Three-Phase Interleaved Boost Converter with Fault Tolerant Control Strategy for Renewable Energy System Applications

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Abstract

This paper presents a fault tolerant control strategy for a three-phase interleaved boost converter applied to renewable energy systems. The structural and operational characteristics of the three-phase interleaved boost converter are described. By interleaving the switching circuit patterns, the input current and the output voltage ripples can be significantly decreased without increasing the switching losses, resulting in the satisfactory converter efficiency. The power and current ratings of each switching components can be lowered. The fault tolerant control strategy with Proportional Integral (PI) controller plus a phase-shift technique for the three-phase interleaved boost converter under healthy and faulty operating conditions is detailed. The simulation results are shown to demonstrate the effectiveness of fault tolerant control capability for the three-phase interleaved boost converter under normal and open-circuited switch failure operations.

Keywords: Interleaved boost converter; Fault tolerant control; Renewable energy; Open-circuit fault; PI controller

1. Introduction

In recent years, renewable energy such as photovoltaic system becomes an increasingly important source of energies. However, the voltage levels obtained from such energy source are typically low and unregulated. Hence a suitable converter is required in order to increase and regulate the output voltage level. A dc-dc boost converter is
widely used for boosting the low input voltage generated from PV arrays up to a higher voltage level to supply load. An interleaved boost converter is considered as a good solution for high-power applications with low input voltage and high input current. Interleaved boost converters have been employed to increase the output power and to decrease the input current and output voltage ripples, leading to size reduction of input inductors and output filter capacitor. Compared to the classical boost converter, the interleaved boost converter provides several advantages such as lower input current ripple and output voltage ripple, higher efficiency, lower electromagnetic emission and improved reliability [1]. In addition, the reliability and continuity of operation are major concerns for renewable energy systems. It is known that the presence of faults in power converters can lead up to malfunction and consequently reduce the renewable energy system performances. In order to obtain the satisfactory system performance and to improve reliability of the converter, the fault diagnostic and fault-tolerant strategies need to be taken into account [2]. In [3] the redundancy components are added to the system to provide the improved reliability. Based on converter topology reconfiguration, the bidirectional switches are required for each phase of the multiple-interleaved boost converter in order to isolate the faulty switch and to connect to one redundant switch for the whole system [4].

In this paper, a three-phase interleaved boost converter with its fault-tolerant control strategy is investigated. The converter reliability has been improved without reconfiguring topological circuitry. By employing fault tolerant control technique, the converter can continue to operate with satisfactory performances under faulty operations. In addition, input current and output voltage ripples can be decreased, nearly the same amplitude as in healthy operating conditions.

2. Three-phase interleaved boost converter

The three-phase interleaved boost converter configuration is shown in Fig. 1(a), which consists of three identical boost inductors, L1, L2 and L3, power switches, S1, S2, and S3, and power diodes D1, D2, and D3. Each converter phase is linked by an output filter capacitor, C, delivering power to the load, R. As can be seen in Fig. 1(a), the three-phase interleaved boost converter can be structured by three elementary boost converters interconnected in parallel. Due to interleaving operation, the input current and output voltage ripples can be significantly reduced and the power rating can be enlarged. The reduction in the size of inductors and output filter capacitor can be obtained.

![Fig. 1 (a) Three-phase interleaved boost converter configuration (b) Timing diagram with 120° phase shift](image)

The input current \(I_{in}\) of the converter is the sum of the currents flowing through the inductors. Therefore, the input current can be shared among the parallel phases, leading to lower current rating of converter components. High reliability and efficiency in the system can be obtained. The power switches S1, S2, and S3 operate in the interleaved manner, with the same duty cycle \(D\) and a phase-shift angle of 120°. As a result, the average values of the inductor currents \(I_{L1}\), \(I_{L2}\) and \(I_{L3}\) are nearly the same with a phase difference of 120°. The input current and output voltage ripples can be minimized due to the ripple cancelation. The timing diagram of switching signals is shown in Fig. 1(b), when the power switches operate with 120° phase shift from each other.
3. Fault Tolerant Control Strategy

In order to regulate the output voltage and to decrease the ripples of the three-phase interleaved boost converter operating under normal and fault conditions, the control strategy based on the Proportional Integral (PI) controller plus phase-shift technique is employed, as shown in Fig. 2. To meet the performance specifications, the parameter gains for the PI voltage and current loops are designed as can be expressed in Eq. (1).

\[
K_{PV} = \frac{2\pi \omega_n C}{R}, \quad K_{IV} = \omega_n^2 C, \quad K_{PC} = \frac{2\pi \omega_n L}{V_{in}}, \quad K_{IC} = \frac{\omega_n^2 L}{V_{in}}
\]

Using the appropriate close-loop PI controller design, the converter can operate satisfactorily and the current sharing of the converter can be adequately balanced. In order to reduce the oscillation of the ripple current, the phase-shift technique with \(2\pi / n\), where \(n\) is the number of phase, is employed. Therefore, the switching signals generated from the PI controller with pulse width modulation (PWM) need to be phase-shifted by \(120^\circ\) for the power switches of the three-phase interleaved boost converter operating under healthy condition. As can be seen in Fig. 2, only one current loop is used to balance the inductor currents in each parallel phase, saving costs of current sensors compared with using three current loops. Another advantage lies in fault tolerant capability. If one phase of the converter fails to operate due to the open-circuited switch fault, the remaining phases can continue operation. Unfortunately, the ripples will significantly increase and the inductor currents will unbalance. To overcome these converter degraded performances, the fault tolerant control strategy is employed without reconfiguring the converter circuitry. The switching signals for the remaining healthy switches need to be rearranged with \(180^\circ\) degrees phase shift.

4. Simulation Results

The simulations of three-phase interleaved boost converter under normal and fault operating conditions have been carried out by using Matlab-Simulink. The converter parameters are \(V_{in} = 20V\), \(L_1 = L_2 = L_3 = 15mH\), \(C = 125\mu F\), \(R = 100\Omega\). The switching frequency is chosen at 10kHz. The desired output voltage \(V_{out} = 80V\) are set, with a duty cycle around 0.75. Fig. 3 shows the waveforms of output voltage, \(V_{out}\), inductor currents, \(I_{L1}, I_{L2}, I_{L3}\), and input current, \(I_{in}\). As can be seen under healthy operation, the output voltage is regulated well with a small ripple. The average values and current ripples of \(I_{L1}, I_{L2}\) and \(I_{L3}\) are nearly the same. By interleaving operation, the input current ripple has decreased due to ripple cancelation characteristics.

At the time \(t = 1.7s\) the open-circuited fault occurs in \(S_3\). The converter continues to operate with only two active phases without modifying the control strategy. The inductor current \(I_{L3}\) associated with the faulty phase suddenly drops to zero whereas the remaining currents \(I_{L1}\) and \(I_{L2}\) flowing through the healthy phases are unbalance. The overloading current occurs in one phase, probably leading to the failure in corresponding switch located in this phase. The input current and output voltage ripples have increased significantly, resulting in large power losses.

After that at time approximately \(2.7s\), the modified fault-tolerant control strategy based on \(180^\circ\) phase shift switching signals is introduced to the converter. As can be seen in Fig. 3, the output voltage is kept constant at the desired level. The inductor currents \(I_{L1}\) and \(I_{L2}\) are equally shared between the healthy phases. Both input current and output voltage ripples are significantly reduced, providing the better performances compared with the fault operation situation. Therefore, fault tolerant control strategy is useful to avoid serious input current and output voltage ripples and imbalance in remaining healthy inductor currents of three-phase interleaved boost converter.
5. Conclusion

This paper has presented the three-phase interleaved boost converter with fault tolerant control strategy for renewable energy system applications. The converter reliability has been improved based on reconfiguration of control strategy for healthy and faulty operations. The PI controller with only one current loop and a unique voltage loop is employed. The proper phase-shift technique is applied to the converter for ripple cancelation. The converter behaviors both normal and open-circuit fault operations have been investigated. The simulation results show the effectiveness of the fault tolerant control strategy. Reliability and satisfactory converter performances can be achieved. The input current and output voltage ripples significantly decreased, providing the similar converter performances compared with healthy operation. In addition, equal inductor current sharing can be obtained even using only one PI current loop control. In the future, a fast open-circuit fault detection technique and a correct switch-fault identification method will be studied. Experimental implementation will be set up to realistically verify the proposed fault-tolerant three-phase interleaved boost converter.

References