FAULT DIAGNOSTIC METHOD FOR PV FED 3-LEVEL BOOST CONVERTER

Shivam Verma[1], Hem Prakash[2], Shrey[3]

[1]*B. Tech Delhi Technological University, Shahbad Daulatpur, Delhi-110042*
[2]*B. Tech Delhi Technological University, Shahbad Daulatpur, Delhi-110042*
[3]*B. Tech Delhi Technological University, Shahbad Daulatpur, Delhi-110042*

---***---

Abstract - *Photo-Voltaic (PV) technology features minimum impact on the environment and is appropriate for a wide variety of applications. The main barrier for an additional in depth implementation of this technology has been the reliability, primarily associated with the power converters.*

In view of this consideration this paper presents a scheme for an open circuit fault diagnosis and fault tolerant mechanism for a three-level Boost Converter. The configuration will be fed with a Photo-Voltaic power system in conjunction with batteries as a storage device. The fault primarily on which we will be dealing is open-circuit power switch fault which is one of the common faults involved in power converter failures. The fault diagnostic methodology makes advantage of only the control variables provided for Maximum Power Point Tracking and voltage balance of output DC link capacitors.

The fault-tolerant strategy is a type of up-gradation of the conventional/original three- level boost converter in which few more components are added so as to make minimum compromise with the cost effectiveness. Also the modified converter provides a feature in which under an open-circuit power switch fault, it can be partly reconfigured into a two-level boost converter ensuring battery energy supply. Simulink based circuits and algorithms are designed to show implementation of the fault tolerance methodology.

Key Words: Fault Diagnosis, DC micro-grid, Grid connected photovoltaic system, MPPT, Boost Converter, Coupling capacitors, MATLAB/SIMULINK.

1. INTRODUCTION

There are 3 basic sorts of PV systems: grid-connected, standalone, and hybrid PV systems. They need specific applications and design considerations. High-energy central power plants with an oversized range of PV modules in an exceedingly vast space and possessor PV systems are the foremost common practices to attach electric power created from the PV cells in the grid. These systems are composed of many PV modules (which will have different arrangements), dc-dc converters with MPPT control, and inverters. Standalone power systems supported by PV technology and storage devices are another resolution for low-power remote instrumentality. DC–DC converters have a main role in learning, the facility created by the PV generator. They track its maximum power point (MPP) at any weather conditions and supply the power interface to a dc bus, within the case of standalone (either only PV or hybrid) systems, or to associate in nursing the converter, within the case of grid connected systems. A failure within the dc–dc converter can have an effect on the whole PV system and it would cause its stoppage, since it is directly connected to the arrays. As in several different power applications, electrolytic capacitors and power switches are the foremost seemingly elements to fail in PV power converters, as a result of which they are exposed to high mechanical and thermal stresses. Short-circuit fault protection is already by a typical application integrated in most power switch drives. An open-circuit power switch diagnostic technique for 2 cascaded buck non-isolated converters is given in [15] and [16]. This technique uses the measured output voltage and current at the supply and load converters. The third applied math moment of the measured signals provides the desired info regarding the location and sort of fault [15], [16]. Diagnostic strategies for isolated topologies square measure conferred in [12], [17] and [18]. The diagnostic technique conferred in [17] solely detects the MOSFET fault of a zero-voltage-switching (ZVS) dc–dc converter at the starting moment that may be a disadvantage because it doesn't stop fault propagation throughout the operation of the dc–dc converter. It uses the integral and maximum values of the dc-link current patterns. Another diagnostic technique restricted to ZVS dc–dc converters is presented in [12]. It detects any open-circuit power switches' fault victimization of the electrical device primary voltage of the converter followed by triggering a full of life part shifted within the system to find it. Afterward, the converter is reconfigured to stay its operation beneath reduced load.
There are alternative works on multilevel inverters [19], [20] that are extended to multilevel dc–dc converters [21], [22], because of their presently important application in modern vehicle styles. These methods are principally supported by the principle of system redundancy and on remedial management. Any of the isolated dc–dc converter topology are often applied in a PV system. Therefore, conduction and switching losses and magnetic force interference noise are reduced.

This paper presents a new style for the three-level boost converter so as to create it fault-tolerant to power switch open-circuit faults. A fault-diagnostic technique is additionally planned based on the converter faulty operation during a PV system supplying batteries. The fault-tolerant strategy is a type of up-gradation of the conventional/original three- level boost converter in which few more components are added.

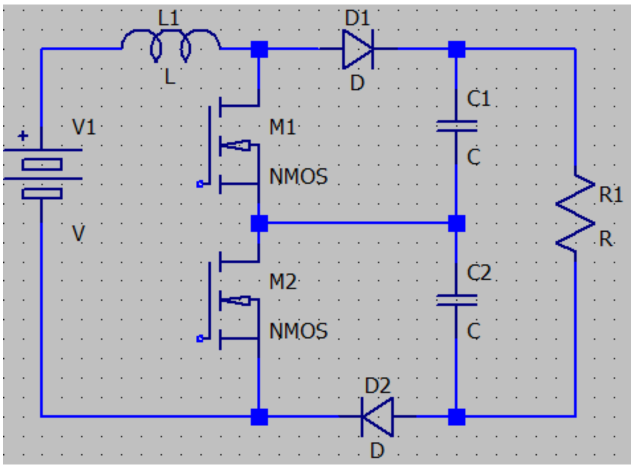


Fig -1: Original 3-level boost converter

2. PV SYSTEM OVERVIEW

2.1 Basic Configuration

The PV system is supported by a standard three-level boost converter, whose application in PV arrays with high output-voltage requirements has proved to be very economical. During this specific case, for fault-tolerant purposes, a really few extra elements are required, when compared to the standard topology, and therefore the PV array must have a minimum of 2 series modules or the other even variety of series modules association, as long because it is feasible to find a middle purpose dividing the module series to attach it to the converter. Examples of attainable combos for the appliance of this fault-tolerant dc-dc converter topology is shown in Fig. 2. This scheme is convenient for several applications, as a result the output voltage of PV modules is incredibly low. Besides the said compulsory feature, the topology needs a minimum of two inductances and 2 capacitors at the input capacitor bank whose values will total up to the initial designed one. It also requires a lot more sensors than the standard topology for measuring the input current and voltage of every division of the series combination of PV modules.

The standard topology only wants the whole input current and voltage measure of the whole PV array, whereas each topology wants voltage sensors at the output capacitors for leveling the dc-link voltage, which is obligatory by the batteries. Finally, a TRIAC is additionally needed connecting the point of the input capacitor bank to the point of the insulated-gate bipolar transistors (IGBTs). This TRIAC is merely triggered within the case of a fault prevalence.

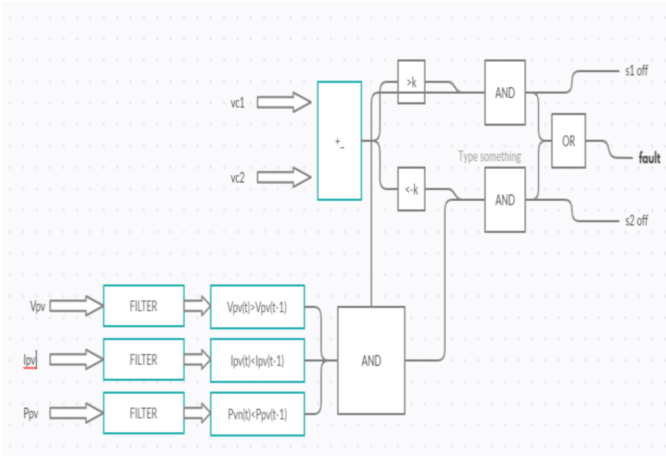


Fig -2: Fault Detection Algorithm

2.2 Operational Process

During a normal state, the circuit behaviour is similar to the conventional topology, though its control has been custom-made for a PV system. Power switch S1 is controlled so as to supply MPPT by suggests that of mistreatment perturb and observe technique and it uses the total array output voltage and one of the motorized currents. Power switch S2 balances the output dc-link electrical device voltages. The circuit analysis is split into normal state (operation of the circuit with none fault), faulty state (transient once an open-circuit power switch fault), and restored state (post fault circuit operation with the projected fault-tolerant strategy that requires hardware and software reconfiguration). The normal state is characterized by four operation modes, according to the ability switches conduction state, which may be both conducting, or each turned OFF, or one of them conducting and the alternative turned OFF. When an open-circuit fault happens in any of the power switches, the converter stops operating before long. Before that happens, a transient state occurs that is illustrated in Fig. 4(a) for an open-circuit fault in S1 and in Fig. 4(b) for an open-circuit fault in S2. Once an open-circuit fault, the remaining healthy IGBT continues operating whereas it receives impulses to show on (until the control stops working). Only 2 in operation modes are possible: each power switch OFF and one power activate (the healthy one) and therefore the different OFF (the faulty one). During the period wherever each S1 and S2 are OFF, diodes D1 and D2 are forward biased and conducting and each output dc-link capacitor is charging. Presumptuous that all components are ideal and the supply voltage is constant throughout one change period, the equations associated with this operation mode are as follows:

$$Vpv1+Vpv2 = (L_1+L_2)\partial i/\partial t+V_{C1}+V_{C2} \quad (1)$$

$$C_1\partial V/\partial t+i_0 = i_L \quad (2)$$

$$C_2\partial V/\partial t+i_0 = i_L \quad (3)$$

According to (2) and (3), the charging current of both capacitors is $iL - io$. During the period where S1 is ON and

S2 is OFF owing to an open-circuit fault, diode D1 is reverse biased and diode D2 is conducting. The charging current of capacitor C1 is iL − io and capacitor C2 will be discharging with a current io . The following equations are related to this operation mode:

$$Vpv1+Vpv2 = (L_1+L_2)\partial i_L/\partial t+V_{C2} \quad (4)$$
$$C_1\partial Vc1/\partial t+i_0 = i_L \quad (5)$$
$$C_2\partial Vc2/\partial t+i_0 = 0 \quad (6)$$

In the case of a fault in switch S2, C2 will charge with a current i_L − io while C1 discharges with a current i_o. This will result in an unbalance between both output dc-link capacitor voltages, according to how much time the control will be sending impulses to the healthy power switch and the rate of the capacitors charging or discharging. As aforementioned, the capacitor which is charging or discharging depends on where the open-circuit fault occurs. After diagnosing and detecting the fault occurrence, the control and the circuit are rebuilt to continue operating, although obviously under worst conditions, such as lower power, higher input ripple, and higher voltage on the power switches (and consequently higher stresses).Based on the fault location, the circuit reconfiguration is slightly different.

3. FAULT DIAGNOSTIC METHODOLOGY

The conventional three-level boost device employs a reduced number of control variables (only the input current and voltage for Maximum Power Point Tracking (MPPT) functions and therefore the output dc-link capacitor voltages for balancing them) and that they also are helpful for fault detection, which is desirable for avoiding further hardware and prices. The fault-diagnostic technique should be reliable and sturdy against transients associated with load variations or atmospheric conditions which have an effect on the PV array. Temperature and radiation changes disturb the MPPT of the PV array output voltage, current, and power in several ways which are illustrated in. If the radiation will increase throughout the day, the MPPT voltage slightly increases and therefore the current MPPT has a higher increment, while the MPPT power will increase. If the radiation decreases, the results are going to be the opposite with the MPPT voltage temperature and irradiation effects on the PV cell behaviour is not significant.

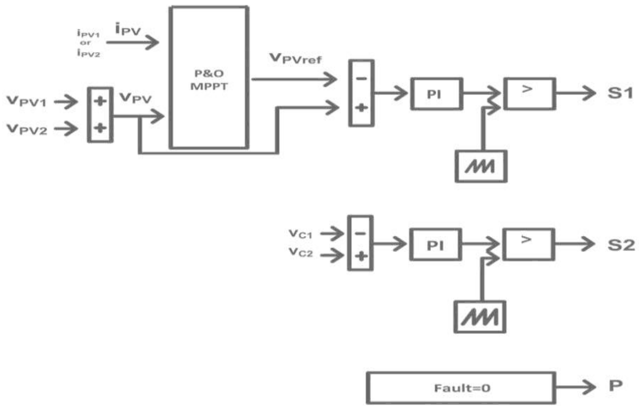


Fig -3: Normal State

According to the mentioned properties of the voltage and current at the PV cell MPPT, the impact of temperature and solar irradiation on most power is simply derived. As the Temperature will increase, the current at PV cell MPPT will increase, but the impact on the voltage is a lot more important. Therefore, the effect of temperature on the PV cell maximum power is going to be similar to the impact that it's on the voltage at the PV cell most point. The star irradiation has similar qualitative effects on both electrical parameters at the PV cell MPPT. Consequently, the impact can qualitatively be an equivalent on the MPPT.

	Voltage	**Current**	**Power**
Temperature Increase	Decrease	Increase	Decrease
Temperature Decrease	Increase	Decrease	Increase
Irradiation Increase	Increase	Increase	Increase
Irradiation Decrease	Decrease	Decrease	Decrease
Fault	Increase	Decrease	Decrease

During a fault transient, the ability and current suddenly drop, while the voltage will increase (until the PV array open-circuit value). Above table summarizes this data that permits diagnosis of an open-circuit fault incidence by observing the input power, voltage, and current. These variables should be filtered so that sensor noises, tiny transients associated with the MPPT management, and variable ripples don't compromise the diagnostic results. This implies the utilization of a little cut-off frequency, which will delay the signal acquisition. The fault detection isn't affected by this reality, as a result of solely the signal qualitative variations (an increase or decrease) are used for fault detection and their price is not vital. Regarding the filter style, a decent performance is obtained with first-order low pass filters with a frequency between 0.5 and 1 Hz.

Such fault-detection method can be applied to any dc–dc converter controlled for PV MPPT, because any power switch open-circuit fault will lead to control failure. While the current and the power are decreasing, the voltage will increase as explained.

After detecting the fault, it is necessary to locate it, because this topology has two power switches. For fault localization, the unbalance between the capacitor voltages is used. A fault diagnostic variable can be made from the voltage difference between the output dc-link capacitors:

$$F1 = VC1 - VC2 \quad (7)$$

If F1 is bigger than a predefined positive threshold k, then the faulty switch is S1. If F1 is smaller than a negative threshold −k, then the faulty switch is S2.

We will take the value k as 3.6v for our modelling. This value k is determined on the basis that the capacitor DC-link voltage should be within 3% of the operating output voltage which is determined by the battery in our case.

The whole diagnostic method is summarized as follows.

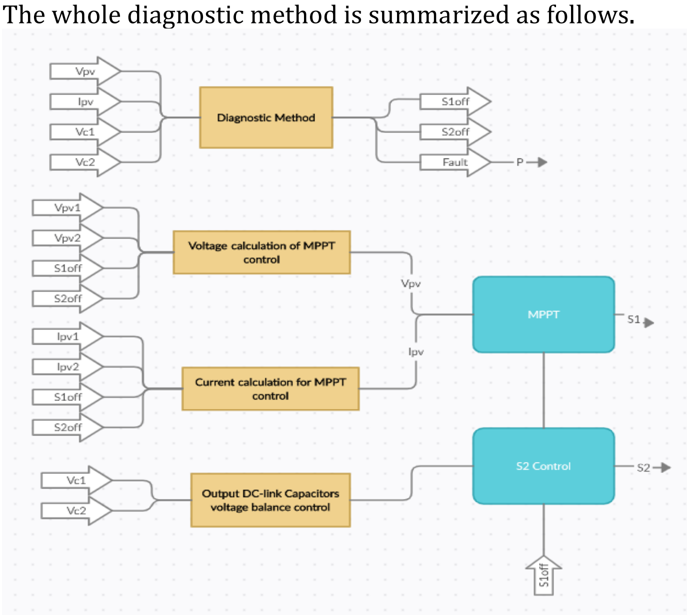


Fig -4

4. RECONFIGURATION METHOD FOR FAULT-TOLERANT OPERATION

The circuit is reconfigured for post fault operation after having detected the fault and identified the faulty switch. The circuit and the whole control system are shown with some more detail in Fig. 7. When the three-level boost converter is in the normal state, the control system uses the PV array total output voltage and current for the MPPT and the output dc-link capacitor voltage for balancing it. Therefore, the PV array output-voltage sensor signals are summed up and only one of the current sensors is used. Power switch S1 is used for MPPT control and power switch S2 is used for balancing the output dc-link capacitor voltage during the normal operation. The control system used to keep the converter operating is different by fault detection depending on whether the fault has occurred in power switch S1 or power switch S2. However, the concept is the same: when one of the power switches stops working, the three-level boost converter is reconfigured into a conventional two-level boost converter with MPPT control for half of the module array while the other half is still operating without MPPT control for not overcharging the remaining part of the circuit. As a result the converter does not stop working, after the fault occurs, although providing less power.

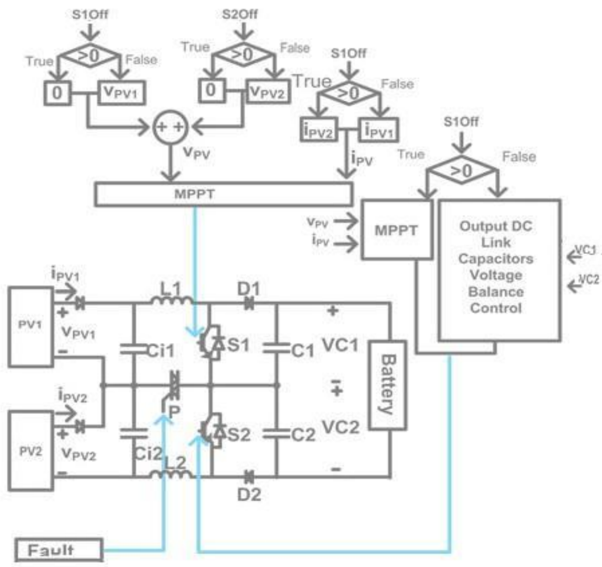
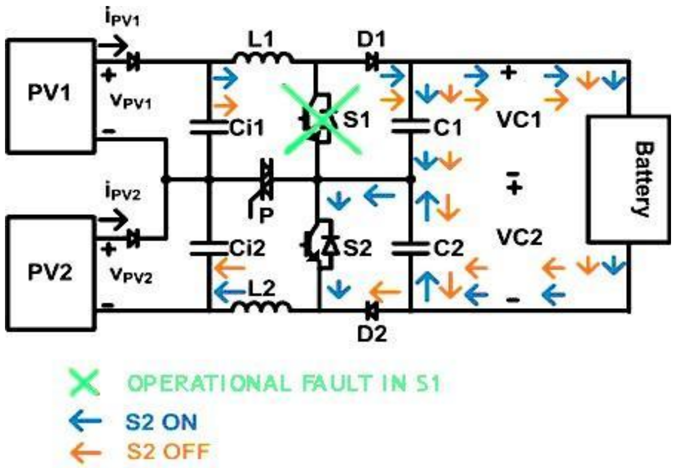


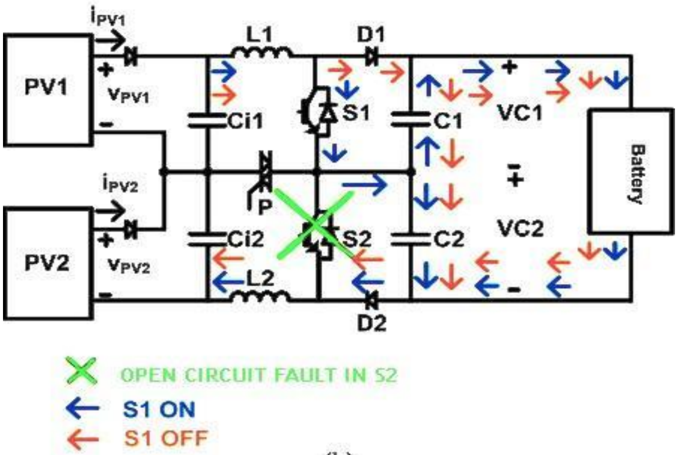
Fig -5: Circuit Operation

After fault detection, if power switch S1 suffers an open-circuit fault, TRIAC P is triggered, providing the hardware reconfiguration for a two-level boost converter. The control system is also reconfigured according to Fig. 8. The measured current is that from the other current sensor, providing only the second half PV array output current and also only its output voltage are observed. Then, power switch S2 stops dominating the output dc-link capacitor voltages and provides MPPT control for this rearranged two-level boost configuration. Alternatively, if power switch S2 suffers an open-circuit fault, after its detection, TRIAC P is also triggered, providing again the hardware reconfiguration for a comparable two level boost converter. The control system is reconfigured much the same goal, but the changes are not the same. Then the current remains the same, which is the first half PV array output current (see Fig. 8), and also only its output voltage is observed. Afterward, S1 continues the MPPT control, but only for a two-level boost converter. The left half of the PV array continues supplying the batteries, but unless of MPPT control.



(a)

Fig -6



(b)

Fig -7

5. CIRCUIT SIMULATION

Following Simulink circuit shows show the implementation of the proposed methodologies for an open-circuit fault in power switches 1 and 2. The current and voltage MPPT control variables of the converter with an open circuit fault in power switches 1 and 2 together with the total input power and the output dc-link capacitor voltages are related to the diagnostic method. Before a fault occurs, during the normal state, both modules are used to track the (Maximum Power Point) MPP of the array. Therefore, the input of the MPPT algorithm control is the sum of both modules output voltages until the instant when a fault occurs. When a power switch open-circuit fault is introduced, the PV array output voltage increases (until its open-circuit voltage, if the fault is not detected) while its output current and power suddenly decrease. Under these conditions, together with the output dc-link capacitor voltage imbalance, the fault-diagnostic variables turn ON when the output dc-link capacitor voltage unbalance exceeds the threshold value which we have taken as 3.6 (3% of the connected battery). The duration from faulty state to normal 2 level converter state depends on the charge/discharge rate of the output dc-link.

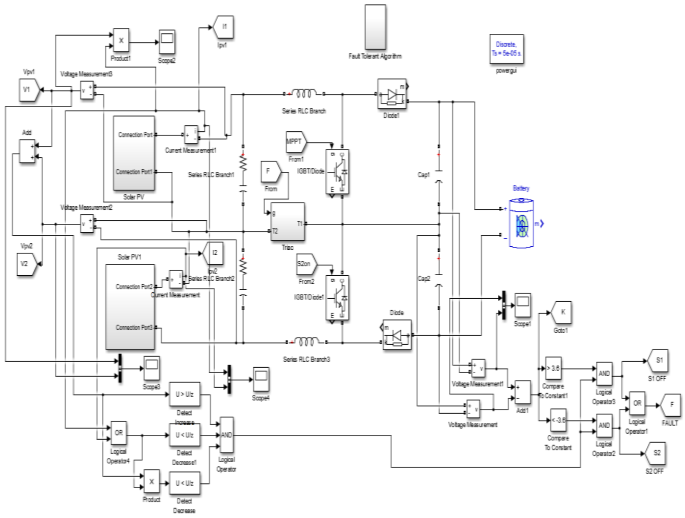


Fig -8: Simulink Model implying the mentioned Algorithm

As soon as the fault is detected the converter is immediately reconfigured into a partly two-level boost converter with MPPT control only for one of the PV modules, while the other still produces energy, but without MPPT control. When the fault occurs in S1, after fault detection, PV module PV1 (see Fig. 6) is monitored for MPPT control. After the reconfiguration for post-fault operation, it produces the same power which it was already producing before the fault occurrence and it presents the same output voltage and current, unless the climatic conditions change. PV module PV2 still produces power, but its output power, voltage, and current are very different from the previous ones, because it's MPP is no longer being tracked; otherwise, it would overcharge the converter.

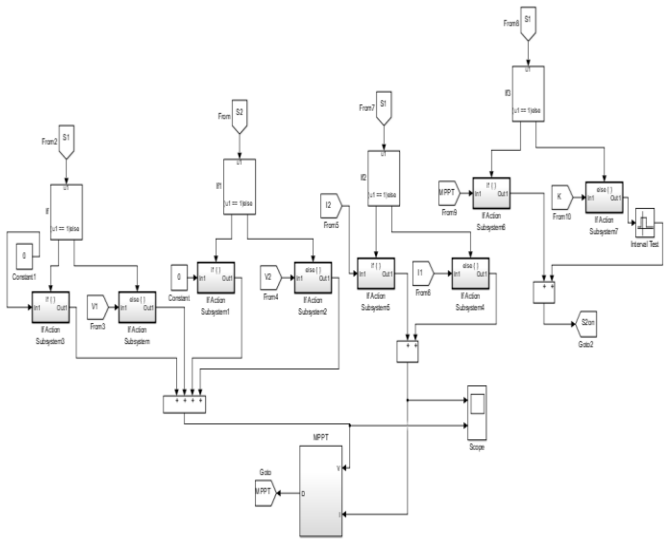


Fig -9: Fault Tolerant Algorithm

Similar results were obtained for a fault occurring in S2, but, in this case, PV module PV2 is monitored for MPPT control while the other is not. The reconfigured converter produces approximately 30% less power than the original one in both cases and for different climatic conditions. At the same time, it introduces higher stresses on the remaining healthy IGBT, due to the output dc-link capacitor voltage unbalance, making the IGBT voltage some 30% higher. Besides, the PV module with MPPT control has higher output voltage and current ripple. These are the main disadvantages and limitations of this strategy, which should be expected, because they are related to the disadvantages of two-level boost power converters over the three-level ones. However, the converter remains operating until it can be replaced without stopping supplying batteries, which can be useful in critical applications where the power supplying should be uninterrupted. The fault-diagnostic method is effective even under variable climatic conditions, whose variation is usually very slow, and under any load condition, because the battery controls the dc-link voltage while working in its safe operating voltages, without overcharging or deep discharging. This is provided by the battery energy management, which is not the concern of this paper.

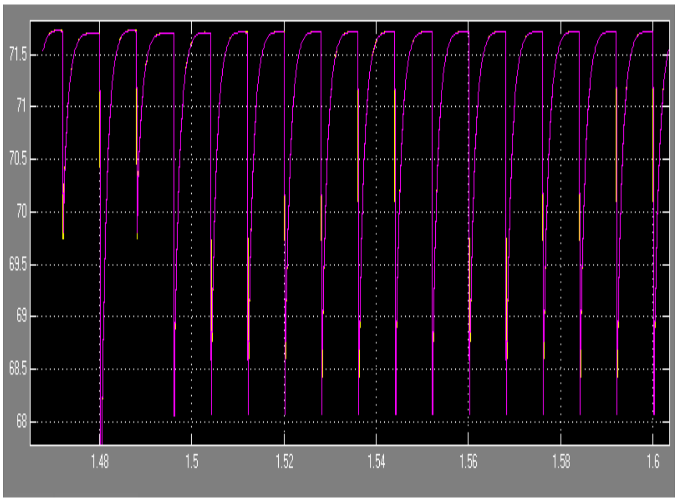


Fig -10: Solar PV1 and PV2 voltages

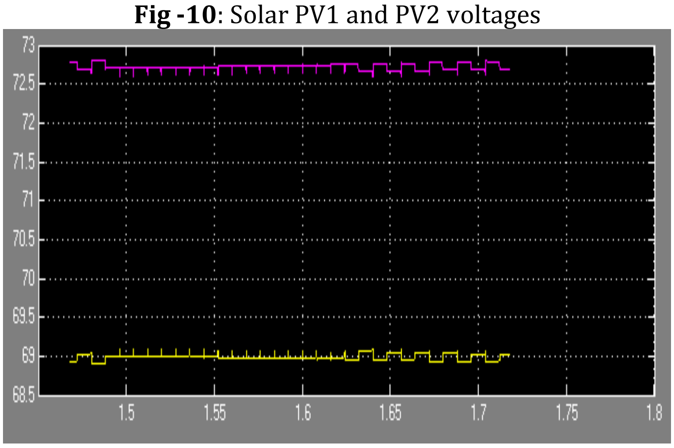


Fig -11: Coupling Capacitors Voltages

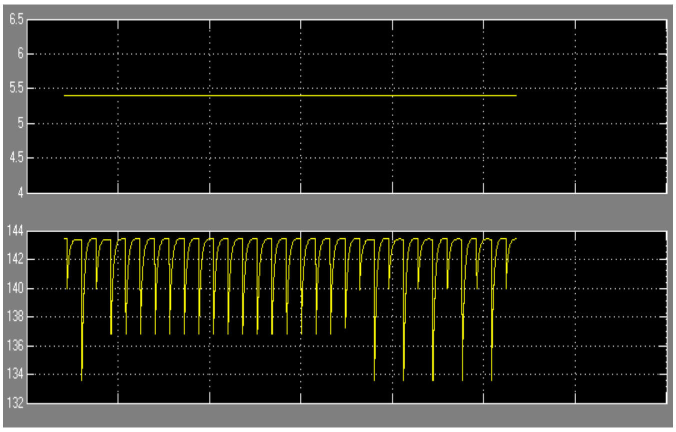


Fig -12: Coupling Capacitors Voltage Difference and PV voltage

6. CONCLUSIONS

A diagnostic method and a fault-tolerant reconfiguration for a three-level boost converter in a PV power system supplying batteries have been presented. The fault diagnostics uses only normal state control variables and its implementation is effortless. It monitors any open-circuit power switch fault while providing its localization. A few components are added to a three-level boost converter for fault-tolerant reconfiguration. The input capacitor bank should have at least two capacitors and its midpoint should be connected to the midpoint of the PV array, which should have no less than two modules. An additional inductance and a TRIAC are also required. Usually, capacitor banks have more than one capacitor and the PV module output voltages are very low for most applications (requiring the series connection of PV modules). Therefore, these issues are not limitative for most implementations. However, this converter is more cost effective than redundancy or multiphase dc–dc converter. The fault tolerant reconfiguration starts as soon as the fault is detected.

It repositions the converter components so that a decent part of the three-level boost converter is changed into a two-level converter. This converter remains operating with MPPT control using only one of the PV modules, which is an advantage as the operation of PV modules without such control is very ineffective.

The other PV module is operating without MPPT control for not overcharging the reconfigured converter. The fault-tolerant operation of the converter results in less produced power, more PV module output voltage and current ripple, and higher stresses on the power components. However, the converter rebuilds itself continues its operation once fault detection and it proves to be an efficient and low-priced alternative for all those applications within which the uninterrupted provision could be an important issue.

Advantages of the methodology are:-

1. The fault-diagnostic method is effective even under variable climatic conditions, whose variation is usually very slow, and under any load condition, because the battery controls the dc-link voltage while working in its safe operating voltages without overcharging or deep discharging.
2. Different from the conventional two-level high boost converter, the implied 3 level converter has the advantage of high voltage gain and thus it is easy to make high voltages from a low voltage. It also reduces the reverse recovery losses of the diodes and increases the overall power efficiency.

REFERENCES

[1] N. G. Dhere, "Reliability of PV modules and balance-of-system components," in Proc. Conf. Rec. 13st IEEE Photovoltaic Spec., Jan. 2005, pp. 1570–1576.
[2] A. Ristow, M. Begovic, A. Pregeli, and A. Rohategi, "Development of a methodology for improving photovoltaic inverter reliability," IEEE Trans. Ind. Electron., vol. 55, no. 7, pp. 2581–2592, Jul. 2008.
[3] F. Nejabatkhah, S. Danyali, S. H. Hosseini, M. Sabahi, and S. M. Niapour, "Modeling and control of a new three-input dc–dc boost converter for hybrid PV/FC/battery power system," IEEE Trans. Power Electron., vol. 27, no. 5, pp. 2309–2342, May 2012.
[4] G. Petrone, G. Spagnuolo, R. Teodorescu, M. Veerachary, and M. Vitelli, "Reliability issues in photovoltaic power processing systems," IEEE Trans. Ind. Electron., vol. 55, no. 7, pp. 2569–2580, Jul. 2008.
[5] S. V. Dhople, A. Davoudi, A. D. Dominguez-Garcia, and P. L. Chapman, "A unified approach to reliability assessment of multiphase dc–dc converters in photovoltaic energy conversion systems," IEEE Trans. Power Electron., vol. 27, no. 2, pp. 739–751, Feb. 2012.
[6] A. Yafaoui, B. Wu, and S. Kouro, "Improved active frequency drift antiislanding detection method for grid connected photovoltaic systems," IEEE Trans. Power Electron., vol. 27, no. 5, pp. 2367–2375, May 2012.
[7] K. Ishaque, Z. Salam, M. Amjad, and S. Mekhilef, "An improved particle swarm optimization (PSO)-based MPPT for PV with reduced steady-state oscillation," IEEE Trans. Power Electron., vol. 27, no. 8, pp. 3627–3638, Aug. 2012.
[8] E. Ribeiro, A. J. M. Cardoso, and C. Boccaletti, "Power conditioning and energy management in a renewable energy based hybrid system for telecommunications," in Proc. IEEE 33rd Int. Telecommun. Energy Conf., Oct. 2011, pp. 1–9.
[9] B. Lu and S. K. Sharma, "A literature review of IGBT fault diagnostic and protection methods for power inverters," IEEE Trans. Ind. Appl., vol. 45,no. 5, pp. 1770–1777, Sep.-Oct. 2009.
[10] J. Estima and A. J. M. Cardoso, "A new algorithm for real-time multiple open-circuit fault diagnosis in voltage-fed PWM motor drives by the reference current errors," IEEE Trans. Ind. Electron., Feb. 2012.
[11] J. Li, A. Q. Huang, Z. Liang, and S. Bhattacharya, "Analysis and design of active NPC (ANPC) inverters for fault-tolerant operation of high-power electrical drives," IEEE Trans. Power Electron., vol. 27, no. 2, pp. 519– 533, Feb. 2012.
[12] X. Pei, S. Nie, Y. Chen, and Y. Kang, "Open-circuit fault diagnosis and fault-tolerant strategies for full-bridge dc–dc converters," IEEE Trans. Power Electron., vol. 27, no. 5, pp. 2550–2565, May 2012.
[13] K. Rothenhagen and F. W. Fuchs, "Performance of diagnosis methods for IGBT open circuit faults in voltage source active rectifiers," in Proc. IEEE 35th Annu. Power Electron. Spec. Conf., Jun. 2004, vol. 6, pp. 4348–4354.
[14] P. Duan, K. Xie, L. Zhang, and X. Rong, "Open-switch fault diagnosis and system reconfiguration of doubly fed wind power converter used in a microgrid," IEEE Trans. Power Electron., vol. 26, no. 3, pp. 816–821, Mar. 2011.
[15] R. Jayabalan and B. Fahimi, "Monitoring and fault diagnosis of cascaded multiconverter systems in hybrid electric vehicles," in Proc. IEEE Conf. Veh. Power Propul., Sep. 2005, pp. 1–5.
[16] R. Jayabalan and B. Fahimi, "Monitoring and fault diagnosis of dc–dc multistage converter for hybrid electric vehicles," in Proc. 5th IEEE Int. Symp. Diagn. Electr. Mach., Power Electron. Drives, Sep. 2005, pp. 1–6.
[17] S. Y. Kim, K. Nam, H. Song, and H. Kim, "Fault diagnosis of a ZVS dc–dc converter based on dc-link current pulse shapes," IEEE Trans. Ind. Electron., vol. 55, no. 3, pp. 1491–1494, Mar. 2008.
[18] Y. Chen, X. Pei, S. Nie, and Y. Kang, "Monitoring and diagnosis for the dc-dc converter using the magnetic near field waveform," IEEE Trans. Ind. Electron., vol. 58, no. 5, pp. 1634–1647, Apr. 2011.
[19] F. Z. Peng, "A generalized multilevel inverter topology with self-voltage balancing," in Proc. Conf. Rec. IEEE Ind. Appl. Conf., 2000, vol. 3, pp. 2024–2031.
[20] A. Chen, L. Hu, L. Chen, Y. Deng, G. Yao, and X. He, "A multilevel converter topology with fault tolerant ability," in Proc. 19th Annu. IEEE Appl. Power Electron. Conf. Expo., 2004, vol. 3, pp. 1610–1616.
[21] K. A. Ambusaidi, V. Pickert, and B. Zahawi, "Computer aided analysis of fault tolerant multilevel dc/dc converters," in Proc. Int. Conf. Power Electron., Drives Energy Syst., Dec. 2006, pp. 1–6.
[22] K. Ambusaidi,V. Pickert, B. Zahawi, and B. Ji, "PSPICE analysis of PWM controlled inductorless fault tolerantmultilevel dc/dc converters," in Proc. 4th IET Conf. Power Electron., Mach. Drives, Apr. 2008, pp. 490–494