

Novel Control of Wind-PV-Battery based Standalone Supply System with LSTM Controllers

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Abstract: Integrated Wind - Photovoltaic (PV) based standalone electric power supply systems are widely used in many areas for various applications. These systems require a battery storage system to ensure a continuous power supply to loads, regardless of fluctuations in loads, wind speed, and solar irradiance. To ensure a reliable and stable power supply to consumers, several changes need to be made in these hybrid systems. Power quality plays a crucial role in standalone power systems, especially in hybrid energy sources based standalone power supply systems. The battery needs to charge when there is surplus power generation and discharge when there is a demand from the loads. To achieve this, a bidirectional DC to DC converter is used to connect the battery to the network, with a proper controlling mechanism. Additionally, maximum power point tracking devices with appropriate algorithms are incorporated for PV and wind turbines to optimize their utilization in all weather conditions. This paper considers multiple PV systems and wind turbines, each with proper arrangements of series and parallel combinations of PV modules, to determine the appropriate rating for the power supply system. Long short term memory (LSTM) based artificial neural network (ANN) controllers are implemented for various control units in this hybrid standalone power system. These proposed control techniques significantly improve power quality under various situations. The performance of the proposed method is evaluated using MATLAB/Simulink, and the results are presented in this paper.

Keywords: Wind, Photovoltaic, MPPT, Power Quality, Standalone System.

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1. INTRODUCTION

Renewable energy sources are becoming increasingly popular for standalone power supply systems in order to reduce pollution. By integrating more renewable sources, the system can become more reliable. The most effective way to create an eco-friendly system is by generating electricity from wind and solar energy. Solar energy is converted into electricity using photovoltaic (PV) modules, while wind turbines produce mechanical power from wind velocity. In medium power applications, permanent magnet synchronous generators (PMSGs) are used to convert this mechanical force into electrical power. As a result, locally placed hybrid PV-Wind energy based standalone power supply systems have gained popularity worldwide. Integrating PMSG based wind and PV systems can further enhance system reliability, but it is essential to incorporate an energy storage system in standalone systems to maintain power balance and provide stable power to consumers despite variations in wind speed, solar irradiance, and load. Among various energy storage devices, batteries are considered the best due to their fast response during the discharging and charging actions. Therefore, this paper proposes the use of a battery bank to enhance the system reliability and stability under various operating conditions. Additionally, a DC to DC bidirectional converter is employed to manage the charging and discharging process of the battery based on the power difference between generation and load.

In order to optimize the performance of wind turbines and PV panels, it is necessary to use maximum power point tracking (MPPT) converters and appropriate algorithms [5-7]. These converters are integrated into the hybrid standalone power generation system as boost converters to serve as MPPT converters. The balance between power generation and load is achieved by regulating the voltage at the dc-link through a bidirectional DC to DC converter. To operate AC loads from the dc-link, an inverter with a proper controlling mechanism is required. Additionally, the distribution system operates single phase loads, which can result in unbalanced voltages at the three phase terminals [4, 7]. Any surplus power available is stored in batteries, so the battery voltage must be kept lower than the voltage at the dc-link to facilitate the fastest charging process. Similarly, when there is a power deficiency from generation, the battery bank needs to be discharged to meet the increased load. Therefore, a boost operation is necessary during battery discharge.

The power difference between generation and load can cause variations in voltage at the dc-link [7]. To ensure power balance, the bidirectional DC to DC converter is designed to compensate for this difference using the battery. Once the voltage at the dc-link is stable, the inverter can regulate the voltage at the AC bus. However, consumers always require high-quality power from the supply, so proper control of the inverter is necessary to provide quality supply at the load bus. It is important to maintain a stable AC voltage at the PCC even under unbalanced load, sudden changes in the load, and random changes in irradiance and wind velocity.

Typically, traditional PI controllers struggle to handle sudden fluctuations in the power system because they are designed with fixed gains. As a result, it is necessary to utilize Artificial Neural Network (ANN) based controllers when designing control techniques for converters used in standalone systems. However, the use of Long Short Term Memory (LSTM) based ANN systems can offer improved responsiveness and faster adaptation to unknown interference signals. Consequently, in this study, an LSTM based deep learning algorithm is developed to design ANN controllers for various converters, aiming to regulate both the voltages at the dc-link and the AC bus.

The paper is structured as follows: Section-2 illustrated a detailed description of the system. In Section-3, the proposed control schemes utilizing LSTM based ANN controllers are elaborated. Section-4 showcases the diverse results obtained, utilizing the MATLAB

package. The conclusion is presented in Section-5, while the appendix contains compressed system ratings.

2. SYSTEM DESCRIPTION

Single wind and PV systems alone cannot generate the required power with a stable voltage over a long period of time. To ensure sufficient voltage and power rating for the PV system, the number of PV modules must be arranged in a combination of series and parallel connections. Each wind turbine is equipped with a PMSG system to generate electricity. The power generated from the PMSG is converted to DC power using a diode rectifier. A boost converter with a proper controlling algorithm is then used to connect the wind system to a common DC-link. The number of wind systems is determined based on the power rating requirement. The parameters of a single wind system and PV module can be found in the appendix. Each PV group has its own MPPT device to maximize energy generation. Similarly, all wind systems are integrated with their own MPPT converters. The battery bank is connected to the DC-link through a bidirectional circuit to maintain a stable voltage. Since all MPPT converters are individually connected to the DC-link using their respective control techniques, they work together to extract maximum energy regardless of wind velocity and solar irradiance. This situation allows the bidirectional circuits to regulate the voltage at the DC-link.

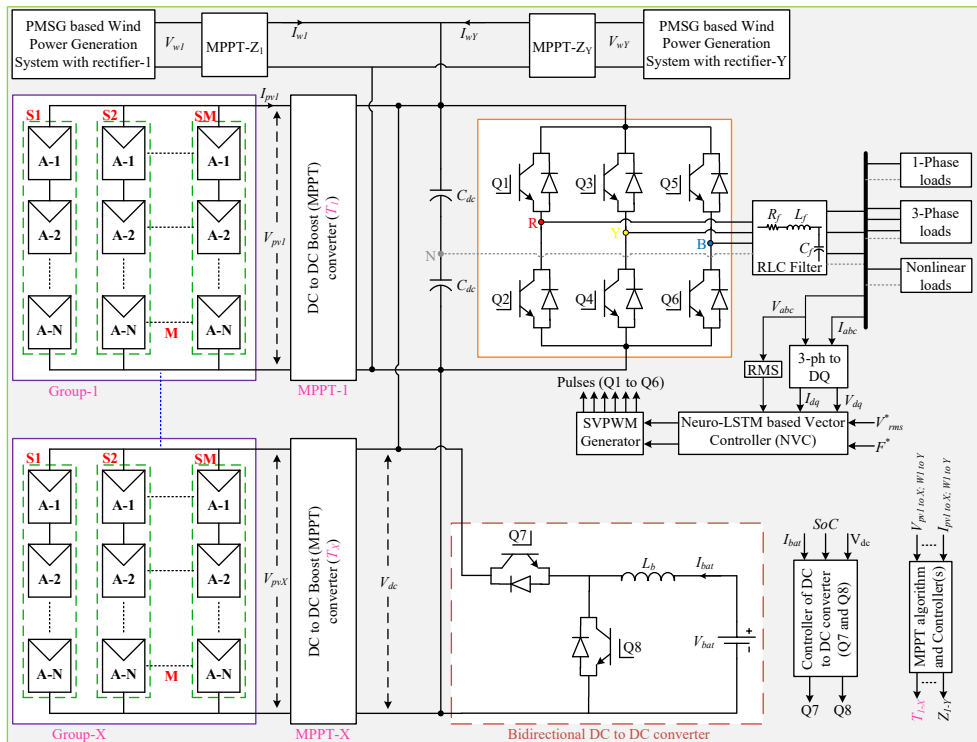


Fig. 1: Wind-PV-Battery operated standalone power supply system.

The conversion of DC power to AC power for AC loads is achieved through an inverter, with a filter placed between the inverter and the load bus. In this paper, a four-wire system is utilized to accommodate different types of loads, particularly single and three-phase loads with nonlinear characteristics. The model layout of a standalone hybrid

PV-Wind-Battery power supply system is depicted in Figure 1. The modeling of the wind turbine, PMSG, battery, PV module, and filters is based on previous works [7, 11-13]. Numerous researchers have conducted similar studies under various conditions, some of which are listed in this section. For instance, the authors of [1] implemented a standalone power supply system based on a hybrid combination of PV, wind, and battery. In [3], the authors focused on determining the optimal location for an energy management system. A novel MPPT technique for PV systems operating under partial shading conditions in a hybrid standalone power supply system was developed by the authors of [4]. Although a PV-based standalone power system was suggested by [12], it failed to take into account the incorporation of a wind system. [8] introduced a TS-Fuzzy based controller for a PV-Diesel-Battery hybrid system, but the inclusion of a diesel generator raised environmental issues. In [13], the authors devised a double loop PI controller for the DC to DC converter in a PV-based standalone system. A comparative study on nonlinear controllers in PV-based standalone systems was presented in [14], although the authors did not consider the integration of multiple power generation systems to establish a common DC-link or implement LSTM-based ANN controllers. Typically, nonlinear loads connected to the PCC can introduce harmonics to other loads. In order to reduce the impact of nonlinear loads, an active power filter is essential [15], while a DSTATCOM is needed to offset the reactive power required by the load [16]. Lastly, the authors of [17] implemented a smart grid that incorporates various renewable energy sources.

3. CONTROL OF DC AND AC VOLTAGES

PV groups receive non-uniform irradiances, resulting in different voltages at the output terminals of MPPT converters. Similarly, wind turbines cannot operate at the same wind speed. To address this, boost converter type MPPT converters can be used to create a common dc-link by connecting all MPPTs. However, the voltage at the dc-link is controlled by a DC to DC converter, which manages the charging and discharging process of the batteries. In situations with rapid changes in the system, ANN-based controllers generally outperform PI controllers. Therefore, this paper introduces LSTM-based ANN controllers for controlling voltages at both the DC and AC bus. Additionally, a deep learning algorithm is implemented to update the weights of the ANN controllers. The LSTM designed model is illustrated in Figure 2, while the complete design of the LSTM-based ANN controller is presented in Figure 3.

$$a_t = \sigma(b_a + h_{t-1} \times w_{ah} + X_t \times w_{ax}) \quad (1)$$

$$f_t = \sigma(b_f + h_{t-1} \times w_{fh} + X_t \times w_{fx}) \quad (2)$$

$$O_t = \sigma(b_o + h_{t-1} \times w_{oh} + X_t \times w_{ox}) \quad (3)$$

$$\hat{C}_t = \tanh(b_c + h_{t-1} \times w_{ch} + X_t \times w_{cx}) \quad (4)$$

$$s_t = f_t \otimes s_{t-1} + \hat{C}_t \times a_t \quad (5)$$

$$h_t = \tanh(s_t) \otimes O_t \quad (6)$$

Single phase consumptions and nonlinear loads are the major loads operated at the AC bus. These loads have the potential to create unbalance in the three phases and introduce '2 ω ' frequency oscillations into the voltage at the dc-link. These oscillations can have a detrimental effect on wind turbines, causing shaking, and can also lead to heat generation at the terminals across PV panels. To mitigate the impact of these oscillations on the dc-link, a dc-link control method is proposed. This method aims to circulate the oscillations through a DC to DC converter and battery. The control method for the DC to DC converter is illustrated in Figure 4.

to its reference to generate the reactive component of the current. The switches generate the necessary signals through a process called space vector pulse width modulation (SVPWM), as illustrated in Figure 6.

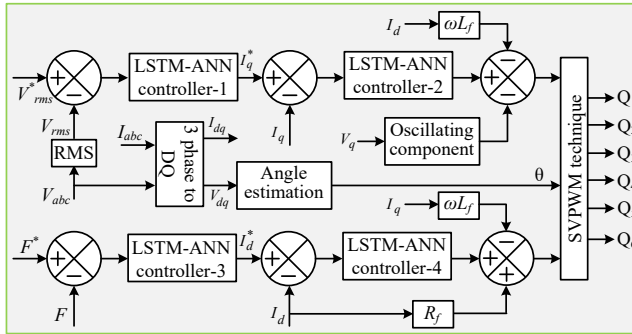


Fig. 5: LSTM-ANN controller based proposed control scheme for inverter.

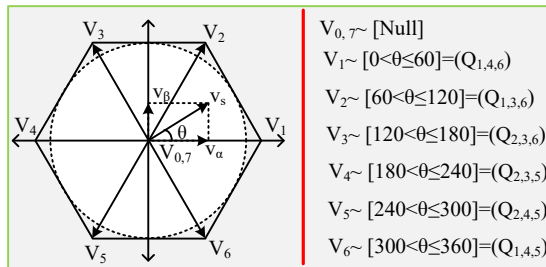


Fig. 6: SVPWM Technique.

4. RESULTS AND DISCUSSIONS

The results of the modeling and design of Fig. 1 are presented using the MATLAB/Simulink package. MATLAB is commonly used for simulating power system models, which can accurately replicate the performance of real-time systems. The PV system is modeled by connecting a number of modules in series and parallel using basic mathematical modeling techniques. Additionally, 100 wind systems are considered in this section to showcase the results. The major components required for the model are obtained from the Simulink library functional blocks. The system is designed in discrete mode with a sample time of $20e-6$. Various scopes are connected to obtain the corresponding results. The designed model in MATLAB/Simulink is depicted in Fig. 7, and the results obtained from the model are listed in the case studies below.

Case-1: performance under changes in generation and load

The cumulative power output of all photovoltaic (PV) systems is combined to represent a unified PV power in order to present the results. Similarly, the combined power output of all wind systems is represented as wind power. The variations in the power outputs of PV and wind systems are depicted in Figure 8(a), along with the changes in power demand from loads at the AC bus.

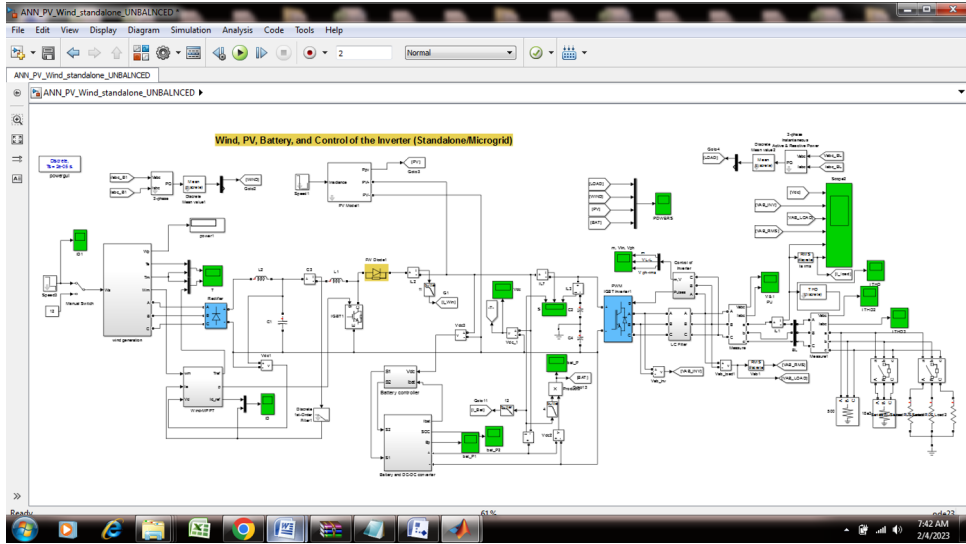


Fig. 7: MATLAB/Simulink of proposed system.

The battery bank serves as a compensator in the system to maintain power balance, adjusting for any mismatch between the load and total generation. When the battery is charging, it represents negative power, while positive power indicates discharging to counterbalance the load. Figure 8(b) shows the regulated voltage across the dc-terminals (dc-link) controlled by the battery. Although there are fluctuations in voltage at the dc-link due to variations in load power, these are minimal compared to the reference voltage of 720V. Figure 8(c) illustrates the corresponding RMS voltages of the 3-phase system, which exhibit stable responses through the proposed control methods using LSTM-ANN. However, for a more realistic assessment of the control methods' performance, Figure 9 provides the instantaneous load currents of the 3-phase system.

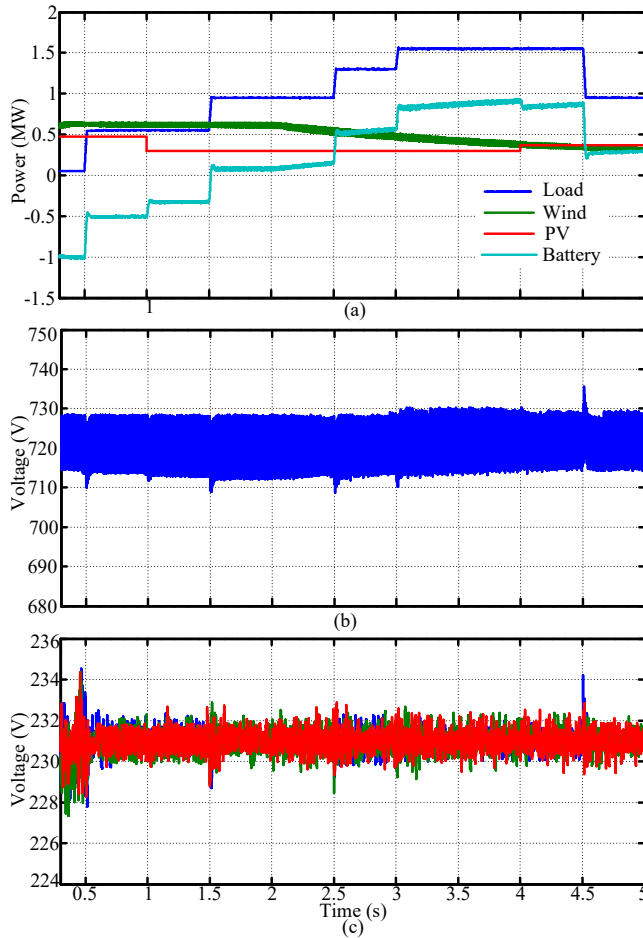


Fig. 8: (a) various Powers, (b) voltage at dc-link, (c) phase-RMS voltages.

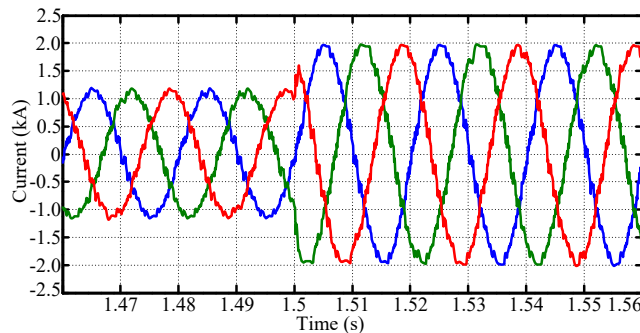


Fig. 9: Instantaneous load bus currents.

Case-2: performance under operation of unbalanced load.

The majority of loads connected to the distribution system in homes are single phase, resulting in an unbalanced load operation in a three-phase power supply system. This imbalance leads to unbalanced voltages at the AC bus. In this particular case, the load profile of a three-phase unbalanced load is illustrated in Figure 10(a). To evaluate the

performance of the proposed inverter controller, the worst-case scenario of the load profile is considered. The objective of the inverter control is to maintain constant three-phase voltages at the load bus in order to enhance power quality. The corresponding RMS voltages of each phase at the AC bus are depicted in Figure 10(b). When sudden changes occur at the load bus, there are slight fluctuations in the load current, which eventually stabilize at the reference voltage of 231V.

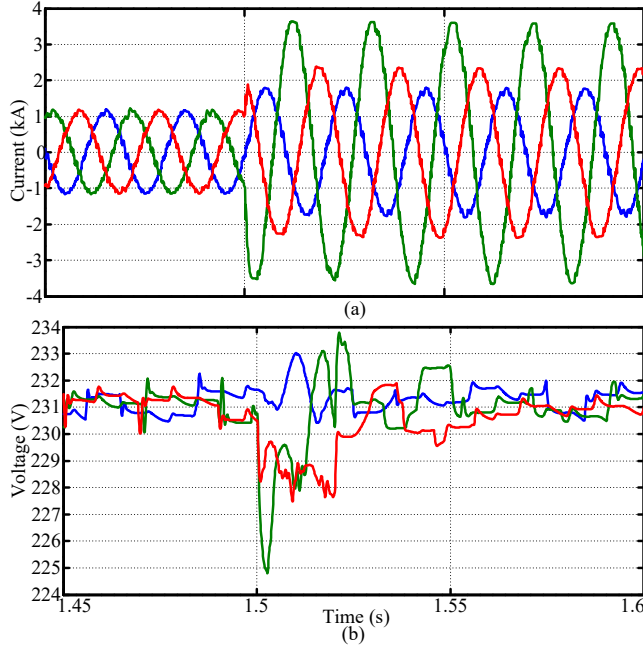


Fig. 10: (a) current in unbalanced, (b) balanced RMS-phase voltages.

5. CONCLUSION

LSTM-based artificial neural network (ANN) controllers have been developed for the control methods of DC to DC converters and inverters in hybrid renewable energy sources powered standalone power supply systems. The battery controller is specifically designed to ensure a balanced power distribution between total generation and load. A novel control scheme for the inverter has been devised to maintain a constant voltage at the AC bus, even in the face of varying conditions such as load fluctuations, solar irradiance, and wind speed. The wind system, PV (photovoltaic) panels, and battery are seamlessly integrated to provide a reliable and stable power supply at the load bus. In order to validate the effectiveness of the proposed control methods, Hardware-in-the-Loop (HIL) simulations are conducted using OPAL-RT modules. The proposed inverter control allows for the maintenance of balanced three-phase voltages at the load bus, even when operating with unbalanced loads. Furthermore, the power quality is significantly enhanced by the proposed control schemes for the inverter and DC to DC converter, regardless of the prevailing operating conditions.

Appendix:

Parameters of 0.5MW PV system are listed in Table-1.

215.0W module		
S.No	Parameter(s)	Rating
1	Current when short-circuit.	8.01A

2	Open-circuit terminal voltage.	36.9V
3	Voltage at MPP (V_{mpp}).	30.3V
4	Current at V_{mpp} .	7.10A
Combinations for Series and parallel of 0.5MW		
5	'N' in String.	21
6	'M' in Group.	7
7	'X' in PV System.	16

Parameters of Single wind-PMSG system are listed in Table-2 [19-20].

Values of a Two Mass Drive Train:

H_t	4.0s.
H_g	$0.10H_t$
K_{sh}	0.30pu./el.rad.
D_t	0.65pus/el.rad.

PMSG-Parameters:

Number of poles	10.
Operating speed.	153rad/s.
Armature resistance (R_s).	0.425 Ω .
Magnetic flux linkage.	0.433Wb.
Stator inductance (L_s).	8.4mH.
Maximum torque.	40.0Nm.
Generated power.	6.42kW.

Ratings of batteries:

The ratings of batteries are determined by carefully considering the appropriate voltage and power. In this section, a simple example is provided with numerical calculations to illustrate this concept. The primary factor in determining the battery rating is the duration of time it can discharge. In this paper, a battery bank with a rating of 480.0V is designed to provide backup for 72.0 hours, with an average load of 0.5MW at the point of common coupling (PCC). The current rating (Ah) of the batteries is estimated using the expression provided below, assuming a state of charge (SoC) of 0.6.

$$I_{bat} = \frac{5,00,000 \times 72}{480 \times 0.6} = 125kAh$$

125kAh-400V rating of battery system.		
S.No	Parameter	Rating
1	Single battery voltage.	48V
2	Single battery current rating.	125A
3	Number of batteries per string (series).	10.0
4	Required parallel strings.	1000

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