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An electromagnetic strategy to improve the performance of PV panel under partial shading☆

Ankur Kumar Gupta [a,*], Tanmoy Maity [a], Anandakumar H [b], Yogesh Kumar Chauhan [c]

[a] Mining Machinery Engineering, Indian Institute of Technology (Indian school of Mines), Dhanbad, India
[b] Computer Science and Engineering, Sri Eshwar College of Engineering, Coimbatore, India
[c] Electrical Engineering department, KNIT, Sultanpur 228118, India

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ABSTRACT

The conventional bypass diodes used in solar photo-voltaic panel have side-effects of forward voltage drop, reduction in efficiency and a few operational problems under partial shading condition. In this work, this bypass diode is replaced by an electromagnetic relay through an efficient alternative approach that consumes less power and offers higher efficiency under partial shading condition of solar module. This approach removes the problems like hotspot formation of the solar cell, open circuit fault under shading condition. A part of this work has been reported and published as an Indian patent. In this extended research work, the different components are designed for the partial shading condition. The hardware setup is developed, and hardware results are compared and validated with the simulated results. The proposed electromagnetic method, with no semiconductor device, works efficiently and effectively under partial shading (low irradiance) scenarios.

1. Introduction

In the present era of renewable energy sources, the solar energy has emerged as one of the most eco-friendly source of usable energy. It is extensively used across the globe since solar cells generate different outputs depending on various environmental factors. The solar modules' performance is reduced to an appreciable extent by the shading effects and hence an urgent need arises for more efficient and reliable solution. Low irradiance and shading conditions are manageable by facilitating the load current through an alternate path and this can be done by using bypass diode. The resistance of the cell under shadow becomes high and this is why the bypass diode requires. The load current determines the amount of power dissipated by the bypass diode. The efficiency of the solar panel is significantly reduced by the bypass diode. That is why it is essential to sensibly arrange the number of bypass diodes in a PV (Photo-Voltaic) module. It is highly significant to reduce the losses in the PV panel having bypass diode.

As the temperature rises, the condition of thermal runaway triggers which further increases the temperature. This results in more power dissipation and current expansion. Thermal runaway behaves like a positive feedback that becomes uncontrolled since the

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* Corresponding author.
E-mail addresses: ankurradikal@gmail.com (A.K. Gupta), tanmoy@iitism.ac.in (T. Maity), anandakumar.psgtech@gmail.com (A. H), chauhanyk@yahoo.com (Y.K. Chauhan).

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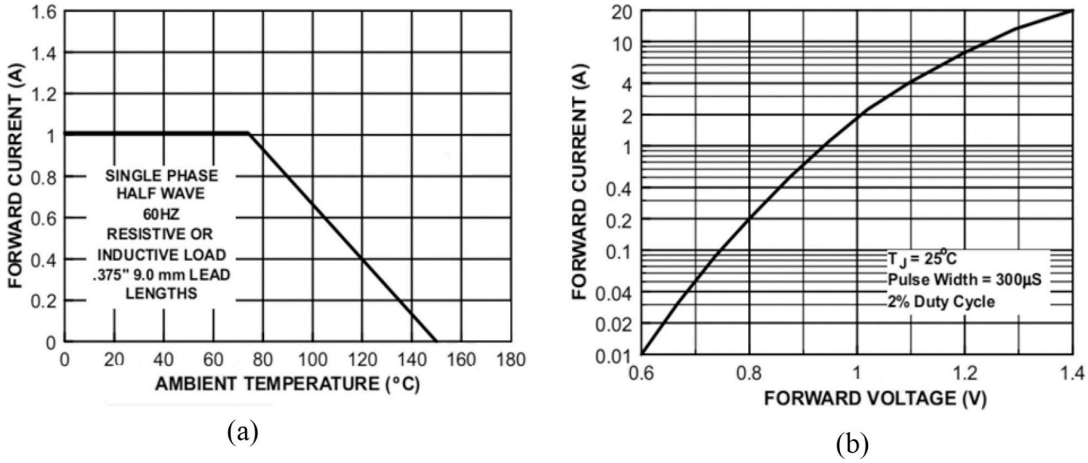


Fig. 1. Characteristicsof IN4007 Diode [4].

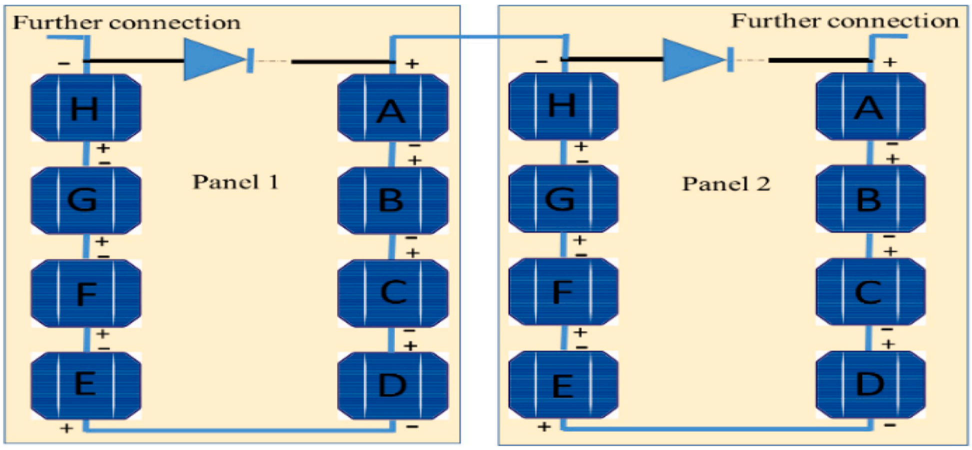


Fig. 2. Traditional connection of PV array with bypass diodes.

temperature keeps rising and current keeps expanding. As a result, it may ultimately damage the diode.

By getting the motivation from above-mentioned problems, it is important to focus on the safety of the working region of the bypass diode. This gives rise to the need for a creative solution that can help in increasing the efficiency of the PV module. The objective is to reduce the temperature effects to minimize the chances of thermal runaway and make the module energy efficient by consuming less amount of power. The main objectives of the proposed research are:-

To reduce the power losses across the bypass device, when the panel is under shading condition

To reduce the forward voltage drop when bypass operation is performed.

To eliminate the chances of open circuit fault of bypass diode.

To reduce the problems associated with temperature variation.

The primary focus of this paper is to propose an efficient alternative approach as a potential replacement of the bypass diode used with the strings of solar cells to efficiently resolve the nagging problems associated with it. The proposed method is compared with the available methods using different circuits and components which are dedicated to the partial shading conditions in solar panel. Diodes are also plagued by the problems, generally associated with the semiconductors [1]. The issues like thermal runaway, open circuit fault, forward voltage drop are mainly responsible for inducing problems in the solar panel [2]. The open-circuit fault creates a serious problem of hotspots in the solar cells [3].

The proposed technique works to remove these problems occurred in semiconductors. In the proposed technique, the total power consumption is 150 mW and is also free from forward voltage drop. It may be possible to reduce the power consumption further if suitable relays of low wattages are employed.

The research work is outlined as follows: introduction of the paper in Section 1, issues in existing semiconductor based bypass technology in Section 2, details of the proposed method in Section 3, setup of the experiment in Section 4, different modes of operation of panel in Section 5, comparison of experimental results in Section 6, mathematical model for simulation in Section 7, results and discussion in Section 8 and finally Section 9 concludes the paper.

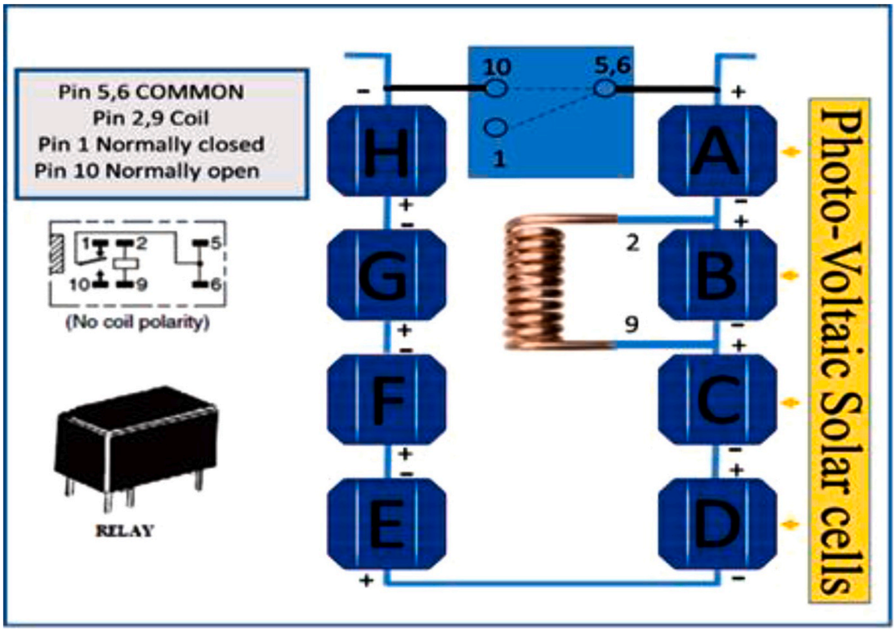


Fig. 3. Configuration of proposed circuit.

2. Issues in existing semiconductor based bypass technology

The semiconductor-based bypass technologies applied in photovoltaic panel pose a number of problems during operation under partial shading conditions. Some of the issues are detailed below,

2.1. Power losses

As per the data sheets offered by the manufacturer, the forward voltage drop (V_f) of the bypass diode is 0.6 V for silicon. The forward power drop is calculated as $P_f = V_f \times I_f$ where I_f represents the load current that depends on the load resistance. If the solar panel rated at 20V-40 W is considered, then it is capable of supplying a load current of 2 A. According to these ratings, the power drop in the bypass diode at $V_f = 1$ V is $P_f 1 \times 2 = 2$ W, calculated using Fig. 1(b) [4]. According to Fig. 1(a), the diode forward current decreases rapidly at a temperature more than 75 °C.

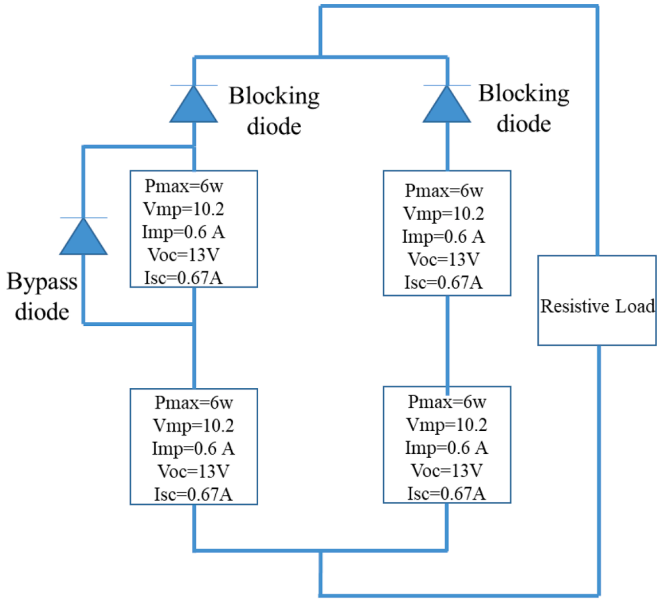
The connection of the bypass diode is shown in Fig. 2. Here, two series strings of solar cells are connected. The first string is called panel 1 and the second string is called panel 2 in which the cells 'A, B, C, D, E, F, G, H' are inter-connected. The bypass diode is connected between the positive of cell A and the negative of cell H. Normally, one bypass diode is connected across 16 cells in series due to cost-effectiveness. Whenever one of the cells is under the shading condition, the bypass diode offers an alternate path for the current and bypasses the inoperative string. In this way, the cells are protected from hotspot formation [5].

2.2. Thermal runaway condition

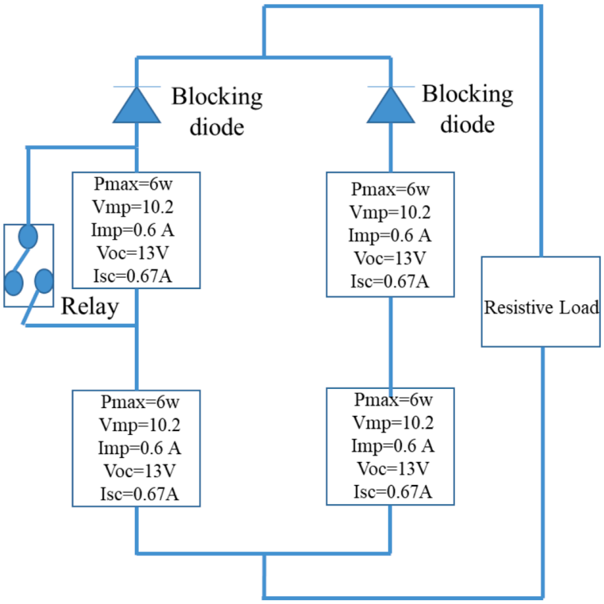
The increment in the operating temperature of the diode offers a high forward current. This will again increase the temperature of the diode due to cumulative property and finally the forward current increases beyond the critical limit of the diode [6]. In this way, the diode gets damaged due to high unsafe temperature [7]. In the proposed approach, the relay is investigated as the solution to this problem. It works independently of temperature effect, unlike in the case of the diode [8–10]. The relay requires only a limited magnetization current to operate and offers a low resistance path for the current. However, the maximum operating temperature for the relay is 90 °C. The diode IN4007 can be damaged if the stress exceeds the absolute maximum ratings. It is recommended by the manufacturer to avoid stress beyond a certain level to protect the diode. If the operating conditions are not met, the diode may be unable to operate properly. If stress keeps exceeding the recommended level, the reliability of the diode will be significantly lost. The absolute maximum ratings correspond only to stress ratings.

2.3. Open circuit fault

Under partial shading condition, the open-circuited bypass diode offers infinite resistance to the current of the solar cells [11–15]. This will not reduce the output power suddenly but can be dangerous because in this case, the diode is not able to protect the solar cell from the high reverse voltage across them [16]. In this way, a hotspot will form and ultimately results in a burnt back sheet [17–19].



(a). Block diagram with bypass diode



(b). Block diagram with relay

Fig. 4. Block diagram of the experimental setup.

3. Details of the proposed method

The proposed arrangement of the circuit under consideration is shown in Fig. 3. The cells A, B, C, D, E, F, G and H are connected in series configuration, the ends of the series strings are connected to the direct contact of the relay. The negative terminal of cell 'H' is connected to the point '10′ of the relay which is normally open point of the relay. The positive terminal of cell 'A′ is connected with a common terminal '5, 6′ of the relay. This common point is connected with point '1′ which is normally closed. The coil of the relay is connected across the cell 'B′. The coil terminals '2, 9′ can be connected parallel to any series cell of the string and do not affect the normal operation of the solar panel. Different relays offering a wide range of voltages and are easily available. So, this methodology can be applied on any voltage and current rating of the solar panel with a suitable relay of specific ratings. In the proposed method, the connections of single pole double throw relay with the solar panel have been suggested. The requirement of relay will be changed with

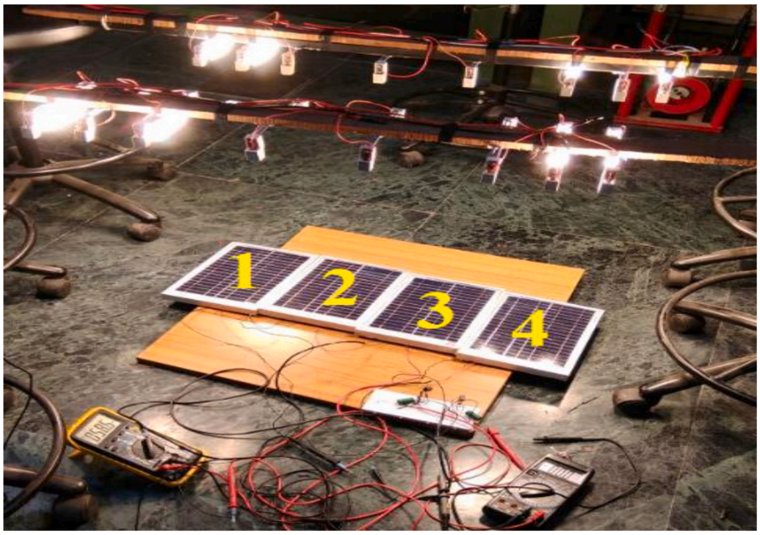


Fig. 5. Laboratory Experimental setup.

the rating of the panel. When the maximum current rating of the panel increases, the relay is also needed to be changed to withstand the increased load current under partial shading condition. There are many low power relays available that can control high operating current.

4. Setup of experiment

The block diagram of the experimental setup is shown in Fig. 4. For the testing purpose, the diode/relay is connected across only one panel that will be affected by the low irradiance. The irradiance level is dropped from 1000 W/m^2 to 50 W/m^2 to create the partial shading on the panel. The series-parallel configuration of solar panel with bypass diode is shown in Fig. 4(a) and the arrangement of solar panel with the relay is shown in Fig. 4(b). A digital storage oscilloscope (DSO) is used for the measurement purpose. The blocking diodes are used for both the conditions to protect the solar panels for reverse current. IN4007 diodes are used in the experiment. All the four panels of the experimental setup are of equal rating.

Fig. 5 shows the experimental setup under multiple halogen lights. Four solar panels are connected in the series-parallel configuration as per the Fig. 4. A low power relay of 960 ohms is also chosen to be used in the experimental setup [21]. In the testing setup of Fig. 5, the panels 1, 2, 3 and 4 are connected in series-parallel. A single pole double throw (SPDT) (1 form C) relay [21] is used for load current bypass. A rheostat is used as a load. The positive terminal of panel 1 is connected with the common contact of the relay and the negative terminal of panel 1 is connected to the normally open (NO) contact of the relay (refer Fig. 6(a)). When one of the cells of the panel 1 (say, A in Fig. 6a) is under shading condition, the resistance of the cell becomes greater than the coil resistance and the relay will actuate. In this mode, the relay terminal will change from normally closed (NC) to NO, the relay offers an alternate path to the current and panel 1 will be bypassed successfully. For current measurement purpose, the standard resistance of 1 ohm is connected as the load resistor and the voltage is measured using the DSO across it. By the Ohm's law, the voltage drop across this resistor is equal to the value of flowing current.

5. Different modes of operation of panel 1

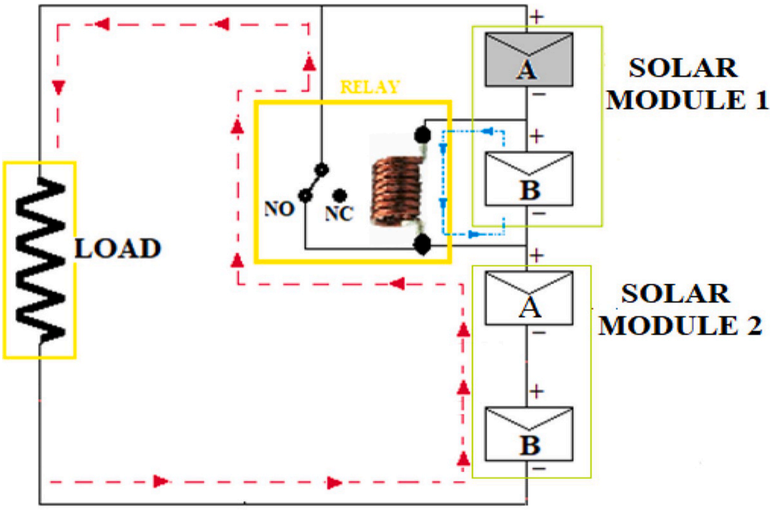
In order to explain the complete operation of the circuit, three modes are considered which depend upon the shading scenario.

5.1. Approach 1 (When cell A of panel 1 is shaded)

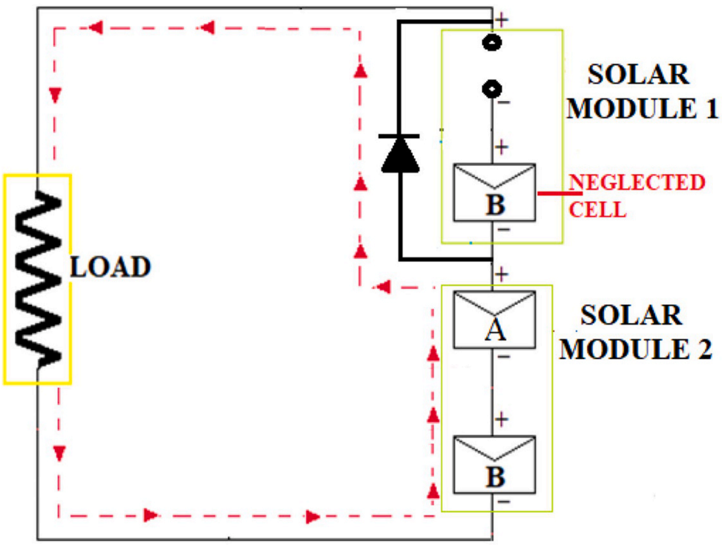
If the panel consists of two solar cells A and B, then assume a condition when cell "A" of panel '1′ is under the shading condition. The second cell is shorted by the relay coil and offers a closed path for the current which is generated by another series panel 2. In this condition, the relay will actuate and set to NO from NC as mentioned earlier. This will offer an alternate path for the current as shown in Fig. 6(a). In this way, the relay consumes 150 mW from cell 2. The red dotted line represents the flow of load current while the blue dotted line shows the coil excitation current. In the case of bypass diode, these strings are not contributing anything, as shown in Fig. 6 (b). This is another advantage that the proposed approach registers over the previous technique of bypass diode.

5.2. APPROACH 2 (When cell B is shaded)

In this case, cell 'B' of panel 1 is under shading condition. The coil current will flow as shown in Fig. 7. So the relay will be switched from NC to NO and offers an alternate path for the load current. In this case, the relay also consumes 150 mW.



(a). When cell A of panel 1 is under shaded condition [22]



(b). Configuration with diode

Fig. 6. (a). When cell A of panel 1 is under shaded condition [22]
FIGURE 6 (b). Configuration with diode.

5.3. *Approach 3 (When cell A and B are shaded)*

This is the third condition when the complete module 1 is under shading condition. In this mode, the coil of the relay will not be energized because none of the cells of the panel will provide the power to the coil of the relay. So to overcome this problem, an additional diode is connected in parallel with the solar module which is shown in Fig. 8 [20]. The diode will be turned on only when the complete module will be under the low irradiance. The test results of different operating modes of the proposed approach and their performance comparisons are shown in TABLE 1. Technical specifications of the components used are given in TABLE 4. Investigation on complete shading condition is not in the scope of this work and may be a potential scope in future. When the affected solar panel is under full irradiation again, the diode will shut down automatically.

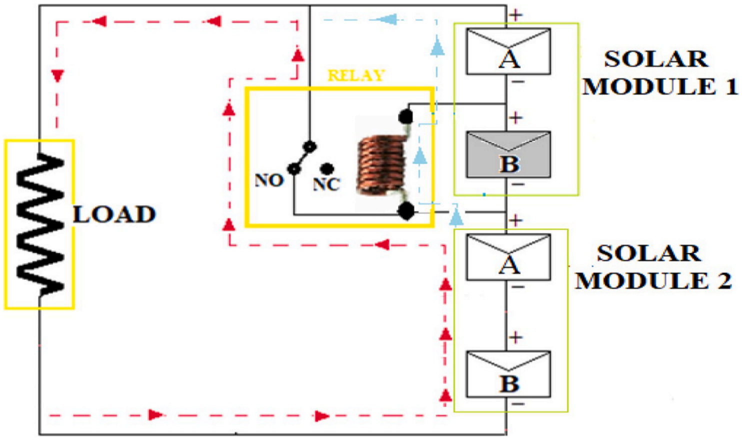


Fig. 7. When cell B is only under shaded condition.

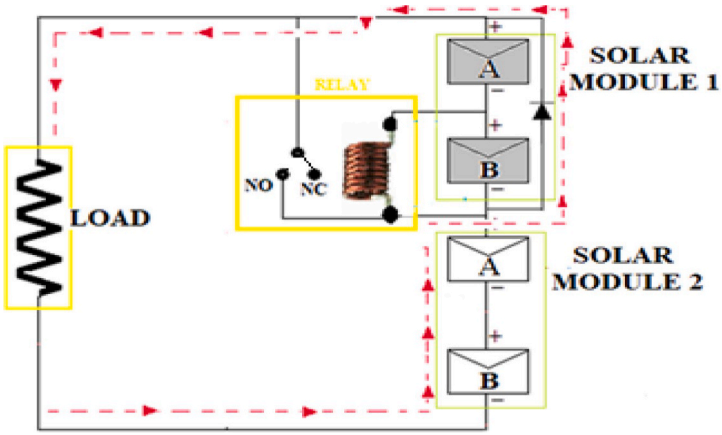


Fig. 8. when cells A, B of panel 1 are under shaded condition.

Table 1
Summary of device rating.

MODE	Operation	Operating Device	Load Current	Required voltage for relay	Required current for Relay (mA)	Diode forward Current If (Amp)	Diode forward voltage Vf (Volt)	Power (mW)
1	When Cell 'A' is shaded	Relay	0.779 Amp	12 Volt	12.5			150*
2	When Cell 'B' is shaded							150
3	When Cell 'A,B,C and D' are shaded	Diode				0.779	0.91	708 [4]

6. Experimental results

The experimental results with the bypass diode configuration are shown in Fig. 9 In the partial shading condition, the voltage is settled at 19.99 Volt and the current is settled at 0.62 Amp. The associated power is 12.39 W for this configuration. The results with the relay are shown in Fig. 10. Here, the voltage is settled at 19.99 Volt and the current is settled at 0.64 Amp, with associated power at 12.79 W. The auto-trigger mode is used for this purpose. The irradiance level is allowed to fall from 1000 w/m^2 to 50 w/m^2 for testing purpose.

7. Mathematical model for simulation

The mathematical model is designed in MATLAB/SIMULINK for the verification purpose and is shown in Fig. 11. A 2 × 2 array sized

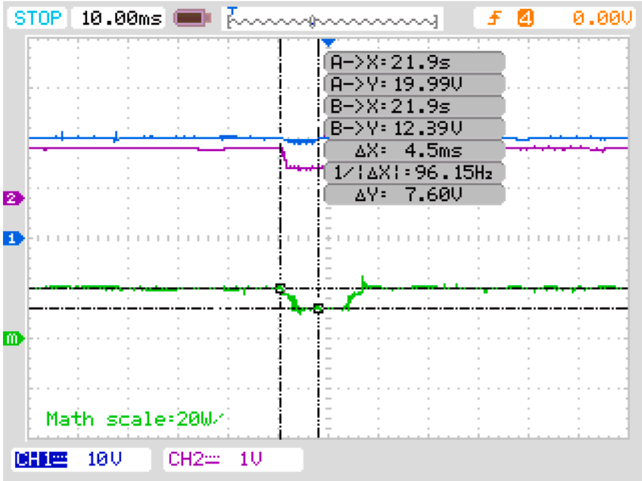


Fig. 9. Current, voltage and power profile during shading condition with bypass diode.

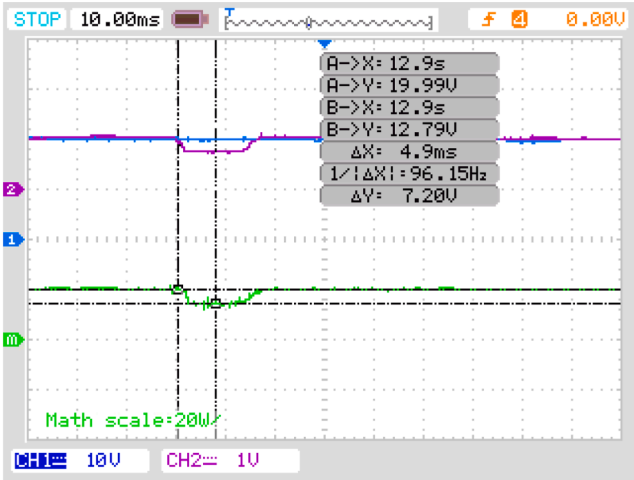


Fig. 10. Current, voltage and power profile during shading condition with relay.

series-parallel configuration of the solar panel is considered for this purpose. The simulation model is designed for both the relay and the diode. The SP1 solar panel is shaded in this configuration and the performance has been compared for both the cases. To evaluate the performance of the solar panel with relay or bypass diode, the scope function has been used. The voltage, current, and power are measured for both the cases and compared.

The simulation results for the comparison of models with bypass diode and relay configuration are shown in Fig. 12. The operation with the diode is shown in the Fig. 12(a), the value of voltage is 20 Volts (yellow line) and the value of power is 12.38 W (shown by channel 2) and the corresponding current after partial shading is 0.619 Amp (shown by channel 1). The operation with relay is shown in Fig. 12(b) and in this case, the voltage is 20Volts (yellow line), the power is 12.80 W (shown by channel 2) and the corresponding current is 0.641 Amp (shown by channel 1).

8. Results and discussion

The results of different operating modes are shown in TABLE 1. In approach 1, the relay does not consume the power from the source. The coil is actuated from the cell, which is neglected in the case of the bypass diode. The power used by the coil is provided by those cells which are neglected in the case of the diode (approach 1) as shown in the Fig. 6(b). This means that the forward voltage drop by the relay is due to the contact resistance of 100 milliohm. In the second case, the relay actuates with the energy consumption of only 150 mW and is independent of load, whereas the diode loss depends upon the load current. In the third approach, when the panel is under complete shading condition, then only the diode will operate.

When one of the panels is under irradiance of 50 W/m^2, then from Table 3, the total available power is 12.94 W. In this case, the

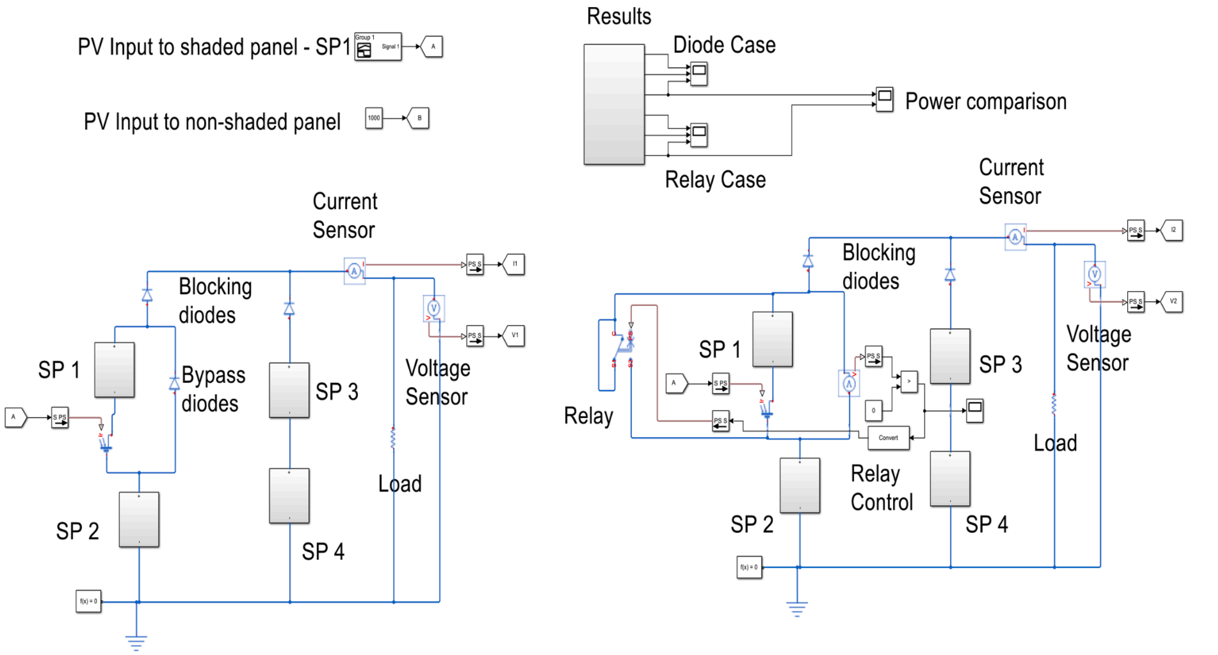
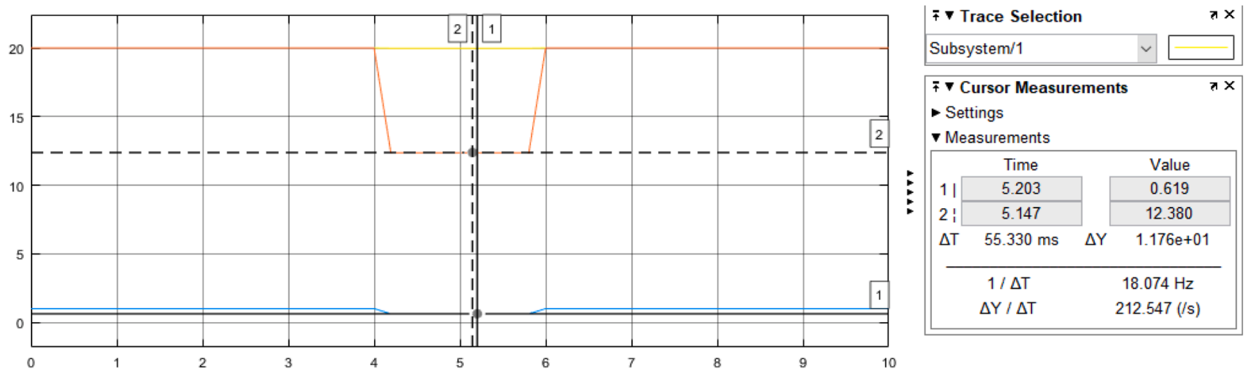
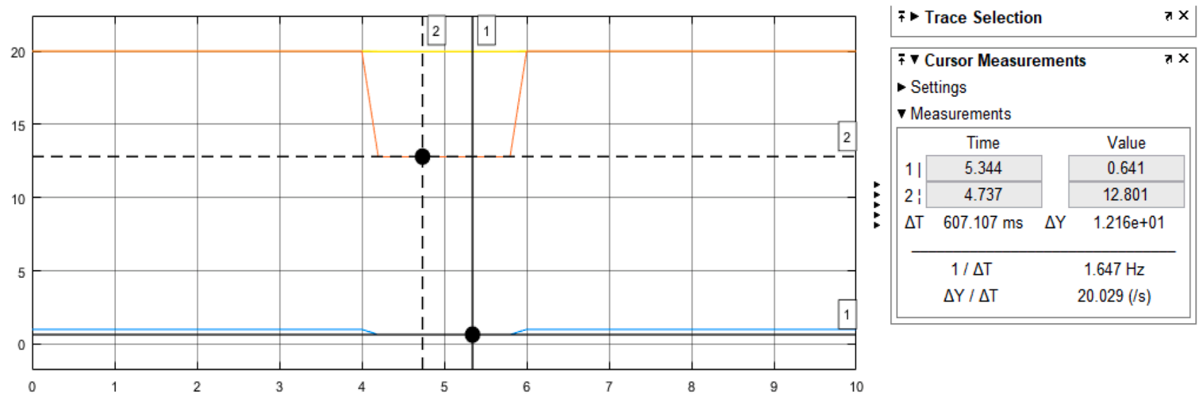


Fig. 11. Simulation model for comparison of the operation of panels with bypass diode and relay.



(a) Characteristics of voltage, power and current with bypass diode



(b) Characteristics of voltage, power and current with bypass relay

Fig. 12. Comparison of Bypass diode and relay configuration.

Table 2
Summary of operating modes and performance comparison.

S.No	Rating of one Panel	Irradiance	Panel Current	Panel voltage	Panel Power	Panel Performance with different components under partial shading				
			Without any bypass device							
1.	10Volt, 6 Watt (Standard)	Same on every cell (1000 W/m2)	1Amp	20Volt	20 Watt					
2.		Under shading condition	0.647 Amp	19.99 Volt	12.94 Watt	Parameter	Current (A)	Voltage (V)	Power (W)	Power Losses (mW)
						Diode	0.62	19.99	12.39	550
						Relay	0.64	19.99	12.79	150

Table 3
Results of partial shading on one panel from 1000 W/m2 to 50 W/m2 of operation with diode and relay.

Conditions		When irradiance is 1000 W/m2 (without shading)			When irradiance is 50 W/m2 on one panel		
		Voltage (V)	Current (A)	Power (W)	Voltage (V)	Current (A)	Power(W)
Power (without any device)		20	1	20	19.99	0.647	12.94
With Bypass diode	(H. results)	20	1	20	19.99	0.62	12.39
	(Sim. results)	20	1	20	20	0.619	12.38
With Relay	(H. results)	20	1	20	19.99	0.64	12.79
	(Sim. results)	20	1	20	20	0.64	12.80

Table 4
Technical details of devices use.

S.No	Device	Max OPERATING Temp.	Relay Voltage	Relay Current (mA)	Resistance (ohms)	Power (mW)
1.	Diode(In4007)	75 °C				950 (for 1 amp current)
2.	Relay	90 °C	12	12.5	960	150

Table 5
Comparison of proposed design with other components.

S. No	Device	Free From Thermal Runaway Condition	Possibility of Open circuit fault	Additional gate circuitry required	Forward voltage drop (mv)	Power consumption current (mW)	Power losses depends on forward current
1.	relay logic	YES	NO	NO	NO	150	NO
2.	SM74611 [23]	NO	YES	YES	26	208	YES
3.	Microsemi LX2400 [24]	NO	YES	YES	45	450	YES
4.	STM SPV1001 [25]	YES	not provide in data sheet	YES	yes (Actual data not provide in data sheet)	420	YES

operation with the diode provides 4.25% less power, whereas with the relay, it provides 1.15% lesser power from the available power. According to TABLE 2, the power consumption of relay can be calculated as total available power minus power in case of the relay which comes as 12.94–12.79 = 150 mW. The total power consumed by the relay is therefore, 150 mW that is equal to the same given in the datasheet of relay [21]. In case of the diode, the forward voltage drop as per the datasheet for IN4007 diode is 887 mV for 0.62 A current.

The comparison chart of the proposed design with other components is shown in TABLE 5. The relay specimen that is used in the experiment is Omron G5V-1-T90. If the value of load current is high, other models of the relay like ALQ112 for 10 A, may be used. The advantage of the relay is that it withdraws only current actually required by its coil to get energized. So, the power consumption is fixed and independent of load current. The SM 74,611 having the power consumption of 208 mW that depends on its forward current [23]. In LX2400, the power consumption is 450 mW and increases with the forward current. The SPV1001 offers 420 mW power consumption and it again increases with the forward current.

The other electrical parameters are also compared, shown in TABLE 5. The relay logic is free from the thermal runaway condition, the open circuit fault and the forward voltage drop. The relay offers the lowest resistance when energized. So, due to the low resistance of this metallic contacts of the relay, the forward loss in the relay is very low. The operating time of the relay is 5 ms which is quite appropriate for this operation. This is the only semiconductor free method for bypassing the current.

Conclusion

The bypass technique for the solar PV panel using electromagnetic relay is tested successfully. The experiments are performed on PV panel setup with conventional bypass diode as well as with the proposed relay. The results of the performance are compared at variable irradiance conditions. Further, the results have been validated through the developed model on Matlab/Simulink. The proposed method works successfully and consumes only 150 mW power losses under partial shading condition which is very low in comparison with the bypass diode, that consumes 550 mW at 0.62 A under the same shading condition. The proposed method is judged as a better alternative, replacing the conventional methods in terms of the absence of thermal runaway condition, a lesser requirement of control circuitry, elimination of open circuit fault, and reduction of forward loss. The other advantages of the proposed circuit are observed as its independence on temperature, offering semiconductor-free alternate path for current, absence of jumble circuitry, offering plug and play option, ability to operate without any external signal or any other device for controlling purpose. The power consumption of the proposed relay is independent of load current and it uses the unutilized power of the cell itself that is neglected in case of bypass diode. Further, it needs no external power supply, no effect on the normal operation of the solar panel and responds rapidly under low irradiance condition.

Declaration of Competing Interest

We don’t have any conflict of interest.

Acknowledgment

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Ankur Kumar Gupta is a research scholar from IIT (ISM) Dhanbad. He has worked as an R&D Engineer in the field of power electronics (AC to DC and DC to DC CONVERTER). His research area includes Power Electronics and Converters, Renewable energy-based electrical power generation.

Tanmoy Maity, received PhD from Bengal Engineering & Science University, Shibpur. He has six years industrial and more than eighteen years academic experience. He is currently working as Associate Professor in Indian Institute of Technology (ISM), Dhanbad, Jharkhand, India.

Anandakumar H, Professor(Associate) and Research Head in Department of Computer Science and Engineering, Sri Eshwar College of Engineering, Coimbatore, Tamil Nadu, India He has received his Master's in Software Engineering and PhD in Information and Communication Engineering from PSG College of Technology under, Anna University, Chennai. His-research areas include Cognitive Radio Networks, Mobile Communications and Networking Protocols.

Yogesh K. Chauhan has obtained Ph.D. on induction generator from Thapar University, Patiala, Punjab. Presently, He is working as Associate Professor, KNIT Sultanpur. He is having more than 20 year of teaching/research experience. His-research interests include Power Electronics and Drives, renewable energy based electrical power generation.