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A Novel Algorithm for detecting OCF and SCF in Boost Converter

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Abstract **-** One major branch in Power Electronics is the area of DC-DC converters. DC-DC converters change an input voltage to a different output voltage as efficiently as possible. In order to improve the reliability, fault tolerant operation is necessary to guarantee service continuity. This paper proposes a novel fault tolerant operation of a Single switch DC-DC Converter under a switch failure. In the case of a switch failure, suitable fault detection is essential to avoid its propogation to the whole system. A redundant switch and a bi directional switch are needed for converter reconfiguration in post fault operation. In this paper, the inductor current slope is used as fault diagnosis criterion and no additional sensors are required and the failure can be detected in less than one switching periods. This work mainly focuses on fault tolerance in a Boost converter under Open Circuit Fault (OCF) or Short Circuit Fault (SCF) on the semiconductor switch. Simulations are done by using MATLAB/Simulink.

Keywords-DC-DC Converter; Diagnosis; Fault Tolerance; FDA

1 .INTRODUCTION

As we all know the use of Semiconductor Power Switches in Power electronic technology has led to a rapid development of this technology in recent years. The switching Power converter plays a significant role in power energy conversion application. DC-DC converters are extensively adopted in Industrial, Commercial and residential application. These converters are power electronic circuits that convert a dc voltage into a different level and providing a regulating output. In the power energy conversion system, the major components are the power semiconductor switches. PWM modulation is the simplest way to control power semi converter switches. In this approach, the power flow can be controlled by interrupting current or voltage through means of switch action with the control of duty cycles.

One of the major branch of power electronics is in the area of DC to DC converters. DC-DC converters change an input voltage to a different output voltage as efficiently as possible. For effective operation of a converter, a fault tolerant operation is necessary. The power semiconductor switches are the major fault affecting part in any DC-DC converter. In this work, we are dealing with the faults that can be caused to the power semiconductor switches and its remedial action. The method used in this paper can be very effectively used for any single switch DC-DC converter like Buck converter, Boost converter, Buck-Boost Converter, Sepic converter and so on. Here we are dealing with simulation of fault tolerant operation of a Boost converter. The only fault detection criterion is the slope of the inductor current. Since the inductor current behavior of all single switch dc-dc converter are same, this method can be effectively used for any single switch DC-DC converters. Fault tolerance in a power converter requires three steps: fault detection, fault identification (also known as “fault diagnosis”), and remedial actions. The two first steps are used to identify the location and nature of the fault. The remedial actions are the process to first isolate the faulty device, if needed, and then, reconfigure the converter to guarantee the service continuity. The two most critical elements in dc–dc converters are aluminum electrolytic capacitors and semiconductors[1].

More than 50% of malfunctions and breakdowns are reported to be due to aluminum electrolytic capacitor failures and 34% due to semiconductor failure and soldering joints failure in power devices. This contribution focuses on fault tolerance in single-switch dc–dc converters under open-circuit fault (OCF) or short-circuit fault (SCF) on the semiconductor switch. Several papers have proposed switch fault detection methods in power electronic converters and FT converter topologies. In some of the papers, fault diagnosis with FT schemes for isolated phase shifted full-bridge dc–dc converters are presented. In some other cases, the primary voltage of the transformer is used as the diagnosis criterion, which has been obtained by adding an auxiliary winding. One of the other method is that the dc-link current and transformer primary voltage, combined with switch gate-driver signal, are treated as diagnosis criteria to detect the switch SCF [2] & [3].

A fault diagnosis method of PWM dc–dc converters by using the magnetic component voltage is presented in [12]. In this method, an auxiliary winding in the magnetic core is used to measure the inductor voltage. In [13] , an alternative OCF diagnosis method for boost interleaved dc–dc converters operating in an unidirectional power flow is studied. This method is based on features of the dc-link current derivative sign during fault and healthy operations [13]. An OCF diagnosis and FT scheme for a three-level boost converter in a PV power system is presented in [7] .The control variables used for maximum power point tracking and output dc-link capacitor voltage balance are treated to fault diagnosis. By adding a few components to the original converter, it can be partly reconfigured into a two-level boost converter for post fault operation.

A MOSFET faults diagnosis based on the integral and peak values of the dc-link current for a zero voltage-switching dc–dc converter is proposed in [11]. It should be noticed that the fault detection methods cited in references [7]–[11] can generally detect only one type of fault (OCF or SCF). Among them, the methods in [8] and [12] are as fast as the one proposed in this paper, while in [12], an analog circuit is used to fault detection. This paper is started from our previous research, first introduced in a precedent introductory paper [10]. The initial fault detection algorithm (FDA) is improved in term of fault diagnosis (OCF or SCF); moreover, remedial actions, such as converter reconfiguration for post fault operation, are also treated in this contribution. The new proposed FDA is capable to identify the type of the failure that is mandatory for fault isolation and converter reconfiguration in post fault operation. To guarantee the service continuity, a FT dc–dc converter topology based on redundancy is then considered. According to the type of the failure (OCF or SCF), two different strategies for system reconfiguration are proposed. This study is particularly dedicated to single-switch dc–dc converters. Fig. 2.1 summarizes this family that consists on buck, boost, buck–boost, Cuk, SEPIC, and dual SEPIC converters.

Fault detection (FD) in power electronic converters is necessary in embedded and safety critical applications to prevent further damage. Fast FD is a mandatory step in order to make a suitable response to a fault in one of the semiconductor devices. The aim of this study is to present a fast yet robust method for fault diagnosis in a Boost Converter. FD is based on time and current criteria which observe the slope of the inductor current over the time. A fault diagnosis algorithm, which is necessary for constructing a reliable power conversion system, should detect fault occurrences as soon as possible to protect the entire system from fatal damages resulting from system malfunction. In this paper, a fault diagnosis algorithm is proposed to detect open- and short-circuit faults that occur in a boost converter switch.

In single switch DC-DC converters, the inductor current behavior is same. Because of this similarity, the proposed fault detection method is applied to the particular case of a boost converter. This method can be applied to any other topology. In the following sections, the proposed FDA and FT converter topology are presented;

. It is shown that by using this fault detection method, both types of switch failure can be detected and discriminated. These actions may be performed in less than one switching period. This minimal needed time is due to the natural delays in the system. One can notice that, in the worst case, two switching periods are needed (in the case of an OCF). In the case of a SCF, the system reconfiguration will be done after the fault clearance time.

2. FAULT DIAGNOSIS

If there is any open circuit fault in the switch, it will remains in its off condition regardless of the firing signal given to the switch. That is whatever may be the firing signal given to the switch, it will remains in its open condition. Therefore the value of inductor current decreases to a very small value. Similarly, if there is any short circuit fault in the switch, it will remain in on condition regardless of the firing signal given to the switch. That is, whatever may be the firing signal given to the switch, it will remains in its closed condition. So the value of inductor current increases to a very large value.

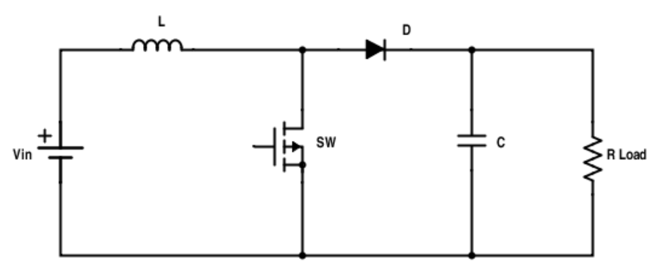


Figure.1. Circuit Diagram for Boost Converter

Figure.1 represents the open and short circuit fault condition in a boost converter. From the figure 2, it is clear that during open circuit condition, the inductor current value decreases very close to zero and during short circuit condition, the inductor current value increases to a very high value.

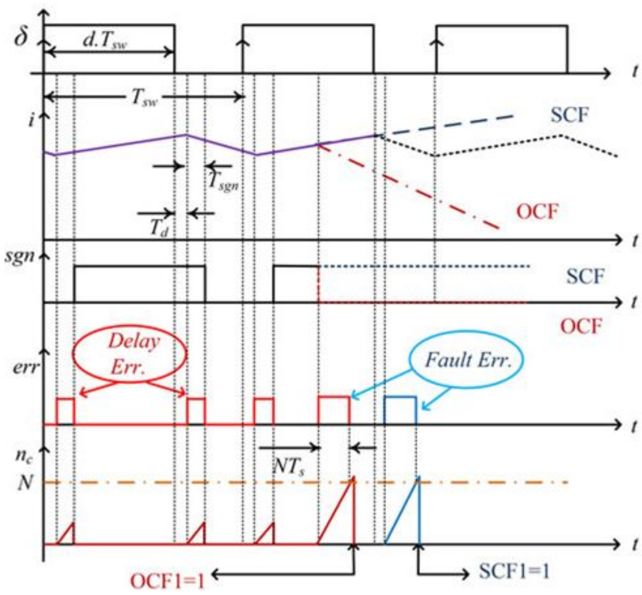


Figure.2 Open and Short circuit fault condition in Boost converter

3. FAULT DETECTION ALGORITHM

Our primary intention is to detect the open and short circuit switch failure. For that we use a fault detection algorithm. For that we are considering the slope of the inductor current at a particular time instant and the time instant below that.The below given equation represents that.

ie, $\Delta i = i(t) - i(t-T_{sgn}) > 0 \;\; => sgn=1$

$$\Delta i = i(t) - i(t-T_{sgn}) < 0 \;\; => sgn=0 \qquad (1)$$

where, Δi = Difference of inductor current at two particular time instant

$i(t)$ = Value of inductor current at present time instant

$i(t - T_{sgn})$ = Value of inductor current at a past time instant

Also here we are considering two signals. 'Sgn' and 'δ' signal, where 'sgn' is the slope of the inductor current and 'δ' is the switch command signal or the switching signal given to the mosfet. When the value of Δi, that is the value of the inductor current at two particular time instant is positive, then 'sgn' is one. Similarly when Δi is negative, then 'sgn' is zero. Thus the fault in the switch can be detected simply by considering two parameters 'sgn' and 'δ'. In normal condition, when a switch command signal is given to mosfet, ie δ=1, the mosfet will turns on and the inductor current begins to increase and the inductor current slope is positive. That is sgn=1. If no switch command signal is given to the mosfet, that is δ=0, then mosfet will be in off condition and the inductor current begins to decrease and and the inductor current slope is negative. So sgn=0. That is, during the normal operating condition 'δ' and 'sgn' have same value[2].

If δ=1 and sgn=0, it means that a firing signal is given to the mosfet but the inductor current slope is decreasing and it is failed to turned on. This is the condition for open circuit fault in the switch. Similarly if δ=0 and sgn=1, it means that, no firing signal is provided to the mosfet but it remains in its on state. This is the condition for short circuit fault in the circuit. So that error signal is the XOR of 'sgn' and 'δ'. Figure 3.4 represents fault detection algorithm.

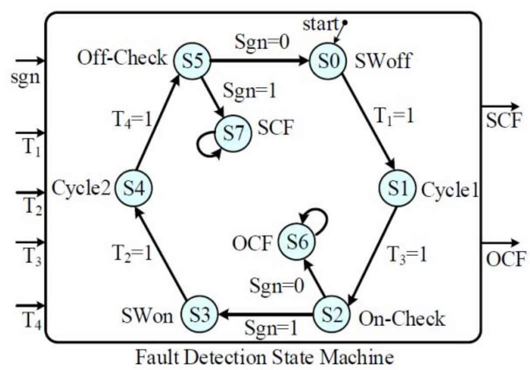


Figure. 3 Fault Detection Algorithm (FDA)

To realize the proposed fault detection method, a State Machine (SM) is used. The SM consists of five inputs (T1, T2, T3, T4 and the sign of the inductor current slope (sgn signal), eight states and two outputs (SCF and OCF), as shown in Figure. 3.

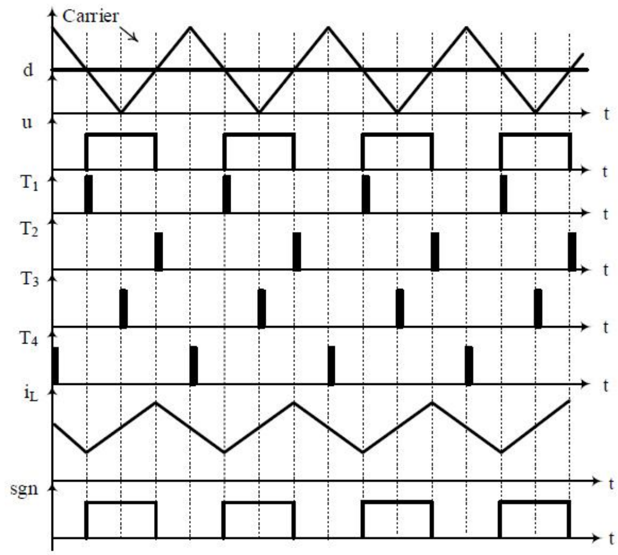


Figure. 4 Input Signals to the state machine

Here a 15kHz carrier signal is compared with duty cycle d to obtain a switch command signal u. T1 is the rising edge of the PWM switch command signal and T2 is the falling edge of u.T3 and T4 is activated at the middle of cycle 1 and 2 where cycle 1 is the rising period of the inductor current and cycle 2 is the falling period of the inductor current. Sgn depends on the slope of the inductor current.

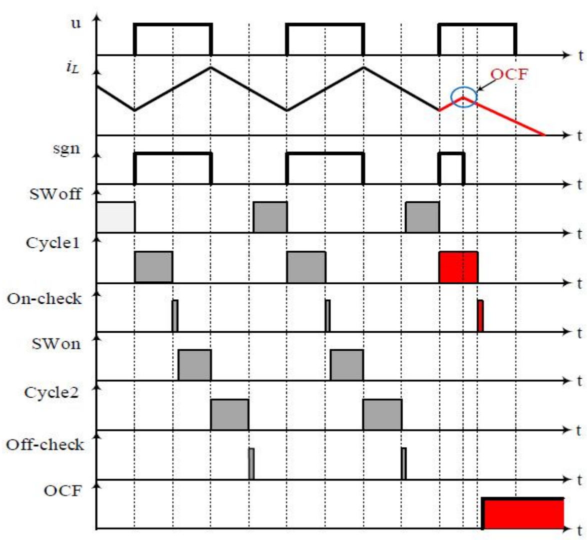


Figure.5 Open Circuit fault detection

Check for open circuit fault is carried out in the middle of cycle 1. In the middle of cycle 1, the only possibility is that to increase inductor current. But if inductor current is decreasing at this point, an Open Circuit fault is detected.

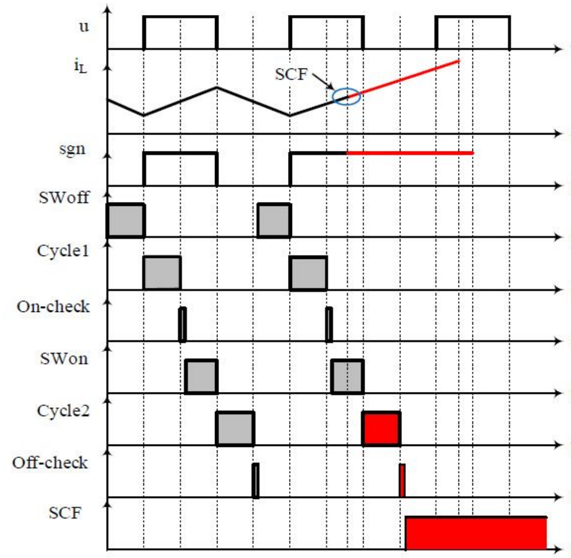


Figure. 6 Short Circuit fault detection

Check for Short circuit fault is carried out in the middle of cycle 2. In the middle of cycle 2, the only possibility is that to decrease inductor current. But if inductor current is increasing at this point, a Short Circuit fault is detected.

4. FAULT RECONFIGURATION STRATEGY

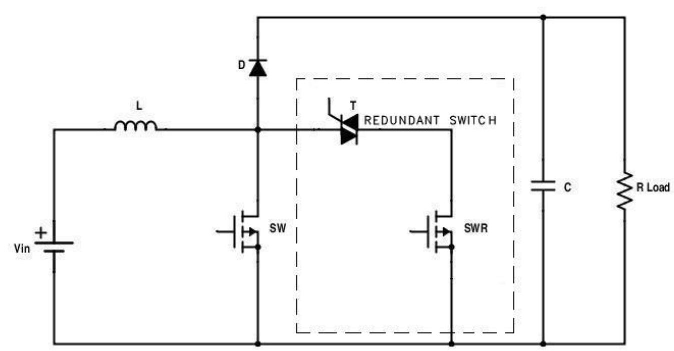


Figure. 7 Fault Diagnosis Circuit

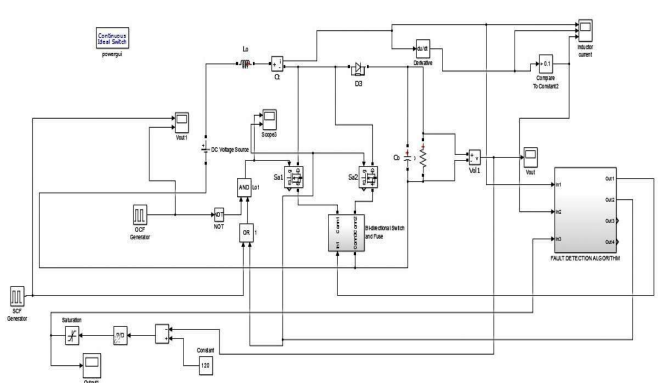
Figure 4. represents the fault tolerant converter with redundant switch and a bidirectional switch. To ensure service continuity of the studied dc–dc converter for post fault operation, a FT topology is proposed. After fault detection and isolation, the faulty switch (SW) will be replaced by SW*R* via a bidirectional switch *T*. Then, the converter can operate in normal conditions, not in degraded mode but without redundancy. There is a fuse in

this circuit. If there is any open or short circuit fault in the switch SW, the fuse will burnt out and the faulty switch is replaced by the redundant switch. By using this novel fault detection algorithm, fault can be detected in a fast manner than the previous algorithm. say less than 1 switching cycle.

5. SIMULATION AND RESULTS

A. Closed loop simulation of Fault Tolerant Converter using PI controller

Simulation of each circuit is done in MATLAB R2014. The focus was on the output voltage V_{out} and the open circuit and short circuit fault condition for the main switch S_{a1} and S_{a2}. In case of fault condition the focus was on the inductor current and the derivative of inductor current. The power circuit (plant) and the sensors are modeled using MATLAB/SimPowerSystems. The interfaces and controllers are done using Simulink toolbox. The studied system is modeled in continuous-time mode.



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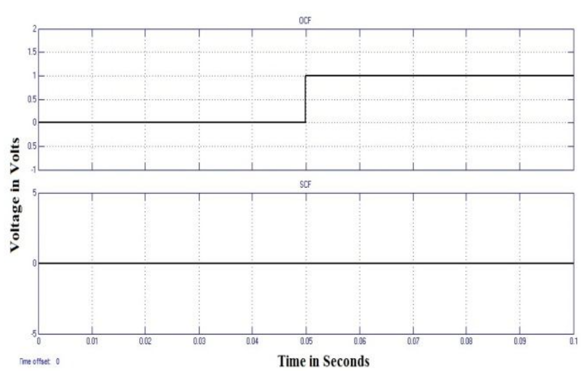

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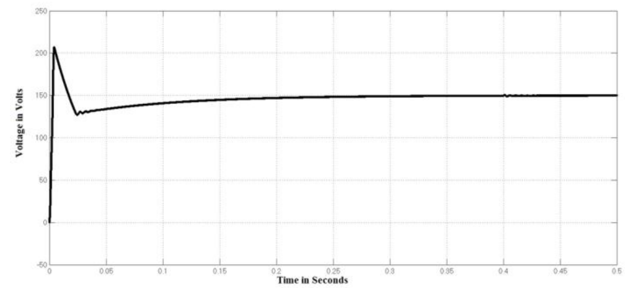

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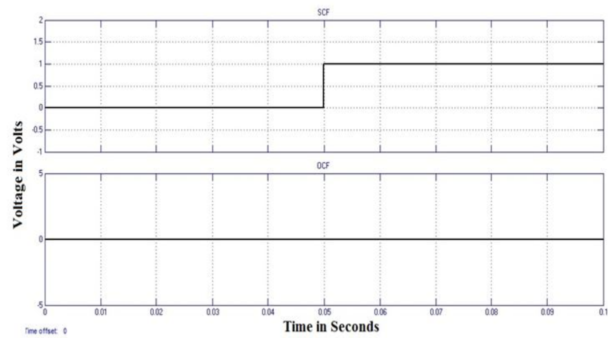

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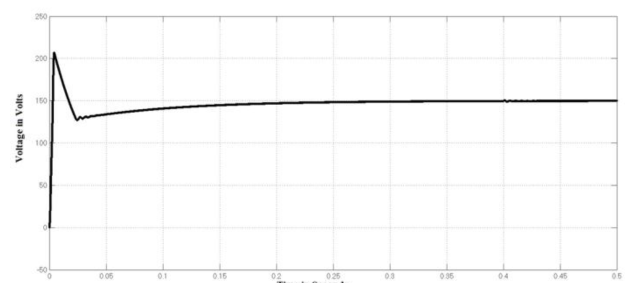
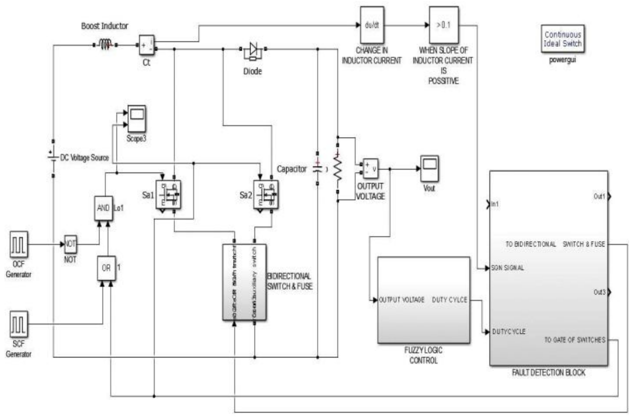


(e)

Figure 8 (a) Closed loop simulation model of a fault tolerant converter using PI Controller (b) Output of OCF generator and SCF generator when there is OCF (c) Output voltage of Boost Converter when OCF(d) Output of SCF generator and OCF generator when there is SCF (e)Output voltage of Boost Converter when there is SCF

The proposed Boost Converter under fault tolerant operation has two switches namely main switch (S_{a1}) and auxiliary switch (S_{a2}). Also L is the Boost Inductor, D is the diode, C is the output filter capacitor and R is the resistive load. A bidirectional switch and a fuse is provided in order to obtain fault tolerant operation. The logic behind this model is that if there is any fault in the main switch S_{a1}, it will isolated from the circuit by using the fuse and the conduction can be continued through the auxiliary switch.

B. Closed loop simulation of Fault Tolerant Converter by using fuzzy logic control



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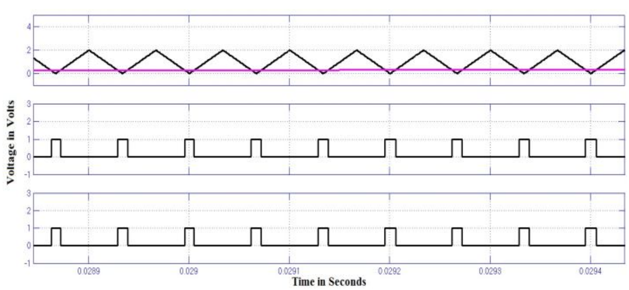

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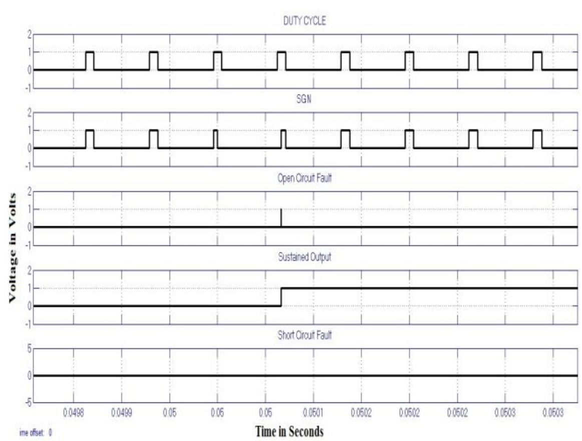

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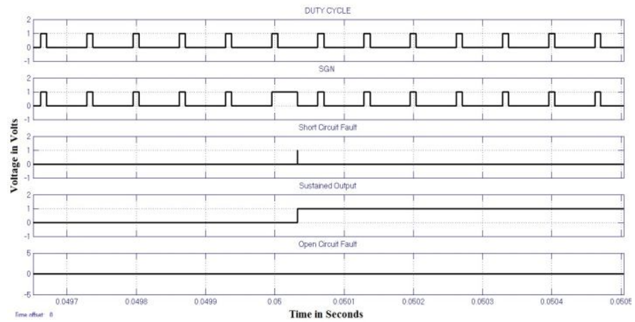

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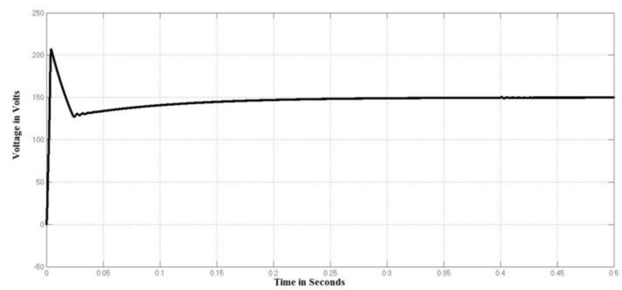

(e)

Figure 9 (a) Closed loop simulation model of a fault tolerant converter using fuzzy logic control (b) Generation of PWM switch command signal u and sgn (c) Open Circuit fault Detection (d) Short Circuit Fault Detection (e)Output voltage of Boost Converter when there is any OCF or SCF

If there is any open circuit fault, the main switch S_{a1} will be in open condition. In order to achieve that condition, make the output of the OCF generator one. This output one is given to the logical NOT gate. So the output of NOT gate will be zero and this is given to the input of the AND gate. If one input of the AND gate is zero, its output will always zero. That zero is given to the gate of the main switch. Thus the main switch S_{a1} will be in off condition and thus open circuit fault is introduced to the main switch S_{a1}.Thus whenever there is any open circuit fault in the main switch S_{a1}, the output of the OCF generator will be one and the output of the SCF generator will be zero.

The triangular carrier wave is compared with reference inorder to get the pwm switch command signal u. sgn depends on the slope of the inductor current. When a switch command signal u is given, the inductor current begins to increase and slope of the inductor current is positive and sgn will be a positive pulse. When the switch command signal u is not given, the inductor current decreases and the slope of the inductor current is negative and so sgn will be zero as shown in fig.9b

When the duty cycle u and slope of the inductor current sgn signal is not same, a fault is developed. When duty cycle u=1 and sgn=0, an Open circuit fault is developed. This OCF is like a small pulse. So inorder to get a sustained output, we take the output of the monostable. And also during the time of OCF, the SCF will be zero. That is also shown in the fig.9c

When the duty cycle u and slope of the inductor current sgn signal is not same, a fault is developed. When duty cycle u=0 and sgn=1, a Short circuit fault is developed. This SCF is like a small pulse. So inorder to get a sustained output, we take the output of the monostable. And also during the time of SCF, the OCF will be zero. That is also shown in the fig.9d.

The output of the boost converter during Open or Short circuit switch failure is shown in fig.9e. A continuous output will get by using the fault tolerant converter. So the service continuity can be guaranteed by using the novel fault detection algorithm.

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6. EXPERIMENTAL RESULTS

Experimental tests are carried out, based on a boost converter with a redundant switch, as shown in Figure. 10. The experimental setup is given in Fig.10. It consists on a Stratix DSPIC 30F2010 microcontroller . The switches are MOSFETs IRF Z44n.

The experimental results for an OCF with a duty cycle is around 50%. The switch SW is kept opened by forcing “δ” to “0”. In this test, an OCF is occurred when the switch SW is OFF.

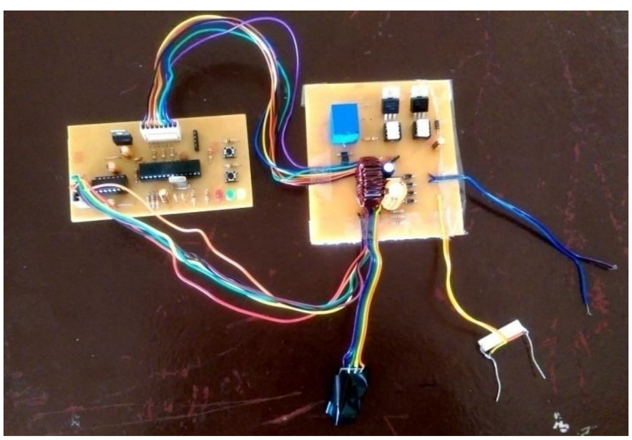
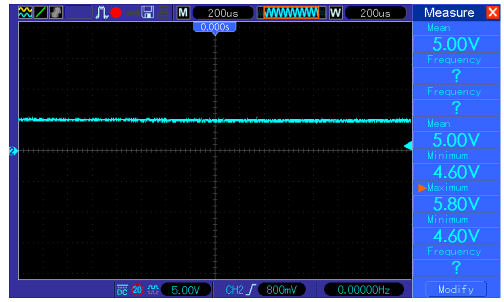


Figure. 10 Hardware Implementation of Fault Tolerant Converer

A hall effect current sensor is used for sensing the current in inductor. A relay is here to isolate the faulty MOSFET. LED Indicators are provided to indicate fault in the converter. A regulator IC LM7805 is provided to get regulated 5V supply to the converter and also 5V input supply is boosted upto 12V by using this particular converter.



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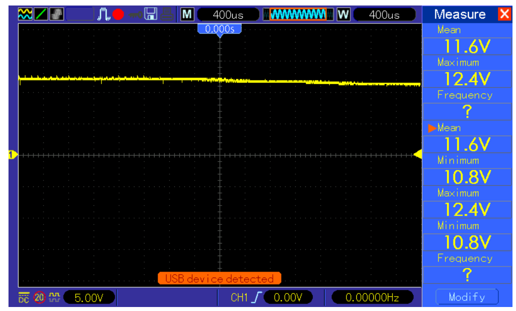

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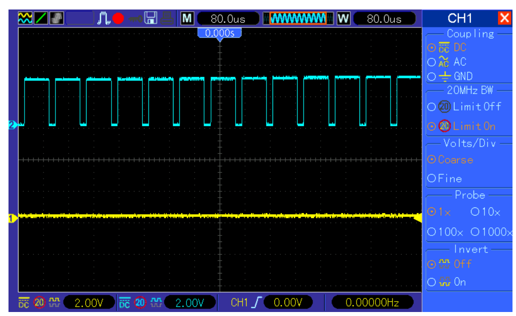

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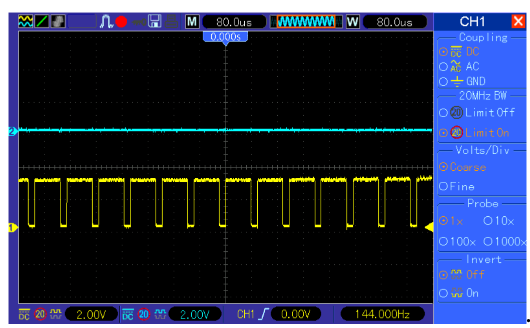

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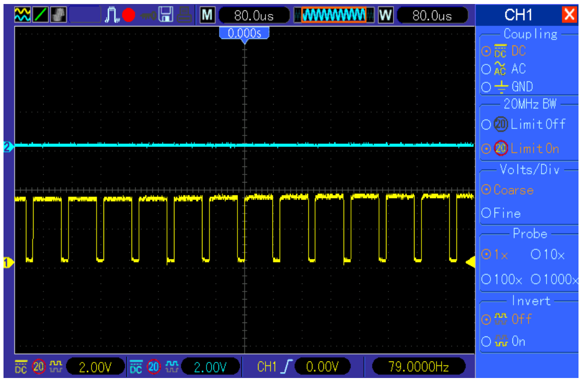

(e)

Figure 11 (a) Input signal 5V to the Boost Converter (b) Boosted output voltage of about 12V of the Boost Converter during fault condition (c) Switching pulses to main switch and auxiliary switch during normal condition (d) Switching pulses to main switch and auxiliary switch during OCF condition (e) Switching pulses to main switch and auxiliary switch during SCF Condition

These results show that the proposed FDM can always detect and identify open and short circuit switch faults correctly. Also the effectiveness of the fault tolerant topology is confirmed by these experimental tests.

7 . CONCLUSION

This paper has proposed a novel algorithm for the Fault Tolerant operation of Boost Converter for open- and short-circuit switch failures. The proposed Fault Detection Algorithm can identify and declare the type of the fault (OCF or SCF), which is not always proposed in similar methods. The inductor current and switch command are only used to detect both failures. The maximum required time to detect a switch failure by this FDM is only one switching period .Then a fault tolerant topology by adding a few components to a boost converter is introduced. In case of an OCF, the faulty switch can be replaced by the redundant switch immediately after the fault detection. But in case of a SCF, the converter reconfiguration can be done after the faulty switch is disconnected physically by a protection element such as a fuse. The proposed Fault Detection Algorithm and Fault Tolerant converter do not require any additional sensor. The FT capability proposed in this paper is one of the fastest fault detection and reconfiguration for single-switch dc–dc converter service continuity, in both open and short-circuit cases.

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