

AI-assisted power quality improvement in PV systems using RNN-based DSTATCOM and HiClampCasBoost converter

Srividhya Jayaraman Panneerselvam^{*1)}, Pramod Kumar Gouda²⁾, Viswanathan Gomathi³⁾ and Immanuel Bright Enoch Yesudhas⁴⁾

¹⁾Department of Electrical and Electronics Engineering, KCG College of Technology, Karapakkam, Chennai, Tamilnadu, India

²⁾Department of Electrical and Electronics Engineering, Aditya Institute of technology and Management, Srikakulam, Andhra Pradesh, India

³⁾Department of Electrical and Electronics Engineering, Dhanalakshmi Srinivasan College of Engineering, Coimbatore, Tamilnadu, India

⁴⁾Department of Electrical and Electronics Engineering, Erode Sengunthar Engineering College, Erode, Tamilnadu, India

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Abstract

The rapid deployment of Photovoltaic (PV) systems in modern power distribution networks has caused major issues related to voltage fluctuations, reactive power unbalance, harmonics, and less efficient systems. It is critical to protect Power Quality (PQ) under these conditions to ensure safe and consistent operation of grid. Flexible AC Transmission System (FACTS) devices are used to mitigate those problems encountered in the network. Hence, this work proposed a grid-tied PV system integrated with Distribution Static Compensator (D-STATCOM) device that help accurate voltage sag, swell, and harmonic distortion at the distribution level. In this work, the interaction of D-STATCOM with the grid is controlled by a Recurrent Neural Network (RNN) based controller with PWM signals adjusted for voltage stability, sag, swell and load disturbances compensation. Further, a high-gain HiClampCasBoost Converter (HiClampCasBoost) converts low PV output voltage and regulates the DC-link, assuring constant output of the D-STATCOM while under voltage conditions prevail. Additionally, a Adaptive Neuro-Fuzzy Inference System (ANFIS) based Maximum Power Point Tracking (MPPT) controller, optimized using the Hummingbird Optimization Algorithm (HOA) for tracking Maximum Power Point (MPP) of PV array under dynamic solar conditions to produce maximum energy from PV array whilst ensuring D-STATCOM DC-link stability. The MATLAB simulations show that the developed system enhances PQ and grid stability in comparison to conventional methods. The proposed system has several benefits, such as superior voltage regulation, reduced THD of 1.63%, superior converter efficiency of 96%, tracking efficiency of 99% superior dynamic operation performance, etc.

Keywords: Photovoltaic, D-STATCOM, Recurrent neural network, HiClampCasBoost converter, HOA-ANFIS MPPT

1. Introduction

Many countries are nowadays exploring the combination of Renewable Energy Sources (RES) into their current electrical grid due to factors like a growing need for electricity, a lack of fossil fuels, dependability difficulties, and significant transmission and distribution losses [1]. This type of distributed generation produces power in relatively proximity to residential or business consumers while suffering low distribution and transmission expenses. Among alternative micro sources, solar PV system is rapidly gaining traction because of their capacity to supply the required dc voltage and low initial cost [2, 3]. On the other side, distribution systems are facing major PQ challenges due to a variety of nonlinear loads and spontaneous expansion. Challenges with PQ include load imbalance, high reactive power burden, and harmonic currents, and other issues [4, 5]. Also, development of non-linear, electromagnetic, and unstable loads in the distribution system has caused several PQ challenges. The increasing number of nonlinear loads, as well as the growing popularity of RES, contribute to PQ issues in distribution and transmission systems, including current harmonics, reactive power consumption, and voltage changes (voltage sag and swell). Harmonics and voltage sag constitute among the finest prevalent and serious concerns in power systems [6]. The primary source of harmonics is the rising usage of power electronic-based electrical device monitoring to improve performances. Using power electronic converters is necessary to meet the utilization side's requirement for a controlled power supply. The power sources generate sinusoidal voltage, although the currents produced by these loads become distorted and imbalanced [7, 8]. The primary causes of voltage sagging have been an increase of load current triggered by the initial acceleration of significant motors, transformer stimulation, switch ON and OFF functioning of circuit breaker failures within the consumer's facility, machinery breakdowns, unpredictable atmospheric conditions, and extremely fluctuating nature of RES associated to supply systems [9].

With the incorporation in recent distributed power generation mechanisms, which constantly redirect energy flow throughout the grid, causing a modern distribution networks become more complex. Power electronics-based technologies and approaches have

*Corresponding author.

Email address: sriviprakash2007@gmail.com

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acquired widespread adoption owing to their conventional, slower, and more expensive electromechanical competitors [10, 11]. In order to maximize the future possibilities of the existing electrical grid, the installation of FACTS devices is essential. To address these concerns, a variety of FACTS devices have been utilized, including the Thyristor Switched Capacitor (TSC), Thyristor-Controlled Reactor (TCR), Fixed Capacitor-Thyristor Controlled Reactor (FC-TCR), and Static VAR Compensator (SVC). Montoya et al. [12] have developed TSC devices has been fast, simple, and reliable reactive power compensation to improve voltage constancy and the overall quality of power. Capacitor banks are switched through thyristors, which allows the capacitor to change states quickly, and deliver switched capacitors without mechanical wear of magnets. However, it constructed very costly and cause resonance within the power system if not tuned properly. It also fails to handle voltage variations, which affect the triggering of thyristors. Singh et al. [13] have presented TCR supports reactive power compensation when tied to a unity Power Factor (PF) and PQ. TCRs deliver reactor compensation needs, when it tied into a system, the TCRs need a significant amount of infrastructure and control, which make them over expensive when not tied to active filters. Terriche et al. [14] have implemented FC-TCR systems are useful for controlling reactive power and improving PF by changing inductance through controlled firing angles. These systems are better for reactive compensation and harmonic mitigation, while the influence of resonance and nonlinear loads on rather complex control requirements is disadvantageous to effective application and even negatively impacts system stability. Absar et al. [15] have designed SVC allows the absorption of reactive power to stabilize voltage and improve PQ for electric arc furnace operation. The SVC supports in reduction of current and voltage harmonics, improves flicker control and improves the overall system PF. However, dynamic characteristics of the system and implementation selections limit the use of SVC technology, yet many of these limits improved when used with a matrix converter. The variety of conventional techniques used to reduce harmonics and voltage sags are insufficient to adequately address these difficulties. Based on multiple research investigations on PV-DSTATCOM are able to minimize harmonics and voltage sags while keeping energy sources connected to the grid during abnormal conditions.

Therefore, to overcome the limits of existing approaches discussed above, in this study implemented a D-STATCOM with the help of advanced control strategy. The proposed D-STATCOM enhances the PQ performance by alleviating voltage fluctuations, harmonics, and reactive power problems, as well as incorporating an adaptive learning contingency of an RNN controller, thereby offering a superior dynamic response and durability under varying load conditions.

Furthermore, the required energy for DSTATCOM is supplied from PV system, which delivers adequate supply power support to maintain compensation. Also, since PV output is highly depended on weather condition, a converter is implemented for boosting voltage level, and an MPPT controller to extract MPP from the PV source. Rao et al. [16] have established soft-switching DC–DC boost converter regulated by Improved Perturb and Observe (IP&O) based MPPT aims to increase operational performance and stability by selecting input capacitance, and sample time through systematic step tests. It delivers tracking efficiency, stability, and noise immunity without complicated model-based mathematics. Nevertheless, an increased complexity of design and execution, which led to higher analytical processing and adjusting. Abdel-Rahim and Wang [17] have created high-gain converter with a Model Predictive Control (MPC)- MPPT algorithm to attain high voltage gain and maintaining an operative and accurate means of MPP extraction from PV systems, providing increased efficiency, and improved transient/steady-state performance. However, the variable switching frequency in the MPC-based MPPT makes the converter design more complex. Moyo et al. [18] have presented DC–DC boost converter and ANFIS-MPPT controller developed to provide MPP extraction from the PV module, achieved faster dynamic response and reduced oscillation while its relatively higher design complexity and computational load due to the neuro-fuzzy inference component. Conventional MPPT controllers are usually affected by slow tracking speed, oscillating around the MPP, and low efficiency in quickly changing irradiance. To overcome these limitations, numerous researchers have employed various optimization-based solutions which improved the tracking precision and performance of MPPT controllers. Mohammed et al. [19] have developed Fuzzy Logic Controller (FLC)-based MPPT optimized using a Genetic Algorithm (GA), enhanced speed and accurateness of MPP through optimizing rule base and membership functions of the FLC simultaneously. The advantages are yielding a faster dynamic response, higher tracking efficiency, and robustness when the climate is changing, while disadvantages included higher computational duration due to GA optimization and training process. The step-up converter with a hybrid Sliding Mode Controller (SMC) optimized with Particle Swarm Optimization (PSO)-based MPPT developed in Djanssou et al. [20] to improve tracking speed, accuracy, and robustness of PV systems with rapidly varying weather conditions. It includes improved tracking performance with sub-features like fast convergence, reduced oscillations, and performance dynamic response, however, there is a limitation of additional complexity due to the hybrid of SMC and the PSO. González-Castaño et al. [21] have designed DC-DC converter with an Artificial Bee Colony (ABC)-MPPT algorithm to optimally extract power from PV systems with fast and accurate tracking under stable and rapid weather variations. It's maintained high efficiency, fast dynamic response, and low computational cost, suitable for inexpensive controllers, however the algorithm has not been completely validated multi-peak conditions under partial shading and requires future development. Pradhan et al. [22] have created DC-DC converter in a stand-alone PV based hybrid microgrid is controlled by a hybrid P&O MPPT and Modified Invasive Weed Optimization (MIWO) methods. This hybrid approach is developed to rapidly converging the global peak with combined benefits of MIWO, maximizing PV power extraction, and maximizing MPPT efficiency under partial shading and fast-changing weather conditions, while also having a faster dynamic response and negating the requirement of a separate MPPT circuit. Nevertheless, hybrid optimization and coordination with multiple subsystems increased algorithmic and control complexity.

In most of the existing traditional optimization techniques suffer from the difficulties of premature convergence, and being computationally intensive and poorly performing during system dynamics. To overcome above mentioned limitation, a Hamming Bird-based ANFIS MPPT controller is proposed in this work to offer higher tracking performance, efficient performance, and less computational overhead.

1.1 Related works

Patel et al. [23] have presented PV-DSTATCOM inverter with Active Current Controller (ACC) enable both active power booster and PQ improvement including harmonic moderation, and Power Factor Correction (PFC). Moreover, it stabilizes voltage during insolation change, to improve the overall dynamic performance. However, its performance is degraded under severe and rapid variations in irradiation which requires careful tuning of its controllers. Dash et al. [24] have implemented single-stage three-phase grid-tied PV-DSTATCOM with a better Proportional Resonant (PR) controller to improve DC offset rejection in response to partial shading events. It improved active current sharing, reactive power support, elimination of harmonics, and unity gain for frequency reference. However, the performance of the controller fails under severe disturbance events in the grid, resulting in reduce compensation efficiency. Nafeh et al. [25] have designed D-STATCOM controlled via fuzzy-PI and fuzzy-PID intelligent current

controllers enhanced voltage stability and PQ during sudden load variation. The benefits of its application included less voltage flying, well-damped dynamic responses, improved system signals smoothing, while the costs included increased complexity of the controller design and tuning related to its practical implementation. Ahmed et al. [26] have developed Fractional Order Sliding Mode Controller (FOSMC) for the D-STATCOM operation, which improve PQ of distribution systems including voltage sag/swell and unstable loads. The FOSMC included minimal chattering, fast convergence output response time, limited THD, robust responses, and fast input tracking. However, implementation requires high design complexity and sensitivity in selection of parameters which affect practical implementation. Irfan et al. [27] have suggested D-STATCOM controlled by an Artificial Neural Network (ANN)-type controller for operates under balanced and unbalanced conditions of nonlinear loads. Also, it reduces harmonics, improve PQ, voltage stability, and better dynamic performance. Nevertheless, considering a requirement of large computational power, and significant complex in real-time training/tuning of the ANN controller.

This work applies and implements a D-STATCOM controlled using an RNN, where the required power is delivered from a PV system through a HiClampCasBoost converter, and MPP harvesting is ensured using an HOA-ANFIS-based MPPT controller. The proposed innovation is addressing the limitation seen in existing methodologies and improve upon PQ, reliability, and efficient integration of renewable energy.

1.2 Objectives

- To improve a three-phase AC distribution system's PQ and voltage stability, an integrated control strategy is introduced.
- To mitigate amount of current and voltage disturbances, along with harmonics and reactive power burden, a D-STATCOM is employed.
- To ensure dynamic and intelligent control of both active and reactive power an RNN-based controller is utilized.
- To deliver auxiliary consistent power supply for a DSTATCOM, a PV system is implemented.
- To enhance adjustable PV voltage to a stable DC-link voltage, a HiClampCasBoost converter is employed.
- To extract MPP from PV system under changing circumstances, a HOA-ANFIS MPPT is formulated.
- To provide an overall integrated system that achieves improved PQ, voltage stability, coordinated system operation, and compensation capability.

1.3 Formation of the paper

The continuing part of this paper is organized as given below. In Section 2, proposed working principle introduced along with the overall block diagram. In Section 3, proposed methodology explained in detail, including the D-STATCOM, RNN controller, PV system, converter, optimized MPPT control strategy, formulation, and basic structure. In Section 4, simulation results, which is executed and determined by discussing the results in detail. Finally, in Section 5, the research is concluded and possible future work will be noted.

2. Proposed system description

The work is focused on improvement of PQ and voltage constancy in power distribution network as exposed in Figure 1. A 3-phase AC source supplies power to the load but due to source impedance and system disturbance issues increases such as voltage stability and PQ thus affected in the system. To attempt to regulate these conditions a DSTATCOM is used to recompense for reactive power and mitigate existing and future harmonics. The operation of D-STATCOM is intelligently controlled by a RNN controller, which continually difference between reference and actual power values to generate respective switching signals for maintaining stable operation. Since the D-STATCOM needs a stable DC supply, a PV system is utilized to supplement the energy supply. However, PV output is extremely variable and it only deliver limited power based on weather.

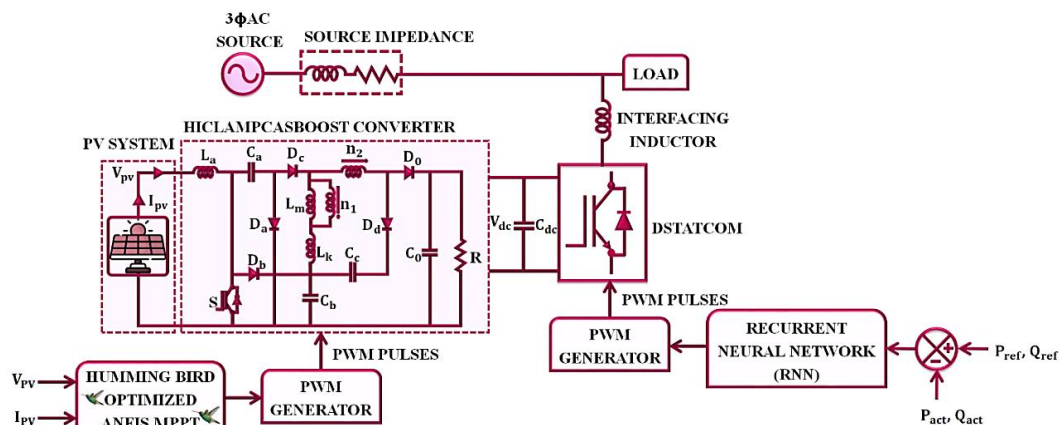


Figure 1 Proposed block diagram of PV-DSTATCOM for improved PQ

For this reason, the HiClampCasBoost converter is employed to enhance voltage from PV system, allowing DC-link voltage to remain steady. A HOA-NFIS-based MPPT algorithm is employed with additional gains to allow MPP extraction with the PV system at various irradiance and temperature conditions. The PWM generators associated with the PV converter and DSTATCOM deliver the respective switching pulses to control operation. Finally, D-STATCOM and its support from the PV system permits for continuous and enhanced power support capacity which allows for increasing the active and reactive power compensation. Therefore, D-STATCOM is maintain voltage stability and PQ for the load with the integration of a PV system.

3. Proposed system methodology

3.1 D-STATCOM

D-STATCOM is a shunt-connected Voltage Source Inverter (VSI) based device that regulates bus voltage and deliver for PQ disturbances along distribution systems as illustrates in Figure 2. It consists of a DC capacitor, a VSI, a coupling transformer or reactor, an AC filter, and a controller. The VSI provides a controllable AC voltage generated from the dc voltage, which appears at the output of the inverter behind the transformer leakage reactance. Therefore, the difference between AC voltage supplied via an inverter and AC voltage of system enables the delicate exchange of active and reactive power at Point of Common Coupling (PCC). The controller measures individual system voltages and currents for compensation, compares them to reference values, and produces the switching pulses for the inverter switching devices (IGBTs) to effectuate the compensation. The D-STATCOM operates effectively as it offers any variable leading or lagging reactive current within its rated capacity, and as a result, that improvement offers some control of the voltage, leading to a more stable distribution network.

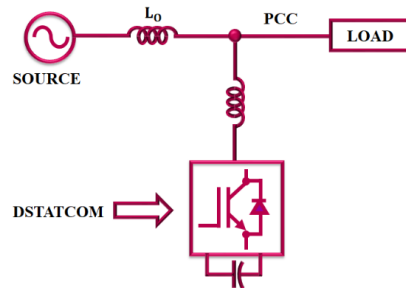


Figure 2 Basic diagram of DSTATCOM circuit

3.1.1 Basic operating principle

The basic operational principle of a D-STATCOM is fundamentally the same as that of a synchronous machine. Essentially, it generates or absorbs reactive power by controlling its Voltage Source Converter (VSC) output. A D-STATCOM supplies reactive power (capacitive mode) when the VSC output voltage is better the system voltage; likewise, if VSC output voltage is lower the system voltage, it essentially engages reactive power (inductive mode). When a D-STATCOM is functioning in this manner, real power is not being exchanged, except when using an external DC source or maintaining DC capacitor voltage, such as during low-voltage situations or faults. This means the D-STATCOM adjusts voltage at PCC by supplying or absorbing reactive power, as well as dynamically exchanging real power. In the distribution level, the D-STATCOM improves PF, maintains voltage stability, and provides balanced source currents at unity PF. In the transmission level, the D-STATCOM generally provides continuous reactive power compensation and voltage support. Figure 3 shows single line structure of D-STATCOM.

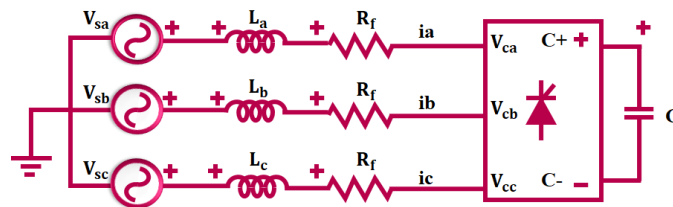


Figure 3 Structure of single line D-STATCOM single line

3.1.2 Mathematical modelling of D-STATCOM:

Modelling equations [3] are given as,

$$R_f I_a + L_f \frac{di_a}{dt} = V_{sa} - V_{sc} \quad (1)$$

$$R_f I_b + L_f \frac{di_b}{dt} = V_{sb} - V_{cb} \quad (2)$$

$$R_f I_c + L_f \frac{di_c}{dt} = V_{sc} - V_{cc} \quad (3)$$

Here, R_f and L_f denotes equivalent filter resistance and filter inductance; V_{sa}, V_{sb} and V_{sc} represents voltage at the PCC, V_{sc}, V_{cb} and V_{cc} represents inverter output voltage.

$$Q_{STAT} = \sqrt{3VI_c} \quad (4)$$

$$V_{DC} = 2\sqrt{2}V/\sqrt{3}Ma \quad (5)$$

$$L_{AC} = \sqrt{3}MaV_{DC}/12af_sI_{p-p} \quad (6)$$

$$C_{DC} = 3V_S \Delta I_L T / (V_{DC}^2 - V_{DC1}^2) \quad (7)$$

Here, Q_{STAT} stands Power rating, I_c and V stands D-STATCOM line current and line voltage. V_{DC} and Ma denotes Link voltage and modulation index. L_{AC} stands AC inductor, a represents over current factor.

Parks Transformation: This block applies the $abc - dq$ transformation to a series of three phase signals. It determines direct axis V_d , quadrature axis V_q , and zero sequence V_o quantities in a two-dimensional rotating reference frame using subsequent transformation:

$$V_d = 2/3 \times [V_a \sin \omega t + V_b \sin(\omega t - 2\pi/3) + V_c \sin(\omega t - 2\pi/3)] \quad (8)$$

$$V_q = 2/3 \times [V_a \cos \omega t + V_b \cos(\omega t - 2\pi/3) + V_c \cos(\omega t - 2\pi/3)] \quad (9)$$

$$V_o = 2/3 \times [V_a + V_b + V_c] \quad (10)$$

In this equation, ω represents the rotating frame's rotation speed (radian per second). This converts three variables represented in a two-axis reference frame into their initial phase variables. The subsequent transformation is applied:

$$V_a = V_d \sin \omega t + V_q \cos \omega t + V_o \quad (11)$$

$$V_d = V_a \sin(\omega t + 2\pi/3) + V_q \cos(\omega t + 2\pi/3) + V_o \quad (12)$$

This controller algorithm achieves voltage regulation in a D-STATCOM via measuring average voltage at load point, with without any reactivity measurements are essential. The sinusoidal PWM approach is utilized, because it's modest and produces a satisfactory response. The angle that establishes the essential phase shift among VSC output voltage and AC terminal voltage is produced by an RNN controller using the error signal obtained by associating estimated system RMS voltage to reference voltage. Coordinating signal required to run the PWM generator is created by combining the acquired angle with the phase angle of the balanced supply voltages, which have been evenly separated at 120° . This method maintains a constant DC voltage by using a different DC source.

3.2 RNN controller

In this study, the RNN is used owing to its capability to capture dynamic and time varying nature of power systems through its memory feature. Thus, precise control of D-STATCOM achieved by employing RNN even in cases where there are disturbances and non-linearities. It is beneficial in terms of good dynamic behavior, adaptability, and tracking accuracy among other qualities. In addition, with the use of memory feature, accurate tracking of reference signals and compensation of voltage sags, surges, and harmonic distortion is made possible even in the presence of varying loads. Although this improves complexity, when compared with traditional techniques, the efficiency of RNN model is noticeably better regarding such aspects as stability, accuracy of tracking, and power quality enhancement. A key component of the proposed D-STATCOM control architecture is the RNN controller, shown in Figure 4. The RNN controller consists of two layers: an input layer and an output layer. In this case, the input layer has mc neurons, and the output layer has a single neuron that produces control signal. The inputs RNN controller is produced by feedback of previously created control signal and a set of system parameters determined from the D-STATCOM model. Thus, select neurons for the input layer denoting the input and output of j -th neuron in input layer as $S_j^{(1)}(t)$ and $T_j^{(1)}(t)$ where the RNN controller accepts five inputs:

$$u(t-1), i_d(t-1), i_q(t-1), V_{dc}(t-1), \text{ and } V_{pcc}(t-1) \quad (13)$$

In this representation, $u(t-1)$ is the previous control signal. In addition, i_d and i_q denotes dq -axis currents, V_{dc} stands DC-link voltage, and V_{pcc} stands PCC voltage. Output layer consists of only one neuron with input equal to $S^{(2)}(t)$ and output $u(t)$, which represents the current control signal.

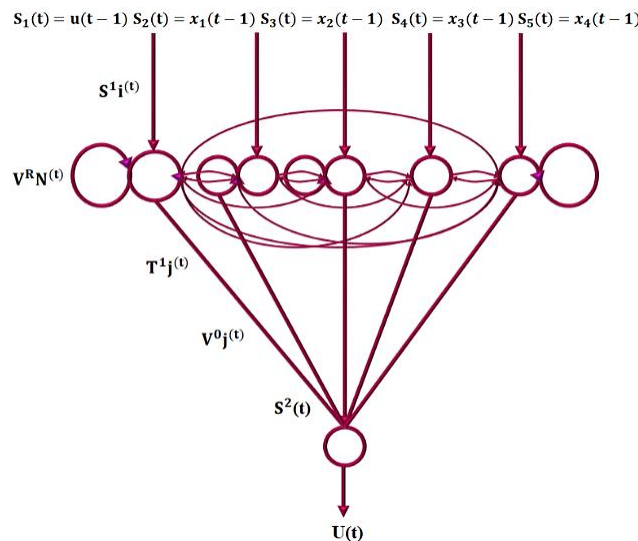


Figure 4 Network structure of RNN controller

The recurrent weights added dynamic memory to the network and referred to as $V_{ji}^R(t)$ and $V_j^O(t)$ for input layer and output layer. Model of RNN controller is given by:

3.2.1 Input layer equations:

$$S_j^{(1)}(t) = S_j(t) \sum_{i=1}^{m_c} V_{ji}^R(t) T_i^{(1)}(t-1) \quad (14)$$

$$T_j^{(1)}(t) = f(S_j^{(1)}(t)) = \tanh(S_j^{(1)}(t)) \quad (15)$$

Output layer equations:

$$u(t) = S^{(2)}(t) = \sum_{i=1}^{m_c} V_j^O(t) T_j^{(1)}(t) \quad (16)$$

The RNN controller learning structure works based on the minimization of error function:

$$E_c(t) = \frac{1}{2} \sum_{k=1}^{m_c} (r_k(t) - x_k(t))^2 \quad (17)$$

Where $r_k(t)$ and $x_k(t)$ represents reference trajectory and actual system output. With the steepest-descent approach, the changes in the weights are:

$$V_{ji}^R(t+1) = V_{ji}^R(t) - \eta_c^R \frac{\partial E_c(t)}{\partial V_{ji}^R(t)} \quad (18)$$

$$V_j^O(t+1) = V_j^O(t) - \eta_c^O \frac{\partial E_c(t)}{\partial V_j^O(t)} \quad (19)$$

Where η_c^R and η_c^O are learning rates. The gradient quantities needed to update the weights are given as:

$$\frac{\partial E_c(t)}{\partial V_j^O(t)} = - \sum_{k=1}^{m_c} (r_k(t) - x_k(t)) W_{k1}^O(t) \left(1 - (O_j^{(1)}(t))^2 \right) T_j^{(1)}(t) \quad (20)$$

$$\frac{\partial E_c(t)}{\partial V_{ji}^R(t)} = - \sum_{k=1}^{m_c} (r_k(t) - x_k(t)) W_{k1}^O(t) \left(1 - (O_j^{(1)}(t))^2 \right) V_j^O(t) T_i^{(1)}(t-1) \quad (21)$$

With this adaptive recurrent structure, RNN controller is able to dynamically adjust the control signal $u(t)$ to control the dq – axis currents, maintain DC-link voltage, and stabilize PCC voltage during disturbances. This result in the D-STATCOM achieving fast reactive power compensation and voltage stability in distribution systems.

3.3 PV System

Solar cell is a primary module of PV system made up of a $p-n$ junction that created in a semiconductor material which resembles diodes. Figure 5 displays circuit model of a solar cell, which comprises of a current generator, I_L , and a diode, as well as series and parallel resistance. Solar PV arrays are created by connecting solar cells in series and parallel to supply output voltage and current. Operation of a PV array or module is ascertained by expanding the model after $I-V$ features of a single solar cell have been established.

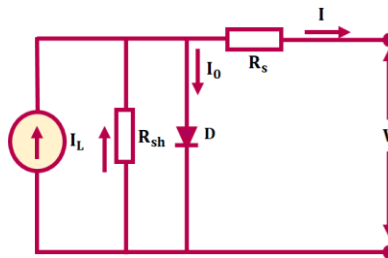


Figure 5 Solar cell equivalent circuit

The Shockley equation [10] describes the current-voltage characteristics of a single cell.

$$I = I_L - I_o \left[\exp\left(\frac{V+I R_s}{n V_{th}}\right) - 1 \right] - \frac{V+I R_s}{R_{sh}} \quad (22)$$

Here I represent output current. It corresponds to the current that is produced under a specific insolation. I_o stands diode reverse saturation current, n stands ideality factor for a $p-n$ junction, R_s and R_{sh} denotes series loss resistance, and shunt loss resistance. V_{th} denotes thermal voltage. For each cell, it is determined from:

$$V_{th} = k \cdot T / q \quad (23)$$

Here, k denotes Boltzmann's constant, T and g stands cell temperature and electron charge. According to the following formula, the solar array's I_0 , changes with temperature:

$$I_0 = I_r \left[\frac{T}{T_r} \right]^3 \exp \left[\frac{qE_{GO}}{n.k} \left(\frac{1}{T_r} - \frac{1}{T} \right) \right] \quad (24)$$

In this formula, T_r represents reference temperature, I_r stands saturation current at T_r and E_{GO} represents band-gap energy. The equation is previously discussed and is defined as a purpose of cell temperature and solar radiation. The expression written as below:

$$I_L = [I_{scr} + K_I(T - T_r)] \frac{G}{100} \quad (25)$$

Here, I_{scr} stands short-circuit current. T_r and K_I represents short-circuit current and temperature coefficient, and G stands solar insolation in mW/cm^2 .

3.4 Hiclampcasboost converter

The HiClampCasBoost converter is considered to deliver a high voltage gain for low voltage renewable sources like PV modules. The converter in Figure 6 consists of an input inductor (L_a), a main switch (S), a clamp capacitor (C_a), an active clamp network (D_a, D_b, C_b), a coupled inductor (L_k, L_m, n_1, n_2), a cascaded multiplier networks (D_c, D_d, C_c), and the output stage (D_0, C_0, R).

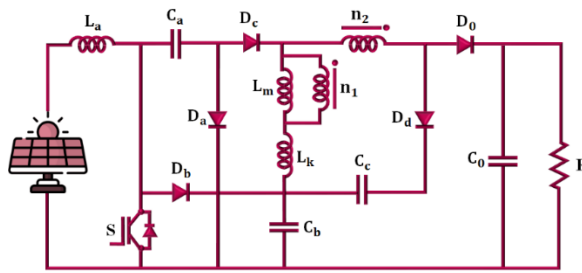


Figure 6 Proposed converter circuit diagram

Mode 1: $[t_0 - t_1]$

At $t = t_0$, switch S is switched ON in Figure 7 (a). Diodes D_a, D_b, D_d and D_0 are reverse-biased, and input inductor L_a is energized directly from the PV source:

$$v_{L_a} = V_{in} \quad (26)$$

The magnetizing inductor L_m and leak inductor L_k are storing energy via the clamp capacitor C_b :

$$v_{L_m} = v_{C_b} \quad (27)$$

$$v_{L_k} = v_{C_b} \quad (28)$$

At the same time, an output load R is energized via discharge of the output capacitor C_0 :

$$i_R = \frac{v_{C_0}}{R} \quad (29)$$

Thus, during Mode 1 energy is being stored in L_m , and L_k whilst the output is powered by C_0 .

Mode 2: $[t_1 - t_2]$

At time $t = t_1$, S is OFF; diodes D_a, D_d , and D_0 conduct and diode D_c is reverse biased, shunting the stored energies to the output in Figure 7 (b). The input inductor releases the stored energy to the clamp/multiplier path:

$$v_{L_a} = V_{in} - v_{C_a} \quad (30)$$

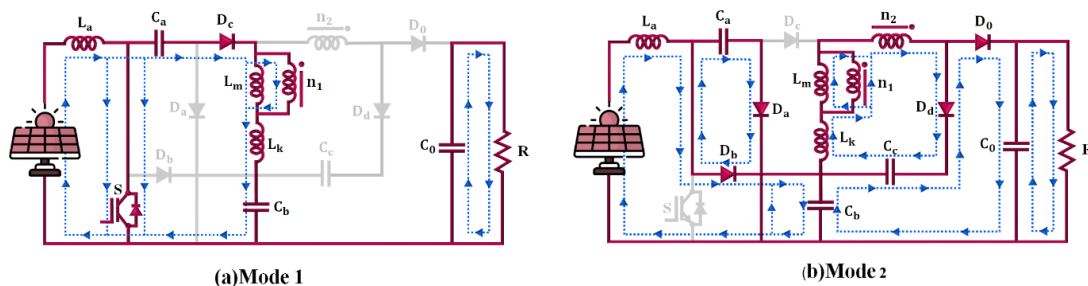


Figure 7 Modes of operations (a) mode 1 (b) mode 2

Leakage/magnetizing energy is re-circulated on the clamp, limiting switch stress:

$$\frac{dv_{C_b}}{dt} = \frac{i_{L_k}}{C_b} \quad (31)$$

Through the coupled inductor, the primary voltage is reflected, to charge the multiplier capacitor via D_d :

$$\frac{dv_{C_c}}{dt} = \frac{i_{D_d}}{C_c} > 0 \quad (32)$$

The output diode D_0 conducts, so the output capacitor is recharged while supplying the load, thus the output voltage is multiplied as approximately the sum of all contributing parts:

$$v_0 = v_{C_a} + v_{C_c} + v_{C_b} \quad (33)$$

$$i_R = \frac{v_0}{R} \quad (34)$$

By applying volt-second balance to L_a :

$$D \cdot V_{in} + (1 - D) \cdot (V_{in} - v_{C_a}) = 0 \quad (35)$$

$$v_{C_a} = \frac{V_{in}}{1-D} \quad (36)$$

In the same respect, the clamp capacitor C_b and multiplier capacitor C_c are also charged via a coupled inductor. With the turns ratio $n = n_1/n_2$

$$v_{C_b} = \frac{D}{1-D} V_{in} \quad (37)$$

$$v_{C_c} = n \cdot \frac{D}{1-D} V_{in} \quad (38)$$

The output voltage combination of these capacitor voltages:

$$v_0 = v_{C_a} + v_{C_b} + v_{C_c} \quad (39)$$

$$V_o = \frac{V_{in}}{1-D} + \frac{D}{1-D} V_{in} + \frac{n}{1-D} V_{in} \quad (40)$$

$$M = \frac{V_{in}}{V_o} = \frac{1+D+n}{1-D} \quad (41)$$

Figure 8 shows ideal timing waveforms of HiClampCasBoost converter. Converter has a very high voltage step-up ratio with a moderate duty cycles and actively recycling the leakage energy through the active clamp to reduce switch stress and switching losses. This ultimately results in better efficiency and better stability of the high voltage output power suitable for renewable energy applications.

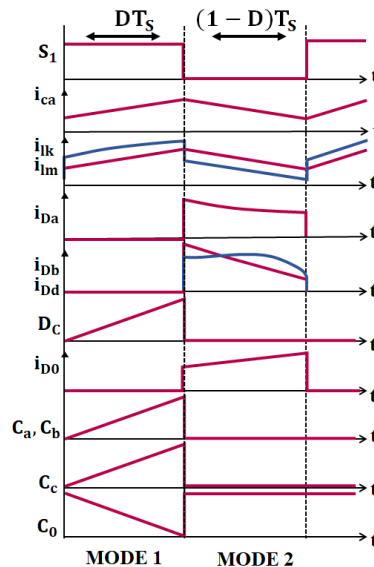


Figure 8 Proposed converter switching waveform

3.5 Hummingbird optimized based ANFIS MPPT controller

3.5.1 ANFIS MPPT controller

The ANFIS is a learning technique that utilizes the generalization capabilities of neural networks and the interpretability of fuzzy logic to create a modeling process that used to create intelligent controllers for greatly complex nonlinear systems. In the case of PV systems, ANFIS has been established to be effective for MPPT and has the capacity to learn the nonlinear functions which relate PV operating parameters to the desired MPP adaptively. A typical ANFIS structure for a two-input first-order Sugeno fuzzy structure with two rules is illustrated in Figure 9, and fuzzy rules [18] are written as:

- Rule 1: if x is A_1 and y is B_1 , then $f_1 = p_1x + q_1y + r_1$
- Rule 2: if x is A_2 and y is B_2 , then $f_2 = p_2x + q_2y + r_2$

The ANFIS architecture comprises five layers and each layer processes different operation:

- **Layer 1 (Fuzzification):** Produces membership grades using parameterized membership functions.

$$O_{1,i} = \mu_{A_i}(x), \quad O_{1,i} = \mu_{B_{i-2}}(y), \quad i = 1, 2, 3, 4 \quad (42)$$

- **Layer 2 (Rule firing strength):** Multiplies signals that came into the layer in order to get the firing strengths.

$$O_{2,i} = w_i = \mu_{A_i}(x) \cdot \mu_{B_i}(y), \quad i = 1, 2 \quad (43)$$

- **Layer 3 (Normalisation):** Normalises firing strengths.

$$O_{3,i} = \bar{w}_i = \frac{w_i}{w_1 + w_2}, \quad i = 1, 2 \quad (44)$$

- **Layer 4 (Rule outputs):** Uses linear functions to calculate weighted outputs.

$$O_{4,i} = \bar{w}_i f_i = \bar{w}_i (p_i x + q_i y + r_i) \quad (45)$$

- **Layer 5 (Output layer):** Associates outputs from rules to give the overall output.

$$O_{5,1} = \sum_i \bar{w}_i f_i = \frac{\sum_i w_i f_i}{\sum_i w_i} \quad (46)$$

For PV systems, accurate and efficient MPPT ensure reliable power extraction under changing environmental conditions. Based on these, an ANFIS estimates the nonlinear $I - V$ characteristics and adaptively predicts MPP. The learning process minimizes the difference between the predicted and realized PV outputs and ensures, which is operating point is driven towards the true MPP depending on the irradiance and temperature conditions.

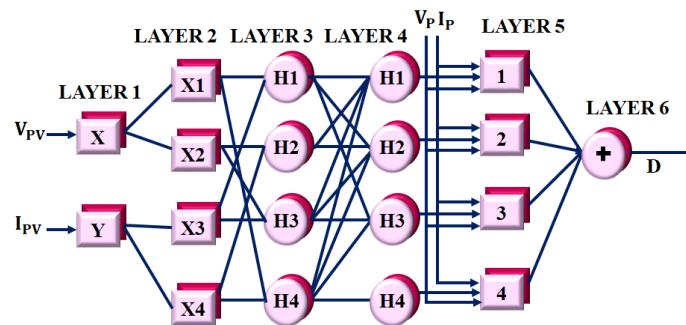


Figure 9 Architecture of ANFIS MPPT

ANFIS-based MPPT controller, is able to take advantage of neural learning for adaptive parameter tuning with fuzzy inference for dealing with nonlinear uncertainties. This makes it particularly viable for use in PV systems when quick convergence to the MPP is required despite changing environmental conditions. Optimization is also useful for adjusting the parameters of the ANFIS-based MPPT controller to improve MPPT performance and overall system performance.

3.5.2 Hummingbird optimized algorithm for tuning ANFIS MPPT controller

The HOA is utilized to optimize parameters of ANFIS-based MPPT controller to increase efficiency. HOA is inspired via a unique ability of hummingbirds to forage efficiently and defend their territory. In this context, hummingbirds indicate candidate solutions which correspond to ANFIS parameters such as membership function widths, pieces, and rules weights. Then, the quality of the food source indicates the proposed fitness function, which distinct as tracking accuracy of MPP in PV system. The best food source represents the best parameter configuration while maximizing the output of the PV as the weather shifts.

The initialization of the hummingbird's population is done by:

$$P_i = ub - rand \cdot (ub - lb) \quad (47)$$

Where P_i signifies position of i^{th} hummingbird with N population size. ub and lb refer to the upper and lower bounds of ANFIS parameters, $rand$ stands random number between 0 and 1.

(a) Self-Searching phase

During the self-searching phase, each hummingbird focused on refining the search for better solutions, by exploiting the local region of its previously visited positions. In terms of parameter tuning of ANFIS, this refers to exploiting the memory associated with past parameter settings that greatly improved MPPT performance. If the (new) current solution improved on the previous solution, then the hummingbird is intensifying its search in this local area:

$$P_i^{t+1} = P_i^t + rand \cdot (P_i^t - P_i^{t-1}) \quad (48)$$

where P_i^{t+1} denote positions of i^{th} hummingbird at iterations t and $t - 1$. If improvement no longer exists, then the hummingbird is performing a Levy flight search, which permits unexpected large jumps in the search space, thus allowing the ANFIS to avoid being entrapped in local optima:

$$P_i^{t+1} = P_i^t + \alpha \oplus Levy(\beta) \quad (49)$$

(b) Guide-Searching phase

During the guide-searching phase, the virtual hummingbirds replicate territorial behaviours to ensure a balance between local exploitation and global exploration. The best performing solution in the population is referred to as the territory bird, which corresponds to the best current ANFIS parameter set. To allow fine-tuning, the territory bird's position is perturbed via:

$$P^{T,t+1} = P^{T,t} + r_d \cdot \lambda \quad (50)$$

Where r_d stands random number in the ranges $[-1,1]$ and λ stands parameter that controls the perturbation distance. This perturbation allows the best ANFIS configuration to escape stagnation, which allows for refined MPPT tracking. The following birds either: 1) move toward the territory bird and found good solutions worth exploiting, or 2) fly away from the weaker neighbors to maintain diversity. These behaviours allow for both exploration (relative search for alternative parameter sets) and exploitation (fine-tuning of ANFIS rules) to maintained.

(c) Boundary management

In order to improve adaptability, HOA incorporates a role-swapping strategy like: if a following bird is finding a better ANFIS parameter set than the current territory bird, it becomes the new leader ensuring that the optimization process is converge towards the global best solution. Boundary management also prevents a solution from exceeding pre-established limit on parameters:

$$P_{i,d} = ub - rand \cdot (ub - lb), \quad P_{i,d} < lb \text{ or } P_{i,d} > ub \quad (51)$$

Here $P_{i,d}$ is the d^{th} dimension (parameter) of i^{th} hummingbird.

Incorporating ANFIS with HOA that the MPPT controller have access to both adaptive learning and global optimal as shown in Figure 10. ANFIS provides fast nonlinear mapping from PV voltage/current to optimal duty cycle while HOA is continuously optimizing the ANFIS fuzzy membership functions and rule parameters of adjusted representations. The combination of ANFIS and HOA ensures rapid convergence to MPP, improved tracking accuracy, and resilience to variations in solar irradiance and temperature over time.

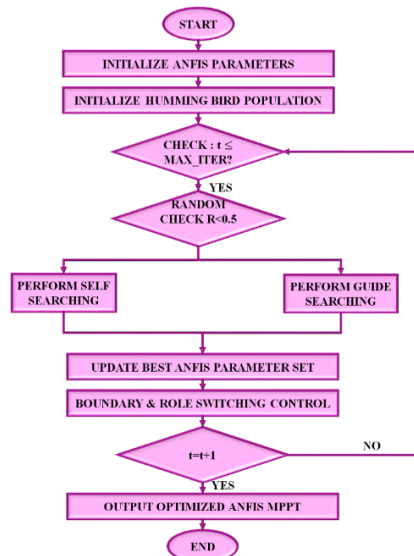


Figure 10 Flowchart of HOA-ANFIS MPPT controller

4. Result and discussion

This work develops a HiClampCasBoost Converter with a PV system with a HOA-ANFIS-based MPPT to stabilize the DC-link voltage, while an RNN-controlled DSTATCOM provides reactive power support and harmonics compensation. Integrated system is established and verified in the MATLAB/Simulink, and simulation results have shown noticeable enhancements in output voltage stability and PQ of distribution system. Specification of Parameters illustrates in Table 1.

Table 1 Parameter Specifications

Parameters	Specifications
PV system	
Open Circuit Voltage	37.25V
Short Circuit Voltage	8.95V
Series Connected PV cell	16
Parallel Connected PV cell	6
Maximum Power Voltage	29.95V
Rated Power	25kW
HiClampCasBoost Converter	
Switching Frequency	10KHz
L_a	4.7 mH
L_k, L_m	45 mH
C_a, C_b, C_c	22μF
C_0	2200μF

Case 1: Constant temperature and intensity condition

Figure 11 indicates the simulation of PV panel characteristics waveforms under constant environmental conditions. The temperature of solar panel is continued at 25 °C and solar irradiance is stable at 800 W/m². Under these simulation conditions, the DC input voltage of HiClampCasBoost converter is continuous at 500 V, with DC input current stably around 45 A after a brief duration of transient response. This simulation result confirms within the stable input range for the converter under the specified temperature and irradiance conditions.

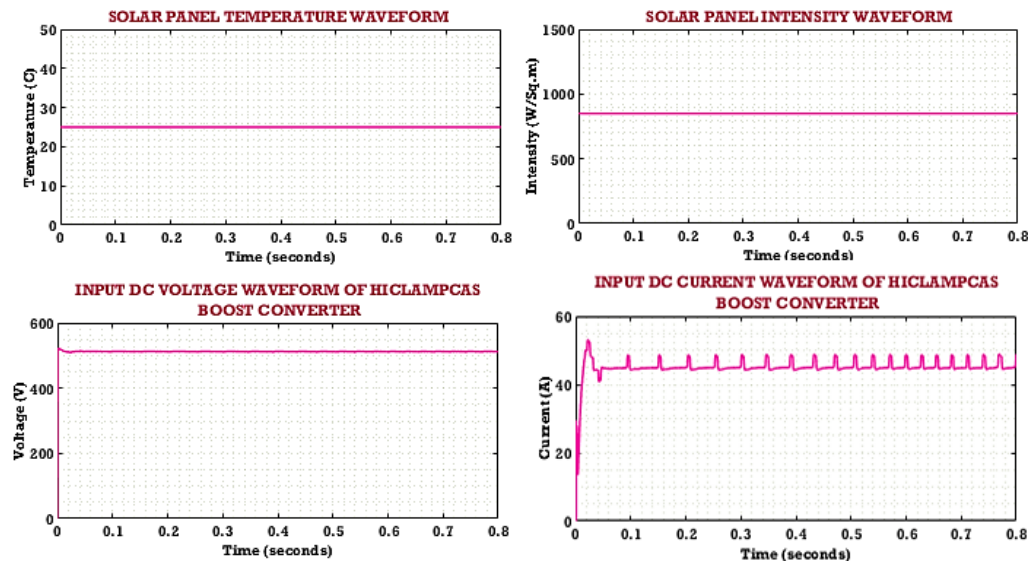


Figure 11 PV panel characteristics waveform under case 1

Figure 12 presents output waveforms of the HiClampCasBoost Converter regulated by the HOA-ANFIS-based MPPT. The output voltage waveform is maintain 800 V after a transient process, remains stable with small ripples. The corresponding output current waveform settles at 27 A confirming that the MPPT operated successfully and the converter is functioning reliably under steady irradiance (800 W/m²) and temperature (25 °C) condition.

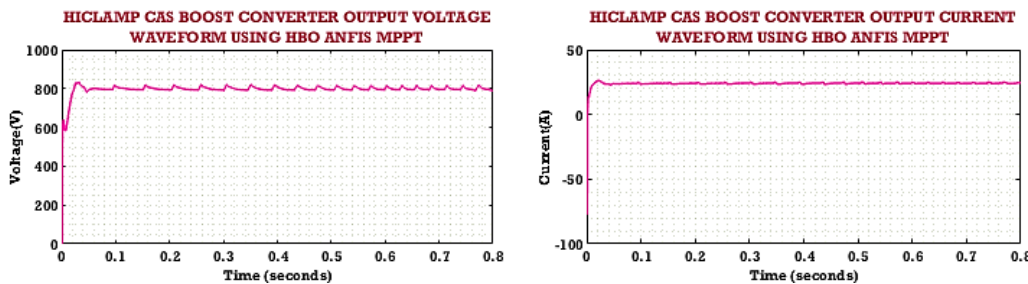


Figure 12 Converter characteristics waveform under case 1

Case 2: Varying temperature and intensity condition

Figure 13 illustrates simulation of PV panel characteristics waveforms under temperature and irradiance levels changed. The solar panel temperature improved from 25°C to 35°C (0.2 s) and the irradiance levels increased from 800 W/m^2 to 1000 W/m^2 (0.5 s). As a result, the input DC voltage of HiClampCasBoost Converter showed a small drop from 550 V to 500 V , and the input current varied dynamically before stabilizing at $45\text{--}50\text{ A}$ with larger ripples. The results showed the PV system exploit the changing circumstances and the converter accepted variations while delivering a continuous supply of power to the PV system.

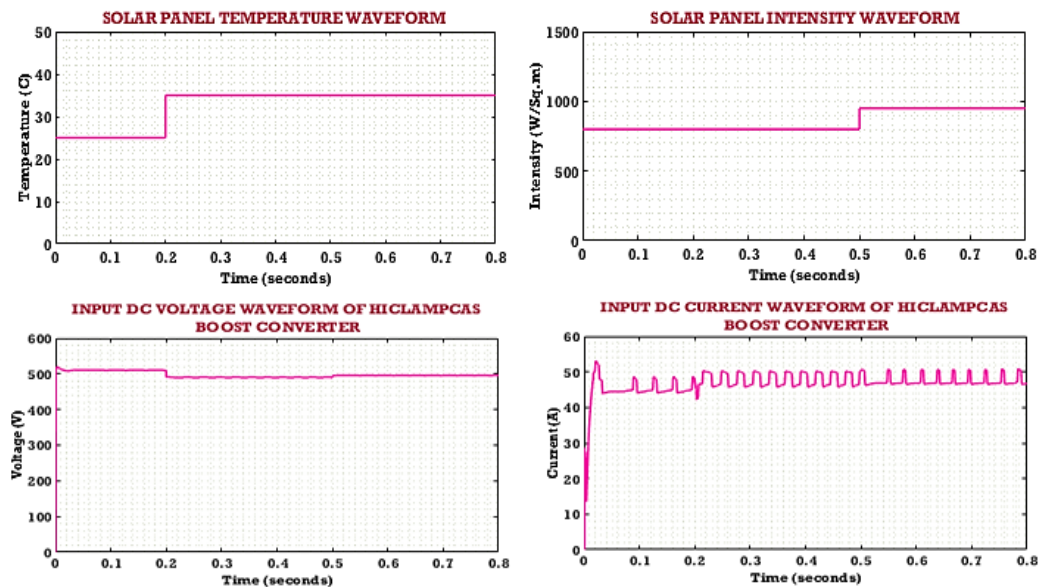


Figure 13 PV panel characteristics waveform under case 2

Figure 14 represents output waveforms of HiClampCasBoost Converter operated with the HOA-ANFIS based MPPT under changing environmental conditions. The output voltage settles in the region of 800 V with small fluctuations while the output current stabilizes after the transient response in the region of 27 A . This shows the MPPT control achieves the conversion with effective power extraction and stable converter performance under environmental variability.

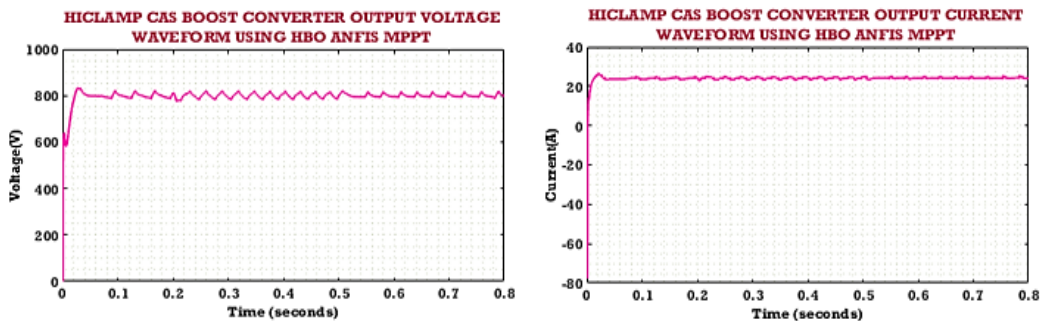


Figure 14 Converter characteristics waveform under case 2

Case 3: Amplitude Sag

Figure 15 represents three-phase load voltage and current waveforms under sag condition. The load voltage waveform displays sag with amplitude where a dip happens before stabilizing to near sinusoidal levels of $\pm 450\text{ V}$. The load current waveform exhibited transient disturbance with reduced amplitude, then equilibrated to a balanced three-phase current of $\pm 40\text{ A}$. These results characterize the way sag affected the system and need compensation method to maintain PQ.

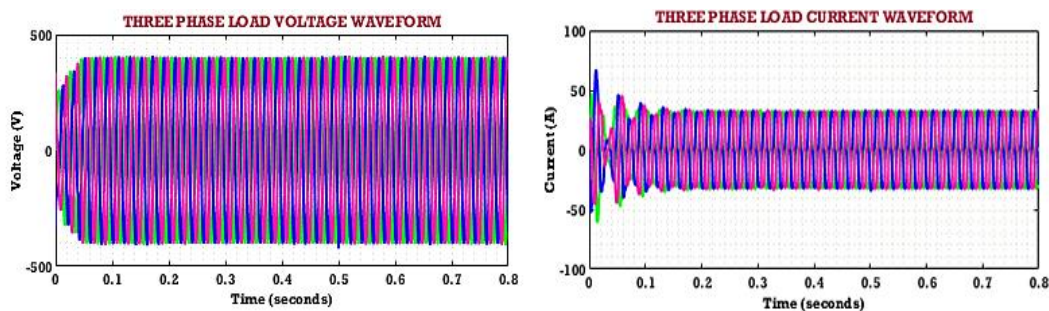


Figure 15 Three phase load change waveforms

Figure 16 represents three-phase AC source voltage and current waveforms. Voltage waveform indicates a sag condition within the time duration of 0.3–0.5 s, while the current waveforms indicate distortion during the same time duration. Post compensation by the DSTATCOM, both waveforms stabilize and return to sinusoidal quality, and the combined AC source voltage and current waveform shows more synchronized behaviour which indicates successful compensation.

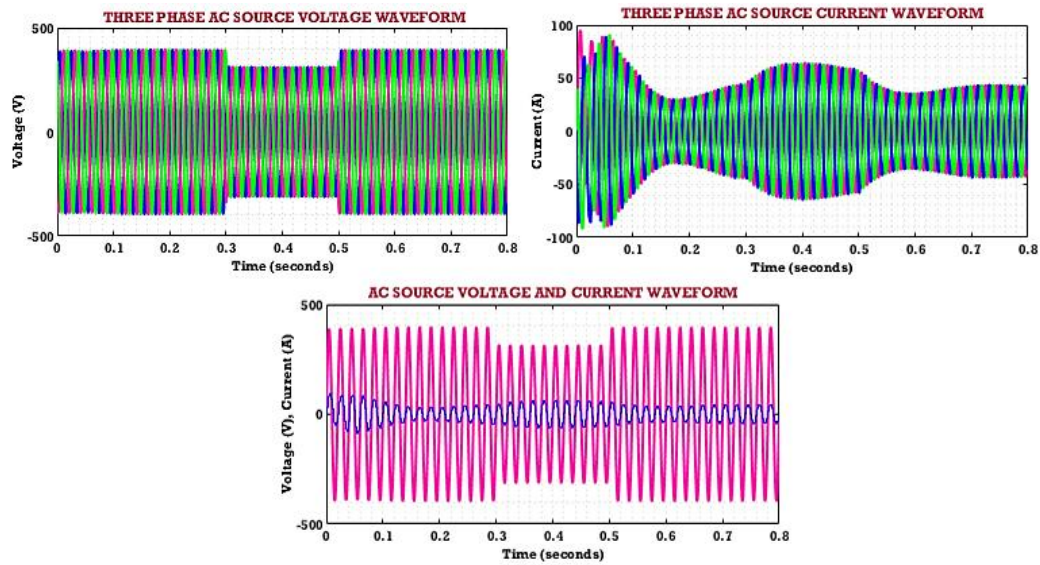


Figure 16 Three phase AC source waveform

Figure 17 indicates PF waveform. PF initially fluctuates due to sag and distortion but then settles to unity (PF=1) quickly after DSTATCOM support, providing indication that the source power is used efficiently.

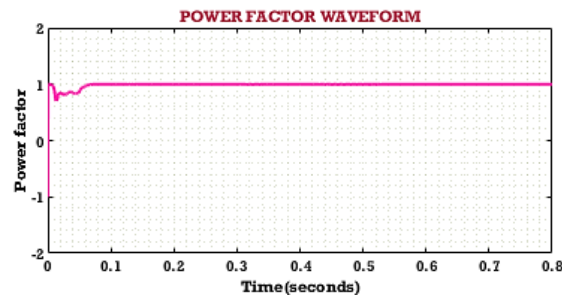


Figure 17 PF waveform

Real and reactive power waveforms as display in Figure 18. After integration of proposed DSTATCOM, the real power profile is maintained steady while the reactive power is reduced. This shows the DSTATCOM's effectiveness in providing PFC by eliminating and supplying reactive power back to the source so that the system performance is stable and effective.

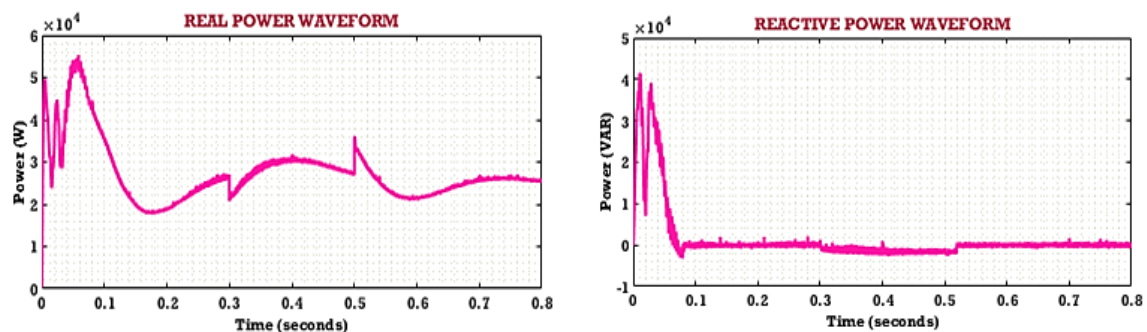


Figure 18 Real and reactive power waveforms

DC-link voltage waveform is shown reference vs. actual in Figure 19. The actual DC-link voltage follows the reference of 850 V exactly, with some minor excursions during transients, which demonstrates that the HiClampCasBoost Converter and HBO-ANFIS MPPT had the capability to keep the DSTATCOM from effective disturbed under stable DC voltage control.

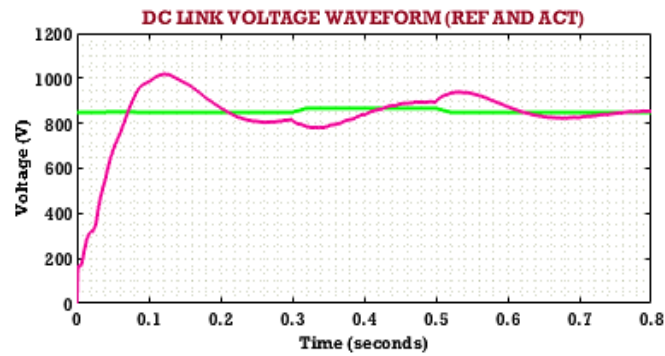


Figure 19 DC link voltage waveform

Figure 20 shows the Reference AC voltage waveform for series converter. The reference control signal delivers for the proper amount of injection to counter the sag and disturbances on the load voltage, hence restoring quality of the load voltage.

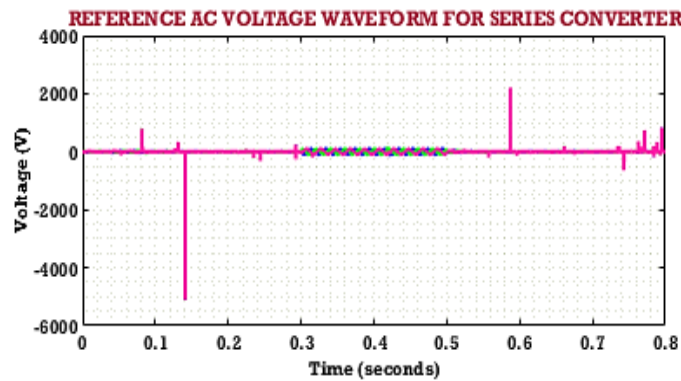


Figure 20 Reference AC voltage waveform for series converter

Case 4: Swell

Figure 21 displays three-phase load voltage and load current waveforms under swell disturbance. Load voltage stays balanced as shown at ± 450 V. The load current goes through distortion and oscillations up to ± 40 A, then eventually stabilizing into a sinusoidal waveform, showing the DSTATCOM is compensate for swell disturbances.

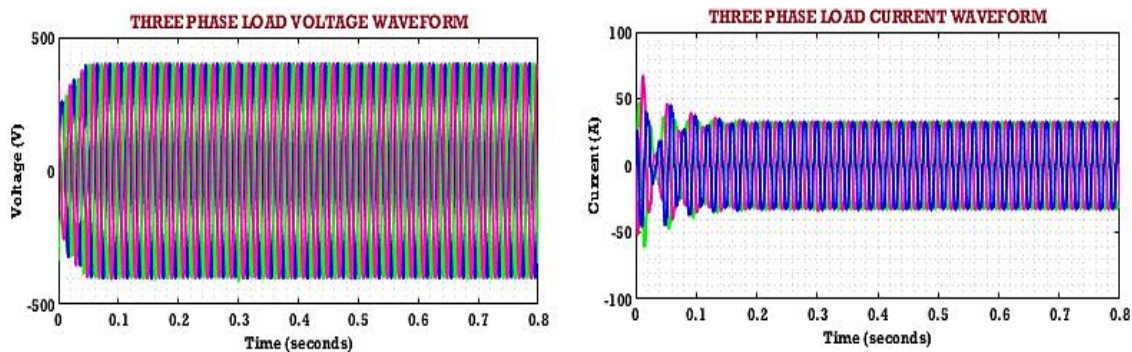


Figure 21 Three-phase load voltage and current waveforms with swell disturbance

Figure 22 displays three-phase AC source voltage swell involving an excursion beyond the nominal supply ± 500 V at 0.3–0.4 s. The source current shows severe distortion at the beginning up to ± 100 A and becomes more uniform after 0.3 s. Together, the combined AC source voltage and current waveform shows synchronization and a corrected PF indicating that the DSTATCOM ensures in fact mitigate swell disturbances.

Figure 23 shows PF starts fluctuating between 0.8 and 1.0 in the first 0.05 s due to the voltage swell, but rapidly settles to unity (PF = 1), which illustrates the reaction of the DSTATCOM–PV-supported system is capable of maintaining an ideal operation.

Figure 24 illustrates real power and reactive power during swell disturbance. Real power has a noticeable overshoot during the swell disturbance; however, that settles to a steady operation level as time progresses. The reactive power has an initial sudden rise and then is quickly suppressed to near zero; these oscillations confirm the effective reactive power compensation and stability restoration the DSTATCOM is able to achieve via the RNN control.

Figure 25 illustrates DC link voltage rises at 1000 V in consequence of the swell disturbance. However, this value converges and settles to the reference value of 800 V after 0.2 s, which shows that the HiClampCasBoost converter with HOA-NFIS-based MPPT is able to deliver a stable DC supply to the DSTATCOM under a dynamic environment.

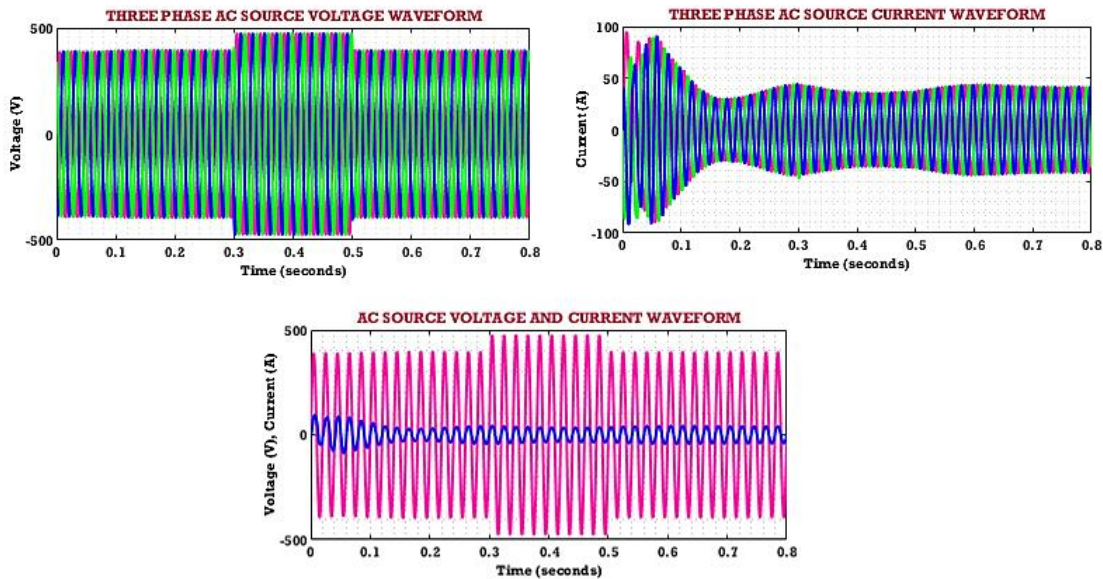


Figure 22 Three-phase AC source voltage and current waveforms with swell disturbance

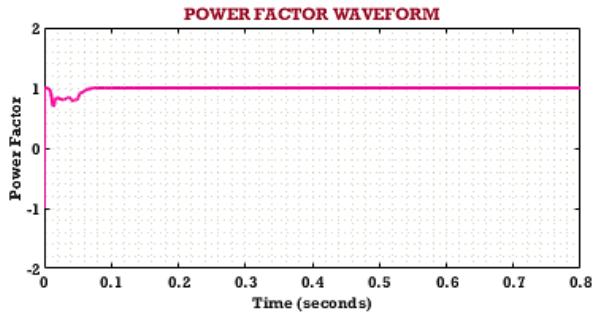


Figure 23 PF waveform during swell disturbance

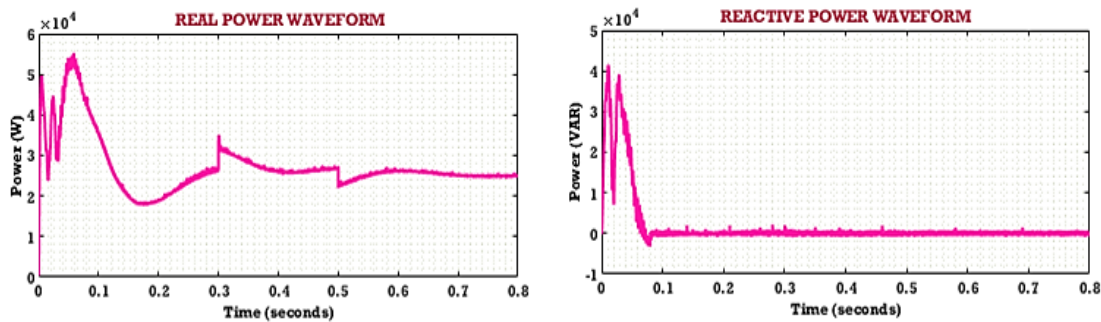


Figure 24 Real and reactive power waveform during swell condition

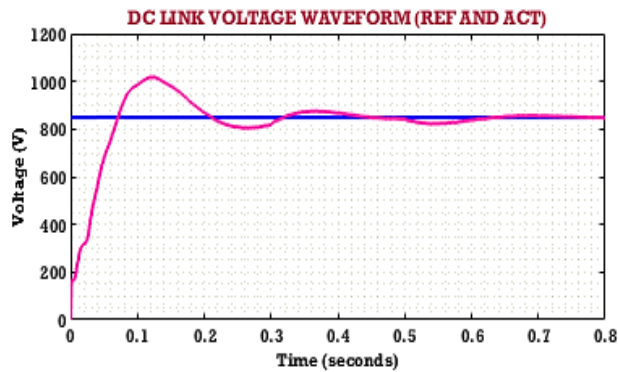


Figure 25 DC link voltage waveform (reference vs. actual) under swell condition

Figure 26 displays reference AC voltage has sharp spikes during the swell disturbance but converges and continues close to zero during the steady-state interval. This evidences effective compensation and harmonic mitigation capacities by the proposed scheme.

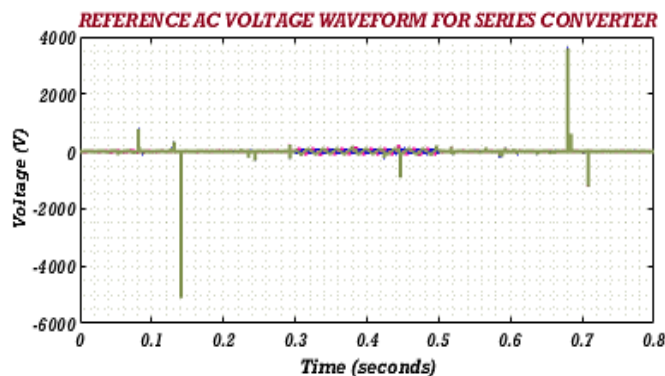


Figure 26 Reference AC voltage waveform for the series converter under swell condition

Figure 27 depicts the harmonic spectra for the three-phase system (R, Y, and B phases) at 50 Hz. The three phase shows a THD value of 1.96%, 1.78%, and 1.63%. The three phases have low THD values, which implies that the three-phase system has better PQ with negligible harmonic distortion.

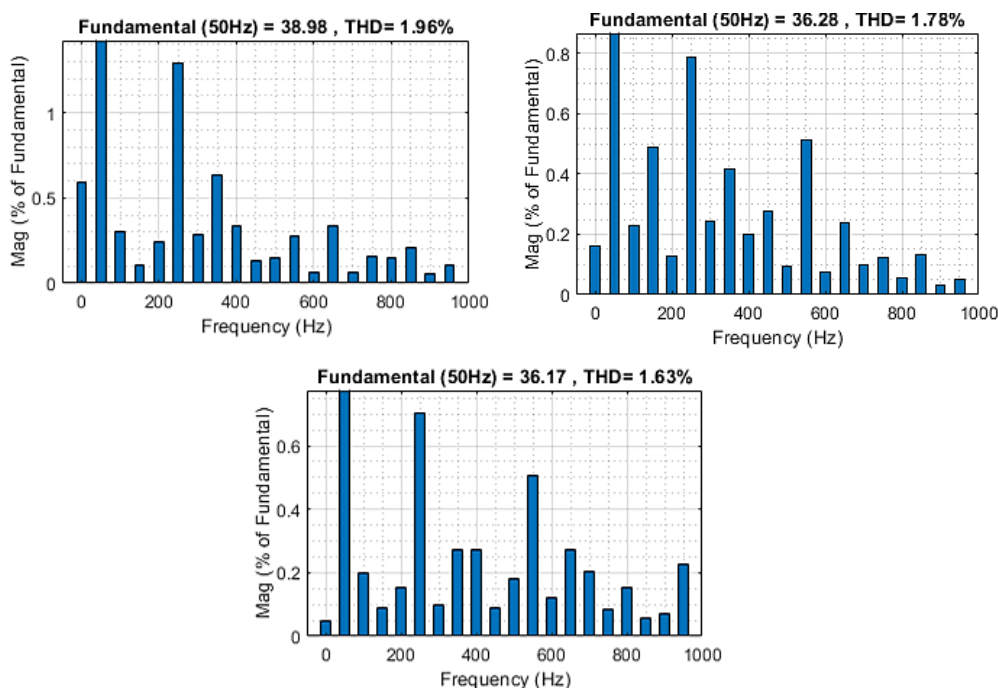


Figure 27 Three phase THD waveforms

Comparison:

Figure 28 depicts efficiency comparisons for the various converter topologies. The efficiency of these converters are: Cascaded Boost-Luo (CBL) 92.6% [28], Modified Cascaded Z-Source (MCZS) 93% [29], High Step-Up Quasi Z-Source (HSQZS) 95% [30]. However, HiClampCasBoost converter has surpassed other converter types at 96%, clearly demonstrating a superior capability to reduce power losses and enhance system performance.

Figure 29 shows the trend of voltage gain with duty cycle for four various converter topologies: CBL [28], MCZS [29], HSQZS [30], and HiClampCasBoost converter. The voltage gain rises non-linearly with an increase in duty cycle for all converters. Among them, the HiClampCasBoost converter always has the highest voltage gain for the whole range of duty cycle, followed by HSQZS, MCZSO, and CBL in sequence. This result specifies HiClampCasBoost converter offers better step-up performance and is more efficient in applications with higher voltage conversion ratios.

Figure 30 depicts the tracking efficiency of various MPPT controllers. The PSO-SMC [20] 96.40% efficiency, while GA-fuzzy [19] slightly increased the efficiency to 96.72%. The performance of the ABC [21] controller has achieved a 98.41% efficiency. However, the proposed MPPT controller achieved the maximum efficiency of 99%, which is the most superior in optimally guaranteeing maximum power extraction under various conditions.

Table 2 depicts THD performance of all the controllers applied in DSTATCOM circuitry. DSTATCOM-ANN controller has THD of 3.9%, the DSTATCOM-PR controller has 2.3% THD and DSTATCOM-Fuzzy controller has 2.1%. The proposed controller, has achieved the lowest THD at 1.63%, thus assure the best possible PQ and lowest distortion while compared to the conventional options.

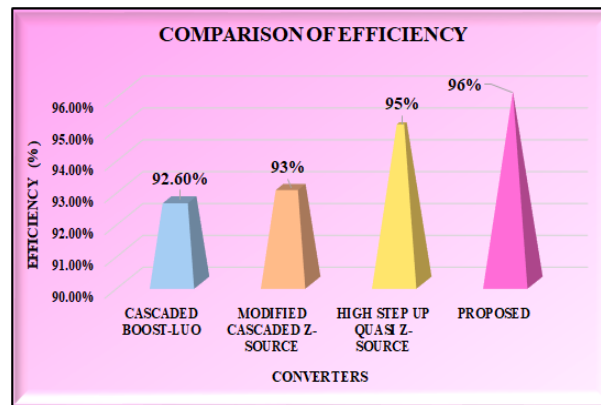


Figure 28 Evaluation of various converter efficiency

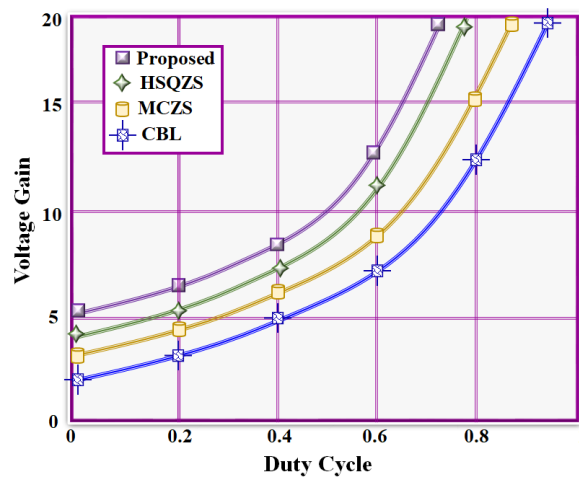


Figure 29 Evaluation of voltage gain

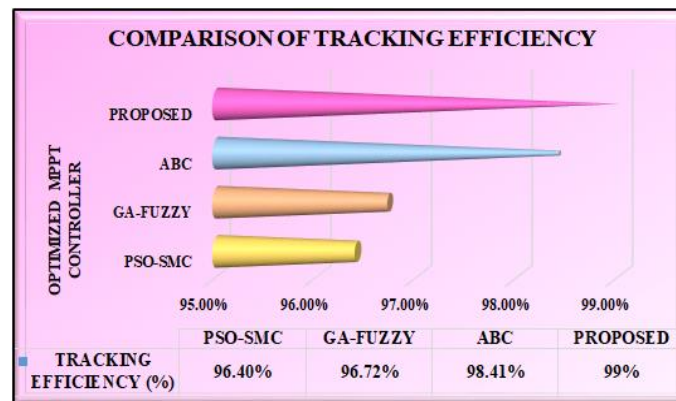


Figure 30 Evaluation of various optimized MPPT controller tracking efficiency

Table 2 Evaluation of THD

Methods	THD (%)
DSTATCOM-ANN [27]	3.9%
DSTATCOM-PR [24]	2.3%
DSTATCOM-FUZZY [23]	2.1%
Proposed	1.63%

The superior ability of proposed controller in terms of optimal tracking accuracy and low THD attributed to combined effect of newest control strategies. The MPPT scheme based on the HOA-ANFIS method offers efficient and precise tracking of MPP by integrating global optimization and adaptive learning algorithms. Moreover, the D-STATCOM controller based on RNN method is identify system parameters' variation with time, hence compensating for reactive power and harmonics accurately in real-time. This makes waveform quality and power losses minimal. Additionally, the HiClampCasBoost inverter guarantees the stability of DC-link voltage and high efficiency, hence offering efficient operation of the D-STATCOM irrespective of varying solar PV parameters. The

interaction between these elements guarantees minimal power losses and dynamic response efficiency as well as accurate compensation for harmonics, thus ensuring low THD and efficient tracking of MPP.

5. Conclusion

This study introduced a hybridized PV–DSTATCOM system to enhance PQ and voltage stability in distribution networks. With the help of DSTATCOM, the system attained voltage sag, swell, reactive power imbalance, and harmonic distortion mitigation, which aided highly stable operation of the grid. By employing the HiClampCasBoost converter, the PV output voltage is boosted and achieved high efficiency of 96% while reduced switching stress. An ANFIS-based MPPT controller effectively support extract the PV system's maximum power under different conditions. With the assistance of the HOA, the MPPT operation is optimized, which enhanced tracking accuracy to 99%, assured rapid convergence, and decreased oscillations. An RNN-based controller, intelligent control of real and reactive power is achieved by the DSTATCOM, enabling highly dynamic response during disturbances. From the MATLAB simulation, with the support of these combined techniques, the system minimized THD to 1.63%, enhanced efficiency, and maintained voltage regulation, demonstrating better performance than traditional methods.

6. References

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