

Performance evaluation of a PMDC motor with battery storage control and MPPT based solar photovoltaic system

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ABSTRACT

This paper analyzes and demonstrates the performance of a solar photovoltaic (SPV)-fed permanent magnet DC (PMDC) motor under various operating conditions. In this configuration, a 5HP PMDC is coupled to a SPV system and a boost converter has been interfaced between them to regulate the DC output voltage acquired from the SPV system. The switching pulse to the converter has been provided by the maximum power point tracking (MPPT) controller (P&O and INC) in order to acquire maximum and desired power across the DC link with varying irradiance. A battery energy storage system (BESS) is often used in association with this configuration caused by the non-linear nature of the SPV system and to overcome the volatility of the DC connection affected by environmental effects. For this purpose, a double loop PI controller is analyzed, and examined the DC link. Additionally, the operation of bidirectional DC-DC converter in buck and boost mode during battery charging and discharging is also performed. This operation ensures maintaining a constant and continuous power across the DC link to regulate the PMDC motor consistently. A comparison of results has also been presented for both incremental and conductance (INC) and P&O controllers. The mathematical modeling of configuration has been performed in MATLAB/Simulink software. The results and key findings have been tabulated and even elaborated graphically.

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1. INTRODUCTION

In recent years, it's become extremely essential to shift away from fossil fuels and to move towards renewable energy sources (RES) to meet the growing energy demand of domestic and commercial applications. Because fossil fuels are finite and have severe and significant environmental consequences, such as hazardous emissions, global warming, and poisonous byproducts [1]-[4]. RESs such as solar, wind, geothermal, biogas, tidal are eco-friendly and abundantly available in nature. In RES, solar and wind energy power generation take precedence over others [5]. Since wind turbines have moving parts that cause wear and tear, require more maintenance, and emit noise pollution, therefore solar-based power generation is a rapidly growing and vital area of research in RES [6]. Even though environmental conditions such as rapidly growing and vital areas of research in RES. Even though environmental conditions such as irradiance, temperature, and non-linearity are a major limitation of solar photovoltaic (SPV)-based power generation [7],

therefore a hybrid system with SPV is required to obtain steady and consistent power. In a hybrid system, a second energy source is coupled with a SPV system as a backup that allows for continuous operation under varying irradiance and temperature conditions [8], [9].

The SPV system employs a power electronic DC-DC converter circuit to convert the unregulated DC voltage of the solar system into regulated DC output voltage across the DC link. The DC-DC converter is characterized into two categories as isolated and non-isolated converters. However, an isolated DC-DC converter has galvanic isolation since the size, weight, and cost are increased due to the transformer. Even though non-isolated DC-DC converters are more efficient, but face the drawbacks of a lower voltage gain than isolated converters [10]-[12]. Generally, an MPPT controller is linked with a SPV system for obtaining maximum power and to perform efficiently [13], [14]. Different MPPT controllers, such as perturb & observe (P&O), incremental and conductance (INC), particle swarm optimization (PSO), fuzzy logic control (FLC), artificial neural network (ANN), and so on, are linked to a DC-DC converter, which provides the appropriate switching pulse based on the load requirement and allows for the maximum power from SPV across the load. For continuous and steady power flow in diverse environmental conditions such as irradiance and temperature, a bidirectional DC-DC (BDC) converter is interfaced between the DC link and the battery storage device with the SPV system. A BDC converter is a fusion of two antiparallel buck and boost converters in which the switching pulse is provided by a double loop proportional-integral (PI) respectively for both the charging and discharging of the battery. Under varying environmental conditions, a double loop PI control examines the voltage and current and delivers the switching that permits the BDC converter to maintain constant and continuous power across the DC link. A permanent magnet DC (PMDC) motor on account of easy control and efficient DC drives are majorly used in water pumping and electric vehicle in low-cost applications [15], [16]. Although brushless DC (BLDC) motors are widely used in electric and hybrid vehicles as these are easy to regulate, inexpensive, and have a larger load capacity, they have the disadvantage of having brushed commutators that induce commutator wear and shorten motor life.

In this article, the configuration of the PV system with particular components is presented in section 2. To perform the function efficiently, both the controller such as MPPT and the double loop PI controller which is implemented with the PV systems, are discussed in section 3. The performance of the PV systems which are analyzed based on mathematical modeling, are carried out in MATLAB with both the MPPT (P&O, INC) controller and has been discussed in section 4.

2. SYSTEM CONFIGURATION

A SPV system is designed in this structure to drive the 5 HP permanent magnet DC (PMDC) motor as depicted in Figure 1. In this configuration, a DC-DC boost converter is interfaced to regulate the dc voltage generated from SPV, using switching pulses i.e., acquired from the MPPT (P&O, INC) controller for extracting the optimal power across the DC link. Since the SPV systems are nonlinear and overly dependent on environmental conditions, a lithium-ion battery storage system is linked to a DC link via a bidirectional converter to perform as buck and boost mode, enabling the battery to be charged and discharged respectively with the PV system. Thus, the system acts as a hybrid system (a combination of SPV and battery storage system). The bidirectional converter's switching signal is provided by a double loop PI controller, which coordinates battery charging and discharging with the PV system while keeping a steady and constant power across the DC link at varied irradiances. The components used in this configuration are discussed in the next section.

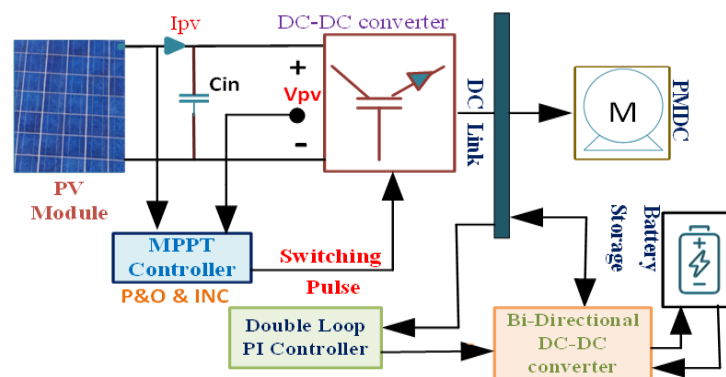


Figure 1. Configuration of SPV system with BESS

2.1. Solar photovoltaic system

When solar photons strike the cell's surface area, these are converted to electrical energy by a SPV cell. A series and parallel solar cell combinations are needed to enhance output voltage and current, respectively. In Figure 2, a single diode PV module having series resistance R_s and parallel resistance R_{sh} is shown. The characteristics of a SPV panel are entirely defined by environmental exposures such as irradiance and temperature. Figure 3 and Figure 4 show the P-V and I-V characteristics of SPV panels under distinct irradiation circumstances.

The PV module output current is represented by (1).

$$I = I_{ph} - I_o \left\{ \exp \left(V + \frac{IR_s}{nV_T} \right) - 1 \right\} - \frac{V + IR_s}{R_{sh}} \tag{1}$$

Where, I_{ph} , I , R_s , R_{sh} , and I_o represent the light generated current, the output current of the model, reverse saturation current, and series and parallel resistance of the single diode PV diode respectively.

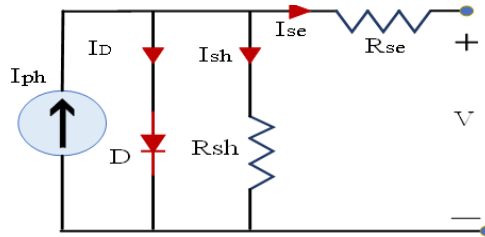


Figure 2. Single diode model of SPV module

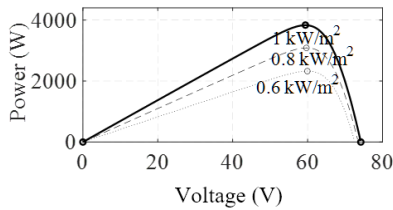


Figure 3. P-V characteristics of SPV array

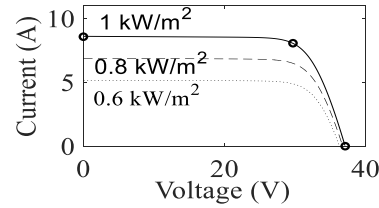


Figure 4. I-V characteristics of SPV array

2.2. Boost converter

A DC-DC boost converter is a power electronics circuit that is used to increase the output voltage by using the diode's switch-mode operation [17], [18]. When the switch is turned off, the diode acts as a reverse bias and the output is isolated from the input, allowing only the inductor to store the energy from the input. In the ON state, the diode operates as a forward-biased switch mode, and output across the load is achieved by utilizing the input and stored energy in the inductor. The characteristics of a DC-DC boost converter are determined by analyzing the circuit of a diode in switching mode. The voltage balance equation represents the converter's output voltage.

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

The inductor current,

$$\Delta I_{L1} = \frac{V_{in} * D}{f_s * L_1} \tag{3}$$

The capacitor ripple voltage,

$$\Delta V_{c1} = \frac{D * I_o}{f_s * C_1} \tag{4}$$

where V_o , I_o , f_s , D , L_1 , and C_1 represent the output voltage, output current, switching frequency, duty ratio, and size of inductor and capacitor, respectively. The size of passive components is designed by the circuit analysis of the DC-DC boost converter based on the converter's switch mode operation, as depicted in Figure 5.

2.3. Bidirectional DC-DC converter

Depending on the switching mode operation, the bidirectional DC-DC converter functions as a Buck or Boost converter to control the charging and discharging of the battery management system [19], [20]. The most important aspect when implementing this converter in a DC link with a battery storage system is to ensure a continuous and consistent power supply in the DC link to maintain the PMDC motor running at a constant speed under varying solar irradiation conditions. Figure 6 illustrates the basic structure of an anti-parallel bidirectional DC converter. When the solar irradiance is consistent, the switch S1 is turned on and the switch S2 is turned off, allowing the SPV system to drive the PMDC motor and store the energy in the battery, however, when the irradiance is irregular, the switch S2 is turned on and the switch S1 is turned off, allowing the DC motor to be powered by both the SPV system and the battery bank.

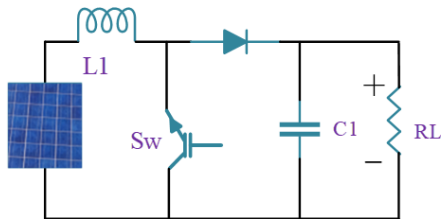


Figure 5. Schematic diagram of the DC-DC boost converter

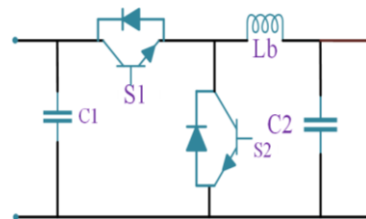


Figure 6. Schematic diagram of a bidirectional DC-DC converter

2.4. Permanent magnet direct current motor

The permanent magnet supplies the field flux for the permanent magnet direct current (PMDC) motor, which converts electrical energy into mechanical energy [21]. Since it is cost-effective and easy to regulate, therefore PMDC is favored in a wide range of DC power applications such as conveyors, car assembly, disc drive, and water pumping. For water pumping, a PMDC motor is used in conjunction with a SPV and a BESS as explained earlier in Figure 1. The armature voltage of PMDC is derived as mentioned in (5).

$$V = V_b + I_a R_a + L \frac{dI_a}{dt} \quad (5)$$

Where V_b , I_a , and V represent the back-emf, armature current, and armature voltage respectively.

3. CONTROL SCHEME OF THE SOLAR PHOTOVOLTAIC WITH BESS

Both the MPPT and the double loop PI controllers are applied in SPV systems. The MPPT controller is utilized to get the maximum or peak power output of the solar PV system [22], [23]. While the double loop PI controller is used to supply the switching pulse to the BDC converter in buck and boost operation for charging and discharging in BESSs, respectively to maintain the constant parameter of DC link for regulating the PMDC motor.

3.1. Perturb and observe

In the P&O MPPT controller, the input voltage and current of the PV module are sensed, and the duty cycle is tuned based on the load requirement. If the change in power ΔP in this method is positive, the algorithm is shifted to a maximum power point (MPP). If the power change ΔP is negative, it moves away from the MPP. This method is simple, easy to control, and provides a quick response. The control algorithm of P&O has been described in Figure 7.

3.2. Incremental conductance

The INC method utilizes the voltage & current derivatives to optimize the peak power point. This method is mainly based on fact that the slope of the PV curve of the SPV is equal to zero at maximum power. This algorithm has a better response but is complex in comparison to P&O. The control algorithm for acquiring maximum power has described in Figure 8.

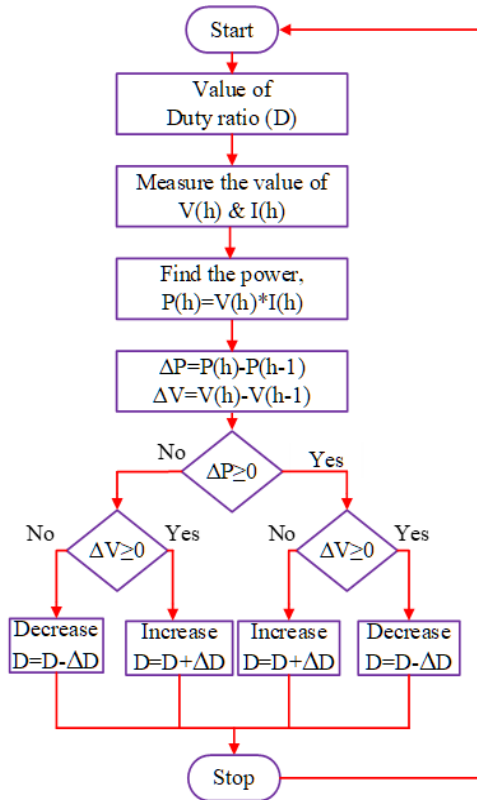


Figure 7. Optimization chart of P&O algorithm

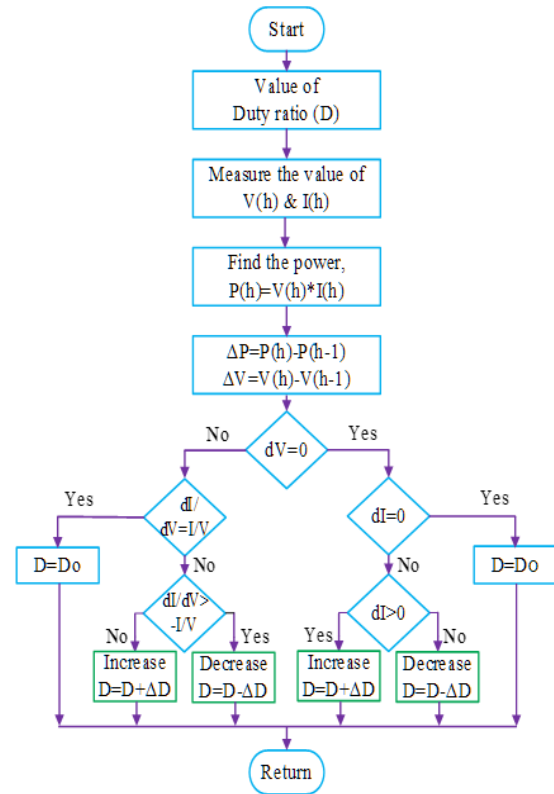


Figure 8. Optimization chart of INC algorithm

3.3. Double loop PI controller

The double loop PI controller as shown in Figure 9, has been used to get the appropriate switching pulse to the BDC converter in order to maintain the constant and consistent power across the DC link. The PI controller is a feedback control loop that examines the input and reference value [24]. It provides the switching pulse according to the error signal for the operation of the boost and buck converter and controls the discharging and charging of the battery.

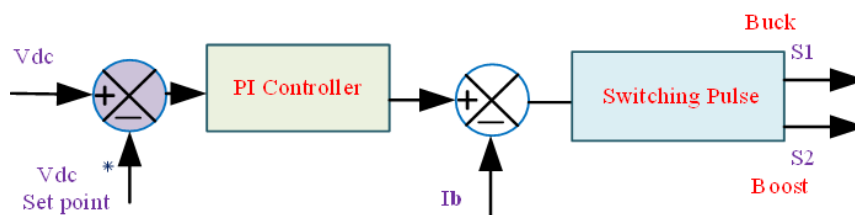


Figure 9. Schematic diagram of double loop PI controller

4. RESULT AND DISCUSSION

4.1. Standard test condition

The entire configuration has been analyzed with a constant and continuous irradiance and temperatures of 1000 W/m² and 25 °C. In both MPPT controllers, the PMDC motor runs at rated speed with the PV system, requiring no power from a hybrid or battery source. The PMDC motor at standard test condition (STC) has rotor speeds of 1448 RPM and 1504 RPM through the P&O and INC controllers, respectively as depicted in Figure 10 and Figure 11. As a result, the INC controller performed well as compared to the P&O method, in terms of less ripple in the DC link, higher efficiency, and being close to the rated speed of the PMDC motor. Table 1 shows the simulation results for various parameters for different solar irradiance as well as for distinct control techniques.

Table 1. Simulation results of solar PV fed PMDC motor

Parameters	MPPT controller	Constant	Varying			BESS		
			Irradiance (W/m ²)			1000	800	600
			1000	800	600			
V _{in} (V)	P&O	64.70	64.80	64.60	64.90	63.61	63.45	63.30
	INC	62.05	62.02	55.05	41.75	62.02	55.05	41.75
I _{in} (A)	P&O	53.10	53.00	43.50	32.50	56.75	46.00	34.60
	INC	60.38	60.04	53.85	41.05	60.40	53.85	41.05
V _{dc} (V)	P&O	105.00	105.00	95.50	82.50	109.25	108.75	108.00
	INC	108.75	109.00	97.04	73.73	109.50	108.50	108.00
I _{dc} (A)	P&O	30.00	29.90	27.20	23.60	31.30	31.00	30.80
	INC	31.10	31.11	27.70	20.93	31.25	31.00	30.75
P _{out} (W)	P&O	3150	3140	2598	1947	3420	3371	3326
	INC	3382.12	3391	2688	1543	3421	3363	3321
Efficiency (%)	P&O	82.15	81.89	84.15	83.74	89.20	87.92	86.75
	INC	88.21	88.44	87.07	66.37	89.22	87.72	86.61
Speed (RPM)	P&O	1448	1448	1313	1144	1509	1502	1491
	INC	1504	1505	1336	1006	1508	1502	1492

4.2. Under varying irradiance

In this context, dynamic insolation is provided to the PV system, and the response of the DC link and the PMDC motor has been thoroughly examined. The solar irradiation of 1000 W/m², 800 W/m² and 600 W/m² has been given to the SPV system at a time scale of 3 sec, 6 sec, and 9 sec respectively. Because of the varying irradiance, the voltage and current across the DC link fluctuate by the insolation level. As a result, the speed of the PMDC motor varies in response to changes in the DC link voltage and current without using BESS which are clearly explained in Figures 12-17. Thus, the INC controller outperformed the P&O controller in terms of efficiency.

4.3. Bess in hybrid systems

A battery has been connected to SPV as a second source of energy, making the system a hybrid one, which charges or discharges with the functioning of a bidirectional DC-DC converter in buck and boost mode [25]-[27]. At 1000 W/m² solar insolation, the buck mode is activated and the battery is being charged and the PMDC motor operates at its rated speed. However, at 600 W/m² and 800 W/m², the PV and battery both power the DC link, which is kept constant and continuous by the double loop PI controller. From the simulation results, it has been observed that the INC controller also performed efficiently with BESS in comparison to the P&O MPPPT controller as shown in Table 1.

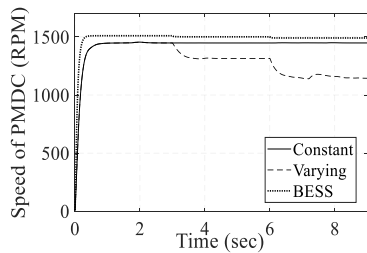


Figure 10. PMDC speed of P&O

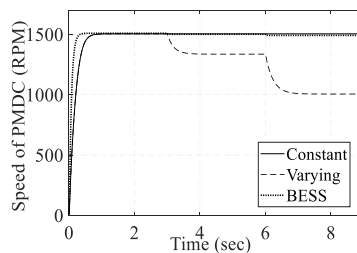


Figure 11. PMDC speed of INC

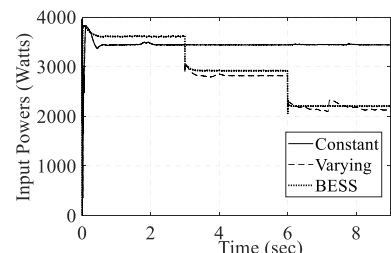


Figure 12. Input power of P&O

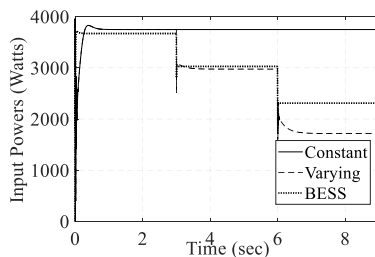


Figure 13. Input power of INC

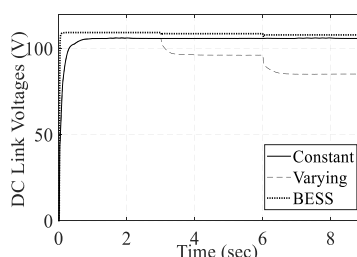


Figure 14. DC link voltage of P&O

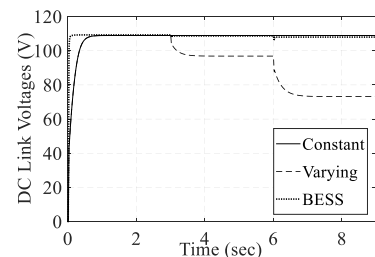


Figure 17. DC link current of INC

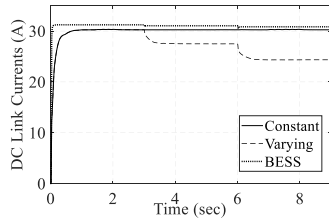


Figure 16. DC link current of P&O

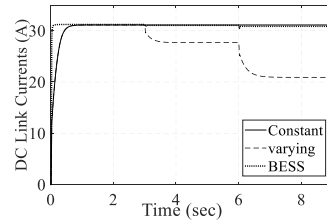


Figure 17. DC link current of INC

5. COMPARISON OF INC AND PERTURB & OBSERVE ALGORITHM OF MPPT

A comparison has been done for the outcomes of both the control algorithm’s performance and described in Figure 18 and Figure 19. The speed of the PMDC motor is found to be closer to the rated speed for the INC controller as compared to that of the P&O controller. Moreover, the system efficiency is found better for INC controllers as depicted in Table 1. The MPPT controller with the INC algorithm performed more efficiently than the P&O controller under STCs because it has a quite desirable response and less voltage and current fluctuations across the DC link, but the INC controller has more fluctuations in DC link voltage and current under varying irradiance conditions as shown in Figure 20 and Figure 21. To overcome the fluctuations in DC link due to the variation in solar irradiance, a battery energy storage system is coupled with an SPV system. At last, it can be concluded that the INC algorithm of the MPPT controller performed better than the P&O algorithm.

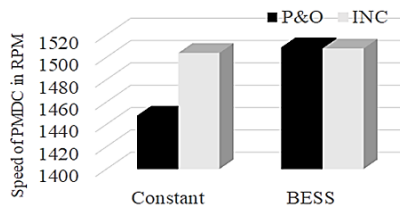


Figure 18. Speed of PMDC motor (RPM)

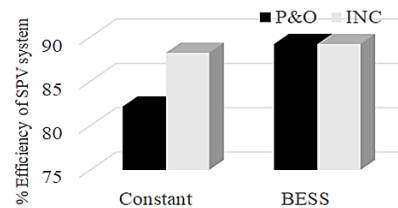


Figure 19. % efficiency of the entire system

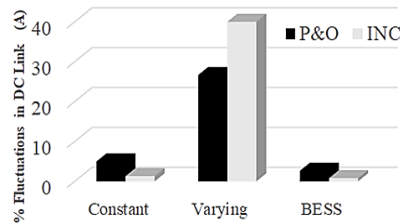


Figure 20. % ripple in output DC-link voltage

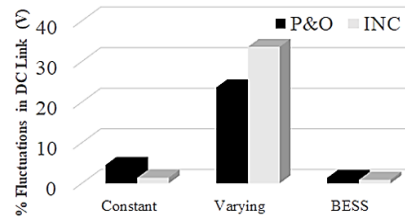


Figure 21. % ripple in output DC-link current

6. CONCLUSION

In this article, the performance of a solar PV fed 5 HPPMDC motor for a solar based water pumping analyzed using BESS to maintain consistent and constant power under intermittent solar insolation test conditions across the DC link using a BDC converter. The operation of the BDC is controlled by a double loop PI controller in buck and boost mode for performing the process of battery charging and discharging, respectively. The switching pulse conveyed to the boost converter is delivered through the MPPT controller with both the P&O and INC algorithms in order to harvest the maximum power from the system. The system's performance has been evaluated using both the MPPT controllers on the basis of PMDC motor speed, DC bus response, and system effectiveness. According to obtained results, the INC controller outperformed the P&O controller in STC mode. However, the P&O controller has a better response resulting in fewer DC-link fluctuations in varying irradiance. It has been concluded that the INC controller performed more efficiently than the P&O controller, but the P&O controller responds faster and is easier to implement than the INC controller. The simulation is carried out in MATLAB software and all the results have been explained graphically.




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