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Voltage Stability Analysis for Grid Connected PV System using Optimized Control on IOT based ANFIS

***Abstract**. The growing prevalence of sensitive power electronic loads and PV system installations in distributed power system have sparked serious concerns about the maintenance of Power Quality (PQ). The non-linear current drawn by these sensitive loads lead to significant amount of voltage instabilities at the Point of Common Coupling (PCC), while intermittency associated with the Photovoltaic (PV) system incites grid instability. Thus, the poor PQ has adverse impact over the lifetime of every components interfaced to the distributed power system, ensuing enormous economic losses. With the aim of enhancing the stability of the distributed power system by curbing the PQ issues, a Static Synchronous Compensator (STATCOM), which is an effective Flexible AC Transmission Systems (FACTS) controller is selected in this work. Moreover, the output from the PV is maximized with the aid of Boost Integrated Landsman Converter (BILC) and Cascaded Adaptive Network-based Fuzzy Inference System (ANFIS) based Maximum Power Point Tracking (MPPT) approach. Moreover, the essential parameters that impact the operation of the proposed topology is tracked and monitored in Internet of Things (IoT) platform. The entire approach is evaluated experimentally and through MATLAB simulation.*

***Streszczenie.** Rosnące rozpowszechnienie wrażliwych obciążeń energoelektronicznych i instalacji systemów fotowoltaicznych w rozproszonym systemie elektroenergetycznym wywołało poważne obawy dotyczące utrzymania jakości energii (PQ). Nieliniowy prąd pobierany przez te wrażliwe obciążenia prowadzi do znacznych niestabilności napięcia w punkcie wspólnego sprzężenia (PCC), podczas gdy przerywanie związane z systemem fotowoltaicznym (PV) powoduje niestabilność sieci. Zatem niska jakość PQ ma niekorzystny wpływ na cały okres eksploatacji wszystkich komponentów podłączonych do rozproszonego systemu elektroenergetycznego, powodując ogromne straty ekonomiczne. W celu zwiększenia stabilności rozproszonego systemu elektroenergetycznego poprzez ograniczenie problemów PQ, w tej pracy wybrano statyczny kompensator synchroniczny (STATCOM), który jest skutecznym sterownikiem elastycznych systemów transmisji prądu przemiennego (FACTS). Co więcej, moc wyjściowa fotowoltaiki jest maksymalizowana za pomocą zintegrowanego konwertera Landsman Boost (BILC) i opartego na kaskadowej sieci adaptacyjnej systemu wnioskowania rozmytego (ANFIS) opartego na śledzeniu maksymalnego punktu mocy (MPPT). Co więcej, istotne parametry mające wpływ na działanie proponowanej topologii są śledzone i monitorowane w platformie Internetu Rzeczy (IoT). Całe podejście jest oceniane eksperymentalnie i poprzez symulację MATLAB-a. (**Analiza stabilności napięcia dla systemu fotowoltaicznego podłączonego do sieci przy użyciu zoptymalizowanego sterowania w oparciu o ANFIS IOT**)*

Keywords: PV system, power quality, FACTS, STATCOM, cascaded ANFIS, Boost integrated Landsman converter, IoT.
Słowa kluczowe System fotowoltaiczny, jakość energii, FACTS, STATCOM, kaskadowy ANFIS, zintegrowany konwerter Landsman Boost, IoT

Introduction

Researchers have recently become more concerned about power quality issues as a result of the massive spike in the use of non-linear loads in distribution systems brought on by advancements in semiconductor technology [1]. To avoid significant financial losses, it is highly essential to alleviate the power quality issues with FACTS device likeSTATCOM. The power system's voltage stability is considered crucial because it enhances the reliability and safety of power system. By installing a STATCOM, a power electronics-based regulating device, effective reactive power compensation, which is needed for voltage stabilization and power quality enhancement is accomplished [2-5]. The generation of electrical power from Renewable sources of energy has augmented significantly in recent decades, primarily as a result of intense global efforts to find an alternative source for the rapidly depleting fossil fuels like coal, natural gas, etc., to mitigate the harmful environmental effects of burning fossil fuels and to meet the rising electricity demand. Solar energy has become the most preferred RES for power generation as it is abundant and able to provide a pollution free energy [6-8].

Both the ambient temperature and solar irradiance have a significant effect over the PV generated power. In an effort to boost power conversion efficiency and lower the cost per kilowatt-hour produced, the most popular and successful energy harvesting technique like MPPT control is introduced. To operate PV modules at their MPP, various MPPT techniques are employed, namely conventional MPPT approaches such as Perturb & Observe (P&O), Hill Climbing (HC), Incremental Conductance (InC), etc. and intelligent MPPT techniques like Artificial Neural Network (ANN),Fuzzy Logic Controller (FLC),etc. Despite the fact that conventional MPPT techniques are simple to implement due to their use of less complicated algorithms, these algorithms tend to fluctuate rapidly around the MPP, resulting in power loss. Moreover, the conventional MPPT control approaches are unable to locate the real MPP as they fail to consider the effects of partial shading conditions. Intelligent MPPT control approaches, with their high tracking accuracy and speed in varying weather conditions, overcome the shortcomings of conventional MPPT techniques. Design and implementation of FLC MPPT is simple as system knowledge is not necessary here. But, deriving fuzzy rules takes a long time and is difficult. Furthermore, the fuzzy rules have a significant impact on system performance. An ANN is a multi-layered network that accurately maps the system's input-output in order to address more challenging issues. A significant amount of training data is necessary for ANN in order to increase tracking accuracy. Therefore, hybrid MPPT technique like ANFIS is developed to address the difficulties encountered with the application of FLC and ANN [9-13]. In [14], to find out the optimum operating voltage, ANFIS MPPT is used.However, for the designers, the updating and training of ANFIS specifications is a difficult task.

A DC-DC converter, whose power conversion efficiency is improved with the proper adjustment of duty cycle by adopting MPPT technique, is absolutely necessary as the PV generates low DC voltage [15]. The DC-DC converters that are implemented successfully to enhance the PV system output, which is generally lowered due to the influence of operating conditions are boost converter [16], buck-boost converter [17], Cuk converter [18], SEPIC converter [19], Zeta converter [20] and Landsman converter [21].In order to achieve high voltage gain, it is imperative to operate the boost and buck-boost converters at high duty cycles, which in turn results in extremely high voltage stress across the switch.Moreover, the presence of high input current ripples influences the performance of both the Cuk and SEPIC converters[22-24].

In [25-27], the Internet of Things (IoT) technology supports multiple network functions and system automation by monitoring, safeguarding and controlling the power system parameters through the use of actuators, metering equipment and sensors.

This work focusses on the operation of STATCOM in effective minimization of PQ-related issues and the enhancement of voltage stability in a distributed power system. A novel boost integrated Landsman converter in addition to cascaded ANFIS MPPT help to boost up the power generation efficiency of the PV system, which is highly intermittent in nature.

Proposed System Description

Owing to the intermittent nature of PV-based power generation system and the use of nonlinear power electronics-based load in a power system fed by three-phase AC source, power quality problems occur.These power quality issues, if not mitigated, affect the voltage stability and results in power losses, equipment failure and power factor reduction.A STATCOM performs the task of improving power quality in this research work as it has the ability to control the voltage at thePCCwith the injectionof harmonic compensation current.

The 3 φ AC source and the PV system both supply power to the load as illustrated in Figure 1.The Boost Integrated Landsman converter, a high voltage gain hybrid DC-DC converter with lower component count, elevates the lower DC voltage V_{PV} obtained from the PV, as it is inadequate for the operation of the load. The three phase VSI, which is coupled to the converter's output side, converts the DC voltage V_{DC} to AC voltage. The cascaded ANFIS MPPT approach is adopted to improvise the PV system's power extraction efficiency of the PV system. For the purpose of lowering the source current harmonics, the reference current I_{ref} is estimated by using CNN based reference current generation method.With the source voltage V_{sabc} and the source current I_{sabc} as inputs, the CNN based reference current generation approach detects the I_{ref} using the DQ theory.The Hysteresis Current Controller (HCC) receives the error as input after comparing the currentsI_{ref} andI_{act}.The HCC output serves as a control signal that the PWM generator (FPGA controller) uses to produce PWM pulses, which are crucial for managing the switching behaviour of the 3φ inverter.The inverter current is fed into the PCC through an LC filter with a specific phase angle and magnitude in order to bring the source current and source voltage into phase with one another. IoT module (node MCU) is used to monitor the parameters likeV_{sabc},I_{sabc},V_{DC}, V_{PV}, I_{PV} and temperature in order to regulate the system operation.

PV-Fed Boost Integrated Landsman Converter

A solar PV system is made up of large number of PV cells, which involve in the conversion of sun light into electrical energy. As shown in Figure 2 (a), each PV cell is designed by using a single diode equivalent circuit entails a current source I_{ph}, a parallel resistance R_P, a forward diode D and a series resistance R_{se}.PV cell output current is determined by Kirchhoff's current law as follows:

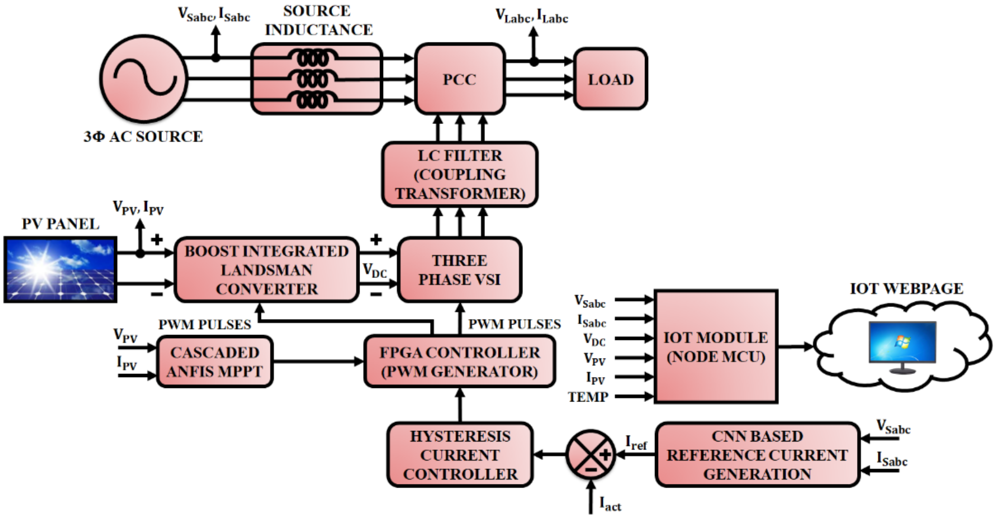


Fig.1. Proposed methodology

(1)

$$I_{PV} = I_{ph} - I_o\left[exp\left(\frac{V_{PV} + R_{se}I_{PV}}{\alpha V_t N_s}\right) - 1\right] - \frac{V_{PV} + R_{se}I_{PV}}{R_P}$$

Here, the termsN_s, α, I_o, V_t and V_{PV} represent the no. of series coupled solar cells,ideality factor, diode saturation current, diode thermal voltage and PV cell's output voltage, respectively. The PV cell's P-V and I-V characteristics is illustrated in the Figure 2 (b).

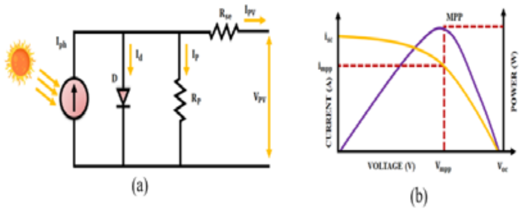


Fig 2:Solar PV cell (a) equivalent circuit and (b) I-V and P-V characteristics

This work introduces a new high gain Boost integrated Landsman converter that boosts the PV system's output voltage, which is typically low and affected by operating conditions like solar irradiation and temperature.This converter is a hybrid converter, which is designed by integrating both boost and Landsman converter as shown in Figure 3. By periodically opening and closing the power switch S, this buck-boost type converter is operated in two modes as illustrated in Figure 4.With the adjustment of the duty ratio D value, the converter is made to perform either buck or boost operation. In the boost integrated Landsman converter circuit, two capacitors(C_1, C_2), two inductors (L_1, L_2), a power switch S and a diode D are present.

Mode 1:

During this mode, the diode D is turned OFF, while the switch S in ON state. The voltage across the capacitor C_1 is responsible for the reverse biased condition of the diode. The inductor L_1 stores energy as the source current I_{PV} flows through it, while the capacitor C_1 discharges and supplies to the load.

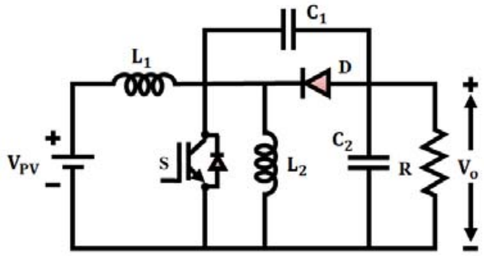
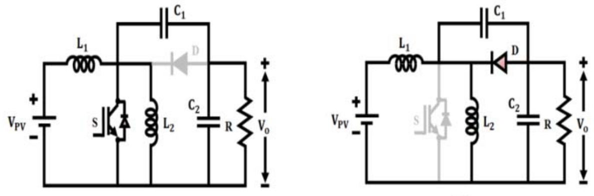


Fig. 3:Boost integrated Landsman converter



(a) (b)

Fig. 4:BILC: (a) mode 1 and (b) mode 2

Mode 2:

When the switch S is in OFF state, the inductor L_1 discharges energy through the diode D, which is forward biased and starts to conduct. The capacitor C_1 stores energy as the inductor current $i_{L_1}$and input current I_{PV} flows through the diode D.

The inductors L_1 and L_2 values are computed as follows:

(2) $$L_1 = \frac{V_{PV}D}{\Delta i_{L_1} f}$$

(3) $$L_2 = \frac{(1-D)V_O}{\Delta i_{L_2} f}$$

The capacitors C_1 and C_2 values are computed as follows:

(4) $$C_1 = \frac{i_{PV}(1-D)}{\Delta V_{C_1} f}$$

(5) $$C_2 = \frac{i_{PV}(1-D)}{\Delta V_{C_2} f}$$

The output voltage equation of the converter is,

(6) $$V_O = \frac{-D}{(1-D)} V_{PV}$$

The attributes such as minimal component count in addition to the simple design of the proposed hybrid Boost integrated Landsman converter results in lower losses.

Cascaded ANFIS-MPPT Controller

A Cascaded ANFIS technique is adopted in this work for carrying out the MPPT operation.The Cascaded ANFIS technique outshines its conventional counterpart in terms of reduced computational complexity. On the basis of the output voltage, current, power, temperature and solar irradiance of PV system, the accurate value of MPP is determined and subsequently the duty cycle of Boost integrated Landsman converter is adjusted and the transference of maximum possible power is facilitated. In the proposed cascaded technique, the process of fuzzification is similar to the conventional ANFIS algorithm, where the fuzzy members are obtained by transforming the input numerical values with the aid of membership function. The major components of the Cascaded ANFIS technique includes the training method and pair selection method. The process of Sequential Feature Selection (SFS) is employed in pair selection method.

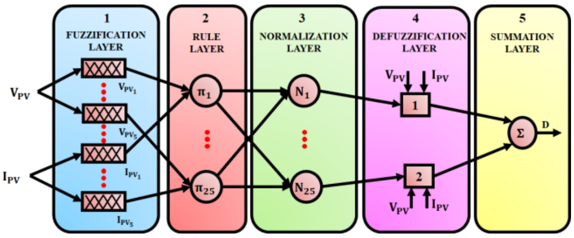


Fig. 5:ANFIS structure

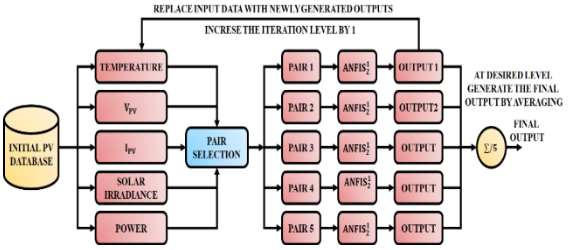


Fig.6: Cascaded ANFIS MPPT model

The 1-output, 2-input ANFIS model as seen in Figure 5 is used in both the pair selection and training method of the Cascaded ANFIS MPPT. It aids with the determination of the perfect match for each input variables in the former method and in case of the latter method, the generation of current output and RMSE is ensured. Moreover, the Root Mean Square Error (RMSE) is compared to a pre-determined goal error for obtaining the resultant output. The structure of the presented Cascaded ANFIS based MPPT technique is given in Figure 6, while Figure 7 illustrates its flowchart.

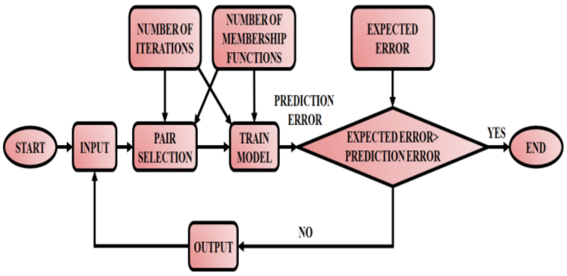


Fig.7:Cascaded ANFIS MPPT flowchart

The values of current, voltage and power attained as output from the PV panel is provided as input to the Cascaded ANFIS MPPT in addition to the external operating conditions such as solar irradiance and temperature. These inputs are then paired into five best pairs and supplied to the second level of the Cascade ANFIS technique, which is the training module. The final change in duty ratio command for the Boost integrated Landsman converter is given as,

$$\Delta D = \frac{\sum_{j=1}^{5} O_{n,j}}{5} \quad (7)$$

In accordance to the variance in PV cell output, the input parameters given to the Cascaded ANFIS also varies, allowing the controller to modify its output appropriately.

IoT based parameter monitoring of PV

The IoT provides valuable and unparalleled contribution towards the enhancement of human life through the intelligent linking of internet with numerous physical devices. Thus, a newest variety of communication is developed between the system, devices and humans, which facilitates the process of data sharing, tracking and managing devices.

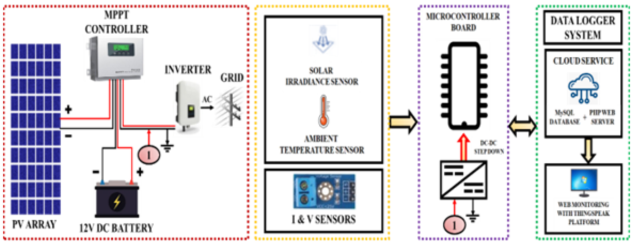


Fig. 8:IoT based PV monitoring system

The vital parameters that influence the output obtained from the PV system is tracked and monitored online by using IoT. These parameters are tracked by the transducer and sensor and are then processed by the microcontroller. The IoT based monitoring greatly aids in enhancing the performance and maintenance of the PV system. The parameters like the PV system output current and voltage are measured in addition to ambient temperature, V_{Sabc} and I_{Sabc}. The tracked parameters are then sent to Node MCU controller and then displayed on the web monitoring platform.

CNN based Reference Current Generation using DQ Theory

The Convolutional Neural Network (CNN) is a biologically inspired feed-forward neural network that typically consist of layers of convolutions that are made up of neurons. CNN consists of fully connected layer, maximum pooling layer and convolutional layer as illustrated in Figure 9.

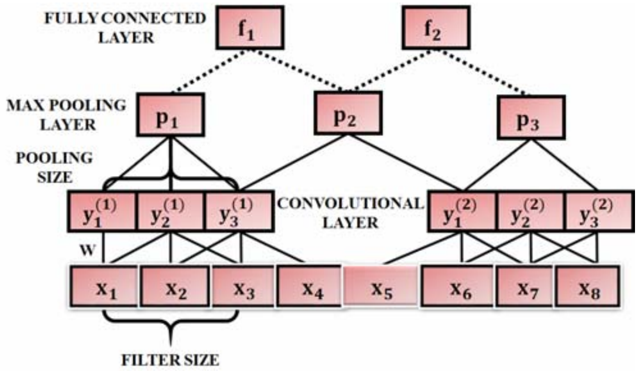


Fig.9:CNN structure

The total harmonic extraction is carried out using CNN in combination with the DQ theory.The reference current for current harmonics compensationis estimated from the source voltage V_{Sabc} and source current I_{Sabc}.As illustrated in Figure 10, the Phase Locked Loop (PLL) is used to calculate the values of $\sin\theta$ and $\cos\theta$ and to transform input currents to the d-q-0 axis reference frame.

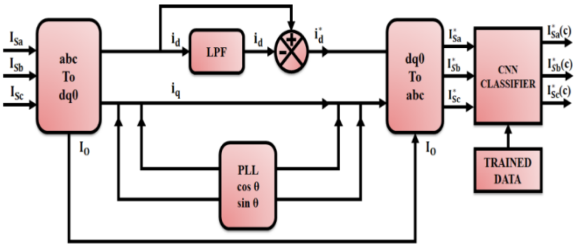


Fig.10:Block diagram of DQ theory

$$i_d = \frac{2}{3}\left[I_{Sa}\sin\omega t + I_{Sb}\sin\left(\omega t - \frac{2\pi}{3}\right) + I_{Sc}\sin\left(\omega t + \frac{2\pi}{3}\right)\right] \quad (8)$$

$$i_q = \frac{2}{3}\left[I_{Sa}\cos\omega t + I_{Sb}\cos\left(\omega t - \frac{2\pi}{3}\right) + I_{Sc}\cos\left(\omega t + \frac{2\pi}{3}\right)\right] \quad (9)$$

As the aforementioned currents $i_d$and i_q, pass through the Low Pass Filter (LPF), it filters the harmonics and gives out the fundamental components. The d-q rotating frame components are modified to the a-b-c stationary frame as follows:

$$(10)\quad i_{Sa}^{*} = i_d \sin\omega t + i_q \cos\omega t$$

$$(11)\quad i_{Sb}^{*} = i_d \sin\left(\omega t - \frac{2\pi}{3}\right) + i_q \cos\left(\omega t - \frac{2\pi}{3}\right)$$

$$(12)\quad i_{Sc}^{*} = i_d \sin\left(\omega t + \frac{2\pi}{3}\right) + i_q \cos\left(\omega t + \frac{2\pi}{3}\right)$$

In order to execute further harmonic extraction, the obtained reference current signals$(i_{Sa}^{*}, i_{Sb}^{*}, i_{Sc}^{*})$ are fed to the CNN. The reference current is analogised with the actual current within the hysteresis band in a HCC so as to produce control signal, which is necessary to generate gating pulses needed for governing the switches of the three phase VSI.

Results and Discussions

This paper discusses the use of STATCOM to improve power quality in a PV-based power generation system that includes a novel Boost integrated Landsman converter and cascaded ANFIS MPPT. MATLAB simulation is adopted for evaluating the effectualness of the presented power quality enhancement scheme. Table 1 lists theoverall parameter specifications required for the implementation of PV panel, hybrid Boost integrated Landsman converter and LC filter.

At 0.2s, the ambient temperature is varied from 20℃ to 35℃ and the solar irradiance is constantly maintained at $1000\, W/m^2$. The PV panel's output voltage and current vary as a result of change in temperature at 0.2 s, which is clearly depicted in Figure 11.

As shown in Figure 12, with the application of cascaded ANFIS MPPT technique, the voltage, current and power generated from the converter become stable at a quick settling time of $0.08\ s$ after experiencing a sudden change owing to influence ofhighly intermittent PV system and the non-linear load.

Table 1: Parameter specifications

PV SYSTEM	
Parameters	Ratings
Short circuit voltage V_{SC}	$12\ V$
No. of PV panels	$500\ W, 20\ panels$
Peak power	$10\ kW$
Short circuit current I_{SC}	$41.66\ A$
No. of series connected solar cells	36
Open circuit voltage V_{OC}	$22.6\ V$
Boost integrated Landsman converter	
Switching frequency	$10\ kHz$
L_1, L_2	$5.2\ mH$
C_1	$44\ mF$
C_2	$2200\ \mu F$
LC Filter	
L_f	$10\ mH$
C_f	$1000\ \mu F$

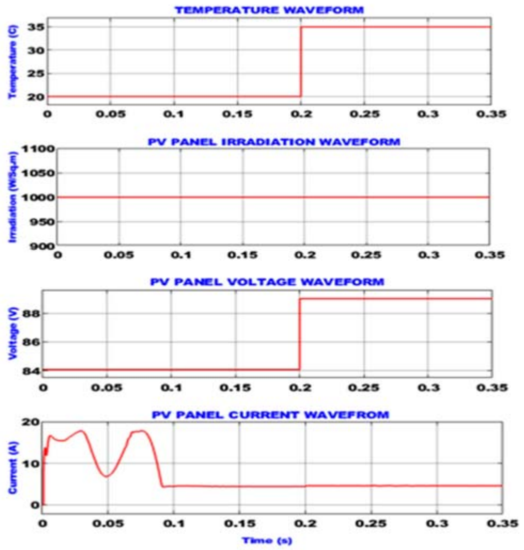


Fig. 11: Waveforms of temperature, solar irradiation, PV voltage and PV current

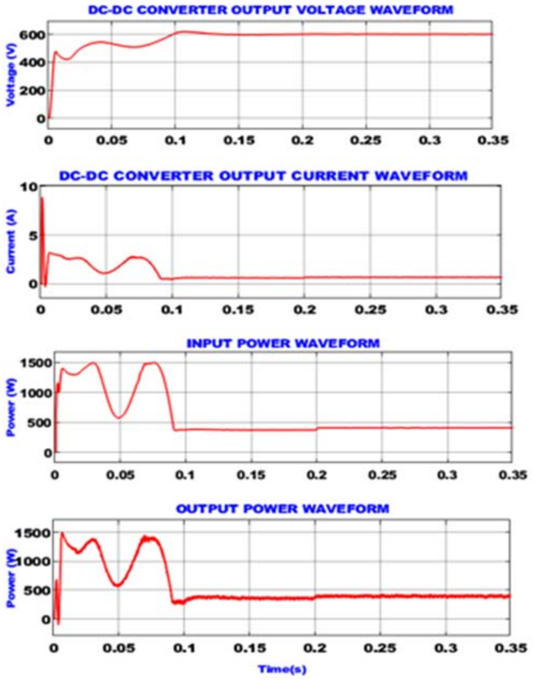


Fig. 12: Waveforms of DC output voltage, DC output current, input power and output power of Boost integrated Landsman converter.

A stable grid voltage and grid current of magnitude 470 V and 15 A, respectively are maintained using STATCOM. Likewise, a real power of 9475 W and reactive power of -220 VAR are obtained without any distortions using the implementation of STATCOM. The proposed power quality enhancement technique effectively lowers the THD value to $0.83\ \%$, as illustrated in Figure 14. As illustrated in Figure 15, The Node MCU controller gathers the information like V_{sabc},I_{sabc}, V_{DC}, V_{PV}, I_{PV} and temperature using the appropriate sensors and displays the data in the web page for carrying out control operations

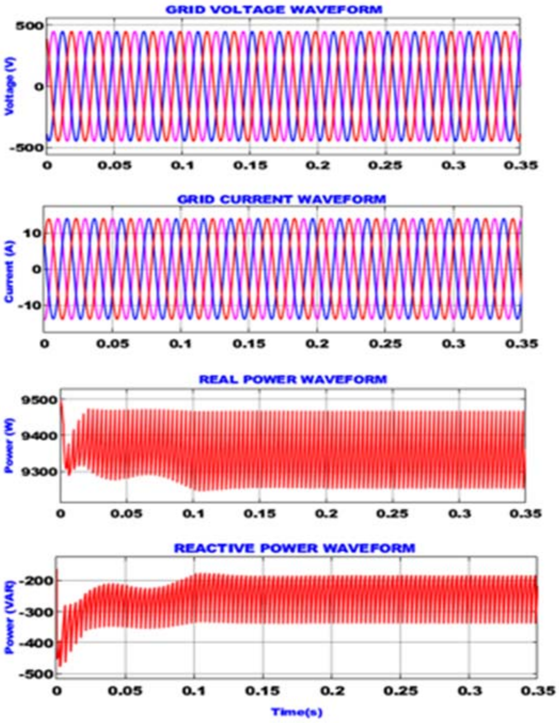


Fig. 13:Waveforms of grid voltage, grid current, real power and reactive power

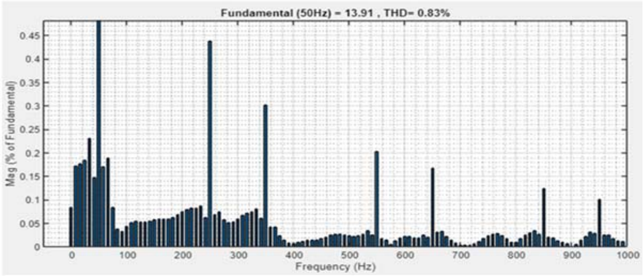
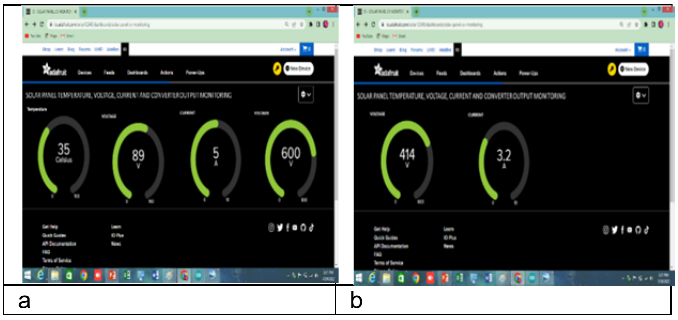


Fig. 14:THD Waveform



a b

Fig. 15:IoT based system parameters monitoring

Hardware analysis

The proposed power quality enhancement technique is implemented in hardware using the Field Programmable Gate Array (FPGA) controller as illustrated in Figure 16 and the effective performance is analysed from the results given in the following section.

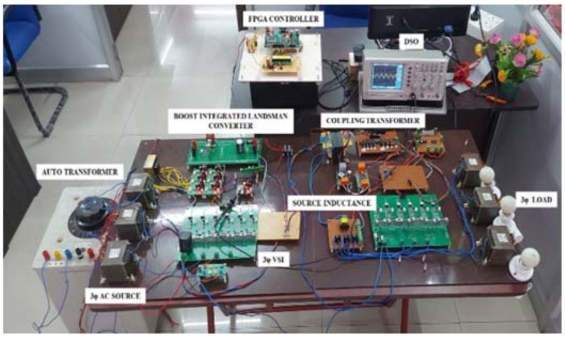
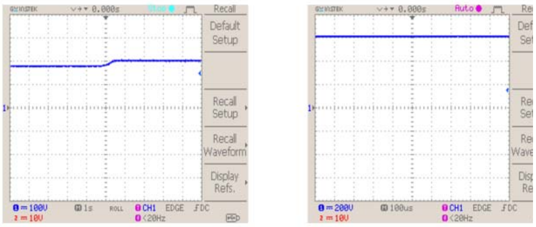
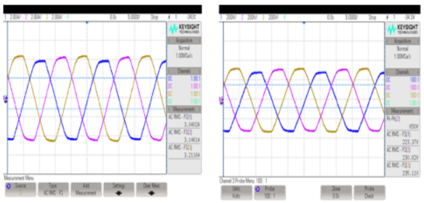


Fig. 16:Hardware setup



(a) (b)

Fig.17:Waveforms of (a) PV output voltage and (b) Converter output voltage



(a) (b)

Fig. 18:Representation of waveforms of (a) grid current and (b) grid voltage

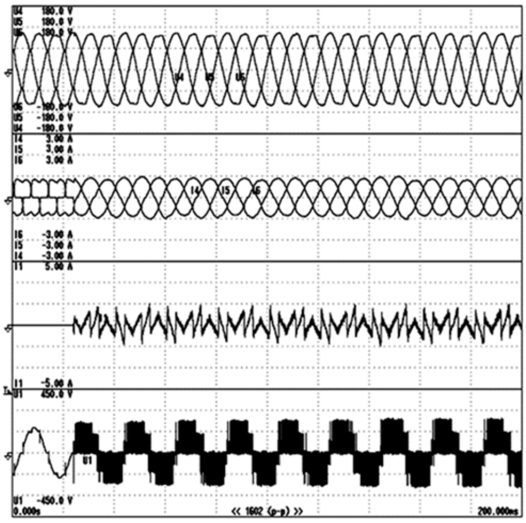


Fig.19:Waveforms ofPCC current, PCC voltage, harmonics compensation current and inverter output

Due to solar energy's intermittent nature, the output voltage of the boost integrated Landsman converter powered by PV system becomes unstable. The use of cascaded ANFIS MPPT results in maximal power extraction from PV. As seen in Figure 17, the voltage output of the BILC stabilises quickly after sudden disturbances due to the implementation of proposed power quality improvement technique.

The Figure 18 shows that after effective harmonic minimization using STATCOM, a stable grid current and grid voltage needed for the operation of non-linear loads are obtained.

Figure 19 clearly illustrates the waveform of harmonics compensation current, which is injected into the PCC to eliminate current harmonics caused by the application of non-linear load and RES in a power system.Additionally, the Figure displays the modifications made to the inverter output, PCC voltage and PCC current following the application of STATCOM.

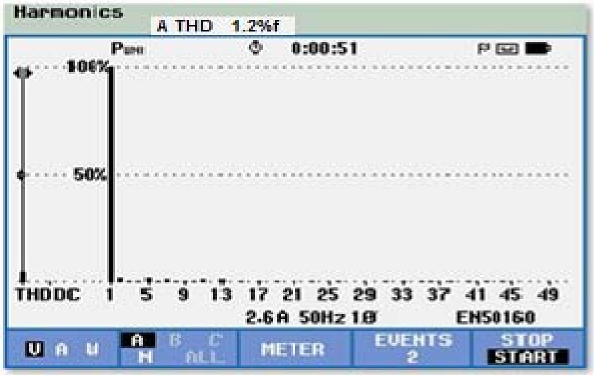
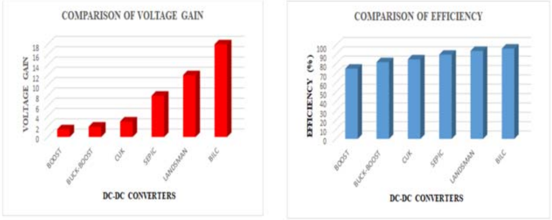


Fig.20:THD Waveform

The proposed power quality enhancement technique effectively lowers the THD value to 1.2 %, as illustrated in Figure 20.



(a) (b)

Figure 21:Comparison of (a) Voltage gain and (b) Efficiency

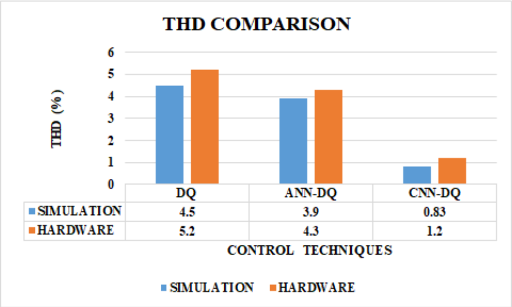


Fig.22:Simulation and hardware THD comparison

The configuration of the novel hybrid Boost integrated Landsman converter is contrasted with other available converters with respect to efficiency, component count and voltage gain in Table 2. The designed topology of Boost integrated Landsman converter outshines every other converters. Moreover, the voltage gain and efficiency of various conventional converters are compared with the

Boost integrated Landsman converter in Figure 21. The Boost integrated Landsman converter's voltage gain is 1:18, whereas its efficiency is 96.8%.
The THD values obtained by using DQ, ANN-DQ and CNN-DQ based harmonic reduction techniques are clearly shown in the Figure 22. According to the graph, the performance of the proposed CNN-DQ based harmonic reduction technique is comparatively better with very low THD value.

Table 2: DC-DC converters comparison

Converter	Components				Voltage Gain	Efficiency
	Capacitors	Diodes	Switch	Total		
M. Kim et al [28]	2	2	1	5	$\frac{N}{1-D}=5$	95.9%
R. Gules et al [29]	3	3	1	7	$\frac{N+1}{1-D}=7.5$	-
E. Babaei et al [30]	4	2	1	7	$\frac{N}{1-D}=5$	94%
S. Mishra et al [31]	3	2	2	7	$\frac{N}{1-D}=5$	95.5%
J. Yao et al [32]	4	3	1	8	$\frac{N+1}{1-D}=7.5$	94.6%
T.-J. Lianget al [33]	3	5	2	10	$\frac{N(2-D)}{1-D}=7$	94.55%
K.-B. Park et al [34]	3	4	1	8	$\frac{1+ND}{1-D}=5.5$	93.8%
C. Rao et al [35]	4	3	1	8	$\frac{2N-1}{(1-D)(N-1)}=7.5$	96.04%
A. Alzahrani et al [36]	5	5	4	14	$\frac{N+1}{1-D}=7.5$	95%
Proposed	2	1	1	4	$\frac{-D}{(1-D)}=18$	96.8%

Conclusion

In this research work, the main emphasis is placed on minimizing PQ-related problems that arise when sensitive loads and RES are introduced in a distributed power system. Harmonic compensation is carried out using the proposed control methodology, which includes STATCOM and CNN-based reference current generation. A novel Boost integrated Landsman converter is designed to improvise the output voltage of the PV system. Moreover, the proposed converter configuration offers excellent voltage gain of ratio 1:18 with reduced component count.
The MPPT controller selected for this work is Cascaded ANFIS MPPT, which is highly effective in tacking the intermittency of the PV and maximizing the power output. The parameters that influence the operation of the entire setup is monitored constantly in IoT. The entire method is tested with MATLAB simulation and the obtained lowest THD value of 0.83% confirms the improved PQ.

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REFERENCES

[1] S. K. Dash and P. K. Ray, "Power quality improvement utilizing PV fed unified power quality conditioner based on UV-PI and PR-R controller," in *CPSS Transactions on Power Electronics and Applications*, vol. 3, no. 3, pp. 243-253, 2018.
[2] S. Hasanzadeh, H. Shojaeian, M. M. Mohsenzadeh, E. Heydarian-Forushani, H. H. Alhelou and P. Siano, "Power Quality Enhancement of the Distribution Network by Multilevel STATCOM-Compensated Based on Improved One-Cycle Controller," in IEEE Access, vol. 10, pp. 50578-50588, 2022.
[3] C. Li, R. Burgos, B. Wen, Y. Tang and D. Boroyevich, "Stability Analysis of Power Systems With Multiple STATCOMs in Close Proximity," in IEEE Transactions on Power Electronics, vol. 35, no. 3, pp. 2268-2283, 2020.
[4] M. Castilla, J. Miret, A. Camacho, J. Matas and L. García de Vicuña, "Voltage Support Control Strategies for Static Synchronous Compensators Under Unbalanced Voltage Sags," in *IEEE Transactions on Industrial Electronics*, vol. 61, no. 2, pp. 808-820, 2014.
[5] R. K. Varma and H. Maleki, "PV Solar System Control as STATCOM (PV-STATCOM) for Power Oscillation Damping," in *IEEE Transactions on Sustainable Energy*, vol. 10, no. 4, pp. 1793-1803, 2019.
[6] L. B. G. Campanhol, S. A. O. da Silva, A. A. de Oliveira and V. D. Bacon, "Single-Stage Three-Phase Grid-Tied PV System With Universal Filtering Capability Applied to DG Systems and AC Microgrids," in IEEE Transactions on Power Electronics, vol. 32, no. 12, pp. 9131-9142, 2017.
[7] Y. Singh, B. Singh and S. Mishra, "An Uninterruptable PV Array-Battery Based System Operating in Different Power Modes With Enhanced Power Quality," in IEEE Transactions on Industrial Electronics, vol. 69, no. 4, pp. 3631-3642, 2022.
[8] L. Farah, A. Hussain, A. Kerrouche, C. Ieracitano, J. Ahmad and M. Mahmud, "A Highly-Efficient Fuzzy-Based Controller With High Reduction Inputs and Membership Functions for a Grid-Connected Photovoltaic System," in *IEEE Access*, vol. 8, pp. 163225-163237, 2020.
[9] H. Rezk, M. Aly, M. Al-Dhaifallah and M. Shoyama, "Design and Hardware Implementation of New Adaptive Fuzzy Logic-Based MPPT Control Method for Photovoltaic Applications," in IEEE Access, vol. 7, pp. 106427-106438, 2019.
[10] K. Y. Yap, C. R. Sarimuthu and J. M. -Y. Lim, "Artificial Intelligence Based MPPT Techniques for Solar Power System: A review," in Journal of Modern Power Systems and Clean Energy, vol. 8, no. 6, pp. 1043-1059, 2020.
[11] J. Ahmed and Z. Salam, "An Enhanced Adaptive P&O MPPT for Fast and Efficient Tracking Under Varying Environmental Conditions," in IEEE Transactions on Sustainable Energy, vol. 9, no. 3, pp. 1487-1496, 2018.
[12] R. B. Bollipo, S. Mikkili and P. K. Bonthagorla, "Hybrid, optimal, intelligent and classical PV MPPT techniques: A review,"

in *CSEE Journal of Power and Energy Systems*, vol. 7, no. 1, pp. 9-33, 2021.

[13] A. Ali *et al.*, "Investigation of MPPT Techniques Under Uniform and Non-Uniform Solar Irradiation Condition–A Retrospection," in *IEEE Access*, vol. 8, pp. 127368-127392, 2020.

[14] S. A. Ibrahim, A. Nasr and M. A. Enany, "Maximum Power Point Tracking Using ANFIS for a Reconfigurable PV-Based Battery Charger Under Non-Uniform Operating Conditions," in *IEEE Access*, vol. 9, pp. 114457-114467, 2021.

[15] T. Sreekanth, N. Lakshminarasamma and M. K. Mishra, "A Single-Stage Grid-Connected High Gain Buck–Boost Inverter With Maximum Power Point Tracking," in *IEEE Transactions on Energy Conversion*, vol. 32, no. 1, pp. 330-339, 2017.

[16] K. Kumar, N. Ramesh Babu and K. R. Prabhu, "Design and Analysis of RBFN-Based Single MPPT Controller for Hybrid Solar and Wind Energy System," in IEEE Access, vol. 5, pp. 15308-15317, 2017.

[17] N. Rana and S. Banerjee, "Development of an Improved Input-Parallel Output-Series Buck-Boost Converter and Its Closed-Loop Control," in IEEE Transactions on Industrial Electronics, vol. 67, no. 8, pp. 6428-6438, 2020.

[18] J. C. d. S. de Morais, J. L. d. S. de Morais and R. Gules, "Photovoltaic AC Module Based on a Cuk Converter With a Switched-Inductor Structure," in IEEE Transactions on Industrial Electronics, vol. 66, no. 5, pp. 3881-3890, 2019.

[19] K. S. Tey, S. Mekhilef, M. Seyedmahmoudian, B. Horan, A. T. Oo and A. Stojcevski, "Improved Differential Evolution-Based MPPT Algorithm Using SEPIC for PV Systems Under Partial Shading Conditions and Load Variation," in IEEE Transactions on Industrial Informatics, vol. 14, no. 10, pp. 4322-4333, 2018.

[20] R. Kumar and B. Singh, "BLDC Motor-Driven Solar PV Array-Fed Water Pumping System Employing Zeta Converter," in IEEE Transactions on Industry Applications, vol. 52, no. 3, pp. 2315-2322, 2016.

[21] A. K. Mishra and B. Singh, "Solar PV powered SRM driven water pumping system using Landsman converter," in *IEEE International Conference on Power Electronics, Drives and Energy Systems (PEDES)*, pp. 1-6, 2016.

[23] Babu V., Ahmed K.S., Shuaib Y.M., Mani M. A novel intrinsic space vector transformation based solar fed dynamic voltage restorer for power quality improvement in distribution system. Journal of Ambient Intelligence and Humanized Computing. 2021 doi: https://doi.org/10.1007/s12652-020-02831-0

[24] Babu V., Basha S.S., Shuaib Y.M., Manikandan M., Enayathali S.S A novel integration of solar fed dynamic voltage restorer for compensating sag and swell voltage in distribution system using enhanced space vector pulse width modulation (ESVPWM). Universal Journal of Electrical and Electronic Engineering, vol. 6, no. 5, pp. 329-350. 2019. doi: https://doi.org/10.13189/ujeee.2019.060504

[25] Manikandan M., Basha A.M. ODFF: Optimized Dual Fuzzy Flow Controller Based Voltage Sag Compensation for SMES-Based DVR in Power Quality Applications. Circuits and Systems, vol. 7, no. 10, pp. 2959-2974. 2016. doi: https://doi.org/10.4236/cs.2016.710254

[26] T. PraveenKumar S. Ganapathy, M. Manikandan, Improvement of voltage stability for grid connected solar photovoltaic systems using static synchronous compensator with recurrent neural network, Electrical Engineering & Electromechanics, Issue, 2 page 69-77. . 2022. doi: https://doi.org/10.20998/2074-272X.2022.2.10

[27] Sathish, Ch. Chidambram, I. A. Manikandan, M. Reactive Power Compensation in a Hybrid Renewable Energy System through Fuzzy Based Boost Converter. Problemele Energeticii Regionale, Issue 1,page 10-26. 2022. Doi: https://doi.org/10.52254/1857-0070.2022.1-53.02

[30] Babu V., Ahmed K.S., Shuaib Y.M., Manikandan M. Power Quality Enhancement Using Dynamic Voltage Restorer (DVR)-Based Predictive Space Vector Transformation (PSVT) With Proportional Resonant (PR)-Controller. IEEE Access, 2021, vol. 9, pp. 155380-155392. 2021 doi: https://doi.org/10.1109/ACCESS.2021.3129096.

[31] Sanepalle Gopal Reddy ; S. Ganapathy ; M. Manikandan Three Phase Four Switch Inverter Based DVR for Power Quality Improvement With Optimized CSA Approach, IEEE Access, vol. 10, pp. 72263-72278. 2022 doi: https://doi.org/10.1109/ACCESS.2022.3188629

[32] SG Reddy, S Ganapathy, M Manikandan, Power quality improvement in distribution system based on dynamic voltage restorer using PI tuned fuzzy logic controller, Electrical Engineering & Electromechanics, Issue, 1 page 44-50.2022. Doi: https://doi.org/10.20998/2074-272X.2022.1.06

[33] Ch Sathish, IA Chidambaram, M Manikandan, Switched Z-Source Boost Converter in Hybrid Renewable Energy System for Grid-Tied Applications, Journal of Electrical Systems, , Issue, 1 , vol 19,page 64-81.2023. Doi:https://www.proquest.com/openview/a8a7bf36a1bbfe9a82c1cd2dbd843e1c/1?pq-origsite=gscholar&cbl=4433095

[34] Ch Sathish, I Chidambaram, M Manikandan, Hybrid Renewable Energy System with High Gain Modified Z-Source Boost Converter for Grid-Tied Applications, Problemele Energeticii Regionale, Issue 1 , vol 57,page 39-54.2023.doi: Doi:: https://doi.org/10.52254/1857-0070.2023.1-57.04

[35] P Balakishan, IA Chidambaram, M Manikandan, An ANN Based MPPT for Power Monitoring in Smart Grid using Interleaved Boost Converter, Tehnički vjesnik, Issue 2 , vol 30,page 381-389.2023, Doi:: https://doi.org/10.17559/TV-20220820194302

[36] Abdul Quawi, Y Mohamed Shuaib, M Manikandan, Power Quality Improvement Using ANN Controller For Hybrid Power Distribution Systems. Intelligent Automation & Soft Computing, Issue 3 , vol 36. Doi: https://doi.org/10.32604/iasc.2023.035001

[37] Ramesh Rudraram, Sasi Chinnathambi and Manikandan Mani, PV Integrated UPQC with Intelligent Control Techniques for Power Quality Enhancement, International Journal of Electrical and Electronics Research (IJEER), Issue 1 , vol 11, page 202-212. 2023 Doi: https://doi.org/10.37391/ijeer.110128

[38] Praveen Kumar Thota, Ganapathy Somaskandan and Manikandan Mani The Voltage stability analysis for grid-connected PV system using optimized control tested by IEEE 14 &30 bus system, International Journal of Experimental Research and Review, , Issue 3 , vol 30. Page 09-118,2023. DOI: https://doi.org/10.52756/ijerr.2023.v30.012