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Real-Time Switch Fault Diagnosis and Fault-Tolerant Control Method for Boost DC-DC Converter

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Abstract

This paper presents a simple and the fast real-time switch open circuit fault (OCF) and short-circuit fault (SCF) diagnosis and fault-tolerant control method for boost dc-dc converter. The method uses an average voltage of the switch as a diagnostic parameter for both the faults diagnosis. The average switch voltage during normal operation always remains equal to the source voltage and is independent of the duty cycle of the switching control signal. The OCF or SCF causes the average switch voltage to increase above or decrease below the source voltage level respectively. This change in the average switch voltage is employed to detect the corresponding fault. The detection of the OCF is followed by the reconfiguration of the converter in which redundant switch is activated for maintaining the converter operation continuous. The proposed method is modeled and simulated using MATLAB/ Simulink software and the results are validated by implementing the hardware using dSPACE DS1104 controller.

Keywords: *Fault diagnosis, fault-tolerant control, open-circuit fault (OCF), switch voltage (Vsw).*

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1. Introduction

Presently, dc-dc converters are extensively used in several industrial applications like electric vehicles, renewable energy power systems, aerospace etc. In all such applications, reliability improvement of the power converters is very essential [1] [2]. The converters often experience excess electrical and thermal stresses that results in the failure in the semiconductor power devices [3]. A questionnaire survey of reliability in power electronic converters is carried out by the authors in [4]. According to the survey, power semiconductor devices ranked the most fragile components in the converters. If such faults in the converters are not diagnosed and repaired timely, the performance and stability of the system are get affected. Hence it is very essential to develop a real-time fault diagnosis technique followed by a suitable remedial action so as to provide continuity of the system operation with required performance and safety [5].

Many approaches have been proposed in the literature for switch fault diagnosis in the power converters. In [6], open and short circuit switch faults diagnosis and fault tolerant control method for interleaved dc-dc converter is proposed. Under faulty condition of the switch, equal current sharing among each phase at desired output voltage is achieved by adapting the current and voltage controller gains. The method needs separate current controller per phase. A new multiple faults indices based algorithm is presented in [7] to diagnosis open phase and single-switch open-circuit faults in six-leg inverter. Open-circuit switch fault detection and identification technique for three phase inverter drive of brushless DC (BLDC) motor has been reported in [8]. The method uses a Discrete Fourier Transformer based pattern recognition of motor line voltages. Fault diagnosis and fault tolerant control method for DC-link, comprises of an inductor and a capacitor, in power traction converter is presented in [9]. The proposed work uses notch filter to diagnose the open-circuit and short-circuit faults of the DC-link components. Switch OCF and SCF diagnosis in boost dc-dc converter based on the inductor current is studied in [10]. Predicted value of the inductor current with the help of control signal is obtained and compared it with the measured one to detect the faults. A step down dc-dc converter with three switching modes with fault-tolerant capability is developed in [11]. A switch open-circuit fault diagnosis and fault-tolerant scheme for three-level boost converter is presented in [12].

It is noticed here that the aforementioned fault diagnosis approaches involve multi-stage signal processing for obtaining a diagnostic parameter. Also some of the methods need signal variable calculations per sampling. This results in the requirement of more electrical components that increases hardware complexity and cost.

This paper presents a new strategy for the switch OCF and SCF diagnosis in the boost converter. The proposed method requires only a few number of components for the fault diagnosis and fault-tolerant control. A fault tolerant-control technique is also proposed which provides continuous operation of the converter with good voltage regulation. A brief basic converter operation is presented in Section 2. The detailed fault diagnosis and fault-tolerant control strategy is described in Section 3. Sections 4 and 5 present simulation results and experimental results of the method respectively. Finally, conclusion is represented in Section 6.

2. Boost Converter Operation

Boost converter, also known as a step up converter, is generally used to step up a low voltage level to a high voltage level. Fig. 1 shows a circuit diagram of the boost converter. The converter comprises of power semiconductor switch sw, which generally can be a power MOSFET, IGBT or BJT, a diode D, a capacitor C, an inductance L and a resistance load R. The output voltage, Vo is a function of a duty cycle/ratio, D of a pulse width modulation (PWM) switching signal, which determines the ON time (ton) of the switch. The Vo can be equal to or greater than the Vs and can be expressed by (1)

$$V_o = V_s \frac{1}{1-D} \qquad (1)$$

where Vs is a source voltage, D =ton/Ts, Ts=1/Fs. Fs is a switching frequency. During normal operation, when the sw is ON then an energy is stored in the L from the Vs. When the sw is OFF, the stored energy is transferred to the load through D. The resultant inductor current, IL with respect to the PWM and the switch voltage, Vsw is shown in the Fig. 2.

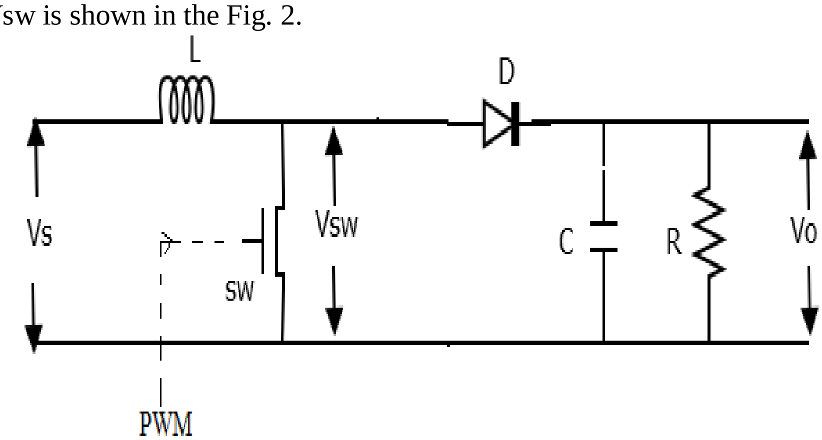

Fig. 1 Boost converter schematic

3. Fault Diagnosis and Fault-tolerant Control

The proposed method uses Vsw voltage to detect the faults. The following analysis is based on the ideal characteristic of the switch. From the Fig. 1, the Vsw can be given by (2).

$$Vsw(t) = Vs(t) + V_L(t) \qquad (2)$$

where V_L is a voltage across the L. During 'ton' time of the sw, the Vsw is given by (3).

$$Vsw(t) = 0 \qquad (3)$$

The instantaneous values of the voltages in (2) can be described in their average forms as given by (4).

$$Vsw_{avg} = V_S + V_{L\ avg} \qquad (4)$$

In continuous current mode of operation of the converter, the inductor stores and dissipates the energy alternately. Accordingly, average voltage developed across the L over a cycle period is given by (5).

$$V_{L\ ava} = 0 \qquad (5)$$

Therefore, from (4) and (5), the Vsw $_{avg}$ can be given by (6)

$$Vsw_{avg} = V_S \qquad (6)$$

This implies that, for given Vs, the Vsw $_{avg}$ is independent of any other parameters. Hence, this parameter is selected as fault diagnostic variable (DV). So,

$$DV = Vsw_{avg} = V_S \qquad (7)$$

As shown in the Fig.2, the DV has average value equal to Vs during normal operation of the converter. The occurrence of switch OCF causes the Vsw to increase transitory due to energy dissipation from the L. A similar effect is get reflected in the DV. So, if threshold (TH1) is set equal to Vs then the fault can be detected for any increase in the DV above the TH1. However, TH1 is set slightly less than the Vs for safe margin.

The DV is also used for SCF detection. For switch SCF, the Vsw remains zero continuously and hence the DV starts falling below Vs level. Comparing this level with voltage level below the Vs level, called threshold (TH2), the fault is detected as soon as the DV falls below the TH2.

Fig. 3 shows an electrical scheme to implement the proposed methodology of OCF and SCF detection. Main switch (MS) denotes a power semiconductor switch. Firstly, Vsw voltage is processed in the signal processing block wherein it is isolated and fed to the R1C1 circuit through high input impedance unity gain amplifier. The R1C1 circuit provides the average value of the Vsw i.e. DV by minimizing the ripple contents. Then, the DV is compared with TH1 and TH2 for detecting the OCF and SCF respectively. FD-OCF and FD-SCF are indicating the fault detection of OCF and SCF respectively. The FD-OCF is further used in the fault tolerant control (FTC) block to reconfigure the converter. The FD-OCF is held at positive value using a latch circuit. The latched signal is further used to connect the PWM signal to the redundant switch (RS). Thus the activation of the RS after the OCF detection ensures the continuity of the operation. The SCF is generally controlled by inserting a fast acting fuse in series with the MS. Alternatively, a dedicated hardware can also be employed to cope with the SCF.

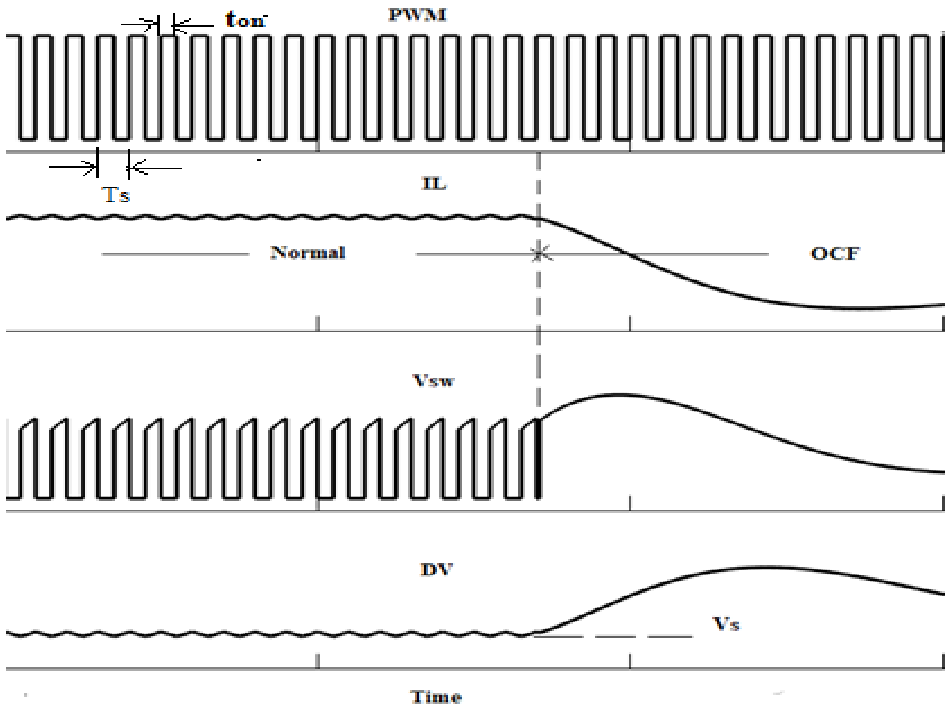

Fig. 2 Boost converter characteristics before and after the OCF.

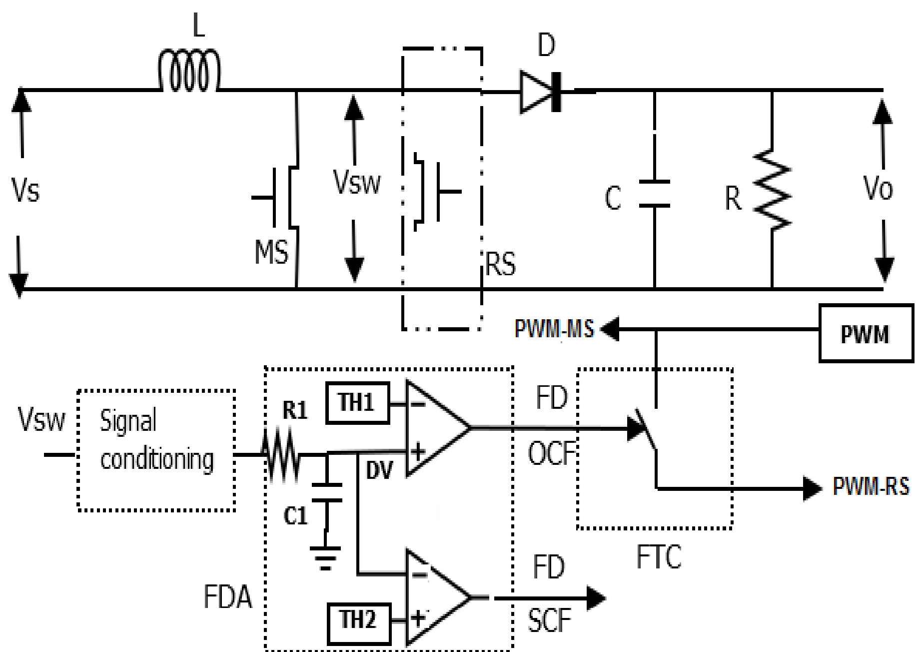

Fig. 3 Block diagram of proposed fault detection algorithm (FDA) and fault-tolerant control (FTC)

4. Simulation Results

The proposed method and the boost converter are modeled and simulated using Simulink. The boost converter is operated for the specifications given in the Table 1. Fig.4 shows OCF detection for D= 40% and TH1=7.15V. The Vo corresponding to the D=40% is expected to be approximately 12V. The Vo signal indicates the output voltage of about 12V. The fault is simulated at t= 20.71 ms which is indicated by the high to low transition in FLT signal. During the normal operation of the converter, DV i.e. Vsw-avg = Vs =7V. The moment the OCF occurs, the transitory increase in the Vsw causes similar increase in the Vpwm-avg i.e. in the DV. Thus, the fault is detected at t= 20.7335 ms, i.e. The fault is detected in 23.5 us. As the DV contains some ripples which are symmetrical to the threshold level, FD contains some pulses during this transient period as shown in the FD signal. However, the first pulse is get latched and a continuous positive pulse, called as fault detection and control (FDC), is generated. The fault detection is followed by the converter reconfiguration. As can be seen, except a very small overshoot of short duration, the Vo is constant and continuous. Moreover, the inductor current, IL is smooth and continuous.

Table 1 Simulation parameters

Parameter	**Value**	**Unit**
Switching frequency, Fs	10000	Hz
Source voltage, Vs	7	V
Inductance, L	3.1	mH
Inductor resistance, rL	0.02	ohm
Capacitance, C	33	uF
Resistance, R	10	ohm
Sampling Time, T	1	usec
Duty cycle, D	60	%
Resistance, R1	100	ohm
Capacitance, C1	10	uF

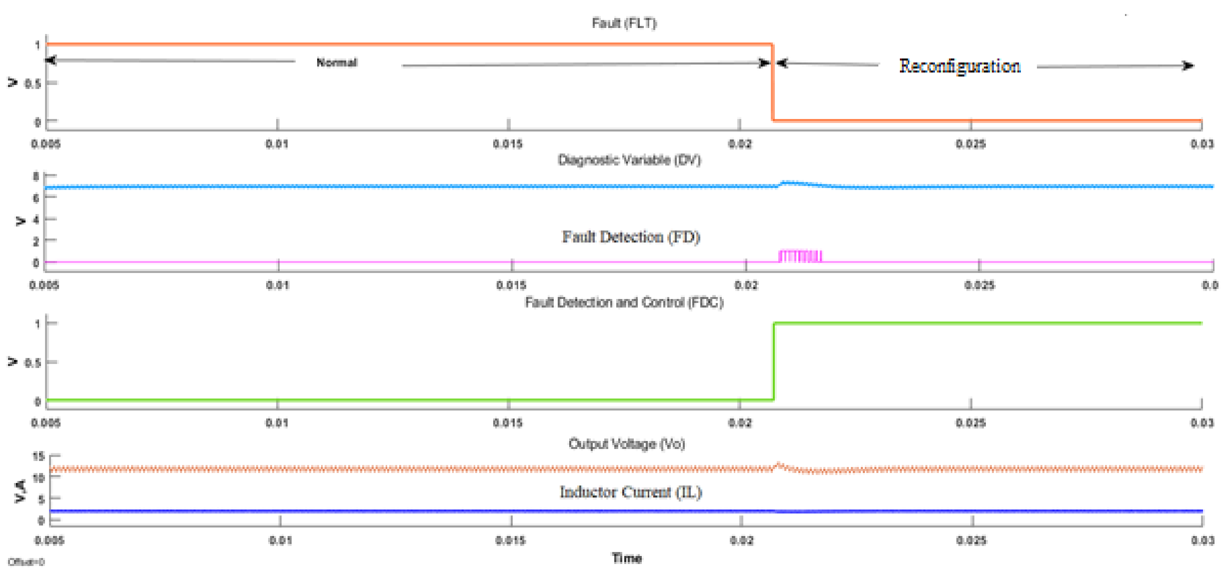

Fig.4 OCF simulation result

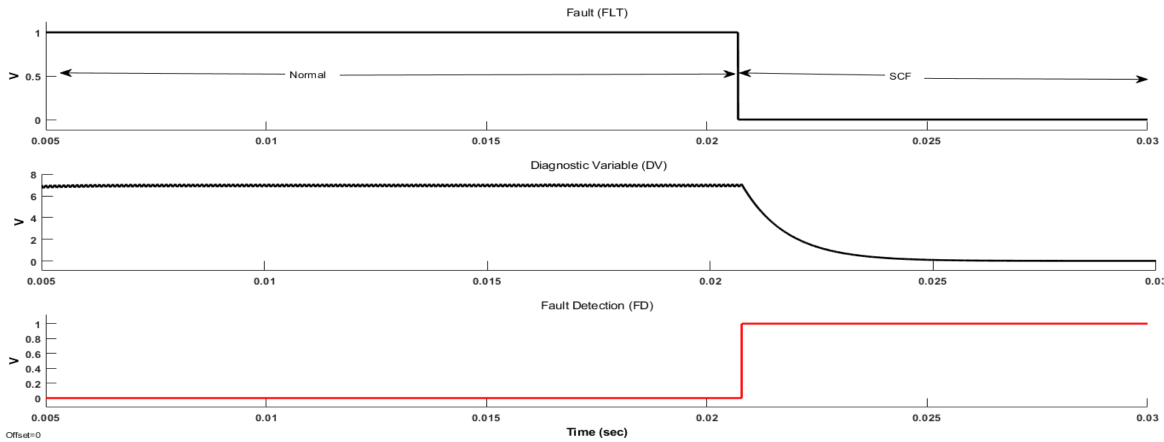

Fig.5 SCF simulation result

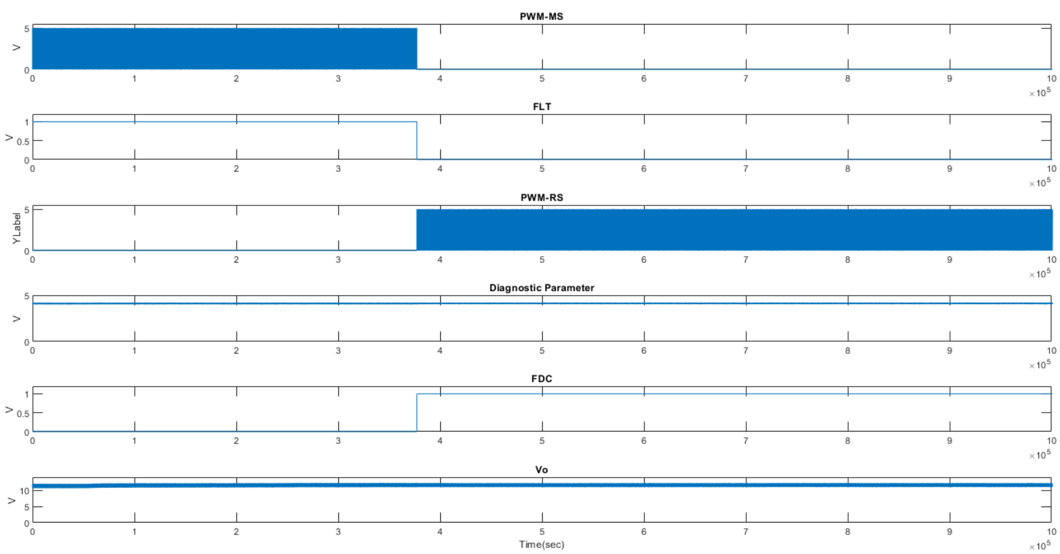

Fig. 6 Experimental result of OCF detection and converter reconfiguration

The proposed method is tested for different D. The fault is detected within the one cycle period of the switching cycle for different D. The short-circuit fault in the switch is simulated at t=20.72 ms as shown by the FLT signal in the Fig.5. The D is set at 20%. A continuous positive signal to the gate of the MS is provided to demonstrate the SCF. The SCF fault causes the DV to fall below its normal level. When it falls below the TH2=6.5V, the fault is detected, as shown by the FD signal. The fault is detected in 62.73 us.

5. Experimental Results

An experimental prototype, for the parameters shown in the Table 1, is built and tested to verify the proposed OCF diagnosis and FTC scheme. The dSPACE software and the dSPACE DS1104 controller board are used to implement the prototype. The real-time signal interfacing between the hardware and the dSPACE controller board is achieved using a dSPACE ControlDesk environment. Digital to analog conversion (DAC) blocks are used to interface the PWM control signals with the switches MS and RS.

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DS1104DAC_Cx unit has output voltage range of +/- 10V. Analog to digital conversion (ADC) blocks are used to interface output voltage, switch voltage and diagnostic signal with the controller board. DS1104ADC_Cx unit has input voltage range of +/-10V. Nevertheless, the dSPACE always scales this by a factor of 0.1. Sampling time is set at 20 us. Simulink model for the controller is developed. After setting the simulation parameters, system description file (.sdf) is generated. Real-time simulation is performed with the help of ControlDesk and results are obtained as shown in the Fig.6. To demonstrate the OCF fault in the MS, the PWM-MS control signal is inhibited from the gate as shown in the Fig.6. A low to high transition of FDC signal indicates the fault detection. The OCF is detected in 20 us. After the fault detection, control signal PWM_RS is connected to the gate of the RS to reconfigure the converter. As can be seen in the Fig.6, the Vo is smooth, continuous and constant even after the converter reconfiguration.

6. Conclusion

In this paper, a simple and the fast real-time fault diagnosis and fault-tolerant control approach based on the switch voltage is proposed for open-circuit and short-circuit switch faults of the boost dc-dc converter. The proposed method is modelled and simulated using Simulink. A low power converter prototype is built and tested to validate the simulated results. The method is able to detect the faults within one cycle of the switching period for different duty cycle of the switching frequency. The fault detection and fault-tolerant control scheme requires very few and general purpose hardware elements that reduces the complexity and thereby the cost. The reconfiguration of the converter is very quick and smooth that ensures continuity of the operation with safety and excellent performance. The method can be extended to other topologies of the dc-dc converters.

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