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Efficient Integration of Renewable Energy to Smart Grid Power Systems

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ABSTRACT

In this paper, some of the aspects associated with the integration of renewable energy sources into smart grid power systems are investigated. The renewable energy sources under study include a photovoltaic (PV) source and a wind energy conversion system (WECS). The PV source yields a variable DC output voltage that is dependent on the solar irradiation and ambient temperature. Therefore, a power conditioning unit (PCU) is needed to integrate its energy to the power system and track its maximum power point (MPP). The power conditioning unit may be a controlled DC-DC boost conveter. The design and implementation of such converter is investigated in the paper. Moreover, wind generators yield an AC output voltage that has variable voltage magnitude and frequency. Hence, a complete WECS has to be developed to integrate this wind energy to the power system. The WECS involves an uncontrolled (diode) rectifier cascaded by a controlled DC-DC converter. Furthermore, the renewable energy system involves a battery storage system that in turns need a converter to control its charging/discharging process. The design and control of this converter will be presented in this paper as well. Simulation and experimental results are included to verify the ideas developed in this study.

Keywords: DC bus, photovoltaic energy, power electronics, smart grid, wind energy

1. INTRODUCTION

Renewable energy sources are gainig an exponentially increasing attention all over the world. They offer a clean and sustainable energy source. However, there are some challenges related to the integration of their power to current electric power systems due its uncertainty. The focus on this paper is on PV systems. However, Wind systems will be also investigated. Photovoltaic systems have become globally accepted as a practical and feasible tool for electric power generation. Researchers' efforts for facilitating PV systems utilization and their integration to currently available systems have been always inspired by the national goal of having renewable and clean energy sources. These efforts successfully solved many of the problems that are attached to PV systems (Khatib et al.). Generally, PV systems are of two types; grid-connected and stand-alone PV systems. Although grid-connected PV systems are designed to operate in parallel with the utility network, grid-connected PV systems may feed local loads independently from the utility grid in an islanded mode during outages. Moreover, they may involve battery storage or other generating sources in order to increase the overall reliability of the system. On the other hand, stand-alone PV systems are designed to supply power to certain loads independently from the utility grid. Therefore, system planning in terms of system sizing and capacity is crucial to satisfy the load demand. The loads can be in a DC form. In this case a DC-DC converter has to be used to regulate the output voltage of the PV panels. Moreover, these PV systems can supply AC loads but in this case an added DC-AC inversion has to be involved. Generally, there are three types of stand-alone PV systems, PV-powered water pumping systems, Remote residential PV systems and PV-powered lighting systems.

One of the major problems of PV systems is that the output voltage of PV panels is highly dependent on solar irradiance and ambient temperature. Moreover, the voltage/power characteristics of PV arrays are nonlinear. An algorithm has to be implemented to track the MPP. Different algorithms have been proposed in literature for maximum power point tracking (Esram and Chapman, 2007), (Rodrigues and Amaratunga, 2007). Hence, loads cannot be directly connected to the output of PV panels. Different power electronic converters have to be used as interfaces between the PV array and the loads. The topology of the PCUs used in a certain PV system is determined based on the application of that system. For instance, a PV system that is feeding a DC load or a common DC bus, under study in this paper, would utilize a single stage DC-DC conversion. However, if the PV system is to supply an AC load, one more DC-AC inversion stage is required.

On the other hand, wind energy has reached a level of development where it is ready to become a generally accepted utility generation technology (Juan et al.). Wind-turbine technology has undergone a dramatic transformation during the last 15 years, developing from a fringe science in the 1970s to the wind turbine of the 2000s using the latest in power electronics, aerodynamics, and mechanical drive train designs (Heier, 1998), (Johnson, 1985). In the last five years, the world wind-turbine market has been growing at over 30% a year, and wind power is playing an increasingly important role in electricity generation, especially in countries such as Germany and Spain (Juan et al.). The variable output voltage from the wind turbines has a variable amplitude and frequency, which cannot be connected to the grid directly. Therefore, an uncontrolled rectifier stage will be used to convert this variable AC voltage to a variable DC voltage. Then, a DC-DC boost converter will be used to integrate this wind energy to the common DC bus. Finally, a bi-directional converter is used to link the renewable erngy sources to the main grid. The renewable energy systems along with their power conditioning units as well as the batteries and their chargers will be investigated in this paper. The paper is organized as follows,

2. System Description

A block diagram of the system under study is as shown in Fig. 1. It can be seen that each of the PV, wind and battery has a power electronic converter that operates as an interface between the source and the DC bus.

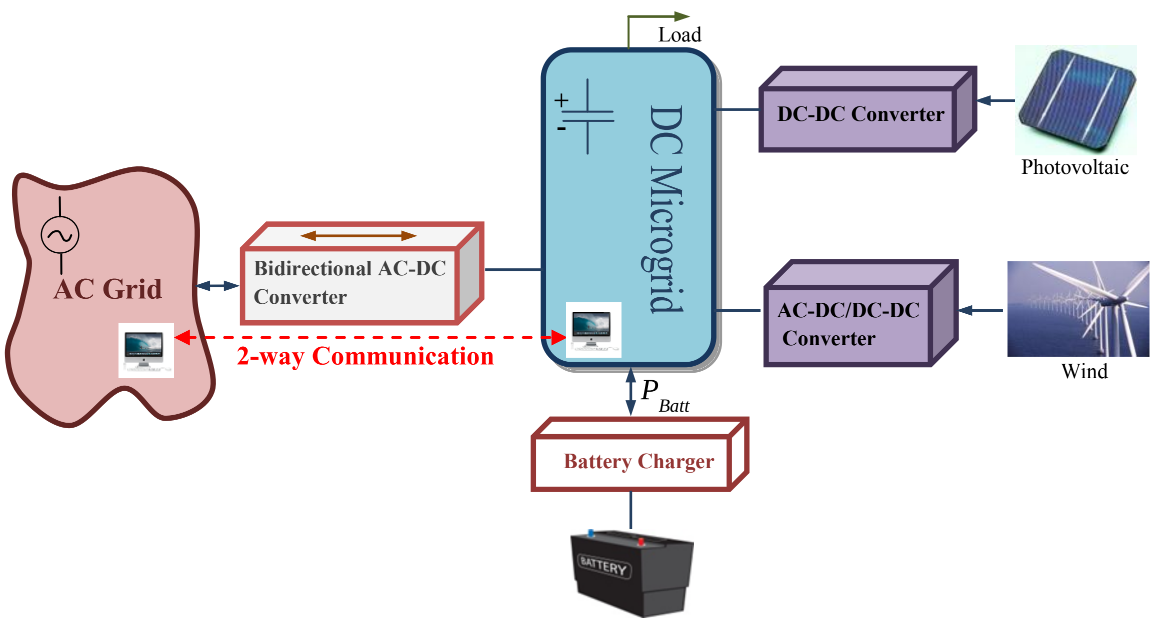

Figure 1: A block diagram of the system under study

2.1 PV System

2.1.1 PV Array Characteristics

The equivalent circuit of a PV panel is given in Fig. 2 (Marcelo et al.). The relation between output voltage and current of PV panels is non-linear. Therefore, the output voltage of PV panels is dependent on the amount of their output power. Moreover, the output voltage of PV panels is dependent on solar irradiation and ambient temperature. On the other hand, a constant voltage level is needed for connecting loads to PV arrays. This imposes an imperative necessity of having a PCU as an interface between PV panels and the loads connected to them. The characteristic equation of solar arrays is given by (1),

$$I = I_{LG} - I_{OS}\left\{\exp\left[\frac{q}{AKT}(V + IR_s)\right]\right\} - \frac{V + IR_s}{R_{sh}} \tag{1}$$

Where:

I_{LG}	Light generated current
I_{OS}	Reverse saturation current
Q	Electronic charge
A	Dimensionless factor
K	Boltzmann's constant
R_s	Series resistance of the cell
R_{sh}	Shunt resistance of the cell

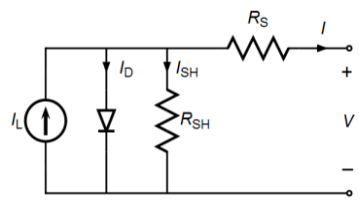

Figure 2: The equivalent circuit of a photovoltaic array

2.1.2 DC-DC Boost Converter

Boost converter is a DC-DC converter that steps up its input voltage based on the formula given in (2)

$$V_{out} = \frac{1}{1-D}V_{in} \tag{2}$$

where V_{out} is the output voltage of the boost converter, V_{in} is the input voltage and D is the duty cycle which is the ratio between the time within which the IGBT. The circuit diagram of the boost converter is shown in Fig. 3. It consists of an inductor, an IGBT switch, a fast switching diode and a capacitor. The configurations of the boost converter circuit during switching ON and OFF intervals are shown in Figs. 4 and 5, respectively. When the IGBT is switched ON ($0 \leq t > t_{on}$), the inductor is directly connected to the input voltage source. In this case, the inductor current rises charging it and the inductor is storing energy while the diode is reverse biased disconnecting the load (R) and output capacitor (C) from the source voltage. During this interval, the pre-charged capacitor assures constant voltage across the load terminals.

When the IGBT is switched OFF ($t_{on} \leq t > T_s$) where T_s is the switching period, the diode is forward biased and both the source and the charged inductor are connected to the load. The inductor releases the energy stored in it. This energy is transferred to the load in the form of voltage that adds to the source voltage. Hence, the converter has boosts the input voltage.

The boost converter proposed in this paper is designed to operate in the continuous conduction modes (CCM) which means that the inductor current is always higher than zero. The inductance value is designed to be higher the minimum inductance required for operation in CCM given by (3) (Rashid, 2001)

$$L_{1,\min} = \frac{(1-D)^2 DR}{2 f_s} \tag{3}$$

where $L_{\min}$ is the minimum inductance, D is the duty cycle, RL is load resistance, and f_s is the switching frequency of the IGBT.

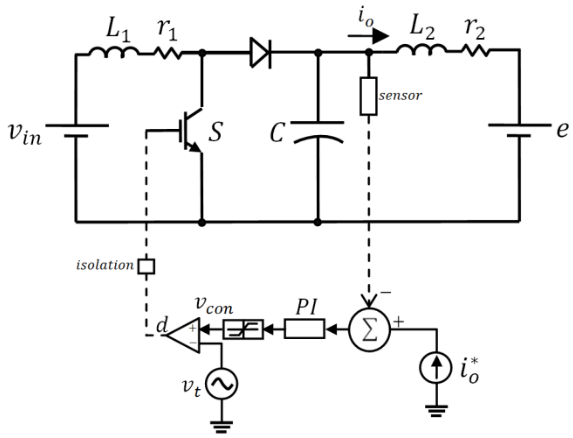

Figure 3: The boost converter circuit

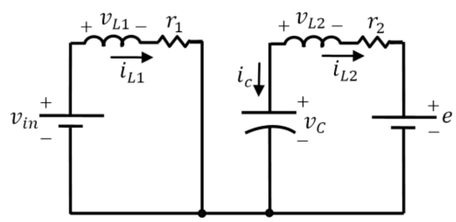

Figure 4: The boost converter circuit during the ON interval

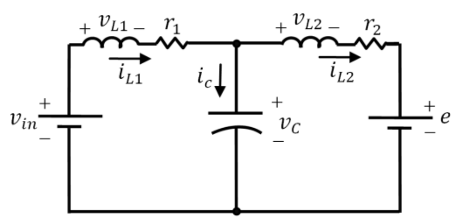

Figure 5: The boost converter circuit during the OFF interval

The capacitance is designed such that the output voltage ripple is within the desired boundary. The minimum capacitance required for certain output voltage ripple is given by (4)

$$C_{\min} = \frac{D}{R f_s V_r} \tag{4}$$

The duty cycle governs how much boosting of the input voltage will be achieved during boost converter operation. In other words, by controlling the duty cycle we can output constant output voltage even in the case of input voltage or loading variation. In this paper, we have utilized a fuzzy- based controller that adapts the duty cycle based on the input voltage and loading conditions such that the output voltage stays constant.

2.2 WIND ENERGY CONVERSION SYSTEM

The WECS under study consists of a diode rectifier then, the same DC-DC converter explained in sub-section 2.1.2 is used.

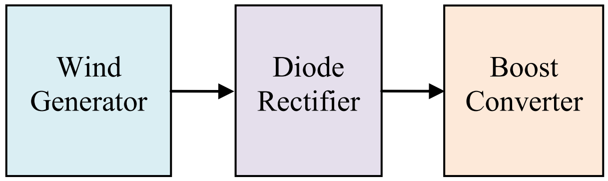

Figure 6: The WECS under study

2.3 BATTERY SYSTEM

The smart power system presented here is also equipped with a battery bank connected to the DC bus. The output voltage of the battery storage system is not constant depending on the state of charge of the battery. Moreover, the amount of charge or discharge from the battery should be controlled depending on the energy management algorithm used for system operation. Thus, a controlled bi-directional DC-DC converter was designed and implemented in the system. In the charging mode, the transfer function of the output voltage to the duty cycle (G_{BC}) is as given by (5):

$$G_{BC} = \frac{\tilde{v}_o}{\tilde{d}} = \frac{\frac{V_{dc}}{D}}{L_{batt}C_{in}[s^2 + (\frac{1}{RC_{in}})s + (\frac{1}{L_{batt}C_{in}})]} \qquad (5)$$

Whereas, the ratio of the output voltage to duty cycle transfer function in the discharging mode (G_{BD}) is given by,

$$G_{BD} = \frac{\tilde{v}_o}{\tilde{d}} = \frac{V_{dc}[\frac{L_{batt}}{R(1-D)^2}]s}{L_{batt}C_{out}[s^2 + (\frac{1}{RC_{out}})s + (\frac{(1-D)^2}{L_{batt}C_{out}})]} \qquad (6)$$

Where:

$\tilde{v}_o$	The small signal of the converter output voltage [V]
$\tilde{d}$	The small signal of the duty cycle
V_{dc}	The large signal of the DC bus voltage [V]
D	The large signal of the duty cycle
L_{batt}	Converter inductance [H]
C_{in}	Converter capacitance on the DC bus side [F]
C_{out}	Converter capacitance on the battery side [F]
R	DC Load Resistance [Ω]

These two transfer functions for the converter in the charging and discharging modes were used to design the PI controller used to control the charge/discharge process of the battery as shown in Fig. 7. The PI controller parameters were set as follows, $K_{pC}= 0.0035$, $K_{iC} =0.3$, $K_{pD}= 0.0035$ and $K_{iD}= 0.0035$. Moreover, the pulse width modulation technique at a switching frequency of 5-kHz was used as a switching strategy for the bi-directional charger/discharger. More details of the design process and the maximum power point tracking algorithm are presented in (Mohamed et al.).

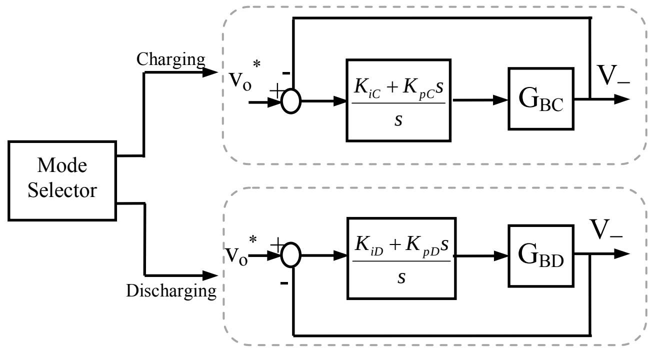

Figure 7: The WECS under study

2.4 BI-DIRECTIONAL CONVERTER

The power circuit of the bi-directional converter is shown in Fig. 8. The voltage equation is derived as

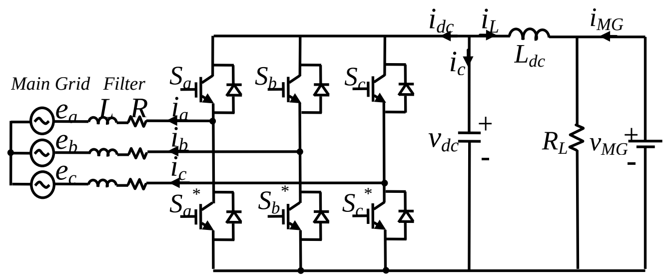

Figure 8: Bi-directional converter

$$e_s = Ri_s + L\frac{di_s}{dt} + v_r \tag{7}$$

where

- e_s source voltage
- i_s source current
- v_r Converter input voltage
- R, L Resistance and inductance of the boosting inductor, respectively.

$$L\frac{di_{de}}{dt} - wLi_{qe} + Ri_{de} = e_{de} - v_{de} \tag{8}$$

$$L\frac{di_{qe}}{dt} - wLi_{de} + Ri_{qe} = e_{qe} - v_{qe} \tag{9}$$

Where w is the angular frequency of the voltage source.

For fast voltage control, the input power should supply instantaneously the sum of load power and charging rate of the capacitor energy. Neglecting the resistance loss and the switching device loss, the power balance between the ac input and the dc output is as follows.

$$P = \frac{3}{2}(e_{de}i_{de} + e_{qe}i_{qe}) = v_{dc}i_{dc} \tag{10}$$

Where v_{dc} and i_{dc} are the DC output voltage and current, respectively. On the dc output side,

$$i_{dc} = -C\frac{dv_{dc}}{dt} - i_L \qquad (11)$$

Where i_L is the load current. From (10) and (11)

$$\frac{3}{2}(e_{de}i_{de} + e_{qe}i_{qe}) = -Cv_{dc}\frac{dv_{dc}}{dt} - v_{dc}i_L \qquad (12)$$

A vector decoupling control technique was used. Two nested loops have been utilized to realize DC voltage and input current control simultaneously. The outer loop is for controlling the DC current (or the DC bus voltage). Whereas, in the inner loop, current control is realized by two PI controllers. As we used the d-q transformation, PI controllers are now working on three DC signals, which helps eliminating steady state errors.

Moreover, in order to enhance the performance of current control loop, the decoupling term (*wL*) has been included while calculating the rectifier's input voltages. This vector decoupling control technique allows control of the active and reactive power drawn from the grid.

3. RESULTS AND DISCUSSION

A 5 kW PV system and 5 kW WECS were implemented and tested experimentally. A programmable DC power supply was used to emulate the variable DC voltage and the PV characteristics. DC-DC boost converters were designed with an input inductance of 3 mH and an output capacitor of 1200 μF. DSpace 1104 was used for control purposes. The DC-DC boost converter employed a PI controller to control its output voltage. The proportional gain of the controller (K_p) was set to 0.002, whereas the integral gain (K_i) was set to 0.2. The switching frequency used was 5 kHz. Figs. 9 and 10 show the voltage and current transient response for a step change in the load from 1kW to 220W then 220W to 1 kW, respectively. The controller stabilizes the voltage at its reference value of 200 V. However, an overvoltage of 1.5% can be seen in Fig. 9. Moreover, an under voltage of 8 Volts can be noticed also when the load is increased in Fig. 10. Both of these under voltage and over voltage values are less than the IEEE standards.

The fully controlled bi-directional converter is operated at an 8 KHz switching frequency and a sampling time of 0.3 ms, which allows the controller to detect and respond quickly to changes in the states of the system at either the AC or DC sides. The converter is designed to operate at a low THD and at unity power factor. A 24 mH inductor with 0.9 ohm losses is connected between the AC grid and the converter to filter harmonics associated with the fundamental current wave form. A 1200 μF capacitor is placed at the converter's DC side. Experimental results were taken for the converter under different operating conditions. The bidirectional was operated in the current controlled rectifier mode, current controlled inverter mode and has also been tested to instantaneously change its mode of operation.

The resistor that links the DC grid to the controlled bi-directional converter has to have a relatively small value to increase the efficiency of the converter. On the other hand, the value of the resistor has a direct relation with the voltage drop across the resistor terminals. This voltage drop has to be within a sensible range in order for the current control to be achieved properly. In this case, a 24 mH inductor with an internal resistance of 0.9 ohms is used to couple between the DC grid and the bi-directional converter. The inductor significantly reduces the ripple in the DC current allowing a smooth current sharing.

One of the most important advantages of the bi-directional converter is its ability to instantaneously change the direction of the current. This is helpful while operating in a smart grid system when real-time management algorithms are to be implemented. Fig. 11 shows the experimental results for the controlled converter when the current reference is suddenly changed from -2.5A to 3A. A positive sign means that the current is flowing from AC to DC side. It can be seen that the converter current is tracking its reference and changing its direction within a very short transient interval, which is around. Moreover, Fig. 12 shows the results for changing the reference current from 3A to -2.5A. In other words, the controller is commanded to switch from the current controlled rectifier mode to the current controlled inverter mode, i.e. the current will flow from the DC microgrid to the main AC grid.

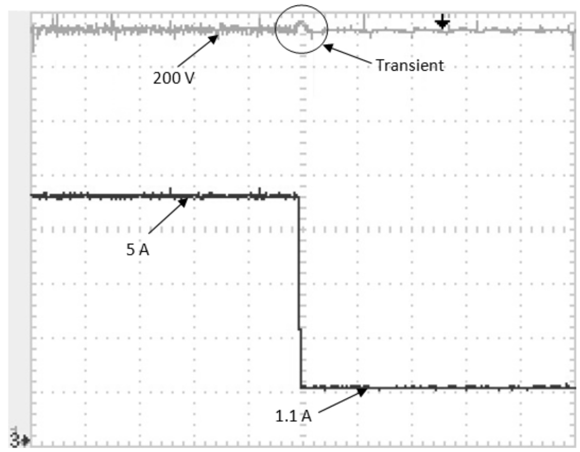

Figure 9: Voltage and current waveform corresponding to a step change in the load from 1kW-220W

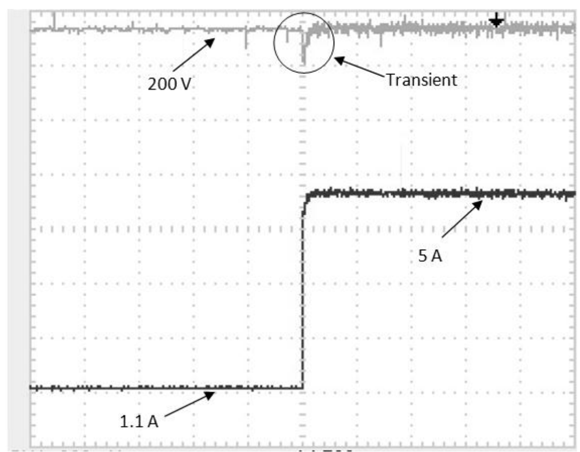

Figure 10: Voltage and current waveform corresponding to a step change in the load from 220W-1kW

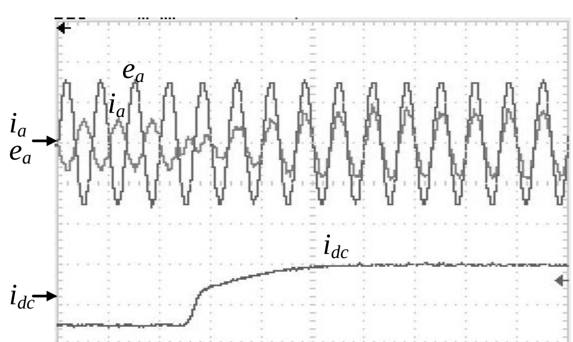

Fig. 11. Response of the bi-directional converter to a step change in the DC current reference from -2.5A to 3A (a) AC current, ia (5 A/div, 2.5 ms). (b) AC voltage, va (100 V/div, 2.5 ms). (c) DC current, idc (3 A/div, 2.5 ms).

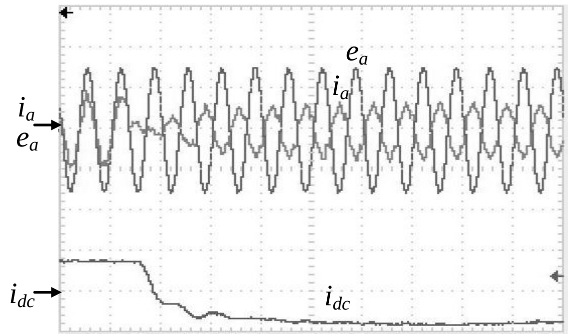

Fig. 12. Response of the bi-directional converter to a step change in the DC current reference from -2.5A to 3A (a) AC current, ia (5 A/div, 2.5 ms). (b) AC voltage, va (100 V/div, 2.5 ms). (c) DC current, idc (3 A/div, 2.5 ms).

4. CONCLUSION

In this paper, a hybrid AC-DC smart microgid was designed and implemented for integration of renewable energy sources. The power electronic converters used as interfaces between the PV system and the wind generator were investigated and their design was included. A bi-directional converter was used to tie the renewable energy sources to the main grid. Experimental results show the effectiveness of the developed system for integration of renewable energy sources.

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