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High Efficient, Fault-Tolerant DC-DC Converter for Wireless Charging of Battery.

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Abstract: *Wireless charging systems are emerged nowadays as a solution to the endless number of cables required to power the household devices. To eliminate the need for wires, these systems rely on the concept of inductive power transfer. The goal of this work is to design and implement a practically efficient wireless cellphone charger which operates normally even in faulty conditions. The design part consists of a primary and secondary circuit which are interfaced via 2 coupled planar surface coils. The primary side of the circuit consists of a 2 stage converter which is responsible for supplying power to a primary source coil. The topology opted here for providing power supply for charging is a reconfiguration scheme for series resonant converter (SRC). This enables it to continue to work even in faulty situations. The secondary side consists of a rectifier with voltage doubler topology. So even if the output voltage drops to half of its original value during fault conditions, it won't affect the output and the output parameters are maintained constant. This output is utilized in an effective manner for wireless charging which eliminates the use of conventional copper cables and current carrying wires. This type of charging provides a far lower risk of electrical shock.*
Keywords: *dc-dc converter, Resonant converters, series-resonant converter.*

I. Introduction

Wireless charging systems have emerged in recent years as a solution to the endless number of cables required to power household devices. Wireless charging is one of the several methods of charging batteries without the use of cable or device specific AC adaptors. Wireless charging can be used for a wide variety of devices including cellphones, laptop computers, and MP3 players as well as large objects such as robots and electric cars. Three types of wireless charging are resonance, inductive, and radio charging. Resonance Charging

It utilize the phenomenon of resonance that cause an object to vibrate when energy of certain frequency is applied. It consists of two copper coils, one act as trasmitter while other act as a receiver. Both of them are tuned to same elecromagnetic frequency. When they are placed close enough, power transfer occurs. This type of charging is employed in equipments that need large power.
Ex: Laptops, Car, Vaccum Cleaner, Robot and so on.

- **Inductive Charging**

It is also known as short distance wireless charging. It works on the principle of electromagnetic induction. In this type of charging, the charger creates an electromagnetic field with alternative polarity using coil of insulated copper wire. A similar coil is placed inside the mobile device which converts electromagnetic field back to electric current and thus charges the battery. This method is utilized for charging mid-sized items.
Ex: Mp3 player, electric tooth brush and so on.

- **Radio Charging**

This mode of charging works on the idea of radio wave transmission and receiving. A radio wave transmitted propagate in all direction till it reaches antenna tuned to a proper frequency to receive it. The transmitter is plugged into a socket. It transmit radio waves. When receiver attached to device have same frequency, it enables charging of the battery. The transmitter here act as a power source that transmits power. The transmission signal is in between the range of radio frequency or microwave range. Antenna is the mediator between transmitter and receiver. The important specifications an antenna should satisfy are the impedance and gain constraints. The impedance of antenna should match output impedance of transmitter and input impedance of the rectifier. A high gain antenna should provide good results. Receiver part charges the battery. For charging, it takes in ac and fed it into a rectifier and thus DC is obtained. Full wave rectifier is used for this purpose because of the fact that they efficient and simple. R and C are added at the output of rectifier for the purpose of smoothing. It is utilized for low power requirement.
Ex: Watches, Hearing aids, Cellphone, Wireless keyboard and so on.

The idea implementing here is Inductive charging. The design consists of 2 sole parts: Transmitter and receiver as shown in Fig.1.

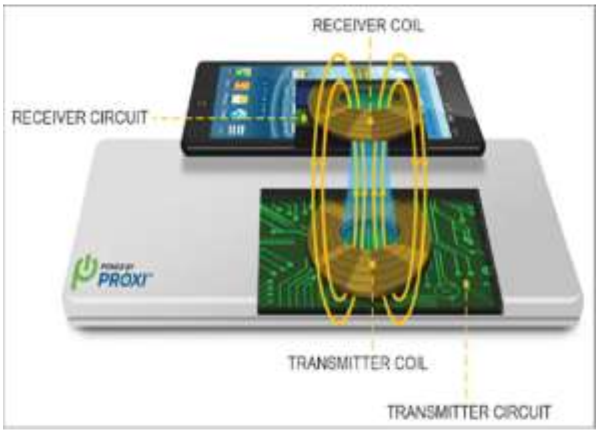

Figure 1: Inductive Charging Setup

Wireless charging of mobile phone is enabled by a Series Resonant DC-DC Converter (SRC) which is fault tolerant. This work is a reconfiguration scheme for the SRC which could drastically reduce the need of redundancy. Using the proposed scheme, the full-bridge based SRC can be reconfigured in a half-bridge topology whenever fault occurs. Inorder to maintain output voltage constant during fault condition, a reconfigurable rectifier based on the voltage-doubler topology is proposed as a solution.

Series Resonant Converter has been frequently used in wireless power transfer application for electrical vehicle [2], battery charger [3], renewable energy system[4], and so on. This topology became very popular in solid-state transformer (SST) [5], mainly because of its output voltage regulation characteristic in open loop. The SRC has been used for traction application [5], where an efficiency of around 98%was achieved. In SST, telecommunication or even in renewable energy system applications, the continuity of operation is important and thus a highly reliable system (preferable with redundancies) is required. The Fault-tolerant feature contributes to increase the availability of the system. Most of these methods include a significant amount of extra hardware or series connection of fuses/switches to isolate the fault, increasing the cost and compromising the efficiency of the system[6]. There are two possible failure types for the semiconductor: open circuit (OC) or short circuit (SC). According to [7], the reasons that imply an OC failure are bondwire lift off or rupture and failure on the gate drive. Meanwhile, the SC failure might be a result of an overvoltage, static or dynamic latch up, second breakdown, or energy shock. Since most of the failures result in an SC condition [7], this work focuses on an SRC resilient to SC failure.

II. Circuit Diagram And Operating Principle

The proposed circuit for this work is derived from the conventional SRC by considering various features. They are described in steps below.

2.1 Full-Bridge SRC (FB-SRC)

The topology of the SRC based on FB configuration is shown in Fig. 2. To simplify the description, an unidirectional topology is considered in this analysis and a diode bridge rectifier is used in the secondary side. To support the analysis,

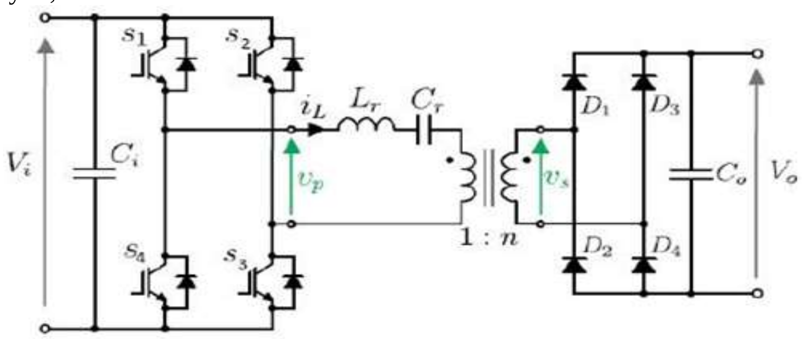

Figure 2: Full bridge SRC

the variables resonant frequency (f_o), resonant angular frequency (ω_o), and characteristic impedance of the resonant network (Z) are defined by (1), in terms of the resonant inductor (L_r) and capacitor (C_r) of the tank circuit as

$$f_o = \frac{1}{2\pi\sqrt{L_r C_r}} \qquad \omega_o = 2\pi f_o \qquad Z = \sqrt{\frac{L_r}{C_r}} \quad \text{------------(1)}$$

The output voltage of the converter is given by

$$V_o = nV_i \quad \text{-----------------(2)}$$

1.2 Half-Bridge SRC (HB-SRC)

The half bridge topology of SRC is shown in Fig 3. The operation of the HB-SRC is very similar to the one of the FB-SRC converter, previously described. This circuit became well known as LLC converter, due to the configuration of the tank circuit, considering the magnetizing inductance of the transformer. It has been widely used in telecommunications power supply applications. Output rectified voltage on the secondary side of the HB-SRC is given by (3), which is half of the value, when compared to the FB-SRC output voltage for the same parameters(Vi and n).

$$V_o = \frac{nV_i}{2} \quad \text{-------------(3)}$$

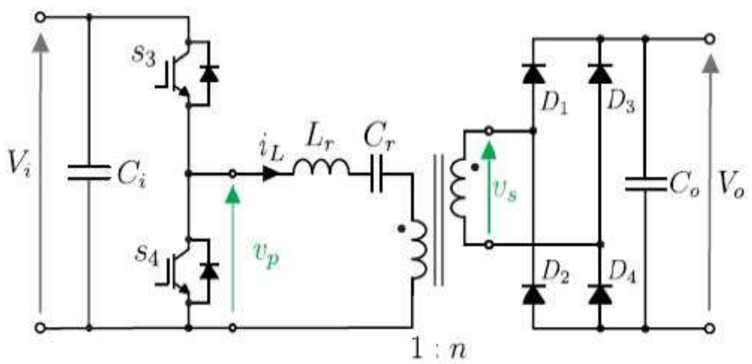

Figure 3: Half bridge SRC

Under normal conditions the proposed converter work as FB-SRC. But whenever a fault occurs it undergoes a topology change and work as HB-SRC. The working of converter under fault condition is explained below.

1.3 Working of FB-SRC as HB-SRC

Depending on the semiconductors failure mechanisms, the device will assume two possible states: OC or SC. For a voltage source converter, which is the case of SRC, the OC fault is not disastrous, since the power transfer will be naturally interrupted. Instead, the SC fault is the main issue, because it can cause destructive damage to the power converter. The reconfiguration scheme proposed in this work is concentrating on the SC fault case, although it can also be used for the OC fault.

Reconfiguration scheme: Operation & control :

The proposed reconfiguration scheme for the SRC consists in configuring the FB-SRC in an HB-SRC after the SC fault of a semiconverter. The detailed analysis is carried out in this section for the FB-SRC shown in Fig. 4 .

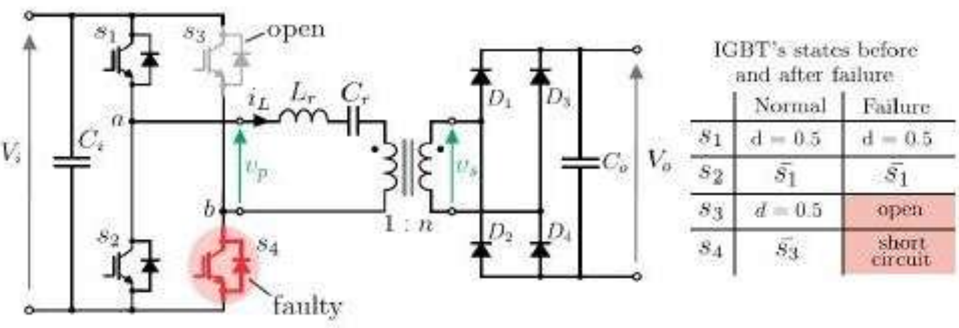

Figure 4: FB-SRC under faulty condition: SC failure on the semiconductor S4.

Initially, as an example, it is assumed that switch S4 is damaged in SC (see Fig. 4); hence, switch S3 must remain open, avoiding SC of the input voltage source. Since switch S4 is short-circuited, the point b is directly connected to the primary side ground and the damaged device is used as a circuit path, resulting in half bridge topology. Meanwhile, the healthy leg (composed of S1 and S2) operates normally. Fig. 5 shows the operation states of the SRC after the fault, i.e., after the reconfiguration, where it can be seen that the damaged switch S4 being used as a circuit path.

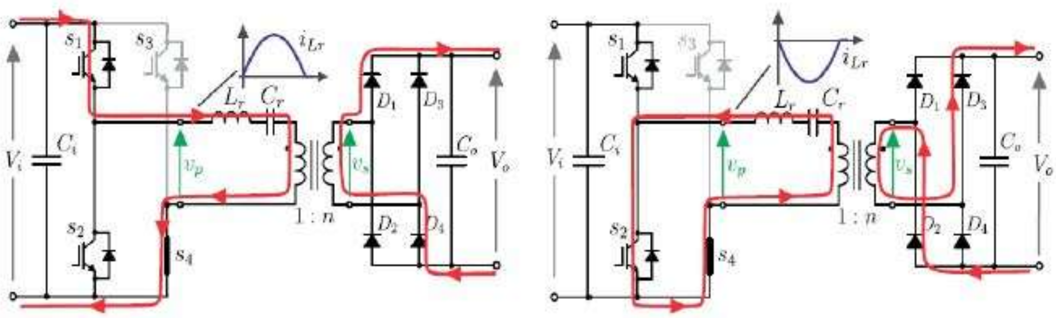

Figure 5: Operation of the FB-SRC as an HB-SRC after the reconfiguration.

States of operation of SRC during faults is shown below. Duing first operating state positive current iL flows and during second state negative current flows. Fig. 6 shows the main waveforms of the FB-SRC when a fault happens.

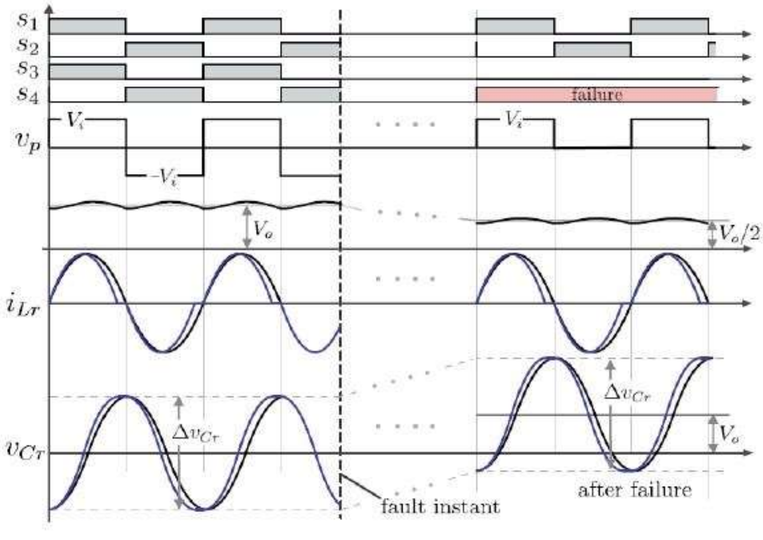

Figure 6: Main waveforms of the FB-SRC when a fault happens

It shows main voltages and currents before and after the fault. As the HBSRC provides only half of the output voltage compared to the FB-SRC, the output voltage after the fault will be half of its original value, which is not desired. To overcome this problem and to keep the output voltage constant after the fault, a modification to the circuit of the secondary side rectifier is done and a reconfigurable rectifier is obtained.

1.4 Topology of Fault Tolerant SRC (FT-SRC)

The circuit that incorporates both reconfigurable converter and inverter is shown in Fig 7. The proposed rectifier has two split capacitors and an additional switch (S_f) that allows us to connect one side of the high-frequency transformer secondary winding directly to the middle point of the capacitors, becoming a VDR.

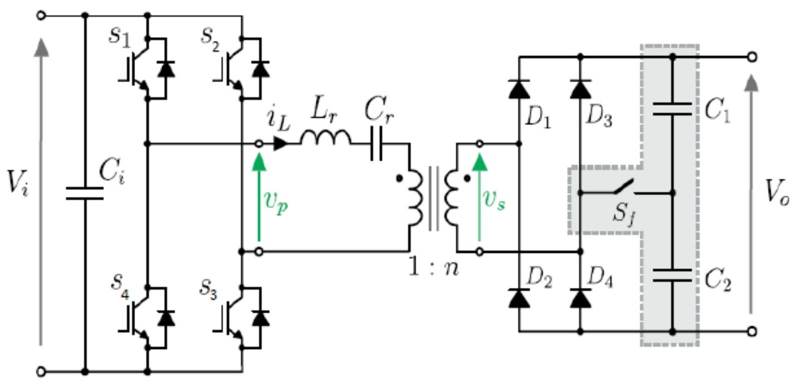

Figure 7: Proposed Fault-Tolerant SRC topology.

In normal operation, switch S_f is open, and the rectifier operates as a standard FBR. In the fault case, switch S_f is ON, the circuit operates as a VDR, and the output voltage value is twice the value in normal operation. The main waveforms for the proposed FT-SRC before and after a failure are depicted in Fig. 8.

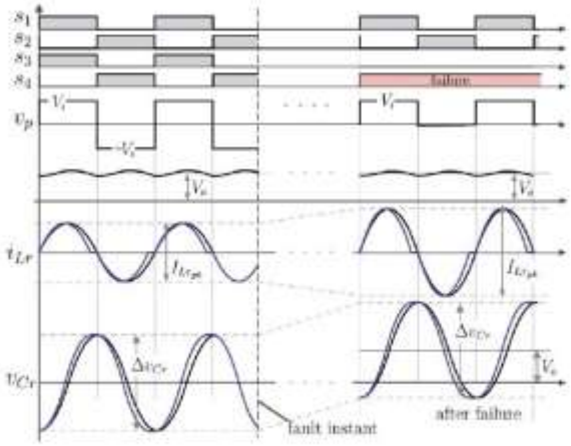

Figure 8: Main waveforms of the FB-SRC when a fault happens

As can be observed, before the failure (normal operation) the voltages V_p and V_{cr} have an average value equal to zero and the output voltage is given by V_o. After the failure, there is the reconfiguration, in which the FB-SRC will operate as an HB- SRC and switch Sf is activated, so that the output stage can operate as the VDR. The output voltage will remain in the same value, as desired. The effect of the reconfiguration is only observed on the voltage V_{cr}, which has an expected offset of V_o , and on the the current i_{Lr} , which must be twice the previous value to process the same amount of power than before. Both characteristics are inherent of the HB-SRC. In case of an OC fault, the proposed solution is still valid. Instead of opening the healthy IGBT of the faulty leg, the logic system must close this IGBT.

III. Design

The design part mainly includes the design of resonant inductor and filter cappacitor. The transformer turns ratio is taken to be 0.7 from the equation below, where input chosen is 10V and output obtained is 7V.

$$n = \frac{V_o}{V_i} \quad \text{---------------- (4)}$$

Resonant frequency of the converter, f0 is given by,

$$f_o = \frac{1}{2\pi\sqrt{L_r C_r}} \quad \text{----------------(5)}$$

Choose f0= 20kHz.
To operate at half-cycle discontinous condution mode (DCM), the converter parameters must satisfy the following condition,

$$I_o < 8 f_s C_r V_o \quad \text{----------------- (6)}$$

Thus the obtained final design values are tabulated as shown below.

Table I. Design Parameters

Simulation parameters	Specifications
Input voltage (V_i)	10 V
Output voltage (V_o)	7 V
Switching frequency(f_s)	20 kHz
Transformer turn ratio (n)	0.7
Resonant capacitance(C_r)	0.7 **µ**F
Resonant inductor (Lr)	76.7 **µ**H
Resonant frequency (f_o)	21.7 kHz

IV. Simulation Results

Simulation of the proposed converter was done as per the design parameters given in table I. Simulation is done for 3 conditions:

- SRC before fault
- SRC during fault
- SRC which is operating as fault tolerant

The simulation circuits and obtained waveforms are shown below.

4.1 Simulation of FB-SRC before faulty condition

A resistive load of 1W is taken as load here. Switches Q1 and Q4 are operated simultaneously at constant 50% duty cycle. Switches Q2 and Q4 are operated for next 50% duty cycle. Transformer turns ratio of 1:0.7, resonant inductor of 76.7mH, output filter capacitor of 0.7mF and DC input voltage of 10V is used for simulation. The MATLAB model for the proposed converter is shown in figure 9. Considering the output requirement as 1A, the output voltage have to be maintained at 7V.Input given is 10V. The output waveforms are shown in figure 10.

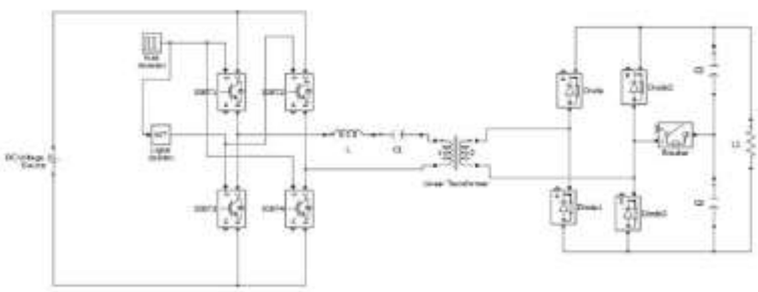

Figure 9: FB-SRC before faulty condition with R load

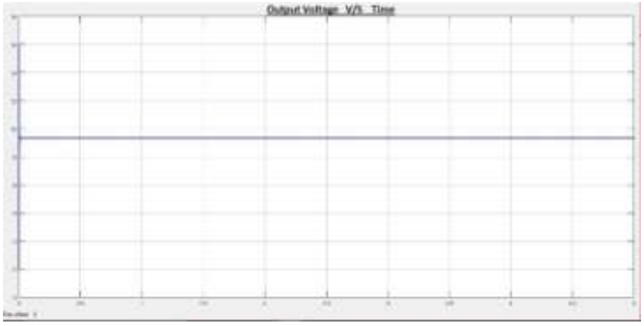

Figure 10: Output voltage of FB-SRC before faulty condition

The efficiency of the converter is found out by measuring both the input and output power. The output power obtained is 9V and input power is 11V. The efficiency around 81% is obtained for the entire system. The waveforms for input and output power is shown in fig. 11.

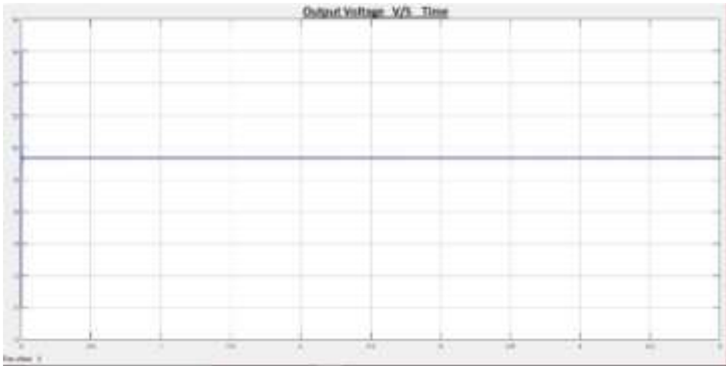

Fig 11. Input and Output power waveforms

4.2 Simulation of FB-SRC during faulty condition

Same circuit under faulty condition is simulated in Fig. 12. The only change here is switch S4 is shorted. The output waveform for FB-SRC during faulty condition is shown in Fig. 13.

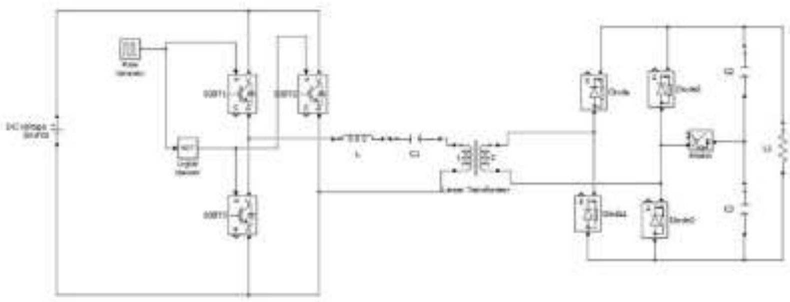

Figure 12: FB-SRC during faulty condition with R load.

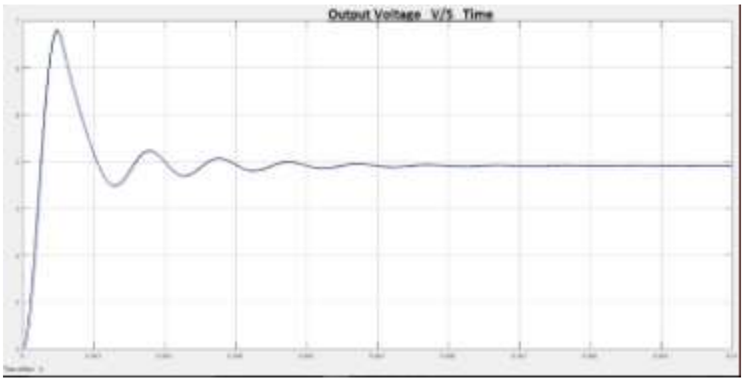

Figure 13: Output voltage of FB-SRC during faulty condition with R load.

From the waveforms in Fig 10 and Fig 13 it is clear that during faulty condition the output voltage gets halved.

4.3 Simulation of FT-SRC which acts fault tolerant during fault

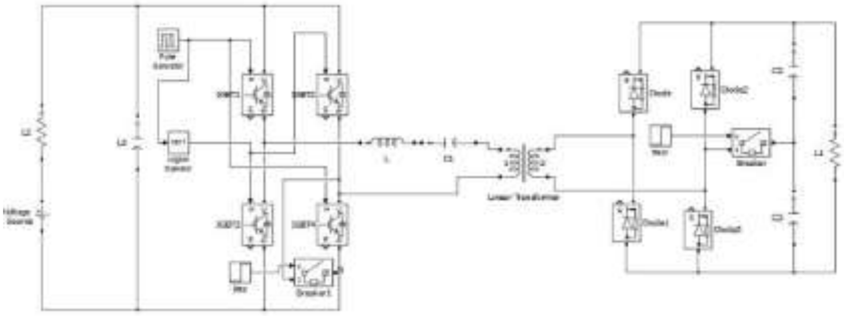

Figure 14. FT-SRC during faulty condition

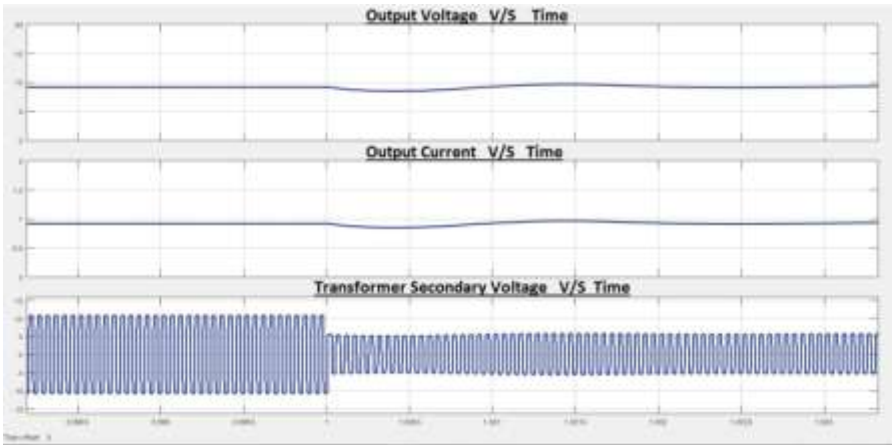

Figure 15: Output voltage of FB-SRC during faulty condition with R load.

Among the waveforms, the first part is of the output voltage. An output voltage of 9V and current of 1A is obtained for the entire system. The third part is of the transformer secondary voltage. Upto the instant of fault, the secondary voltage was of the range 10V. When the system is stuck with fault, that voltage get reduced to 5V. Eventhough the output is maintained at a constant value of 9V. Thus it can be inferred that the system is fault tolerant.

V. Conclusion

A fault tolerant SRC is introduced to set up wireless charging of mobile phone. For this, the conventional SRC is modified by incorporating reconfigurable scheme for both converter and rectifier part. The working of circuit topology is studied and circuit parameters are designed. Simulation of proposed circuit with designed parameters are conducted in MATLAB/ simulink software for normal, failure and fault tolerant conditions and required output waveforms are obtained. Working on the hardware now.

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