

EV Battery Swapping Stations Using RES Based Optimized MPPT and Modified Quadratic Boost Converter

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ABSTRACT: The need for sophisticated, renewable-powered charging infrastructure that guarantees quick, effective and continuous energy delivery is driving increased demand for Electric Vehicles (EVs) and the global movement toward sustainable energy. The time-consuming and grid-dependent nature of traditional plug-in EV charging techniques restricts their scalability and reactivity, particularly in high-demand urban or fleet conditions. A smart hybrid EV Hub that combines solar and wind energy sources for a smooth EV charging and battery swapping experience is proposed in this study to address these issues. Wind turbines and Photovoltaic (PV) panels are used as clean energy sources in the system. The PV array's low DC voltage output is effectively increased via a Modified Quadratic Boost Converter (MQBC). Artificial Neural Network (ANN), optimized by the American Zebra Optimization (AZO) algorithm, which acts as an extract Maximum Power Point Tracking (MPPT) controller that extract highest amount of energy from fluctuating environmental conditions. To enable quick battery replacement and less downtime, energy harvested from renewable sources is either used to charge swappable EV batteries in a specialized battery bank. In order to balance system load, these swappable units also function as distributed energy storage. The system is linked to the electric grid, gets supply from PV and it acts as an energy management for EV battery. The validation of the proposed model is simulated in MATLAB/Simulink and achieves the efficiency of 95%.

Keywords: Electric vehicle, Renewable energy, PV, Wind, MQBC, ANN, MPPT, AZO, MATLAB simulation.

1. Introduction

The proliferation and acceptance of EV technology in the transport industry resulted in a significant reduction in the emission of Greenhouse Gases (GHG) in the atmosphere of the Earth, thereby reducing carbon footprint levels. In terms of environmental sustainability, it is

important to achieve such objectives for the beneficial heating, cooling, and sustaining of the atmosphere. Therefore, to meet the above mentioned objectives it is necessary to introduce clean energy resources and clean emissions free vehicles, into the market for consumers [1-3]. With consideration to these implications, EV range anxiety and long charging times addressed

through advanced charge modes and methods of charging, swapping stations, or hybrid models. Fast battery charging stations, are one of the likely solutions to EV range anxiety and long charging times; but, while they initially alleviate the issue for EV a consumer, the accelerated battery degradation leads to increased costs associated with not using fast charging stations [4-6]. To make this system more sustainable and reduce dependency on grid power, integrating RES, such as solar or wind energy, into battery swapping stations has gained considerable attention.

By reference, there are different types of converters to step up the voltage such as, the DC-DC Boost Converter is one of the most commonly used converters in PV systems due to its ability to step up the low output voltage of solar panels to a higher level suitable for grid integration. Therefore, the energy output of the solar cell varies with weather conditions, requiring the use of a converter to increase power for EV applications. Conventional DC-DC converters such as SEPIC, Zeta, and Buck-Boost are extensively used because of their ability to handle a wide range of inputs and adjust output voltage. SEPIC and Zeta converters support non-inverting step-up/step-down and continuous current flow, enabling effective MPPT. However, these converters typically face limitations, including reduced efficiency, a greater component count, and complex control and thermal requirements. Similarly, while Buck-Boost converters offer variable voltage control, they suffer from switching losses and increased design complexity as power levels rise. To overcome these constraints, MQBC emerges as a more efficient and streamlined alternative, offering superior performance for PV powered EV charging. The control performance is essential for achieving stable output without oscillations ANN MPPT controller is used to maintain a constant voltage and ensure AZO operates efficiently. Several existing algorithm such as Golden Eagle Optimizer (GEO) and Particle Swarm Optimization (PSO), are commonly used to

improve the performance in EV applications, resulting in improved system stability, dynamic response, and energy efficiency. However, these algorithms usually suffer from drawbacks such as high processing complexity, sensitivity to initial parameters, and a proclivity to converge prematurely to local optima, which affect real-time reliability [7-11]. To address these constraints using AZO based ANN MPPT controller. This technique enables faster convergence, more accuracy, and greater real-time flexibility, resulting in consistent and efficient power conversion in EV systems.

1.1 Contribution of the Work

This study proposes a novel EV charging and battery swapping infrastructure that utilizes solar and wind energy to deliver continuous, grid-independent electricity. MQBC is used to efficiently boost low DC voltage from RES, resulting in better energy conversion. The MPPT controller maximizes energy extraction under environmental conditions by tuning ANN using AZO approach. The system contains swappable batteries to reduce EV downtime and improve load balancing, and smooth grid connectivity allows for efficient control and distribution of renewable energy for charging and storage.

2. Proposed System Description

The block diagram represents an advanced EV battery Swapping Station powered by RES, incorporating both solar and wind energy to ensure efficient and sustainable power supply as shown in Figure 1. The PV panel with low DC output voltage is stepped up by a MQBC controller with PWM generator. This converter is regulated by ANN based MPPT controller optimized using AZO algorithm, enabling maximum energy extraction from fluctuating environmental conditions. In parallel, wind energy feeds power through a PWM rectifier, whose output is stabilized by a PI controller before integrating into the common DC bus. The DC bus serves as the central node, managing power flow from both renewable sources to downstream components.

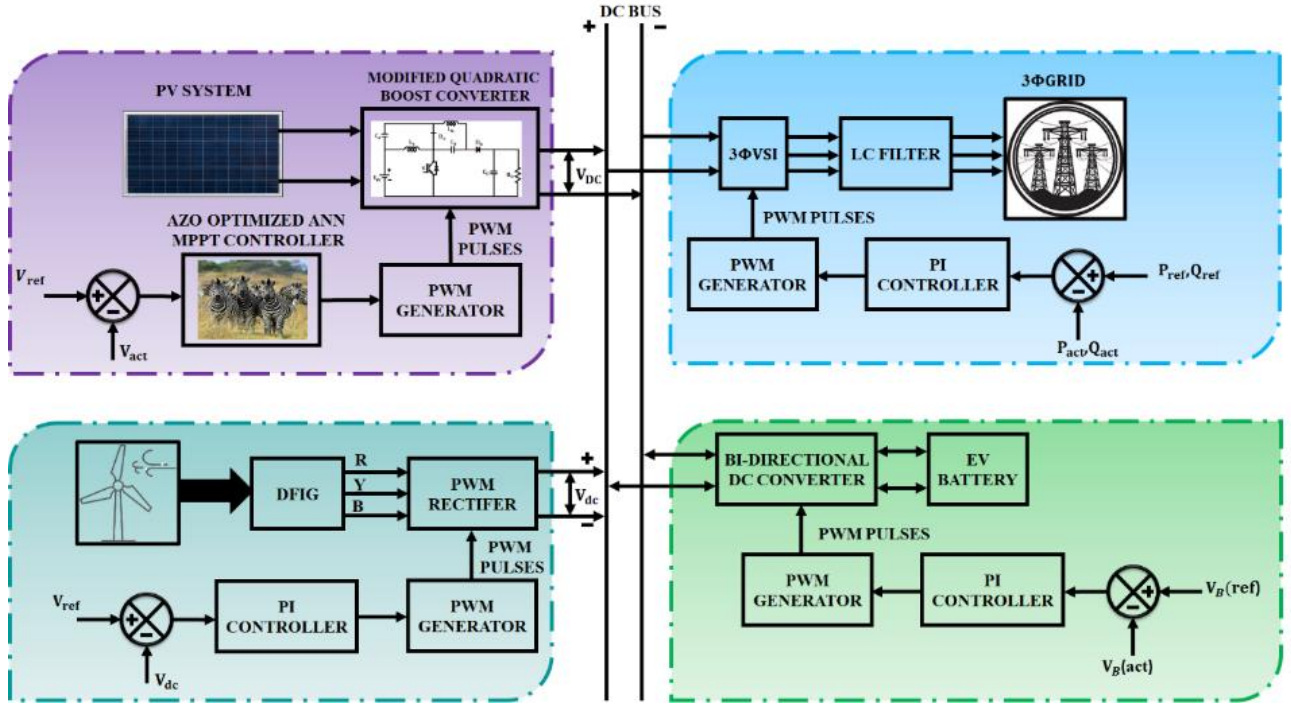


Figure 1: Block diagram of the proposed work

From the DC bus, energy is directed to a three phase VSI, which converts the DC power into AC for grid connection. The system includes a bi-directional DC-DC converter that manages charging and discharging of the EV batteries. Controlled through PWM signals and regulated by a PI controller, this converter ensures stable battery voltage and enables quick battery swapping, reducing EV downtime. By integrating advanced MPPT control, efficient power converters, and smart energy management, the system provides a reliable, clean, and intelligent solution for renewable energy-based EV battery swapping stations.

3. Proposed System Modelling

3.1 PV System

A PV is a semiconductor device that converts light into electricity. A module consists of several PV cells, and when several modules are combined, they form PV panel. A PV array consists of panels that are connected in both series and parallel. Figure 2 displays the equivalent circuit of a solar cell, which includes a current source connected in parallel with a p-n junction diode.

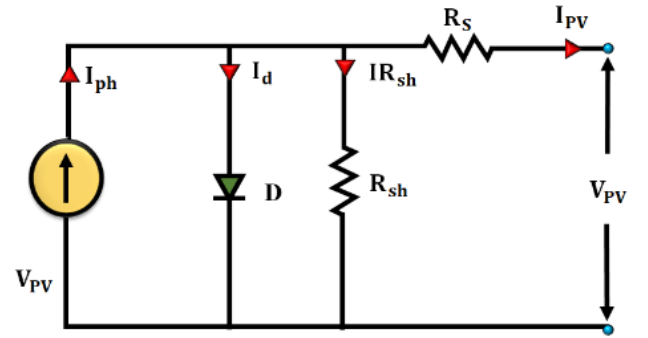


Figure 2: Equivalent model of PV

The current flowing through the diode is determined by

$$I_D = I_0 \left(e^{\left(\frac{q(V_{pv} + I_{pv}R_s)}{kBT} \right)} - 1 \right) \quad (1)$$

Also, the cell's output current,

$$I_{PV} = I_{ph} - I_D - I_{sh} \quad (2)$$

$$I_{PV} = I_{ph} - I_0 \left(e^{\left(\frac{q(V_{pv} + I_{pv}R_s)}{kBT} \right)} - 1 \right) - \frac{V_{pv} + I_{pv}R_s}{R_{sh}} \quad (3)$$

The photocurrent (I_{ph}) is the highest short circuit current, whereas (q) represents the electron

charge, (I_0) represents the reverse saturation current of p-n junction, (T) is the temperature in Kelvin, and (k_B) is the Boltzmann constant. The energy output of the solar cell varies with weather conditions, requiring the use of a converter to increase power for EV applications.

3.2 Modified Quadratic Boost Converter (MQBC)

The MQBC is a non-isolated step-up converter that produces higher output voltages. Its basic architecture allows for the use of a smaller controller while maintaining a stable output voltage with minimal ripple. Fig 3 depicts a circuit diagram for the proposed MQBC.

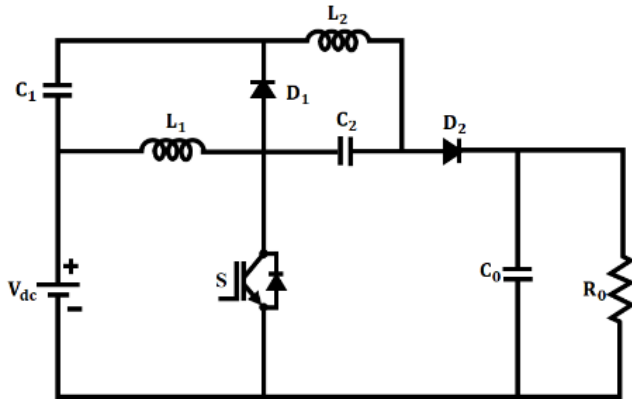


Figure 3: Modified QBC converter

In ideal conditions, the MQBC reduces switching losses and voltage stress on active switches, making it an effective choice for high-output voltage applications. A large output capacitor maintains a constant voltage (V_0) , and all semiconductor components are assumed to be ideal. The MQBC operates in two distinct modes, and switching waveform as shown in Figure 4 and 5.

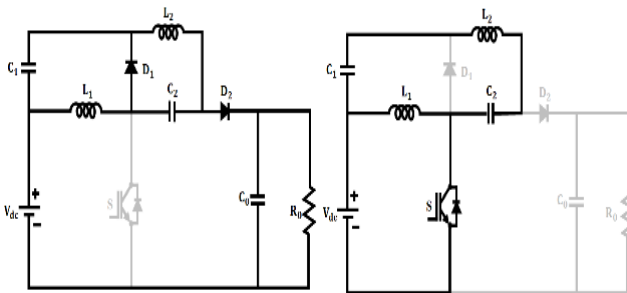


Figure 4: Modes of operation

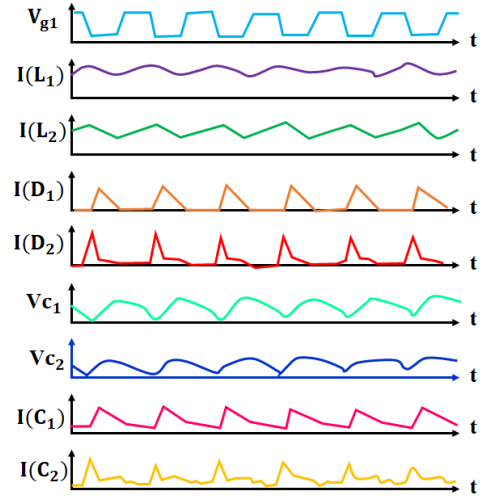


Figure 5: Waveform of MQBC

Mode 1:

When the switch (S) closes in Mode 1, the inductors and capacitors charge. The diode (D_1) is reverse-biased, with the anode more negative than the cathode. In this mode, the current through inductors $(L_1 \text{ and } L_2)$ increases linearly, while the voltage across (L_1) equals the gate voltage. The voltages of inductors and capacitors are represented as follows,

$$V_{L1} = V_g \quad (4)$$

$$V_{c1} = V_{c2} = \frac{D \cdot V_g}{(1-D)} \quad (5)$$

$$V_{L2} = V_g + V_{c1} - V_{c2} \quad (6)$$

Mode 2:

When the switch (S) is turned off, which the diode (D_1) become forward biased. The inductors begin to discharge, and the inductors and capacitors are connected in parallel, delivering the entire voltage of the capacitors the DC source to the output. In this mode, currents across inductors (L_1) and (L_1) decrease linearly, while the voltage across (L_1) remains equal to the gate voltage. The inductor and output voltages are computed using the following equations,

$$V_{L1} = V_{c1} \quad (7)$$

$$V_{L2} = V_{c2} \quad (8)$$

$$V_0 = V_G + V_{c1} - V_{c2} \quad (9)$$

Voltage gain

$$\frac{V_0}{V_g} = \frac{1}{(1-D)^2} \quad (10)$$

The MQBC offers a higher step-up capability than ordinary boost converters, with a gain of $(\frac{1}{(1-D)^2})$. The MQBC employs an MPPT controller to maintain a stable output voltage, as defined in the following section.

3.3 AZO Optimized ANN MPPT Controller

The ANN based MPPT system uses solar temperature and irradiance as inputs to determine the ideal duty ratio for the DC-DC converter, allowing for precise and dynamic maximum power point tracking in changing environmental conditions.

The ANN is trained using American zebra optimized control algorithm that maps duty ratios

to various solar irradiance and temperature combinations. Network weights are adjusted to avoid errors and ensure efficient operation. The mean squared error is used to evaluate performance, it is calculated as the average squared difference between output and target values.

$$F = \frac{1}{N} \sum_{i=1}^N (t_i - a_i)^2 \quad (11)$$

The proposed ANN-MPPT controller lowers tracking errors by constantly updating its control function, and performance is further improved by adjusting parameters using the AZOA algorithm, as shown in Figure 6. Inspired by the social behavior of American zebras, AZOA is mathematically modelled into five crucial phases to efficiently drive the optimization process.

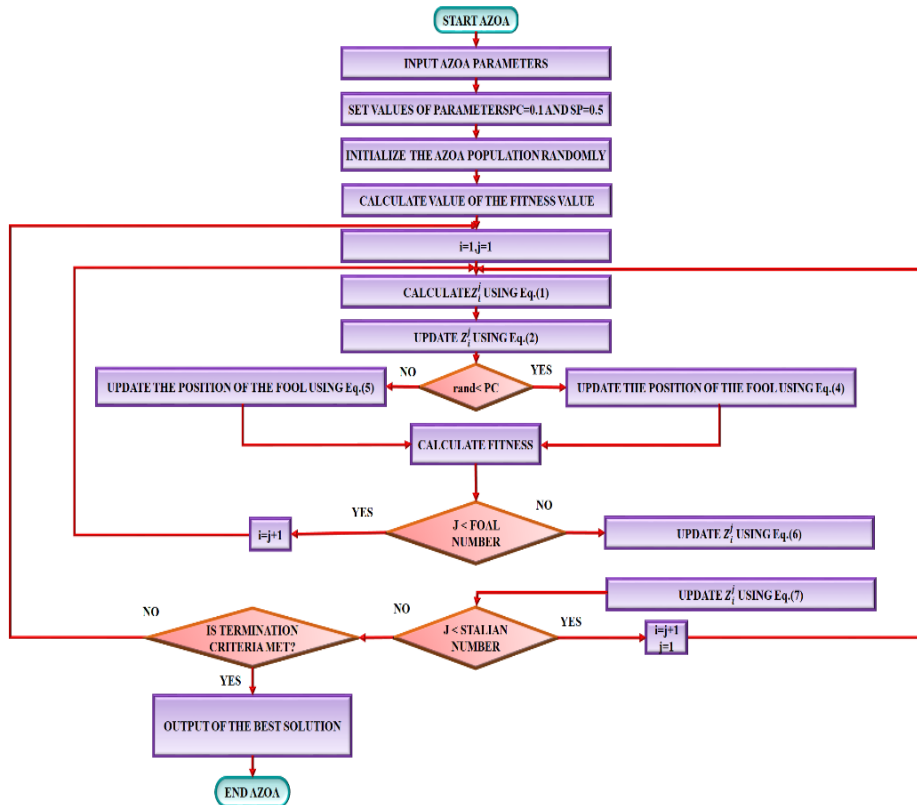


Figure 6: Flowchart of AZO

Phase 1: The AZOA algorithm proceeds by forming random zebra groups that mimic natural herd behavior. Each group, led by a stallion, represents a potential solution cluster in the search space. The number of groups (n) is defined by population size and stallion probability. Individual zebra positions are assigned at random under the

search criteria. This method ensures that various solutions are considered for optimal MPPT optimization.

Phase 2: Zebras' feeding behavior models cooperative search, where candidate solutions follow the leading stallion to efficiently converge toward optimal MPPT parameters.

$$Z_i^j = \begin{cases} \bar{Z}_i^j, & \bar{Z}_i^j < Z_i^j; \\ Z_i^j, & \text{otherwise} \end{cases} \quad (12)$$

The group members update their positions using random factors and trigonometric functions to move around the leader, enhancing MPPT accuracy for EV battery swapping systems.

$$R_2 = 1 - t \times \left(\frac{1}{T}\right) \quad (13)$$

Phase 3: In AZOA, zebra breeding behavior enhances diversity by having young zebras join unrelated groups, preventing inbreeding. This promotes broader exploration and avoids premature convergence in MPPT optimization for EV battery swapping systems.

$$Z_k^q = \text{Crossover}(Z_i^a, Z_j^b) \text{ if } r \geq pc, i \neq k \forall i, j, k \in N \quad (14)$$

Phase 4: Zebra group leadership is intended to reflect the leader's function in guiding the group toward additional resources. Stronger leaders dominate and secure optimal areas, which others can then use.

$$Z_s^i = \begin{cases} \bar{Z}_s^i, & \bar{Z}_s^i < F_s^i \\ F_s^i, & \text{otherwise,} \end{cases} \quad (15)$$

Here, R_4 and R_6 are uniform random values in $[-2, 2]$, R_5 and $[0, 1]$, respectively. R_5 is an adaptive parameter from Eq. (16).

$$R_5 = 1 - t \times \left(\frac{1}{T}\right) \quad (16)$$

Phase 5: The leadership transition stage ensures a strong leader maintains group discipline and resource management. If the current leader weakens, the algorithm replaces it using a formula that models this selection process.

$$Z_s^j = \{Z_s^j, \text{ if } F(Z_s^j) < F(Z_s^j), \forall i \in N_j\} \quad (17)$$

An effective power interface is critical for ensuring efficient power management between renewable sources, energy storage, and EV. A bidirectional DC-DC converter, controlled by PWM and a PI controller, efficiently manages energy flow between the DC bus and EV batteries, ensuring consistent voltage during charging and discharging for faster battery swapping and reduced downtime. Integrated with the AZO-optimized ANN-MPPT controller and the MQBC, this system provides a reliable, clean, and efficient renewable energy solution for EV battery swapping stations, enhancing power quality, operational flexibility, and overall performance.

4. Results and Discussion

ANN optimized AZO MPPT method is implemented using MQBC integrated RES to improve energy extraction. The system is simulated in MATLAB/Simulink, result and parameter specification are discussed below,

Table 1: Parameter specification

Parameter	Specification
PV System	
Rated Power	10KW
No. of panels in parallel	5
Open circuit voltage	37.25V
Cell linked in series	36
No. of panels in series	8
Short circuit current	8.95A
MQBC Converter	
L_1, L_2	4.7mH
Switching frequency	10KHz
C_0	4.7 μ F
C_1, C_2	22 μ F

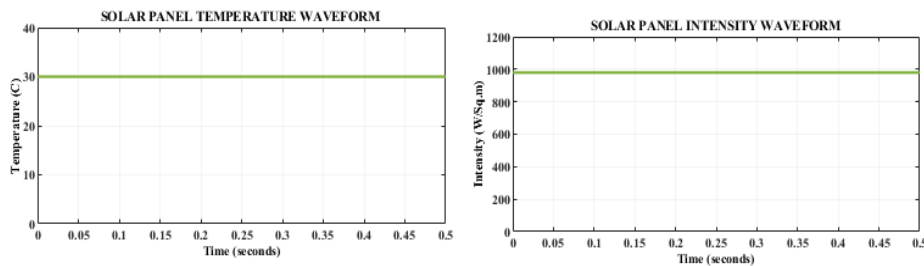


Figure 7: Waveform of solar panel

Figure 7 represents temperature and intensity waveforms of PV panel under constant conditions. The temperature remains consistently maintained at (30°C) throughout the duration, ensuring a

stable operating condition. Similarly, the intensity waveform shows a steady irradiance level of 1000 W/sq. m, indicating uniform solar exposure on the PV panel.

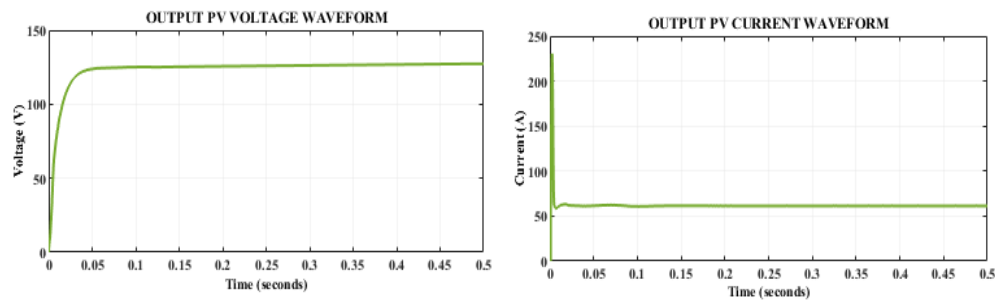


Figure 8: Output waveform of PV

Figure 8 illustrates the converter output waveforms, where the output voltage remains stable at 125 V and the output current settles at

60 A, indicating consistent and reliable converter performance.

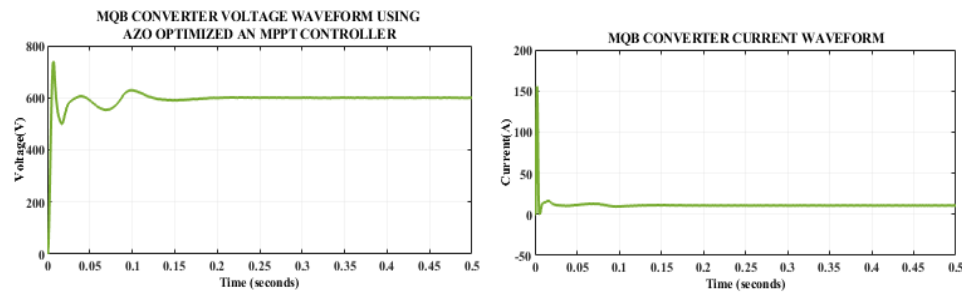


Figure 9: Converter waveform

Figure 9 shows the MQB converter’s performance using an AZO optimized MPPT. The voltage stabilizes around 600 V and current settles near

80 A within 0.1 seconds, indicating fast and stable regulation under dynamic conditions.

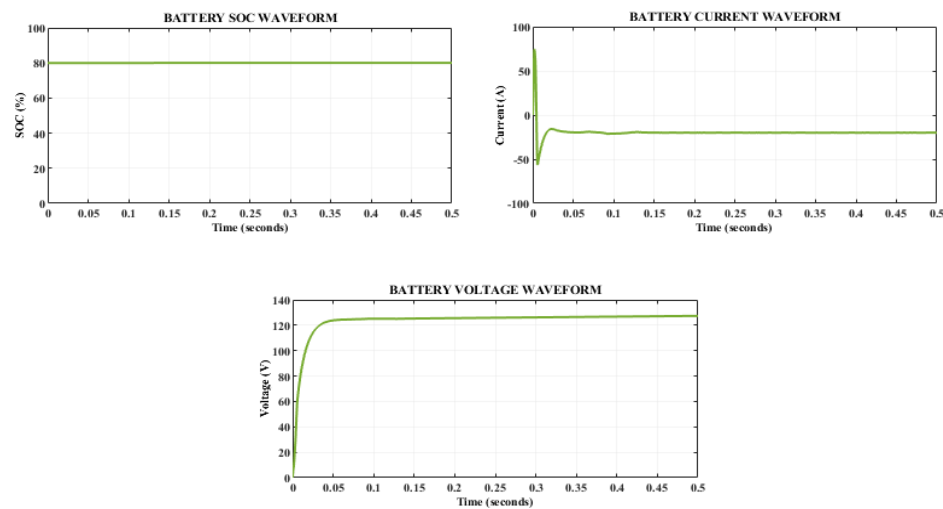


Figure 10: Battery waveform

Figure 10 illustrates the battery’s performance under constant conditions, with SOC stable at 85%, voltage regulated at 90V for reliable EV

charging, and current peaking at 10A before stabilizing at 3A, ensuring efficient power delivery.

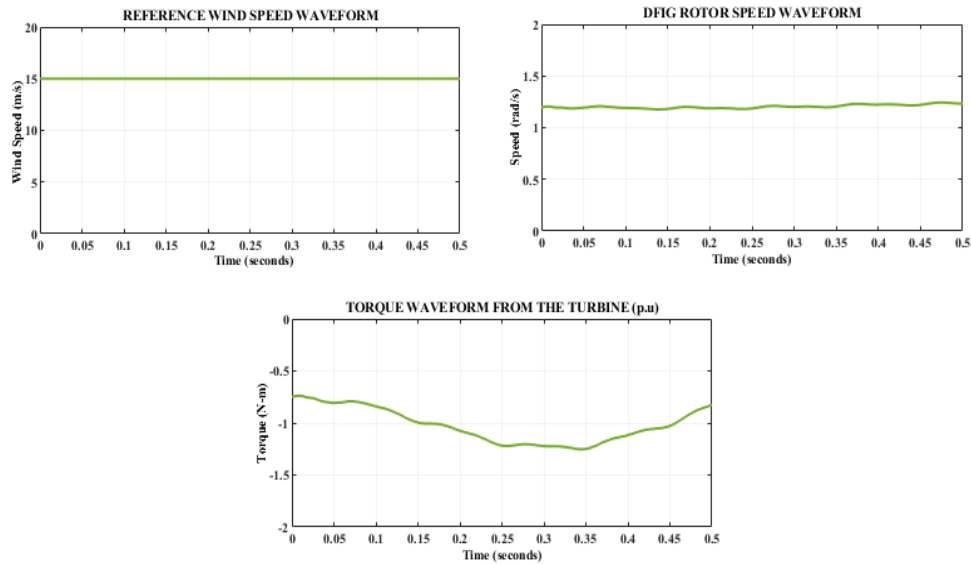


Figure 11: *Waveform of DFIG*

Figure 11 shows the system response in a wind energy setup. The reference wind speed remains constant at 12 m/s. The DFIG rotor speed shows slight fluctuations around 1.5 pu, while the turbine torque gradually decreases with minor oscillations over 0.5 seconds.

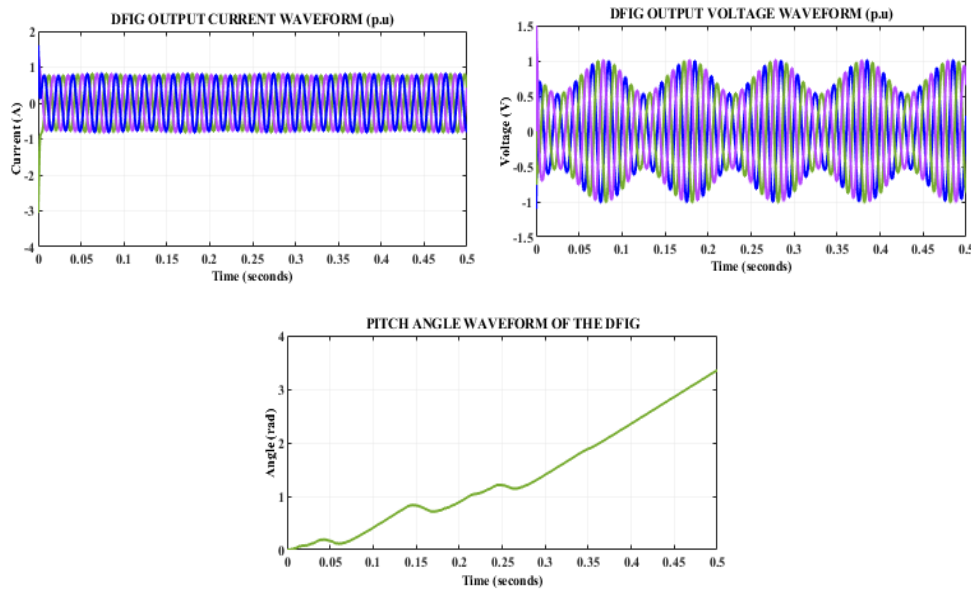


Figure 12: *DFIG output waveform*

Figure 12 shows DFIG performance waveforms. The output current and voltage oscillate within ± 4 pu, indicating stable operation. The pitch angle increases steadily from 0 to around 8° over 0.5 seconds, reflecting effective pitch control.

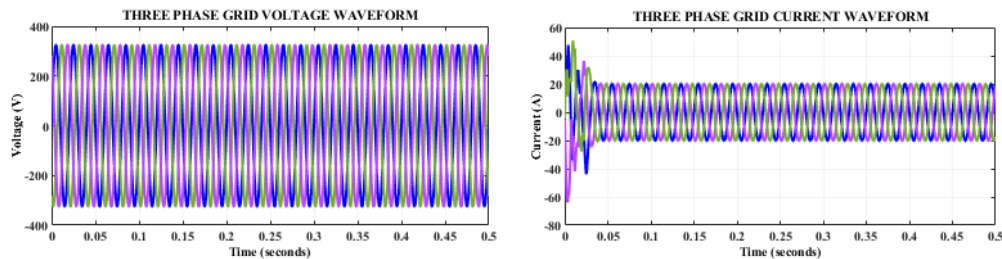


Figure 13: *Grid waveform*

Figure 13 shows grid settings, including waveforms for grid voltage and current. The grid voltage waveform stays stable at 350V, which shows that the grid produces a consistent voltage

level. Similarly, the grid current waveform remains steady at 21A, indicating a consistent current flow.

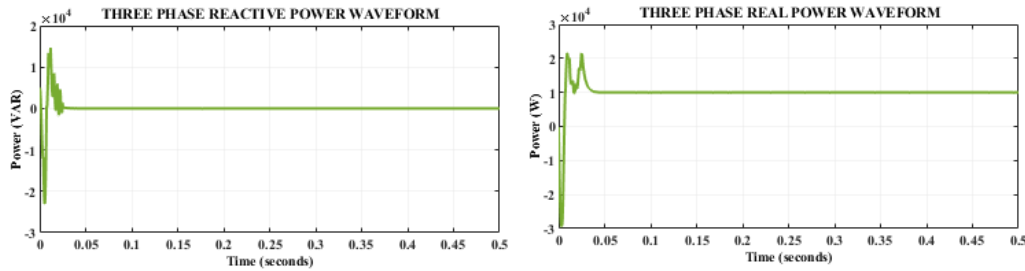


Figure 14: Real and reactive power waveform

The reactive and actual power waveforms are shown in Figure 14, which illustrates both powers fluctuate in AC systems while preserving a steady power flow, providing stability and effective energy transmission.

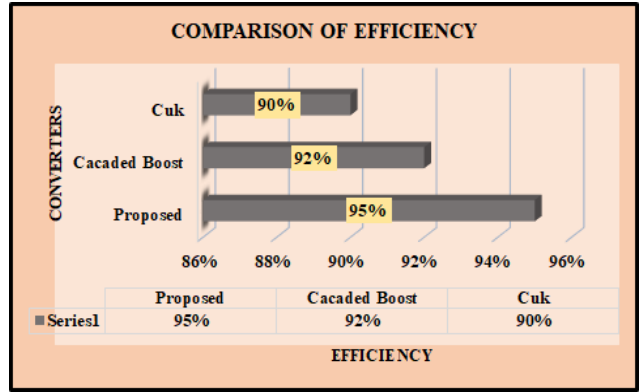


Figure 15: Comparison of efficiency

Figure 15 compares the efficiency of various converters, showing that the proposed converter achieves the highest efficiency of 95%, outperforming the Cascaded Boost converter (92%) [12] and the Cuk converter (90%) [13].

Table 2: Comparison of tracking efficiency

Controller optimizer	Tracking Efficiency
Proposed	98%
PSO [14]	96.52%
CSO [15]	95%

Table 2 compares tracking efficiency, showing that the proposed approach is the most efficient at 98%.

5. Conclusion

The proposed smart hybrid EV Hub effectively integrates RES, enhanced power conversion, and intelligent MPPT control to provide fast, reliable, and efficient EV charging and battery swapping. MQBC with AZO optimized ANN controller, allows for maximum energy extraction in a variety of climatic conditions, while swappable batteries improve system flexibility and load management. The MATLAB/Simulink simulation validates the model's performance, achieving 95% efficiency and confirming its potential as a long-term and scalable solution for future EV infrastructure in urban and fleet applications.

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