ANALYSIS AND DESIGN OF ROBUST CASCADED PV SYSTEM

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ABSTRACT

This paper proposes multi-level cascaded DC/DC system for Photovoltaic (PV) application. Three PV generators each coupled to a half-bridge buck cell. Each PV-generator-buck-converter channel is controlled such that maximum power is capture independently under different irradiation and temperature levels. The system operation under normal and abnormal conditions was comprehensively investigated. Simple and robust remedial strategies were proposed to mitigate different anticipated faults. Comprehensive simulation results in Matlab environment were illustrated for corroborating the performance of the advised cascaded DC/DC system under normal/abnormal conditions.

Keywords: Multi-level DC/DC, Half-bridge Buck Converter, Internal Mode Control, Faulty Operation, Remedial Strategies.

I. INTRODUCTION

Energy independence and environmental compatibility are two salient features of PV systems. The fuel is free, and no noise or pollution is created from operating PV systems [1-3]. Thus, PV systems are considered to be from the future trendsetters for securing eco-friendly, sustainable and albeit inexpensive electricity.

The basic solar cell usually operates at less than 1 V. Therefore, these cells are arranged in series-parallel configuration (PV module) to increase the output voltage, current and power [1-2]. For high voltage/power levels, the PV modules are arranged in series arrangement (PV panel) to ensure high operating efficiency. However, such arrangements have many disadvantages such as [4]: a mismatch between the characteristics of the modules in the same panel always exists due to modules different orientations and/or manufacturing processes. These modules, however, are restricted to conduct the same current, which limits the panel efficiency to that of the least efficient module/cell. Moreover, the generated current/power drops significantly, when a single cell/module is
partial/fully shaded. To limit the power loss, a bypassing diode around the shaded module has to be utilized. However, the power from the shaded module is lost under these circumstances [5-7].

A proposed solution [4-11] is to place a separate DC/DC chopper across each PV module. The outputs of the choppers are series connected to obtain high DC voltage level. This allows the system to be transformer free, which boosts the efficiency and reduces cost, volume and weight. Furthermore, attaching a separate DC/DC chopper to each module has the advantage of decoupling the modules. This allows the maximum power point of each module to be tracked independently. Moreover, a shaded module has no impact on the remaining modules, as it could be bypassed through the corresponding DC/DC converter. Furthermore, a fault within PV module/converter disables only the faulted module-converter, while the system can continue functioning albeit at reduced capacity.

A little was reported about cascaded DC-DC choppers particularly for PV applications [4-7]. A simple and efficient maximum power point tracker is introduced in [4]. This MPPT is claimed to allow the DC-DC converters to be serially connected in the output side and operate correctly without any additional requirements, however, no detailed analysis is reported in [4] of such series connection.

Buck, boost, buck-boost and cuk C-DC converter topologies were compared regarding steady-state efficiency in [8] for the cascaded operation. The buck-boost and cuk topologies suffer from poor switch utilization achieving maximum of 25% at a duty cycle of 50%. Moreover, the buck-boost topology has discontinuous input/output currents, and the cuk topology has extra energy storage components. Ref. [8] concluded that buck and boost topologies should be subjected to further comparison to identify the optimal topology. However, [8] introduces neither control techniques nor dynamic performance.

In a cascaded PV system, the DC/DC converter forces the corresponding PV generator to operate at Maximum Power Point (MPP) under varying conditions. Various MPP tracking techniques were reported in literature [12-15]. The incremental conductance is a wide adopted MPP tracker, due to its ability of tracking MPP at wide range of irradiation and temperature levels [12-15].

In this paper, a multi-level cascaded DC/DC converter system for PV application is proposed. An innovative implementation of incremental conductance MPPT is also proposed. This modified MPPT allows almost instantaneous tracking for MPP of each PV generator irrespective to climatologically conditions and/or other PV generators. Therefore, each module PV generator-DC/DC converter is decoupled from the remaining to achieve fault-tolerant system. The proposed compensator is tuned using Internal Mode Control (IMC). The paper introduces also a detailed analysis for the system operation under steady-state and transient conditions. Moreover, the system performance under different types of faults is thoroughly examined.

II. TOPOLOGY OF DC/DC CONVERTER

The boost and buck are most promising topologies for cascaded system. The boost characteristics allow the use of minimum number of PV modules to obtain a high DC voltage level. Moreover, the input inductor reduces the ripples in currents of the PV generators. However, the boost topology in PV cascaded system has a serious problem. The series connection forces equal output currents, and in the boost cell $I_{in} > I_{out}$ is an operational constraint. Therefore, if a PV generator is shaded, its current drops significantly and hence the power of the entire system. Thus, the boost topology is inappropriate for series connection. However, it may work satisfactory in the parallel cascaded systems. In the parallel operation of boost-based cascaded system, the system output current is a summation for the output currents of the parallel modules. Thus, if a PV generator encounters shading, its current drops and hence the output current of this faulty module. The
remaining modules are still functioning normally, and the system output power/current is albeit reduced, Fig. 1.

Fig. 1. Multi-level cascaded DC/DC boost converters attached to PV generators, faulty PV generator (grey), series connected (left), parallel connected (right)

The buck topology can track the MPP at wide climatological conditions. Moreover, in the buck based cascaded system, each channel, PV generator coupled to a buck converter, is entirely decoupled from the remaining channels. Furthermore, in the buck topologies, the semiconductors arrangement ensures continuous system operation under fault disabling a PV generator. As the freewheeling diode provide alternative path for the current under PV generator failure. This scenario is shown in Fig. 2.

Fig. 2. Multi-level cascaded DC/DC buck converters attached to PV generators, faulty PV generator (grey)

III. SYSTEM ARCHITECTURE

The system under concern, Fig. 3, is composed of three PV generators, each coupled to a half-bridge buck converter. The unit composed of a PV generator, buck converter and the associated controller is defined here as a channel.

The half-bridge is used in the system under concern due to its availability, modularity and ease of packaging. Moreover, the half-bridge allows the deployment of a modulation strategy, which reduces the generated harmonics and filter size without comprising the efficiency. The half-bridge buck cell has also bidirectional power flow capability, which could be utilized in interfacing different types of energy storage devices into the DC bus. These energy storage elements are usually deployed in cascaded system to optimize system performance and ensure interruptible system operation.

The half-bridges are in series in the output side. An independent controller for each bridge is used. The controller forces the PV generator to operate at their MPP independently. Moreover, it maintains the decoupling between the PV generators and the buck converters.
A. PV Generator

Different models are proposed for stimulating PV cell, these models vary in accuracy and complexity. Moderate model is proposed here, the PV cell is modeled as a solar irradiation and temperature dependent current source $I_{\text{ph}}$ in parallel with diode. This combination is in series with a series resistance $R_s$ [8]. This model of the PV cell has the advantages of accuracy, robustness and simplicity.

Basically the PV cells are grouped in series to deliver a reasonable voltage/power, these structures as mentioned before are themed modules. The module has an equivalent circuit similar to that of the cell.

$$I_t = I_{\text{ph}} - I_o \left( e^{\frac{V + IR}{V_{\text{th}}}} - 1 \right)$$  \( \text{(1)} \)

where $I_o$, $I_{\text{ph}}$, $I$ and $V$ are saturation current, photo current, current and voltage of the module respectively. $V_{\text{th}} = nN_s kT/q$ is thermal voltage of the module; $n$, $N_s$, $K$, $T$ and $q$ are ideality factor, number of cells in series, Boltz’s man constant and electron charge respectively. The PV modules under concern are from Kyocera KC200GT type. The parameters of KC200GT module are given in Table 1 [16].
TABLE I
PARAMETERS OF KC200GT SOLAR MODULE AT 25°C AND 1000W²M⁻²[16]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of cells</td>
<td>54</td>
</tr>
<tr>
<td>Short circuit current</td>
<td>8.21A</td>
</tr>
<tr>
<td>Open circuit voltage</td>
<td>32.9V</td>
</tr>
<tr>
<td>Current at MPP</td>
<td>7.61A</td>
</tr>
<tr>
<td>Voltage at MPP</td>
<td>26.3V</td>
</tr>
<tr>
<td>Maximum power</td>
<td>200.143W</td>
</tr>
<tr>
<td>Voltage coefficient</td>
<td>-0.1230V/K</td>
</tr>
<tr>
<td>Current coefficient</td>
<td>0.0032A/K</td>
</tr>
</tbody>
</table>

The value and series resistance $R_s$ calculated by iterative method in [8] is 0.221Ω. The PV modules are grouped in series-parallel arrangement to form array, which is termed here as PV generator. Each PV generator is consisting of 30 Kyocera KC200GT modules. The relation between the PV array/generator terminal voltage $V_{pv}$ and current $I_{pv}$ could be expressed by a relation similarly to (1), however it more meaningful to express the PV array/generator current in terms of the voltage, short-circuit current $I_{sc}$ and open-circuit voltage $V_{oc}$ of the module, as these data are commonly supplied by the manufacturers at standard conditions. Thus the terminal current $I_{pv}$ is given in terms of terminal voltage $V_{pv}$, short-circuit current $I_{sc}$ and open-circuit voltage $V_{oc}$ by,

$$I_{pv} = M_{ss} I_{sc} \left(1 - \exp \left( \frac{V_{pv} - N_{ss} V_{oc} + N_{ss} I_{pv} R_s}{N_{ss} V_{th}} \right) \right)$$  \hspace{1cm} (2)

where $M_{ss}$ and $N_{ss}$ are number of shunt and series connected modules respectively. The current $I_{pv}$ and the voltage $V_{pv}$ of the PV array/generator under concern calculated at 25°C and different radiation levels are given in Fig. 5.

![Fig. 5](image-url)  

**Fig. 5.** Current and power of a PV generator against terminal voltage for 25°C temperature and different levels of solar irradiance, locus of maximum power (black)

Figs. 5 reveals that the voltage at maximum power is less dependent on the solar irradiation [13]. Moreover, the generator current/power varies almost linearly with the insolation.
In the series-connected system, Fig. 3, the steady-state output currents are equal $I_1 = I_2 = I_3$. Assuming lossless system, the output voltage of each bridge $V_{oi}$ depends on the DC-link voltage $V_{DC}$ and the ratio of cell power to that of the entire system as given in (3),

$$V_{oi} = \frac{V_{DC} \cdot P_{ini}}{\sum_{i=1}^{m} P_{ini}}$$  \hspace{1cm} (3)

where $m$ is number of the series converter/channels. Equation (3) indicates that for series-connected system, Fig. 2, when the PV generators have the same solar irradiance levels, the output powers are nearly equal, and thus the output voltages of the correspondences buck bridges. However, as a PV generator is partially/fully shaded, the output voltages of bridges are affected. The shaded module experiences reduction in the output voltage, while the unshaded modules undergo over voltage. Moreover, although the unshaded PV generators still deliver the same power, the system output current will be reduced.

**B. Half-bridge Converter**

In the system under concern, a separate inductor filter is attached to each half-bridge converter, Fig. 3. These inductors can be lumped into a single inductor allocated in output side without affecting either dynamic or static performances. However, the distributed inductor topology has the advantages of modularity, ease of upgrading and cost-effectiveness. Since the system can be expanded/contracted by adding/removing a half-bridge with its associate filter inductor.

Employing shift switching modulation strategy in the proposed system reduces the current ripple and inductor size, while maintaining high efficiency. As the switching frequency is kept constant at $f_s$, meanwhile the harmonics in the inductor voltage are shifted to $m \cdot f_s$. In the shift switching technique, the carrier waveforms are delayed by $2\pi/m$ from each another.

The total output inductance could be calculated by,

$$L = mL_1 = \frac{(V_{max} - V_{min}) (1 - D_{max}) D_{max}}{m f_s \Gamma_{o}}$$  \hspace{1cm} (4)

where $\Gamma_{o}$ is ripple in the output current; $D_{max}$ is equivalent duty cycle, where maximum ripple occurs, and it is equal to 0.5. $V_{max}$ and $V_{min}$ are defined by,

$$V_{max} = V_{pvi} \left( D - \text{mod} \frac{1}{m} + \frac{1}{m} \right)$$  \hspace{1cm} (5)

$$V_{min} = V_{pvi} \left( D - \text{mod} \frac{1}{m} \right)$$  \hspace{1cm} (6)

where $D$ is the operating duty cycle and mod is the modulus function. The total inductance $L$ computed for 5% ripple in the output current at 1000w/m² solar irradiance and 25°C temperature is 0.9mH.
C. MPPT

The slope of power-voltage curve of a PV generator could be expressed by,

\[
\frac{dP_{pv}}{dV_{pv}} = I_{pv} + V_{pv} \frac{dI_{pv}}{dV_{pv}},
\]  
(7)

The slope of power-voltage curve of a PV module, Fig. 5, is positive on the left of MPP, negative on the right and zero at MPP. Thus the relation between the incremental and instantaneous conductance is given by,

\[
\frac{\Delta I_{pv}}{\Delta V_{pv}} > \frac{I_{pv}}{V_{pv}}, \text{ left MPP}
\]

\[
\frac{\Delta I_{pv}}{\Delta V_{pv}} = \frac{I_{pv}}{V_{pv}}, \text{ at MPP}
\]

\[
\frac{\Delta I_{pv}}{\Delta V_{pv}} < \frac{I_{pv}}{V_{pv}}, \text{ right MPP}
\]  
(8)

MPP is tracked by continuously comparing the incremental and instantaneous conductance and incrementing/decrementing the PV voltage/current until MPP is reached. This technique is reported in the literature under Incremental Conductance Controller (ICC) [13-15].

An innovative implementation for ICC is proposed here under the theme of Modified Incremental Conductance Controller (MICC). According to (7), the sum of the incremental and instantaneous conductance is equal to zero at MPP; therefore employing a sufficiently fast PI controller ensures that sum is settled at zero.

\[
E = \frac{\Delta I_{pv}}{\Delta V_{pv}} + \frac{I_{pv}}{V_{pv}},
\]  
(9)

D. Tuning of the controller

Each channel, PV generator coupled to buck converter, is controlled individually, thus the cascaded system is modeled for control purpose as single PV generator converter channel as shown in Fig. 6.

![Fig. 6. Schematic of single channel and control circuit](image)

To simplify the controller design, the cascaded system is assumed to be loaded by a pure resistive load. The sum of incremental and instantaneous conductance is compared with zero, to force system operation at MPP; then the error is supplied to Proportional Integral (PI) controller. The output signal of the PI compensator is used to generate the switching signal.
The top and bottom switches operate in complementary fashion; for example, when the top switch is on the bottom one is off and vice versa. Thus, when the top switch is on, the system in Fig. 6 could be expressed mathematically by,

\[ V_{pv} = \frac{L_v}{R_L} \frac{dv_o}{dt} + v_o \]  

(10)

During the top switch off state, the system is expressed by,

\[ 0 = \frac{L_v}{R_L} \frac{dv_o}{dt} + v_o \]  

(11)

Averaging (10) and (11) over a switching cycle,

\[ V_{pv}D = \frac{L_v}{R_L} \frac{dv_o}{dt} + v_o \]  

(12)

where \( d \) is duty cycle. The voltage of PV generator at MPP is assumed constant, thus the system could be considered as single pole system as,

\[ \frac{V_o(s)}{G(s)} = \frac{V_{pv}}{1 + sL_v/R_L} \]  

(13)

A PI controller is tuned using IMC technique. The IMC is extracted from the internal mode principle that states the control can be achieved if the control system encapsulates, either implicitly or explicitly, some representation of the process to be controlled. A thoroughly discussion for the IMC are given in refs. [17,18]. In this work, the design of the controller is only addressed.

Assuming that the model of the process, controlled system, \( G_p(s) \) has the same transfer function as the process itself, \( G_s(s) \).

\[ G_p(s) = G_s(s) = \frac{V_{pv}}{1 + sL_v/R_L} \]  

(14)

Separating the model of the process into invertible \( G_{p^+}(s) \) and non-invertible \( G_{p^-}(s) \) components respectively, the controller of the IMC is given by

\[ C_{IMC}(s) = G_{p^-}(s)^{-1} = \frac{1 + sL_v/R_L}{V_{pv}(1 + sL_v/R_L)^k} \]  

(15)

where \( t_f \) and \( k \) are the parameter and the order of the filter. The parameter and the order of the filter are chosen such that the bandwidth of this controller is high enough to provide acceptable tracking for any abrupt change in solar irradiation/temperature. In meanwhile, the controller has the ability to provide adequate attenuation for switching ripples in the PV generator voltage and current. The merits of the IMC technique are [17,18]:

1. simplicity,
2. cost-effectiveness,
3. time-delay compensation,
4. offset free response and
5. good tracking for the setpoint and disturbance rejection.
The frequency response of closed loop transfer function $\Delta V_o/\Delta E_{ref}$ is shown in Fig. 7.

![Frequency response graph](image)

**Fig. 7.** Closed loop frequency response of the $\Delta V_o/\Delta E_{ref}$ with IMC controller

The IMC controller introduces adequate bandwidth of around $1.5 \times 10^6$ rad/sec Fig. 7, which might result in adequate tracking for the solar irradiance variations. Moreover, the system behaves as a low pass filter particularly for switching harmonics, Fig. 7.

An equivalent classical PI feedback controller $C_{PI}(s)$ of the IMC controller $C_{IMC}(s)$ could be obtained from,

$$C_{PI}(s) = \frac{C_{IMC}(s)}{1 - C_{IMC}(s) G_p(s)}$$ (16)

The parameters of the PI controller, $C_{PI}(s)$ are given in Table 2.

<table>
<thead>
<tr>
<th>TABLE 2</th>
<th>PARAMETERS OF THE PI CONTROLLER</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proportional gain $K_p$</td>
<td>5</td>
</tr>
<tr>
<td>Integral gain $K_i$</td>
<td>200</td>
</tr>
</tbody>
</table>

**IV. STATIC PERFORMANCE**

The static performance of the proposed system is estimated by computing the efficiency at different solar irradiance levels. The following assumptions are considered:

- The losses in the input and output capacitors are ignored.
- The different channels share the load equally, thus the efficiency is calculated per channel.
- The input and output filters suppress the ripples in the input and output currents.

The efficiency of a channel is given by,
where \( P_{\text{ini}}, P_{\text{pv_cu}}, P_{\text{ind_cu}}, P_{\text{c_cond}} \) and \( P_{\text{c_swit}} \) are a channel input power, the copper losses in a PV generator and the output inductors, conduction and switching losses in a converter channel respectively.

The switch and the power diode in the converter channel were modeled during the on-state as a constant voltage element; thus the converter steady-state average conduction losses is given by,

\[
P_{\text{c_cond}} = V_{\text{ce(sat)}} I_{\text{avg}_Q} + V_{\text{on}} I_{\text{avg}_D}
\]  

(18)

where \( V_{\text{ce(sat)}}, I_{\text{avg}_Q}, V_{\text{on}}, \) and \( I_{\text{avg}_Q} \) are the on-state switch voltage drop, average switch current, diode on-state voltage drop and diode average current respectively.

The switching frequency was determined as a compromise between the inductor size and switching losses; a value of 10 kHz was chosen. The switching losses of a switch in the three converter topologies are determined from switching frequency \( f_s \), turn on \( E_{\text{on}} \), and turn off \( E_{\text{off}} \) energies. The turn on \( E_{\text{on}} \) and turn off \( E_{\text{off}} \) energy curves of the proposed switches could be considered to vary linearly with the switch current, thus the switch steady-state average switching losses can be approximated by,

\[
P_{\text{c_swit}} = f_s (E_{\text{on}} + E_{\text{off}}) I_{\text{avg}_Q}
\]  

(19)

where \( E_{\text{on}} \) and \( E_{\text{off}} \) are on-state constant and off-state constant respectively. Substitute (18) and (19) into (17) and simplify the efficiency is given by,

\[
\xi = 1 - \frac{1 - \frac{P_{\text{pv}}}{I_{\text{pv}}} R_s V_{\text{ce(sat)}} V_{\text{on}} \left( 1 - \frac{I_{\text{pv}}}{D L} \right)}{\frac{V_{\text{pv}}}{D^2} R_s f_s \left( E_{\text{on}} + E_{\text{off}} \right)}
\]  

(20)

Equation (20) indicates that the efficiency depends on the operating strategy of the converter channel. The converter drives the associated PV generator at MPP by modifying the duty cycle according to solar irradiance and temperature levels. The efficiency of the proposed cascaded PV system at different solar irradiation is illustrated in Fig. 8.

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**Fig. 8** Efficiency of cascaded PV system at different solar irradiation levels
Fig. 8 shows that the efficiency of the proposed system increases with the solar irradiance. The system efficiency drops significantly below 100W/m^2 insolation level. The graph illustrated in Fig. 8 shows the efficiency of the proposed system only when all modules are subjected to the same solar irradiance level. The efficiency of the proposed system is anticipated to be likely albeit lower than Fig. 8, due to the ignored losses.

IV. DYNAMIC RESPONSE

In the following, the system performance for different irradiation levels is investigated. The convergence speed of MPPT and the effectiveness of the decoupling between the different channels are assessed by forcing step change in the solar irradiance in Figs. 9 and 10. This is realized by stepping the solar irradiance of generator 1 from 1000W/m^2 to 100W/m^2 at 0.1sec, 100W/m^2 to 600W/m^2 at 0.2sec, and 600W/m^2 to 1000W/m^2 at 0.3sec; the solar irradiance of generator 2 is stepped from 1000W/m^2 to 500W/m^2 at 0.1sec and from 500W/m^2 to 1000W/m^2 at 0.3sec. Generator 3 operates at 1000W/m^2 over the time span under concern.

Fig. 9. Top graph: voltages of PV generators, Middle graph: currents of PV generators, Bottom graph: powers of PV generators for 25°C and solar irradiance of generator 1 (blue) stepped from 1000W/m^2 to 100W/m^2 at 100msec, 100W/m^2 to 600W/m^2 at 200msec and from 600W/m^2 to 1000W/m^2 at 300msec; solar irradiance of generator 2 (black) stepped from 1000W/m^2 to 500W/m^2 at 100msec, and 500W/m^2 to 1000W/m^2 at 300msec; solar irradiance of for generator 3 (red) constant at 1000W/m^2

Fig. 9 shows that MICC achieves fast tracking for MPP even under hypothetical conditions, as abrupt change for solar irradiance. Moreover, the controller achieves full decoupling between different channels. A channel responds only when its operating conditions change, and there is no response for conditions affecting other PV generators/buck converters, although they share the same DC-link. The figure show also that the output currents/powers of the PV generators vary linearly with the solar insolation. This was predicted in Fig. 5, where static performance of a PV generator was computed and drawn. The voltage of the PV generators, is less affected by solar irradiance change, as shown in ref. [13].
Fig. 10. Top graph: DC-link voltage, Middle graph: output current, Bottom graph average values of channels’ voltages for channel 1 (blue) solar irradiance stepped from 1000W/m\(^2\) to 100W/m\(^2\) at 100msec, 100W/m\(^2\) to 600W/m\(^2\) at 200msec and from 600W/m\(^2\) to 1000W/m\(^2\) at 300msec; for channel 2 (black) solar irradiance stepped from 1000W/m\(^2\) to 500W/m\(^2\) at 100msec, and 500W/m\(^2\) to 1000W/m\(^2\) at 300msec; for channel 3 (red) solar irradiance constant at 1000W/m\(^2\).

The output current of the system varies nearly linearly with solar irradiance, Fig. 10. The switched switching modulation strategy reduces the ripples in the output currents and the DC-link voltage. Equation (2) predicts that in a cascaded PV system when a generator/channel encounters shading, its output power/voltage drops and hence the DC-link voltage. The output voltage of the shaded channel undergoes voltage reduction, while unshaded channels experiences increase in their output voltages. Fig. 10 validates this conclusion. In this Figure, generators/channels 1 and 2 encounter shading starting from 100msec with different degrees of solar irradiances, while generator 3 is unshaded. Consequently the output voltages of channels 1 and 2 encounter reduction during the shading while the output voltage of unshaded channel 1 increases.

IV. SYSTEM RESPONSE UNDER ABNORMAL CONDITIONS

The reliability of the system is assessed by examining its performance under abnormal conditions. In the following, the system behavior under different fault scenarios is investigated. The faults affected cascaded PV system could in the PV generator and/or the DC-DC converter and the associated control circuits. The PV generators are subjected to variety of abnormal conditions such as shading, breakdown, and thermal runaway. Except the shading, the PV generators are less likely to develop abnormal conditions.

The focus in this work is on the faults in half-bridge. Open and short circuit faults are the major faults that semiconductors in the half-bridge could develop. These faults could be physically developed or resulted due to mail function in the gating circuits. The half-bridge has two switches; each switch composed of a parallel transistor and diode. In the following analysis, the switch is considered as a unit. Thus the open/short circuit fault disables the whole switch, which is practically valid.

A. Open-circuit fault

If the top-switch in the converter develops an open circuit fault, the output current circulates through the freewheeling diode of the bottom switch. Accordingly, the current of the PV generator in the faulted channel drops to zero.

Fig. 11 shows the system performance under such fault. In this Figure, PV generators 1 & 3 operate at 1000Wm\(^{-2}\) and 25°C, while generator 2 runs at 500Wm\(^{-2}\) and 25°C; whereas, the system
runs under these conditions, switch in buck cell attached to PV generator 2 encounters an open-circuit fault.

![Graphs showing DC-link voltage, load current, PV currents, and PV powers for open circuit fault in the top switch of converter in channel 2 at 150msec.](image)

**Fig. 11.** Top graph: DC-link voltage, Middle top graph: load current, Middle bottom graph: currents of PV generators, and Bottom graph: powers of PV generators for open circuit fault in the top switch of converter in channel 2 at 150msec, PV generators 1 (blue), 2 (black) and 3 (red) for 1000w/m² solar irradiance and 25°C temperature

The current and hence power of PV generator in the faulted channel ceases to zero immediately after the fault, Fig. 11. The output current and DC-link voltage drop slightly, which is attributed to the loss of the power of PV generator 2, bottom graph in Fig. 11. This scenario could be predicted by (2). The voltage of that PV generator in the faulty channel was found to rise to open-circuit voltage level.

The sustained open-circuited switch has less damaging impact on the cascaded system; as the losses in PV generator in faulted channel(s) drop to zero. However, the system operates at reduced output power. Fig. 10 shows that the un-faulted channels still operate at MPP and are not affected by the fault. This reflects the advantage of the proposed MPPT technique in decoupling the system into totally independent channels.

If the bottom switch encounters open-circuit, the load current has to circulate through the PV generator in the faulty channel. This may damage the generator and the top-switch, as the output current is usually greater than the generator short-circuit current. The remedy strategies for this fault are limited. The allowed option is to permanently open the top switch and disable the whole system. This is to protect the faulty channel from damage due to conducting the output current, which is much higher than the ratings of PV generator and solid-state devices. The open circuited bottom switch could be identified by monitoring the voltage drop of the top switch. If this voltage drop exceeds the value corresponding to the system operation at short circuit operating point, the controller should command the top switch to permanently be opened.

### B. Short circuit fault

When a top switch in half-bridge develops short circuit, the captured PV power drops to zero. The PV generator in the faulted channel operates at short-circuit point, provided that the output current is greater than the short-circuit current of the PV generator $I_{SC}$. For this case, the current in the bottom switch $I_D$ is given by,

$$I_D = I_o - I_{SC} \quad (21)$$
The system behavior during short circuit fault in top switch in converter attached to PV generator 2 is shown in Fig. 12. Before the fault the three generators were operating at MPP corresponding to 1000W/m² solar irradiance and 25°C temperature.

![Graph](image)

**Fig. 12.** Top graph: DC-link voltage , Middle top graph: load current , Middle bottom graph: currents of PV generators, and Bottom graph: powers of PV generators for short circuit fault in the top switch of converter in channel 2 at 150msec, PV generators 1 (blue), 2 (black) and 3 (red) for 1000w/m² solar irradiance and 25°C temperature.

The operation of the PV generator in the faulted channel altered from MPP before the fault to short-circuit point instantaneously during/post fault, Fig. 12. Although the harvested PV power from the faulted channel is zero for open and short circuit faults; however, the sustained operation with short circuit fault stress PV generator more than that of open circuit fault, due to elevated ohmic losses.

Fig. 12 shows that again the healthy channels in the proposed system still are running at MPP irrespective to the status of the faulty channel.

The short circuit fault of the bottom switch is similarly to that of the top-switch. In both cases the captured PV power drops to zero. However for bottom switch short circuit failure, an extra degree of freedom is existed that the top switch could be permanently opened. This protects the corresponding PV generator from severe copper losses, while allowing the cascaded system to continue functioning albeit at reduced power level.

**VI. CONCLUSION**

The operation of autonomous cascaded PV system under different operating scenarios was thoroughly studied; the following conclusions could be drawn:

1. The buck topology is the proper circuit for series operation of PV generators.
2. The boost topology may have a satisfactory performance for parallel connection of PV generators. However, for series connection of PV generators, the boost topology fails to maintain the decoupling between the channels under abnormal conditions such as partial shading.
3. The series connection of PV generators has more advantages than the parallel one such as: higher efficiency and elimination of second DC/DC conversion.
4. The half-bridge buck converter is preferred in cascaded PV system due to its availability and bi-directional power flow capability, which allows interfacing the batteries/super-capacitors to the cascaded system.

5. Employing shift switching techniques reduces the ripples in the output/input waveforms without comprising the efficiency, weight or volumetric dimension.

6. The diode in the buck topology provides adequate freewheeling path for the output current in case of the corresponding PV generator is partially/fully shaded.

7. Forcing the error between the incremental and instantaneous inductance to be zero, allows faster tracking for MPP.

8. The IMC controller has the merits of simplicity, time-delay compensation and adequate tracking for the reference.

9. The short-circuit switch fault encounters excessive copper losses inside the PV generator.

REFERENCES


