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GRID-CONNECTED PHOTOVOLTAIC SYSTEM WITH ARTIFICIAL NEURAL NETWORK CONTROL USING THREE-PHASE MULTILEVEL INVERTER

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Abstract
This study explores the performance comparison of a grid-tied photovoltaic system utilizing three-phase Multilevel Inverter (MLI) topology Voltage Source Inverter (VSI) governed by an Artificial Neural Network (ANN). Multilevel inverters have undergone significant advancements, offering numerous benefits compared to classical topologies, generating alternating AC output voltage with multiple levels, resulting in reduced Total Harmonic Distortion (THD). The Multilevel Inverter (MLI) configuration utilizes diodes, switches and power sources, which can be modelled to optimize control signals with the presented controller. The grid-tied photovoltaic system efficiency relies heavily on efficient DC–AC conversion to optimize power output from PV generators amidst environmental fluctuations; a novel neural network-based Maximum Power Point Tracking (MPPT) technique has been launched. The fuzzy logic controller-based MPPT generates training datasets for the neural network MPPT. The presented procedure targets improved power quality and network responsiveness under shifting environmental and grid parameters. The presented methodology is realized on MATLAB/Simulink and benchmarked against existing techniques. Performance metrics illustrate improved performance, with reduced switching losses and lower Total Harmonic Distortion (THD).

Keywords: Photovoltaic (PV) system; voltage source inverter; artificial neural network; total harmonic distortion; fuzzy logic controller; MATLAB/Simulink; DC to DC converter; MPPT.

1. Introduction

Recently, the call for cheap, clean, reliable and renewable energy has grown greatly. Of the many renewable energy resources, photovoltaic energy systems have proven to rise as the most promising contender due to their vastness in availability and their pollution-free conversion to electrical energy [1]. The presence of large energy storage systems with exotic costs and the relatively low efficiency of Photovoltaic (PV) panels impede them from standing up against traditional energy resources; to overcome this, optimizing overall PV system performance is essential. One way of doing so is by making the new topology converters observe all the system parameters and behave in a manner to increase the network efficiency up to a noticeable extent [2, 3]. The latest research works on power converter topologies are discussed in the literature to integrate the photovoltaic energy resources from a localized level to the high voltage level in the power network, enabling the efficient conversion and distribution of power with sufficient power quality [4]. Nonetheless, due to growing power requirements in high-power applications, there is a demand for semiconductors with a high-voltage rating [6].

Series-connected Photovoltaic Arrays (PVAs) with conventional bipolar inverters often result in lower than maximum output power for the photovoltaic generation systems [9]. As compared to fully connecting the systems together, connecting the PVA to a Multilevel

Inverter (MLI) can help to alleviate this limitation. Specifically, using a three-level inverter with Pulse-Width Modulation (PWM) regulation technology can provide independent regulation of every PVA's voltage [7]. Relative to conventional bipolar level inverter techniques, the presented strategy should help to maximize output power, reduce semiconductors voltage rating, minimize output voltage distortion and increase system efficiency [5]. The photovoltaic arrays exhibit output characteristic that are highly complex and dependent on sunlight intensity and thermal conditions of the cell [20]. Under the specified sunlight intensity and thermal conditions of the cell, the PVA presents a unique Maximum Power Point (MPP). The presented method uses a DC-DC converter with Maximum Power Point Tracking (MPPT) to effectively track [8, 9, 7]. A fuzzy logic controller is implemented with the aid of determining the most optimal conditions [8, 9].

The accelerated evolution of power electronics or power electronic systems has experienced a progressive growth in the utilization of grid-tied solar systems. Main rectifiers, boost converters and inverters are effectively used for converting power from renewable resources [8]. Meanwhile, those different types of inverters and complex loads generate disturbances on the grid – tied systems. These disturbances also cause the high harmonic currents to result in more heating, more losses, insulation breakdown, etc. In order to overcome harmonics and loss minimization, Multilevel Inverter (MLI) topologies are used. The MLI topologies are more appropriate to most high- and medium-power conversion systems [3, 10]. Thus, the present research work used the MLI topology due to its benefits. The MLI is capable of being friendly to high voltage, producing less noise, having better electromagnetic compatibility and causing less voltage stress over the switches [11].

Different procedures for Maximum Power Point Tracking (MPPT), such differential conductance, observe and perturb are used to optimize energy harvesting [19]. Many procedures or algorithms calculate MPP online and oscillate around MPP on the sudden change of meteorological conditions. To address these disadvantages, a new control approach based on an Artificial Neural Network (ANN) that is trained with fuzzy logic MPPT data has been introduced. The ANN-MPPT controller is capable of finding MPP instantly with a single shot even on sudden changes in meteorological conditions [14]. A consistent and sufficient power supply is very important for the industrial and economic development of any country. Unfortunately, the electrical energy generation capacity of Nigeria is grossly insufficient [1].

Therefore, there is a need for a photovoltaic grid injection network that can provide a reliable and sustainable energy supply [2]. Traditional grid-tied photovoltaic systems face challenges like power quality issues, grid stability concerns, and harmonic distortion. To overcome these challenges, advanced and robust power electronics and control strategies are essential [6, 8].

2. Multilevel Inverter

The multilevel inverter has greater benefits for medium- and high-power systems, as they can synthesize an output higher than the voltage rating of individual switching devices [12]. The steeped output voltage decreases harmonics in the voltage and current waveforms during the switching frequency and the semiconductor voltage levels. Fig. 1 presents the schematic diagram of a Neutral Point Clamped (NPC) three-level inverter [13]. Due to the load current being alternate, four transistors with anti-parallel diodes are necessary. Additional steering diodes clamped one terminal of each transistor to the capacitor midpoint. Controlling the capacitors voltages to equal half of the full DC voltage; each transistor in an off-state bears half of the full DC voltage.

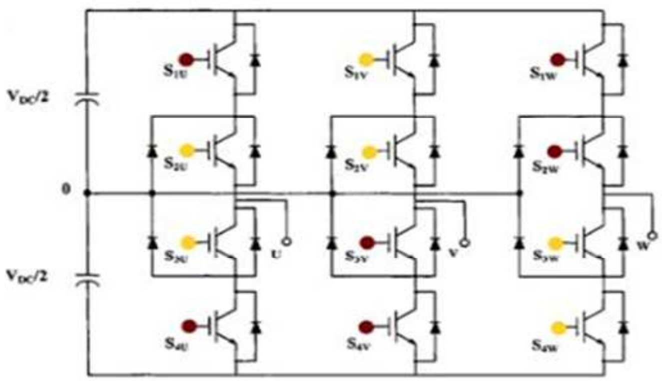


Fig. 1: Neutral Point Clamped (NPC) Three-level Inverter

The Output Voltage Levels are simply

$$\begin{bmatrix} V_{AM} \\ V_{BM} \\ V_{CM} \end{bmatrix} = \begin{bmatrix} F_{11}^{b} \\ F_{21}^{b} \\ F_{31}^{b} \end{bmatrix} U_{C1} - \begin{bmatrix} F_{10}^{b} \\ F_{20}^{b} \\ F_{30}^{b} \end{bmatrix} U_{C2} \tag{1}$$

The simple output voltages are calculated as

$$\begin{bmatrix} V_{A} \\ V_{B} \\ V_{C} \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix} \left\{ \begin{bmatrix} F_{11}^{b} \\ F_{21}^{b} \\ F_{31}^{b} \end{bmatrix} U_{C1} - \begin{bmatrix} F_{10}^{b} \\ F_{20}^{b} \\ F_{30}^{b} \end{bmatrix} U_{C2} \right\} \tag{2}$$

The currents fed into the inverters are

$$\begin{cases} i_{di} = F_{11}^{b} i_1 + F_{21}^{b} i_2 + F_{31}^{b} i_3 \\ i_{d2} = F_{10}^{b} i_1 + F_{20}^{b} i_2 + F_{30}^{b} i_3 \end{cases} \tag{3}$$

While the current i_{d0} governed by the relation

$$i_{d0} = (i_1 + i_2 + i_3) - (i_{d1} + i_{d2}) \tag{4}$$

where F_{i1}^{b} *and* F_{10}^{b} are the half arms connection functions affiliated with the upper and lower half arms correspondingly.

$$\begin{cases} F_{11}^{b} = F_{11}F_{12} \\ F_{10}^{b} = F_{13}F_{14} \end{cases} ; \begin{cases} F_{21}^{b} = F_{21}F_{22} \\ F_{20}^{b} = F_{23}F_{24} \end{cases} ; \begin{cases} F_{31}^{b} = F_{31}F_{32} \\ F_{30}^{b} = F_{33}F_{34} \end{cases} \tag{5}$$

$i_{1,2,3}$: arm number

3. Maximum Power Extraction

3.1 Fuzzy Logic MPP Tracking Controller

The grid-tied photovoltaic system in this presented method is a three-phase system composed of a solar array, a back-boost DC-DC boost converter with a Maximum Power Point Tracker

(MPPT) controller, a DC link, a three-phase inverter, RL filters and a grid. The solar cells are interconnected in a series-parallel connection to achieve the desirable solar voltage and power rating. This three-phase inverter with a filter inductor produces an AC sinusoidal current that aligned with grid voltage phase as it converts the DC input voltage to AC voltage using the corresponding switch signals. Tracking the Maximum Power Point (MPP) from the solar output can be performed by different algorithms which includes differential conductance, perturb, observe and fuzzy logic MPPT [15]. To address the drawbacks of the method brought about by the classical strategies of the MPPT approach, a new controller that depends on a Neural Network (NN) which is trained by the fuzzy logic MPPT as a database has been presented. With this model, the NN-MPPT controlled which can directly determine the Maximum Power Point (MPP) in a single step even with sudden changes in climate [16].

In this presented method, control of the voltage, current and system harmonics reduction is performed where a control signal is generated and fed to the Pulse Width Modulation (PWM) module. PWM pulses are utilized to provide the switching pulses to the Multilevel Inverter (MLI).

3.2 Artificial Neural Network (ANN) – based MPPT

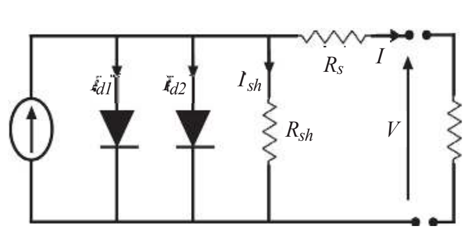
To achieve maximum power output from a PV system, an ANN (Artificial Neural Network)-based MPPT (Maximum Power Point Tracker) method has been applied as a control technique. Switching of inverters is controlled through ANN to maintain the desired quality of power and stability of the grid. For proper implementation of ANN, it uses supervised learning. During supervised learning, previous data and the knowledge specific to the grid have been used. [7]

3.3 Photovoltaic (PV) Model

The equivalent circuit of the solar cell is represented in Fig. 2. The circuit configuration used in this model contains a photovoltaic current (I ph) source, two diodes, and resistors in series and parallel.

The current-voltage characteristic of a solar cell is defined in an equation given by Eq. (6), where the parameters are described as:

$$I = I_{ph} - I_{s1}\left[exp\left(\frac{q(V+R_S I)}{n_1 kT}\right) - 1\right] - I_{s2}\left[exp\left(\frac{q(V+R_S I)}{n_2 kT}\right) - 1\right] \quad (6)$$



$-\frac{V+R_S I}{R_{sh}}$

Iph RLoad

Fig.2: Equivalent Electrical Circuit of a Cell.

The variables used in the equation are as per the below. I: Solar Cell Output-Current (A) V: Solar Cell Output Voltage (V) Iph: Light-generated current (A) Is1 and Is2: Unit less deviation parameters from the first and second diodes K: Boltzmann's Constant (1.3807 x 10^{-23} J/k) T: Thermal conditions of the cell (K) Rs: Internal Resistance (2) Rsh: Parallel resistance (Ω)

3.4 Multilevel Inverter Model

The multiple voltage-stepping process carried out by the Multilevel Inverter (MLI) aids in power conversion. MLI results in an enhanced power quality alongside an improved voltage level [14]. The multilevel bridge topology of MLI is connected in series.

The total number of voltage levels (Ns) achieved by the inverter can be formulated as:

$$v_{o/p} = v_{o/p}^{1} + v_{o/p}^{2} + \ldots v_{o/p}^{n} \quad (7)$$

The number of the voltage level of the inverter is described by

$$N_s = 2n+1 \quad (8)$$

The maximal output voltage of n level inverter is,

$$v_{out}^{max} = n * v_{dc} \quad (9)$$

The quantity of voltage step for n level inverter is provided as,

$$\text{For } j = 1,q2,\ldots n,\ N_s = \begin{Bmatrix} 2^{n+1} - 1 \ if \ v_{j= 2^{j-1}} v_{ac} \\ 3^{n} \ if \ v_j = 3^{j-1} v_{ac} \end{Bmatrix} \quad (10)$$

The maximum output voltages of these n level inverters are written as,

For j = 1,2 …n,

$$v_{out}^{max} = \begin{Bmatrix} (2^n - 1) v_{dc} \\ (\frac{3^n - 1}{2}) v_{dc} \end{Bmatrix} \begin{matrix} \text{if } v_j = 2^{j-1} v_{dc} \\ \text{If } v_j = 3^{j-1} v_{dc} \end{matrix} \quad (11)$$

3.5 Electrical Grid Modelling

The grid phase equivalent electric circuit is shown in Fig. 3. It includes three series variables, a voltage source (Vneti), an inductance (L1net), and a resistor (Rnet) [17]. In park components and grid circuit model, the grid voltage can be written in the q-p domain as [18].

$$\begin{bmatrix} V_{dnet} \\ V_{qnet} \end{bmatrix} = \begin{bmatrix} R_{net} & - L_{net}\omega \\ L_{net}\omega & R_{net} \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \\ + \begin{bmatrix} 0 & L_{net} \\ L_{net} & 0 \end{bmatrix} \frac{d}{dt} \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \begin{bmatrix} V_d \\ V_q \end{bmatrix} \quad (12)$$

where,

The inverter’s output voltage in the d and q axes are denoted as Vd and Vq, correspondingly; the direct and quadrature voltage components of the inverter are denoted as Vd net and Vq net correspondingly; the line current is denoted as -id and iq, splitting into d and q axes correspondingly; the grid inductance and resistance are denoted as Lnet and Rnet correspondingly; and w symbolizes the rate of change of phase angle.

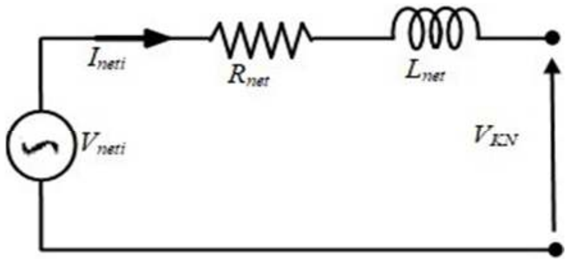


Fig.3: Electric Grid Modelling

4. Grid Integration

The inverter's output AC waveform is synchronized with the grid voltage and frequency to ensure efficient power injection. This synchronization is achieved using Phase-Locked Loops (PLLs), which enable the Multilevel Inverter (MLI) output to be seamlessly integrated with the grid. An LCL filter is also employed to eliminate any residual harmonics from the inverter output, ensuring a high-quality power injection into the utility grid [16].

5. Simulation

The conceptualized system is validated utilizing MATLAB/Simulink and shows the simulation result in Fig. 4. The Total Harmonic Distortion (THD), efficiency, and power factor are some of the variables obtained for performance evaluation of the network in different conditions of environment and grid.

The PV-Boost converter Simulink model also shown in Fig. 5 consists of constituent blocks of the PV array, pulse generator, MPPT and other components of the system. The simulation parameters, such as solar irradiation, temperature, loading conditions, etc., are set in the model to yield the expected simulation results. The performance efficiency and stability of the system can be analyzed based on the model output.

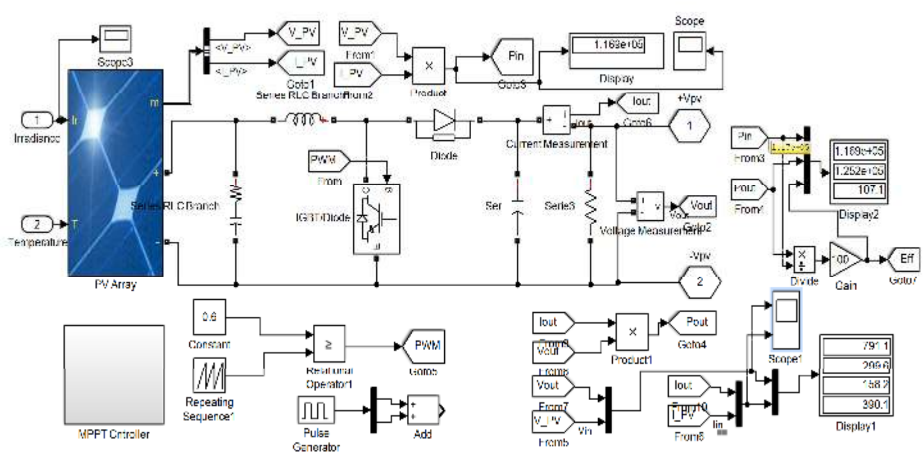


Fig.4: A General Simulink Model for the Proposed System

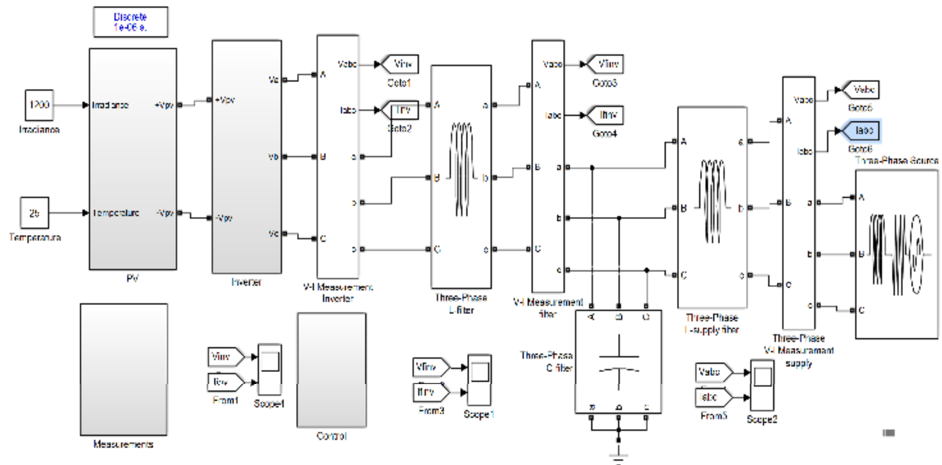


Fig. 5: PV-Boost Converter Simulink Model

6. Simulation Results and Discussion

This paper proposes a fuzzy logic controller (FLC)-based boost converter for maximum power point tracking, and a three-level inverter is used for grid-tied PV system stability. The boost converter is controlled based on a space vector modulation strategy with two bipolar carriers. The PV system is made of two photovoltaic arrays, each with 16 series solar panels, producing a total of 1500 W power. A multilevel inverter (MLI) is used to reduce harmonics of the system and is designed based on the least number of switches, diodes and sources to optimize control signals. The presented method has been implemented in MATLAB/Simulink, and various variables such as voltage, current, irradiation, temperature, active and reactive power are studied to understand the system's performance in detail.

As illustrated in Fig. 6, the results clearly show that solar irradiance is the sole determining factor for total power output from the PV system under varying conditions.

Fig. 7 illustrates the analysis of PV and DC boost converter output voltages. Here, the DC voltage profile shows an initial rise from zero to 350V, a subsequent drop to –175V, and then rebounding to 320V. The voltage varies dynamically between 0 and 0.05 times per second. Finally, it converges to 300V with a slight ripple.

The DC boost converter output voltage follows a pattern of rising to 730V, falling to 650V, rebounding to 800V, and then oscillating between 800V and 700V.

The power inverter output voltages range from -500V to 500V, as depicted in Fig. 8, exhibiting significant distortion due to harmonic content.

Fig. 9 illustrates the filtered inverter output voltage waveforms, fluctuating between -230V and 230V consistently across the entire time frame.

As illustrated in Fig. 10, the PV grid voltage injection peaks from 0 to 230 V within 0 to 0.05 seconds, followed by oscillations between –230 V and 230 V. Also, Fig. 11 clearly demonstrates that the PV input-output power closely matches its reference, indicating excellent.

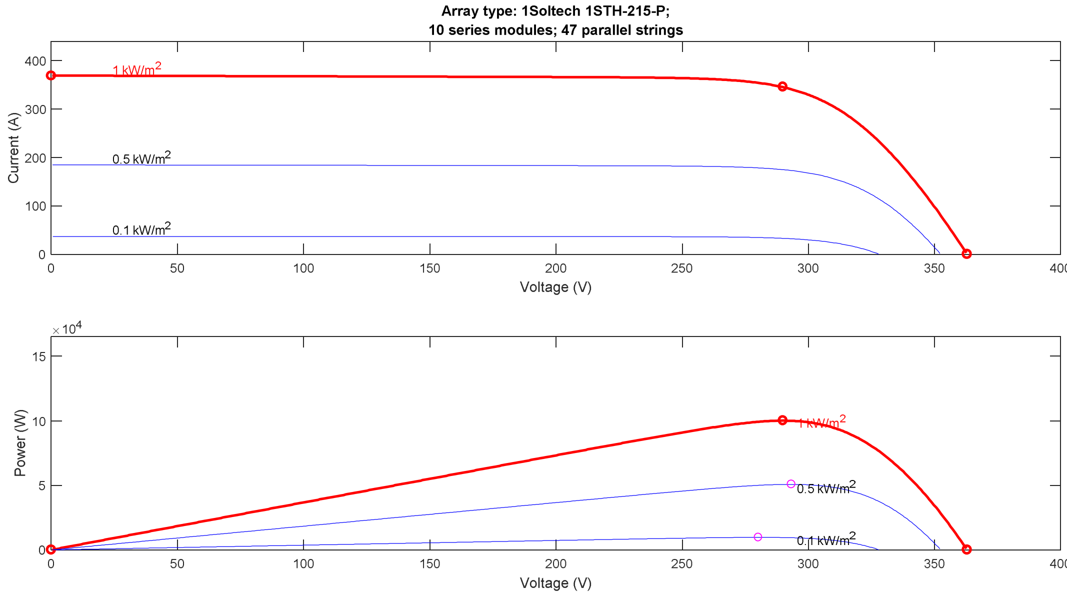


Fig. 6: Power and current waveforms for PV solar system.

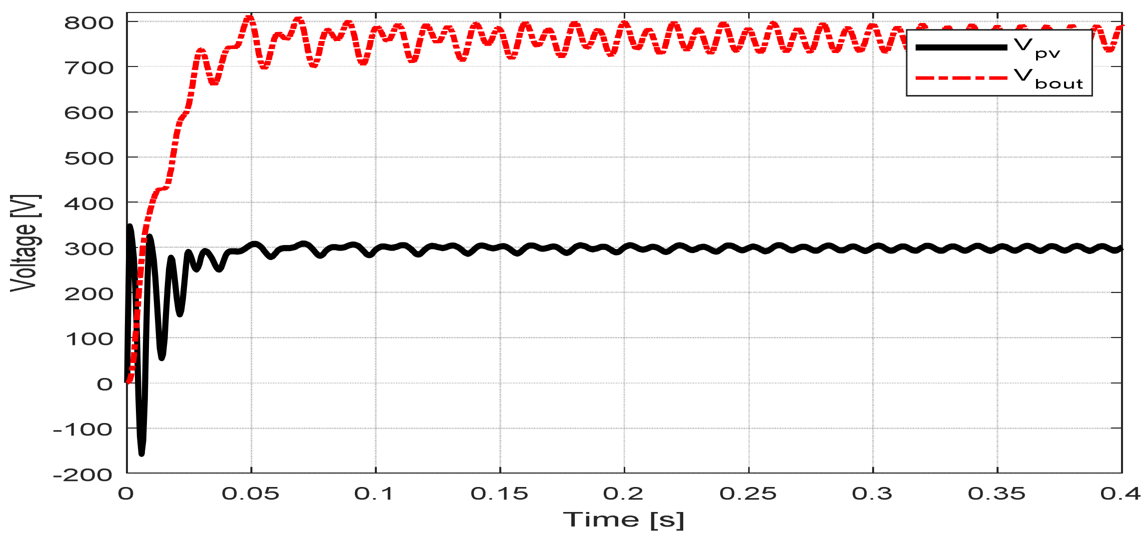


Fig. 7: PV and DC boost converter output voltages.

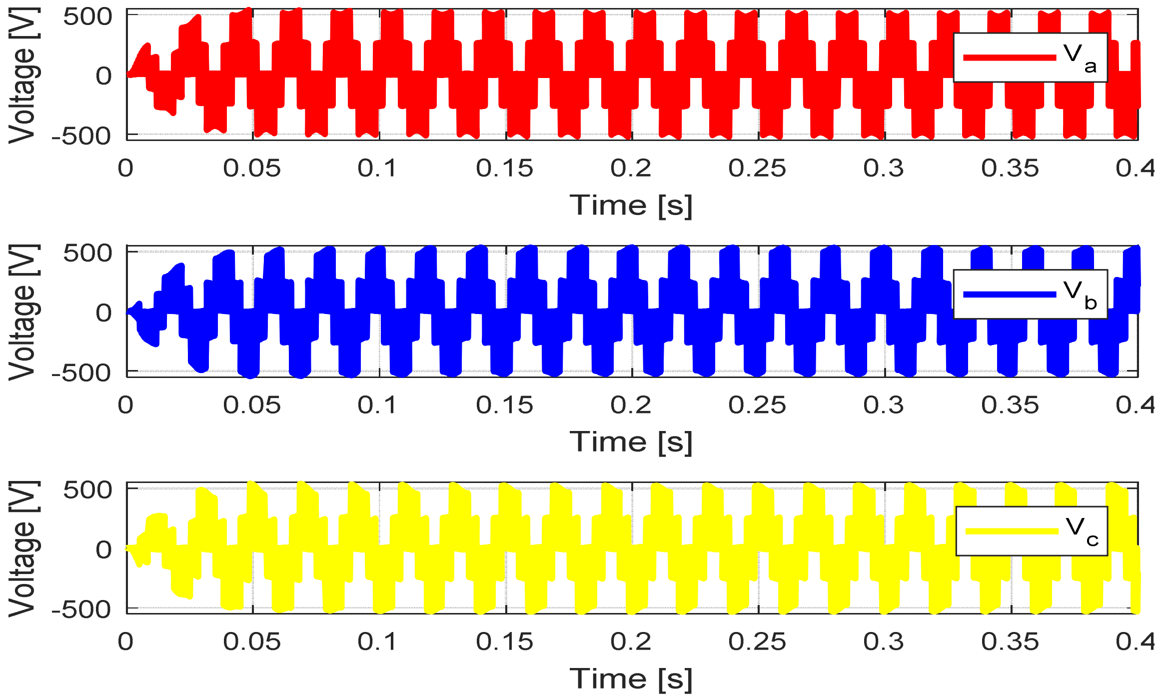


Fig. 8: Power Inverter output voltages.

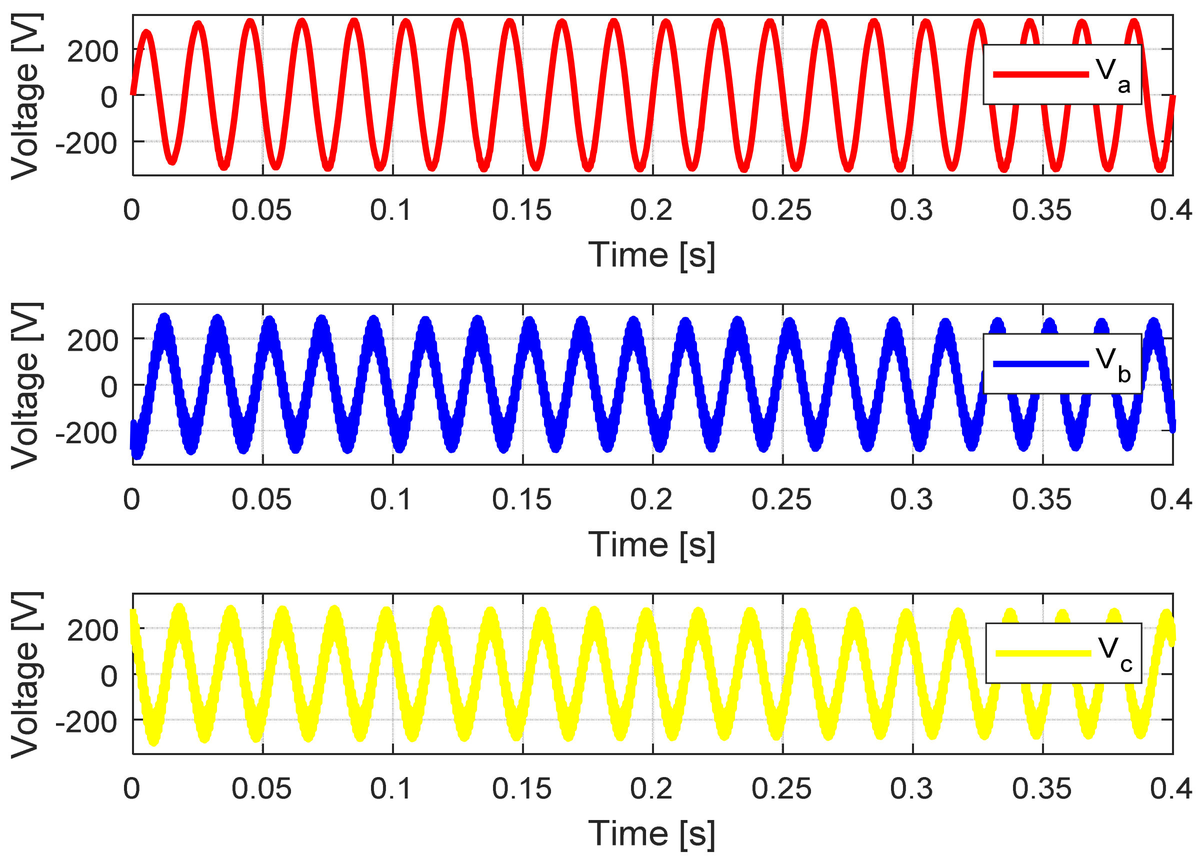


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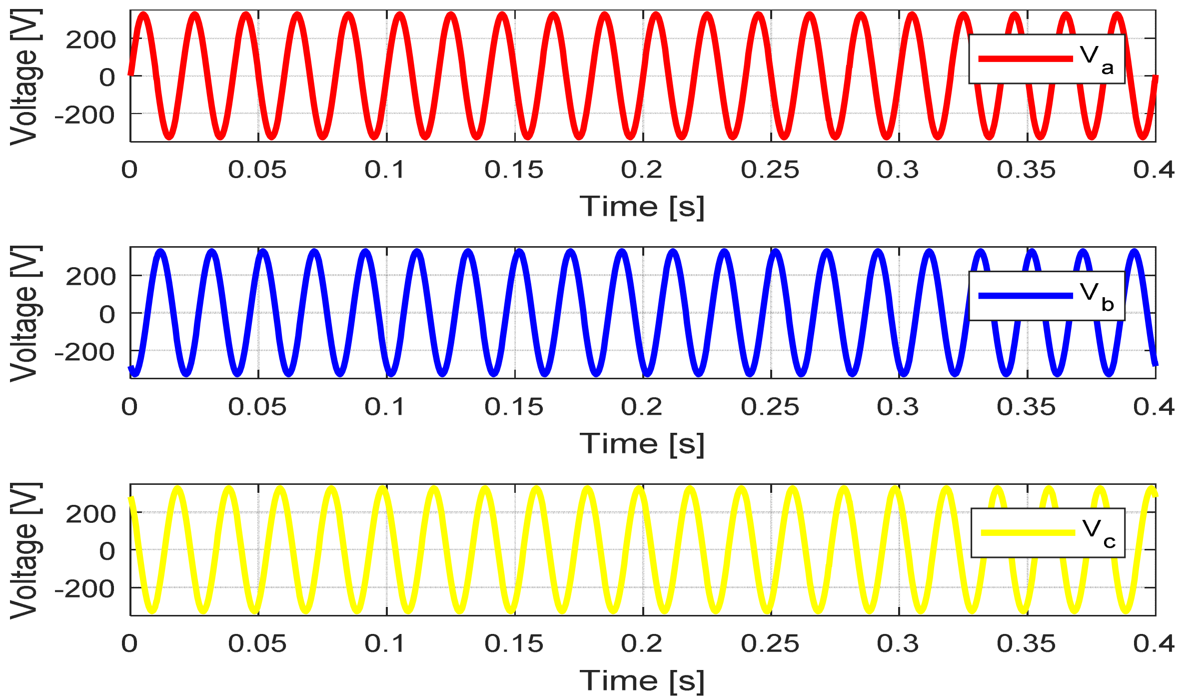
Fig. 9: Filtered output voltage waveforms from inverter side.



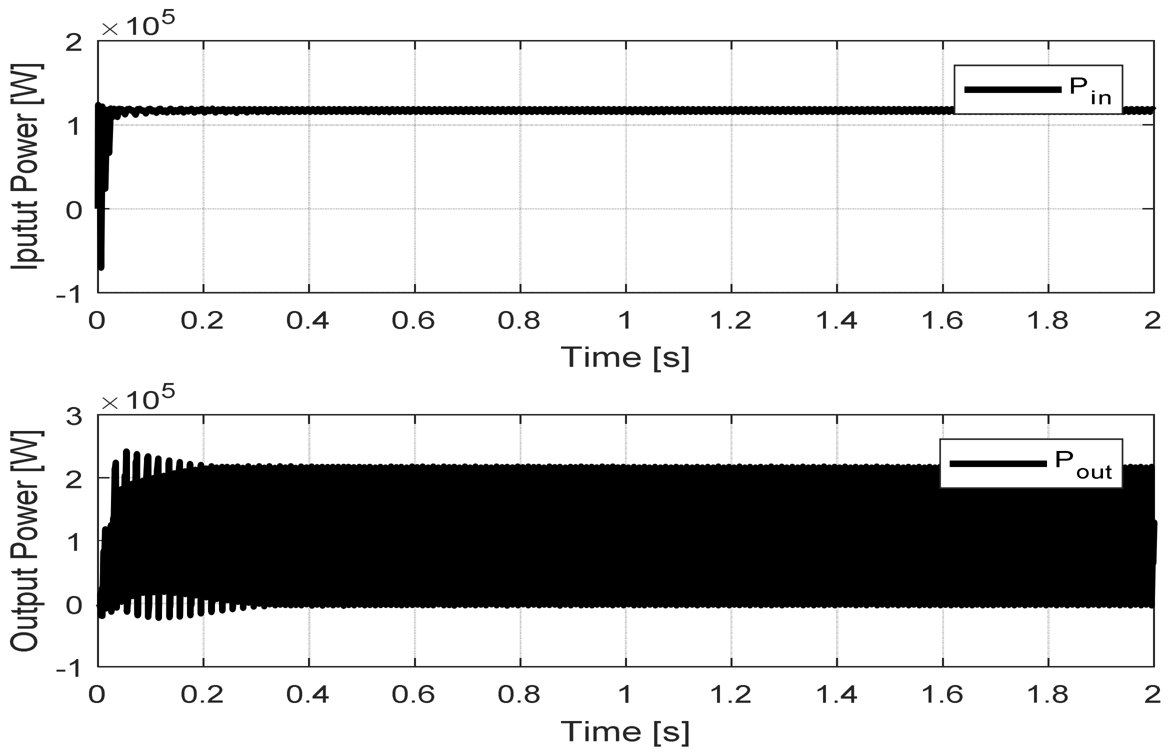


Fig. 10: PV-Grid voltage injection.

Fig. 11: PV input-output power waveforms

Conclusion

This proposed work seeks to develop a photovoltaic grid injection system using three-phase multilevel inverter topology with ANN-based control strategy. The integration of ANN within the system would enhance the performance of the system with respect to adaptability and power quality, strengthening system resilience and performance. The proposed system after implementation can be considered as a prototype for integration of renewable energy sources in future grid-related solutions.

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