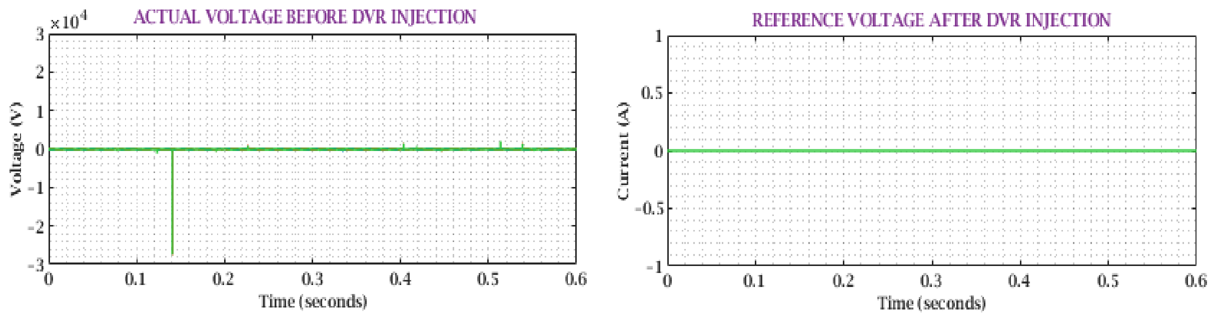


Fig. 10. Waveform of actual and reference voltage.

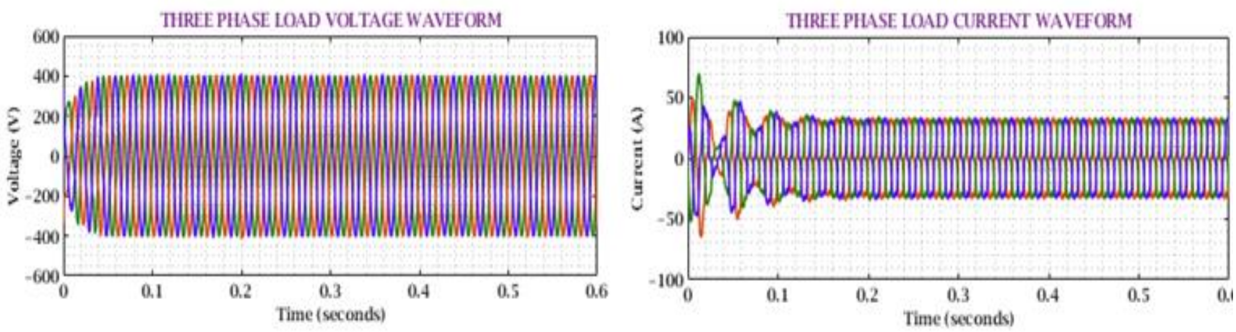


Fig. 11. Waveform of load.

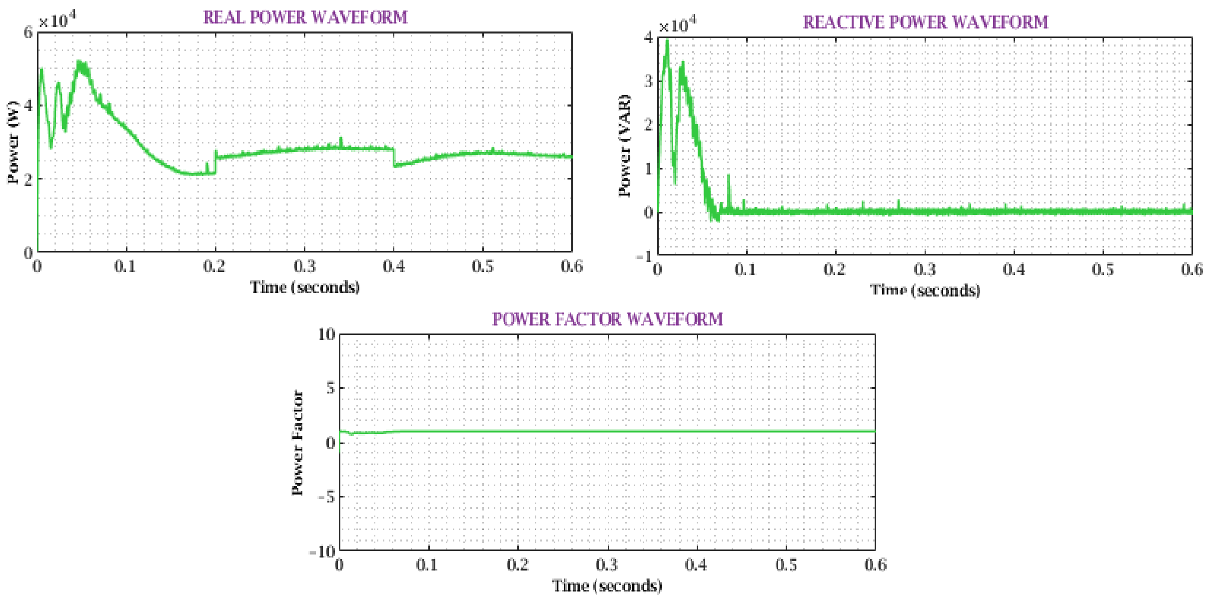


Fig. 12. Waveform of power.

Fig. 12 displays the waveform of power**.** At first, the real power is randomly changed and settled at a small value and reactive power is reduced, denoting the efficacy of overall system is enhanced. Also, the power factor is maintained a constant value throughout the system. Waveform of AC source for voltage and current is depicted in Fig. 13. The source voltage has the voltage sag from $0.2-0.4s$ and it sustained at $400V$ with the help of DVR. Although a voltage sag existed between $0.2-0.4s$, the source current is sustained at $40A$. Fig. 14 presents the behaviour of solar panel. An input voltage to the converter is sustained at $60V$ in the entire system. Meanwhile, an input current has initial variations and then it maintained with a reduced constant value of $20A$

Also, an output voltage is varied in the beginning and sustained at $801V$. Subsequently, an output current is randomly changed and settled at $11A$.

Case 2: Voltage Sag Condition with Step Magnitude -0.2

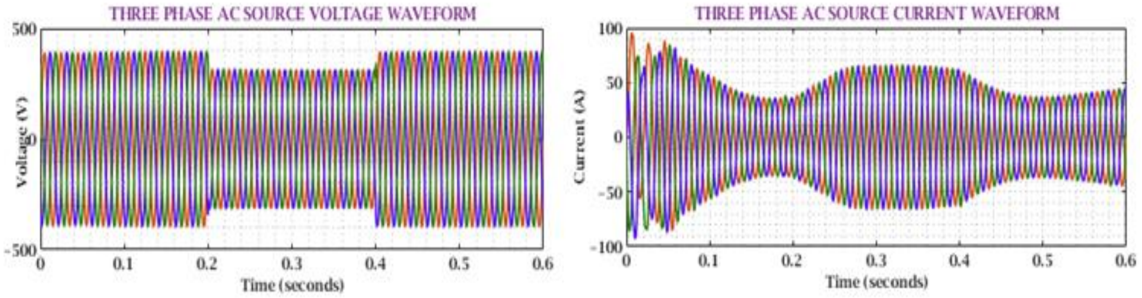


Fig. 13. Waveform of AC source current and voltage.

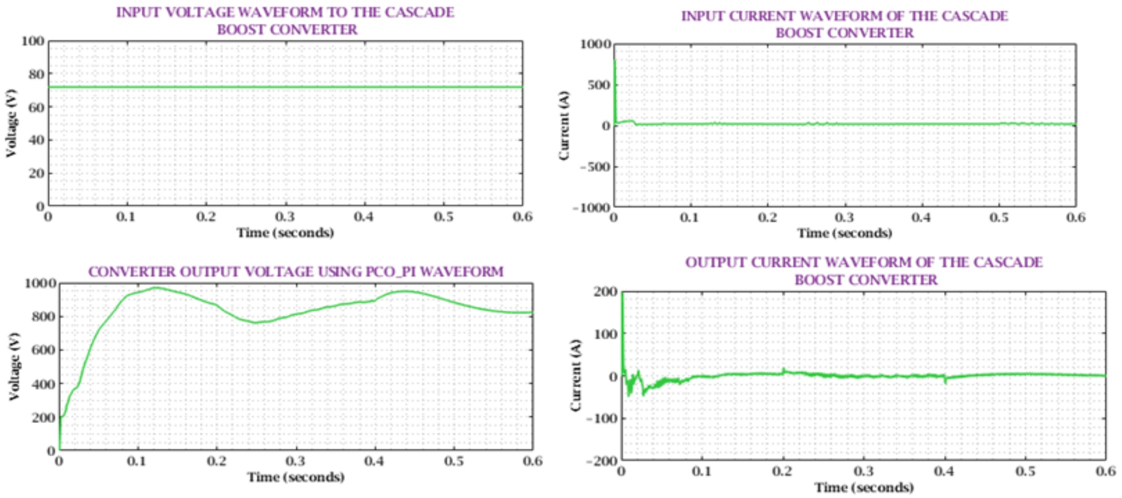


Fig. 14. Behaviour of solar panel.

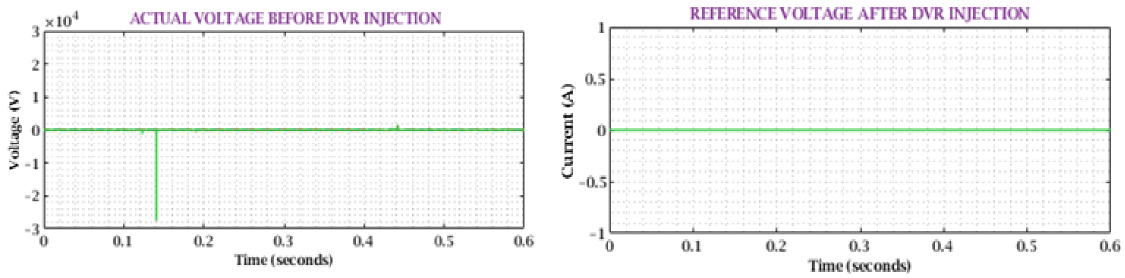


Fig. 15. Waveform of actual and reference voltage.

The waveform of actual and reference voltage is presented in Fig. 15. Actual voltage is settled at a reduced value with little distortions. Likewise, the reference voltage is maintained a stable value in the entire system.

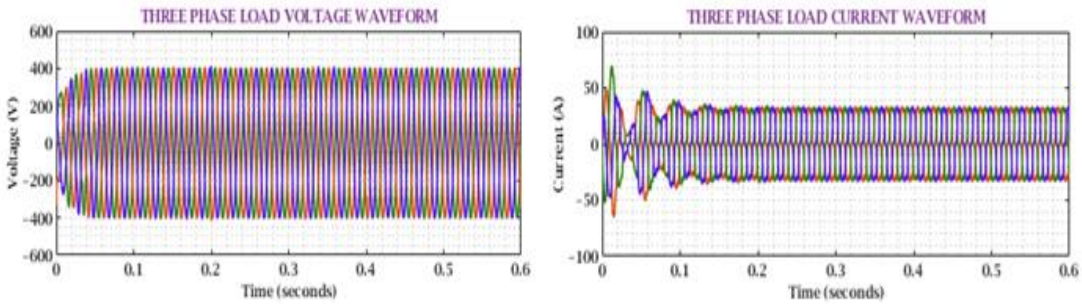


Fig. 16. Waveform of load.

The waveform of load is indicated in Fig. 16. The load voltage is gradually raised and maintained at $400V$ in the entire system. Meanwhile, the load current is varied in the starting time and settled at $30A$ throughout the system.

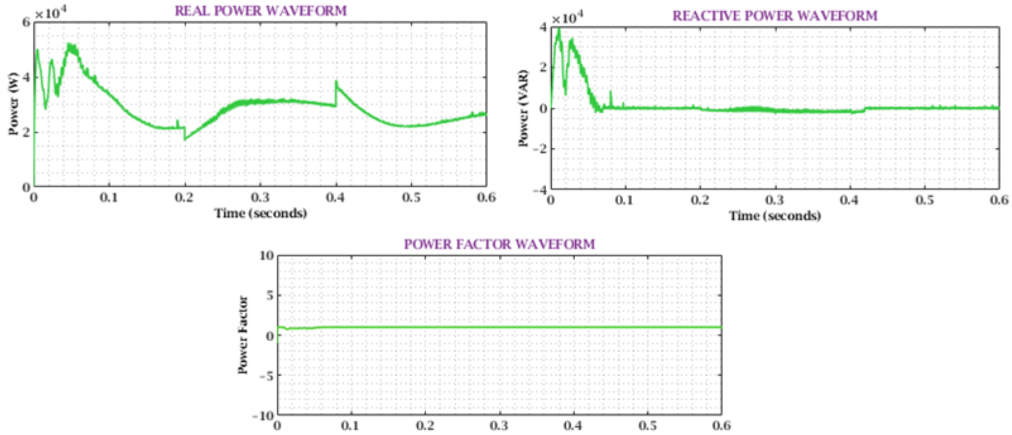


Fig. 17. Waveform of power.

Fig. 17 illustrates the waveform of power. Initially, the real power is arbitrarily varied and sustained at a constant value whereas the reactive power also maintains a stable value, denoting the performance of system is enhanced.

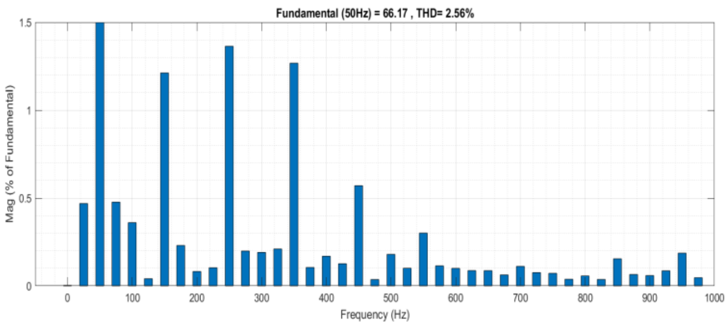


Fig. 18. Waveform of THD.

The waveform of THD is presented in Fig. 18. The proposed research attains the lowest THD of 2.56 %, ensures the overall power quality is enhanced. The THD is computed by,

$$THD = \left(\sqrt{\left(V_2^2 + V_3^2 + V_4^2 + \cdots + V_n^2\right)} / V_1 * 100\% \right) \tag{46}$$

Where, fundamental frequency's RMS voltage is denoted by V_1 and $V_2, \cdots, V_n$ are the second…n^{th} harmonic components.

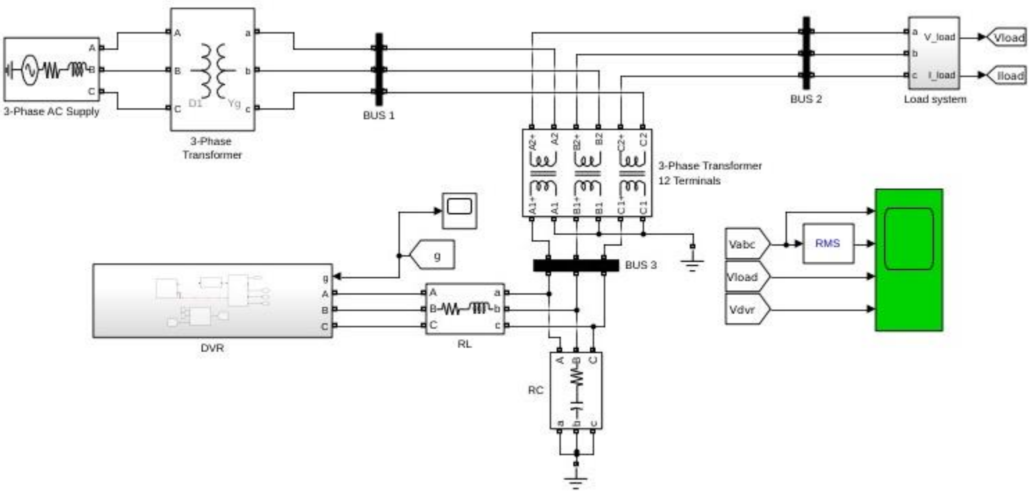


Fig. 19. Functional diagram.

The functional diagram in MATLAB is revealed in Fig. 19. Here, the DVR is incorporated to mitigate voltage disturbances by injecting the compensation voltages. Current and voltage measurements are monitored and processed by RMS blocks for the analysis.

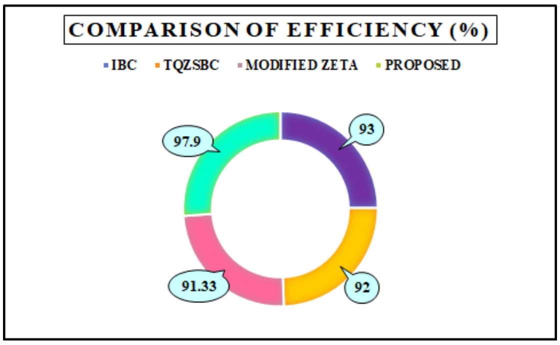


Fig. 20. Comparison of efficiency.

The comparison of efficiency for Interleaved Boost Converter (IBC) [28], Trans Quasi Z Source (TQZS) boost converter [29], Modified Zeta [30] and developed converter is seen in Fig. 20. The developed converter has the maximum efficiency of 97.9 %, indicating the performance of system is enhanced.

Table 4

Comparison of power factor

Approaches	Power factor
Nagarajan et al [31]	0.995
Reddy et al [32]	0.997
Developed work	0.998

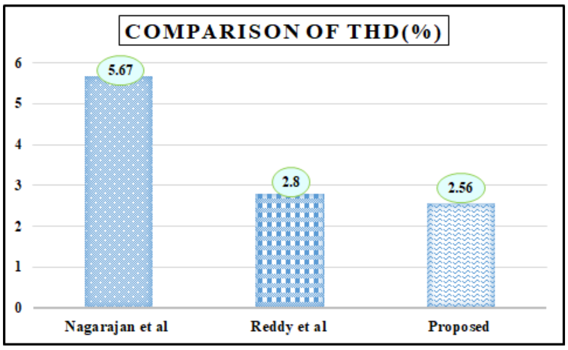
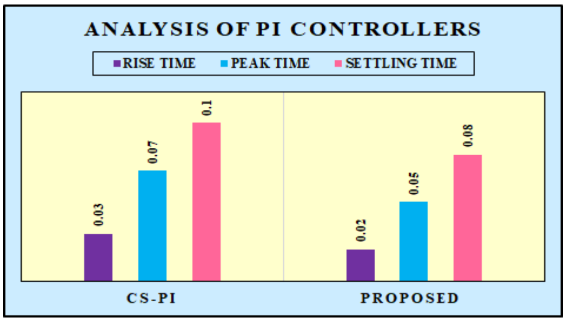


Fig. 21. Analysis of THD.

Table 4 reveals the analysis of power factor with previous works. The highest power factor of 0.98 is attained by the developed approach than others. Fig. 21 depicts an analysis of Total Harmonic Distortion (THD) for developed approach with existing works (Nagarajan et al [31] and Reddy et al [32]). The developed approach has the lowest THD of 2.56 %, indicates an enhanced power quality and efficacy.



The performance analysis of developed PI and CS-PI [33] controller is illustrated in Fig. 22. The developed approach has the better rise time of 0.02, peak time of 0.05 and settling time of 0.08 than CS-PI controller, representing the stability of system is improved.

IV. CONCLUSION

In this research, a PQ improvement approach is developed by incorporating a DVR with PV system aided by a SICBC and PCO-PI controller. The DVR efficiently alleviates the voltage sags and swells by injecting suitable compensating voltage, assuring voltage stability and enhanced power reliability. To offer an uninterrupted power source for the DVR, a PV system is exploited, providing clean energy. The SICBC offers high voltage gain with reduced losses and enhanced efficacy of 97.9%, improving the energy transfer from the PV source. Furthermore, the PCO-PI controller assures the improved control accuracy, diminished steady-state error and faster dynamic response. The developed work is applied in MATLAB/Simulink tool, reveals the reduction in THD to 2.56%. Thus, the developed approach demonstrates its practical viability for modern grid-connected PV applications.

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