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Research Article

Implementation of Resistor based Protection Scheme for the Fault Conditions and Closed Loop Operation of a Three-Level DC-DC Converter

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Abstract

Abnormal conditions or faults may occur in the circuit due to inherent problem of the devices connected to the circuit or may due to some external factors. Hence there is a chance for the occurrence of fault even in carefully designed circuits. The implementation of protection scheme is always desirable for any power converter. In this paper, the conditions which can create abnormal voltage stresses in the circuit are initially investigated and analyzed, there after a resistor based protection scheme is implemented for each faulty condition. Closed loop operation of parallel resonant converter is also designed. Design, simulation development and study were accomplished using MATLAB Simulink tool box.

Keywords: *Input capacitors, flying capacitors, fault (abnormal conditions), protection, three-level dc-dc converter, parallel resonant converter*

1. Introduction

Power electronic systems always demand for reliable, improved quality, small, lightweight and highly efficient power supplies. For low power applications linear regulators can provide output of better quality. Electronic devices in linear regulators operate in their active modes, meanwhile the higher power levels uses switching regulators. Switching regulators use power electronic semiconductor switches in ON and OFF states. Normally during ON state, there will be low voltage across a switch and in the OFF state no current flow will occur through switch. High energy conversion efficiency can be achieved by using switching regulators. Operating frequency and size of components are dependent on each other. Higher the operating frequency, smaller the transformer, inductors and capacitors. Therefore to achieve faster dynamic response to rapid change in load current and input voltage, high operating frequency are preferred. Power electronic often operate from utility mains and hence they are exposed to the disturbances associated with it. Owing to the disturbances, several protection scheme must be implemented for the protection of converters. It is necessary to protect the main terminals and the control terminals. Some of these techniques are common for all devices and converters. However difference in essential features of devices call for special protection scheme (H.S. Choi and D.Y.Huh *et al,* 2004), (E. R. da Silva ,W. S. Lima, A. S. de Oliveira, C. B. Jacobina, and H. Razik *et al*, 2006). In this paper, parallel resonant converter is taken as an example the conditions which can create abnormal voltage stresses in the three-level parallel resonant converter circuit are initially investigated and analyzed, there after a resistor based protection scheme is implemented for each faulty condition. Fig.1. shows the topology of parallel resonant converter. Furthermore, it is possible to protect the system from various faults by the protection scheme through the monitoring of flying capacitor voltage.

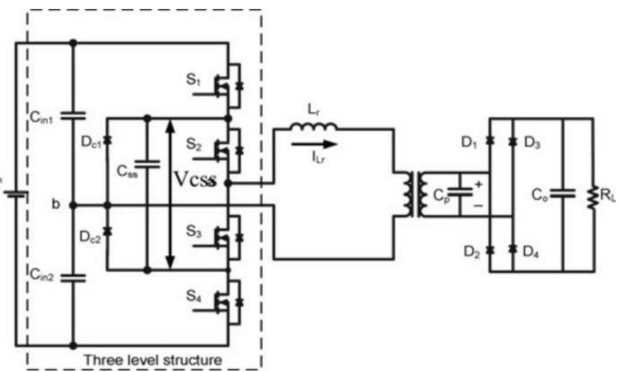

Fig.1.Topology of a three-level parallel resonant converter

One of the advantage of three-level DC-DC converter is that lower voltage rating switches with better performance can be used owing to the withstanding capability of input capacitor to half of the supply voltage. To ensure proper operation there should be balanced voltage across the input capacitors. A flying capacitor is added to achieve true ZVS (F. Canales, P. Barbosa, and F. C. Lee *et al*, 2002), (F. Canales, P. M. Barbosa, and F. C. Lee *et al*, 2000), (J. A. Carr, B. Rowden, and J. C. Balda *et al*, 2009) under phase shift control. The flying capacitor can help to

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decouple the switching transition between outer two switches (S_1 and S_4) and the inner two switches (S_2 and S_3). Turning OFF of outer switch causes the charging of parallel capacitor to it and at the same time, there occur discharging in the capacitor which is connected in parallel to the other outer switch. This is the way the Zero Voltage Switching (ZVS) (K. Jin and X. Ruan *et al*, 2007),

(X. Ruan, D. Xu, L. Zhou, B. Li, and Q. Chen *et al*, 2002), (X. Ruan, Z. Chen, and W. Chen *et al*,2005) is achieved. For inner switches the flying capacitor will act as a snubber capacitor during the normal operating period, voltage across the flying capacitor, Vcss will be half of the input voltage. The basis for the fault identification is the variation the flying capacitor voltage from its balanced condition. Earlier neutral point protection method is used for the fault diagnosis. The disadvantage of neutral point protection is its less sensitivity. The proposed protection method is based on the detection of voltage across flying capacitor, Vcss. The advantages of this protection scheme include:

- Since there is no need of any additional components the converter operation will remain unaffected
- Sensitivity to unbalanced switch voltages and the ability to detect multiple faults.
- Fast response time that is very critical in short-circuit and shoot-through protection.
- Low cost and easy implementation.
- Can replace under/over input voltage lockout

2. Categorization of unbalanced voltage stresses

Good knowledge about the converter operation and faults in the circuits are necessary to design the protection scheme. Mainly the abnormal conditions are categorized into three, it includes:

2.1 Abnormal Input Capacitor Voltages Due to Input Voltage

In order to split the input voltage equivalently and the neutral point, Point b in Fig.1, which has a voltage of half the input voltage, two input capacitors (Cin1 and Cin2) are needed. So the neutral point voltage and the voltage across flying capacitor, Vcss depends on the input voltage. Hence by monitoring the flying capacitor voltage, Vcss it is possible to analyze the over/under input voltage variation under abnormal input voltage conditions.

2.2 Abnormal Input Capacitor Voltages Due to Unbalanced Neutral Point Voltage

Unbalanced voltage is another problem, which will bring abnormality in the input capacitor voltages. Charging of flying capacitor takes place through clamping diodes (Dc1 and Dc2). Flying capacitor will get charged through down clamping diode, Dc2 when the voltage across Cin1 is higher than half the input voltage, Vin/2, shown in Fig.2. Likewise, through the upper clamping diode, Dc1 the flying capacitor will get charged when Cin2 voltage is higher than half the input voltage, Vin/2, shown in Fig.3. There after the flying capacitor will become parallel to that particular input capacitor this has more voltage stress. Flying capacitor helps to alleviate the voltage unbalance of the input capacitors. The flying capacitor voltage will be charged to the peak voltage of the input capacitor inspite of neutral point voltage, which may be higher or lower than Vin/2 or which input capacitor has high voltage. Unbalanced input capacitor voltages will results in abnormal flying capacitor voltages. Unequal capacitances of input capacitors, unbalanced duty cycles, mismatched switching timings etc bring abnormality in the circuit. Moreover, even if the voltages across the input capacitors are balanced, the Vcss still can be influenced by the voltage ripple on the input capacitor. According to the earlier analysis, the peak voltage on the input capacitor will pump energy to the flying capacitor.

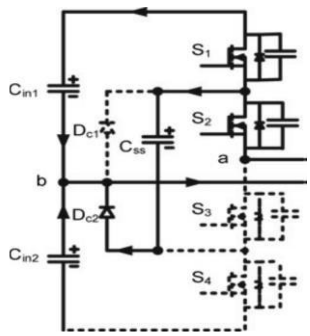

Fig.2. Charging loop when the voltage of Cin1 is higher than half of the input voltage.

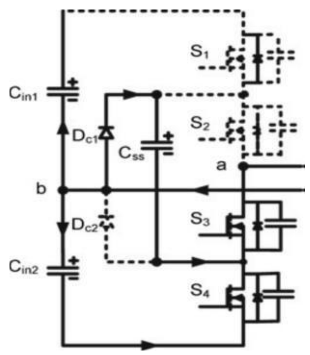

Fig.3. Charging loop when the voltage of Cin2 is higher than half of the input voltage.

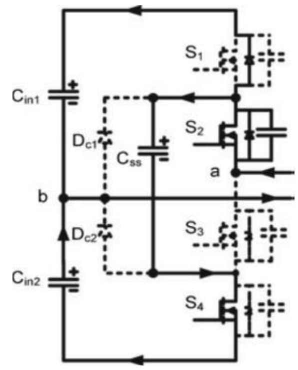

Fig.4.Charging loop for wrong operation mode of ZCS instead of ZVS.

2.3 Losing Discharging Path Even With Normal Input Capacitor Voltages

The flying capacitor is charged is through clamping diodes Dc1 (or S1) and Dc2 (or S4) under normal operation. The only possible path of discharging for flying capacitors is through S2 or S3. In some abnormal conditions the flying capacitor will get charged through S2 or S3 instead of discharging, thus the flying capacitor voltage will increase and crosses the safe range of operation. When the ZVS operation is desired, the commutation of the phase shift provides a discharge loop for flying capacitors. The flying capacitor will get charged instead of being discharging when the converter loses ZVS(such as light load or when S2 is turned OFF before S1 or S3 is turned OFF before S4).In all these cases , the voltage across flying capacitor will increased nearly to input voltage. Fig.4 shows accidental ZCS operation mode instead of ZVS. At light load conditions, ZVS operations for both lagging and leading switch losses and mechanism becomes as same as the ZCS condition. ZVS has to be ensured even in light load to heavy load condition. Fig.5 shows a case of reverse switching timing. Turning OFF of S2 before S1 makes the upper side of the flying capacitor connected to the input voltage through s1 and lower side of the flying capacitor is connected to the ground through the body diode of S4. Hence a voltage equal to the input voltage will appear across the flying capacitor. In order to overcome this issue a proper and correct switching sequence has to be assured.

3. Multiple faults in the three-level converter

In this section, the variation of voltage across flying capacitor, Vcss in response to various abnormal condition is explained. The most common faults associated with the active devices and load, includes open- short circuit of inner and outer switches, open - short circuit of clamping diodes, open-short circuit of antiparallel diodes D1 and D2, open- short circuit of rectifier diode Dr1 and finally, open-short circuit of load. When the main switch is MOSFET, its body diode is commonly used as antiparallel diode instead of the external diode. Any failure to the body diode will affect the functioning of main switch. Fig.6. shows the most common faults associated with three-level parallel resonant converter.

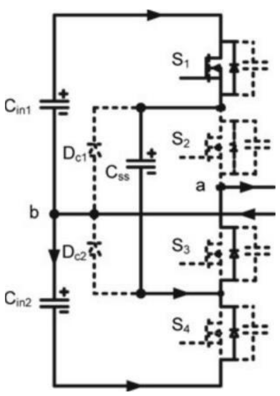

Fig.5.Charging loop due to reverse switching timing.

3.1 Outer Switch Open Circuit

Consider the case with outer switch s1 open circuited and the switches s3 and s4 in ON state. Since the inductive current loop in the circuit is remaining as undisturbed, there will occur continuous energy flow to the load from bottom capacitor, Cin2. But once S2 is turned ON along with that S3 and S4 are turned OFF, the upper input capacitor will get isolated, this is due to the short circuit loop for the inductor current by the upper clamping diode (Dc1).It is illustrated in Fig.7, this will create unbalanced voltage across the flying capacitor. Owing to the negative biased dc voltage stress, the transformer will get saturated.

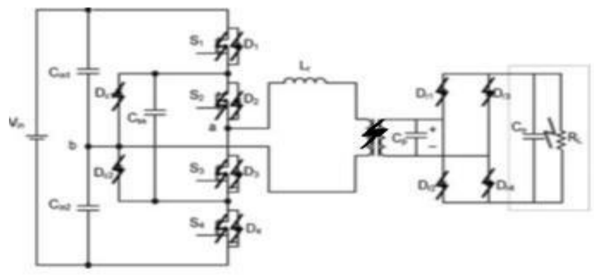

Fig.6. Possible faults on the three-level parallel resonant converter.

3.2 Outer Switch Short Circuit

Consider the case outer switch short circuited with switches S3 and S4 ON. If S1 is short circuited, the voltage across the flying capacitor becomes equal to the input voltage due to the direct connection of flying capacitor to the input power source. This fault is independent of the neutral point voltage.

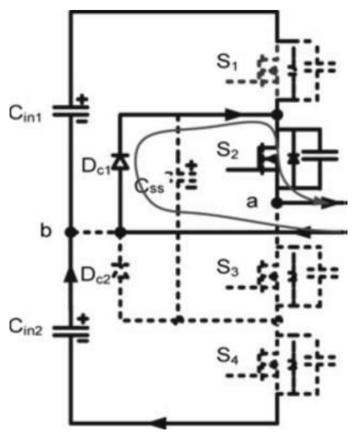

Fig.7. S1 has an open circuit when S3 and S4 are OFF.

3.3 Inner Switch Open Circuit

In case of occurrence of open circuit of inner switch(say S2) input voltage ,as a whole will appear across the flying capacitor through the outer switch,S1 and the body diodes of S3 and S4,shown in Fig.8. Open circuit of S2 violate the rule that's1 has to turn OFF before S2 turns OFF. Due to this fault no power is delivered to the load.

3.4 Inner Switch Short Circuit

Consider the inner switch (say S2) short circuit with S3 and S4 ON. Owing to this condition flying capacitor and bottom input capacitor (Cin2) will get shorted. The flying capacitor will get shorted through switches S2 and S3, and bottom input capacitor will get shorted through the upper clamping diode and switches S2, S3 and S4, shown in the Fig.9. When S3 and S4 turn OFF, flying capacitor and bottom input capacitor will get charged to half of the input voltage with a frequency equal to the switching frequency. Faults caused due to this condition do not affect the converter operation. Positive biased voltage causes transformer saturation.

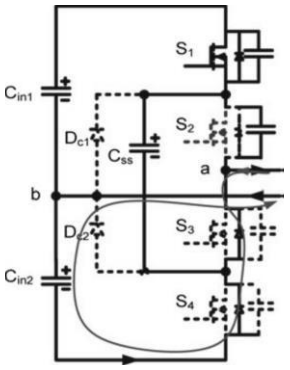

Fig.8. S2 has an open circuit when S1 is ON.

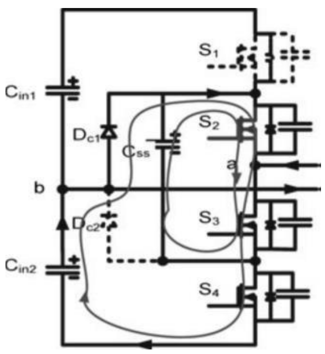

Fig.9. S2 has a short circuit when S2 and S4 are ON.

3.5 Outer Switch Body Diode Open Circuit

Consider the case with open circuit occurred to the body diode,D1 of outer switch S1. Fig.10 shows when S4 turns OFF and S3 is still ON, the inductor current will go through the bottom clamping diode back to the resonant tank instead of D1 after the S4's switch capacitor is charged to half of the input voltage and S1's switching is discharged to ZERO. The outer switch S1's body diode D1 will never conduct. The circuit operation remains unaffected by this fault. Detecting this fault by monitoring flying capacitor is not easy task.

3.6 Clamping Diode Open Circuit

If the clamping diode Dc1 fails due to open circuit, the operation of converter will remain unaffected shown in Fig.11. But without the clamping diode the converter will practically lose the advantages of the three-level structure. The fault can be analyzed by monitoring the voltage across the flying capacitor as long as the unbalanced switch voltage stresses persists.

3.7 Clamping Diode Short Circuit

When there occur short circuit in the clamping diode with switch S1 ON, the neutral point voltage will be connected with the positive polarity of the input voltage and charged to full input voltage. Under this fault condition, when S1 is ON it will suffers huge current, or then S2 suffers over-voltage when it is OFF. Either one could fail before the neutral point voltage or the voltage across the flying capacitor, Vcss will become equal to the input voltage. The transformer suffers a negative dc bias voltage owing to this.

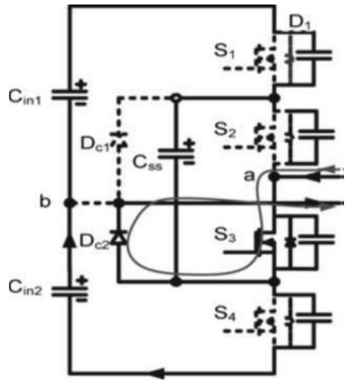

Fig.10. D1 has an open circuit when S4 starts to turn OFF while S3 is still ON

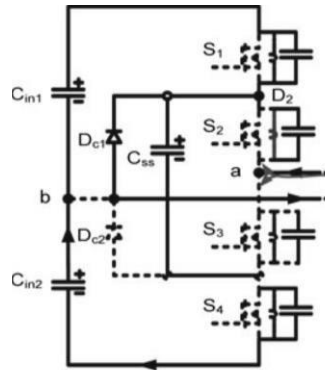

Fig.11. D2 has an open circuit when S3 and S4 turn OFF.

3.8 Rectifier Diode Open circuit

When the rectifier diode Dr1 fails due to open circuit, energy transferred to the load under positive resonant capacitor voltage will cease. But the converter keeps transferring the energy to the load when the resonant capacitor is negative. This unbalanced energy transfer will result in a positive dc biased voltage stress to the transformer. Finally the neutral point voltage will drops to zero while the voltage across flying capacitor, Vcss increases to the full input voltage. If the rectifier diode in opposite bridge is open circuit the neutral point voltage will increase and also the flying capacitor voltage, Vcss.

Transformer primary open circuit

Occurrence of primary winding of transformer open circuit may due to mechanical and thermal stresses in the transformer winding, finally it affect the insulation of transformer cooling system. The fault results in the unbalanced voltage across the flying capacitor,Vcss.

3.9 Transformer primary short circuit

This fault may occur due to bushing flash over and also due to faults in tap changer equipments. Thus the transformer must be isolated instantly during fault, otherwise electrical failure will occur to the system, Finally increase the flying capacitor voltage,Vcss.

3.10 Transformer secondary open circuit

Whenever the secondary windings experience stresses due to some external or internal factors, there may occur secondary side open circuit. This will results in deviation of flying capacitor voltage, Vcss from its balanced condition.

3.11Transformer secondary short circuit

Arcing ground if neutral point is isolated or switching operation of different electrical equipments may results in surge voltage, it causes breakdown in the insulation between turns adjacent to the line terminal which may create short circuit between turns of secondary windings. This fault results in increased current in the circuit, obviously the flying capacitor voltage increases. The transformer suffers a positive bias voltage due to this fault.

4. Closed loop operation of a parallel resonant converter

Fig.12. shows the closed loop circuit for parallel resonant converter. The closed loop system includes comparator and PI controller. The output voltage is sensed and it is compared with the the reference voltage. The error signal is applied to the PI controller. The output of PI controller is given to the MOSFET. The steady state error can be reduced by properly tuning of the PI controller. Figure.13. shows the response of closed loop system.

5. Design of proposed circuit

For three-level structures, balance resistors are needed for the capacitors voltage balance. The value of the potential resistor must be less than the circuit resistivity. Resistor based protection circuit is implemented with resistors of 0.018Ω .

5.1 Flying Capacitor Design

Though the flying capacitor design is not directly related with the protection circuit design, the proposed protection method has to be based on the flying capacitor. In the conventional three level converter with phase-shift control, flying capacitor will perform the following functions:

- Decoupling the switching transition between inner and outer switches.
- Maintaining balanced voltage across the input capacitors.
- For inner switches it can act as a snubber capacitor

Vcss can be calculated with the following:

$$V_{css} = \frac{(1+K)}{2} V_{in} \quad (1)$$

Where V_{in} is the input voltage ,and k is the allowed voltage ripple percentage for input capacitors, which usually determined by (2). This can explain why the Vcss increases slightly even in a normal operation

$$k = \frac{2 * I_O}{C_{in} * f_s * V_{in} * V_{in} * \eta} .100\,\% \quad (2)$$

6. Simulation results

A three-level parallel resonant converter was simulated using MATLAB software with 600V dc input voltage and 200 kHz switching frequency. 600V voltage rating MOSFET modules are used as main switches.

Table 1 parallel resonant converter circuit key parameters

Parameters	Values
Input DC source voltage	600V
Input capacitors(V_{Cin1} & V_{Cin2})	10μF
Flying capacitor(Css)	2μF
Resonant capacitor(Cp)	1.24nF
Resonant inductor(Lr)	3.63μH
Transformer turn ratio	1:11

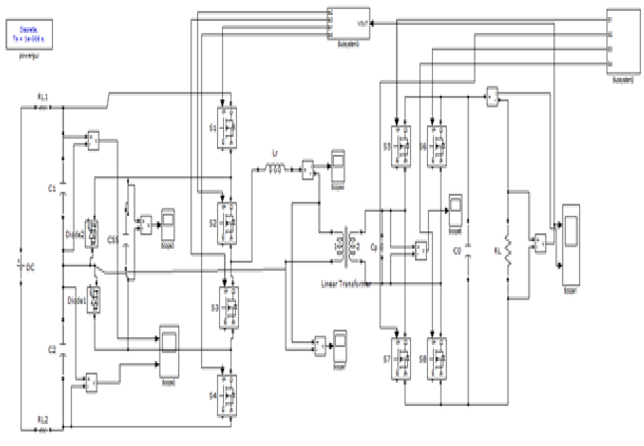

Fig.12. closed loop circuit for parallel resonant converter

The abnormal conditions which cause failures in the circuit was successfully protected by the proposed protection scheme. The fault conditions are generated by a timer and a fault signal. Based on previous analysis, the flying capacitor voltage is also abnormally increased.

Therefore, the proposed protection is triggered and successfully protects the converter against the system failure. Fig.12 below shows the Simulink model of the parallel resonant circuit.

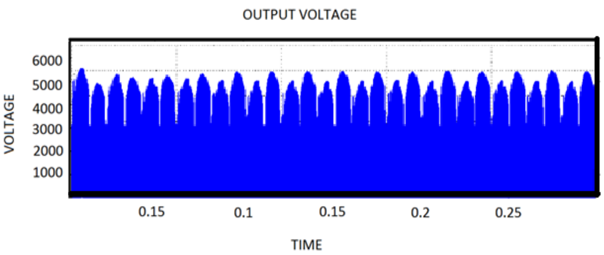

Fig.13. Response of closed loop parallel resonant converter

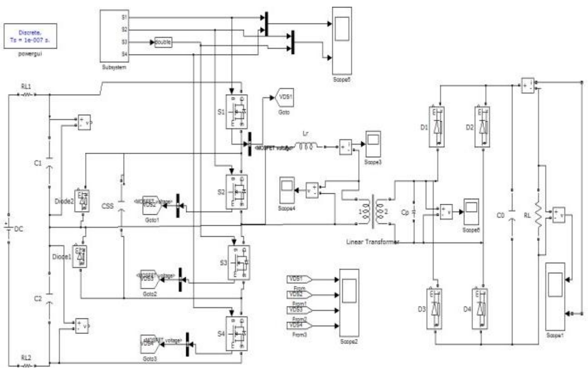

Fig.14. Simulink model of three-parallel resonant converter

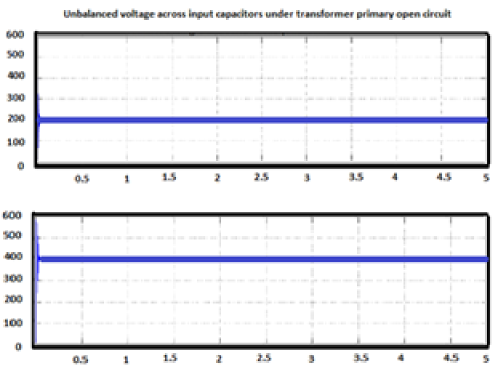

Fig.15 Simulation output under transformer primary open circuit

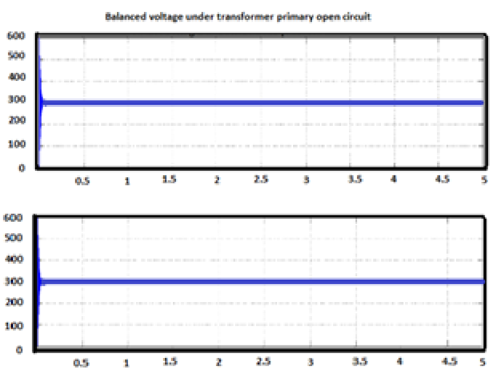

Fig.16. Simulation output of protection circuit with transformer primary open circuit

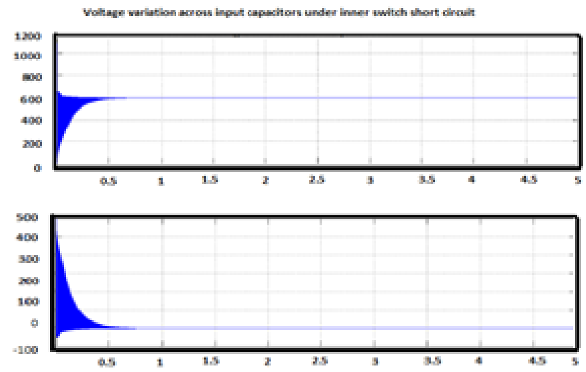

Fig.17.Simulation output with inner switch short circuit

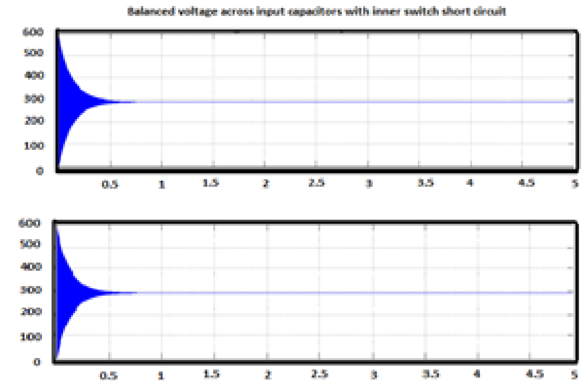

Fig.18. Simulation output of protection circuit with inner switch short circuit

Conclusion

A protection scheme based on flying capacitor voltage detection and closed loop operation of parallel resonant converter is presented in this paper. The proposed protection scheme helps to implement a resistor based protection method for three-level parallel resonant converter by monitoring flying capacitor voltage. It is simple, can be implemented easily with fast response time and also cost efficient. Since there is no addition on the power stage, converter performance and operation will remain unaffected. The protection method can effectively avoid the device failure caused by unbalanced voltage stresses on switches in the three-level structure, and will protect the system even if abnormal condition persists. Closed loop operation is determined for getting desired output even in varying input conditions. The theoretical analysis and simulation results are verified by experimental results.

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