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Failure Modes Analysis of Two Switch Forward Converter based DC Power Module

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***Abstract* - A two switch forward converter based 50 V, 150 A water-cooled DC power module has been developed for biasing solid state RF amplifiers. A detailed analysis has been carried out on various failure modes of this power module and the results are presented in this paper. The simulation of various failure mode scenarios has been carried out in OrCAD PSpice Cadence software. These failure mode scenarios include open circuit and short circuit across IGBT switches, short circuit across output capacitor and bridge rectifier diodes etc. The response of power module during these failures is studied through various waveforms obtained during simulations and necessary measures are taken to reduce the occurrence of these failures. The wound components of this power module have been designed to withstand short circuit for sufficiently long duration. Suitable multilevel circuit protections have been implemented in this power module through fuses, MCB, contactor and digital module controller for its reliable operation.**

Keywords: Water-cooled DC power module, Forward converter, Failure mode analysis, Solid state RF amplifier (SSRFA).

I. INTRODUCTION

The advent of solid-state RF amplifiers (SSRFAs) has provided a new alternative to fulfill the RF power requirements of particle accelerators [1]-[3]. However, the successful implementation of SSRFAs necessitates the development of robust and reliable DC power supplies to provide the required bias voltages [3].

SSRFAs implement modular architecture wherein power from multiple low power amplifiers are combined to deliver high RF power at output end [4]-[8]. A 50 V, 1950 A water-cooled DC power supply including 13 nos. of parallel connected 50 V, 150 A DC power supply modules and 3 nos. of active redundant modules is designed to bias 40 kW, 650 MHz SSRFA. As availability of the system depends upon the individual availability of SSRFA and DC power supply, therefore, to increase availability of the system, the availability of DC power supply also needs to be increased. To achieve the same, active redundancy of 3 modules has been incorporated in 50 V, 1950 A DC power supply. This means that power supply will continue to function at its rated capacity till the failure of 3 nos. of DC power modules. To achieve high system availability, the failure rate of each individual 50 V, 150 A DC power module has been minimized through careful design, and various failure mode scenarios have been modeled and analyzed in the OrCAD PSpice Cadence software. The scope of this paper includes failure mode analysis of this power module to improve its reliability. This power module is based on two switch forward converter topology. The two switch forward converter topology is designed to address the issue of transformer reset and reduce voltage stress on the switching transistors [9]. This DC power module has been theoretically designed and verified through simulations conducted in OrCAD PSpice Cadence software [8]. These simulations have provided valuable insights into the performance of the converter, enabling optimization of key parameters such as efficiency, voltage regulation etc. Major power dissipating elements have been mounted on water-cooled heat sink for effective heat transfer, which reduces heat stress on switching devices and other crucial components of power supply. These steps aid in achieving higher overall system availability of DC power supply [10]-[12].

Section II of this manuscript provides insight into design of individual 50 V, 150 A water-cooled DC power module. The DC power module has been simulated in OrCAD PSpice Cadence software and simulation results are presented in Section III. The failure mode analysis has been discussed in Section IV. Thermal stress withstand capability of wound components, such as transformer and inductor windings, to withstand short circuit has been presented in Section V. In the end, summary and discussion are presented in Section VI.

II. 50 V, 150 A DC POWER MODULE

The scheme of a two-switch forward DC-DC converter is shown in Figure 1 and various voltage, current waveforms at multiple points of this converter are shown in Figure 2. The two switch forward converter topology has various advantages such as no dead time requirements, no snubber circuit requirements and no Insulated Gate Bipolar Transistor (IGBT) body diode conduction [13]-[14].

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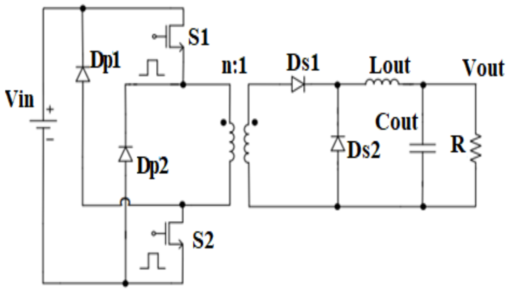

Figure 1: Two switch forward DC-DC converter

As shown in Figure 1, the input voltage source Vin is connected to transformer (turns ratio n:1) through IGBTs S1 and S2. During power transfer cycle (t = 0 to DT, D = duty cycle and T = time period), IGBTs S1 and S2 are turned on and power transfer occurs through transformer and secondary side diode Ds1. When IGBTs S1, S2 are turned off (t = DT to t = T), transformer magnetizing current flows through diodes Dp1 and Dp2 respectively, and then back to source. The transformer achieves proper reset if the ON duration remains shorter than the OFF duration. The detailed schematic of 50 V, 150 A water-cooled DC power module based on two switch forward converter topology is shown in Figure 3.

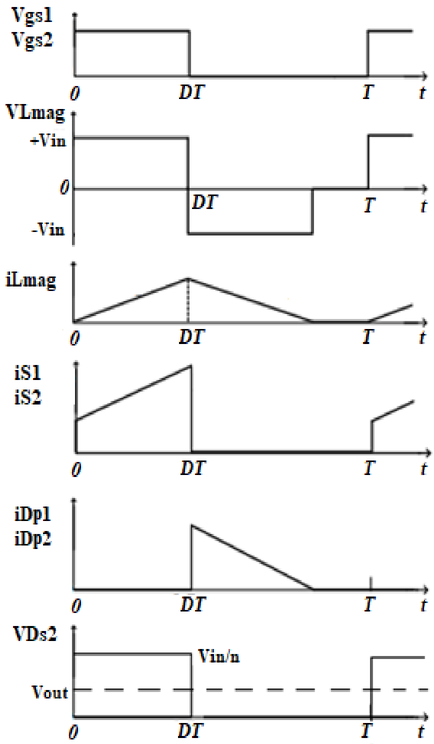

Figure 2: Waveforms of two switch forward converter

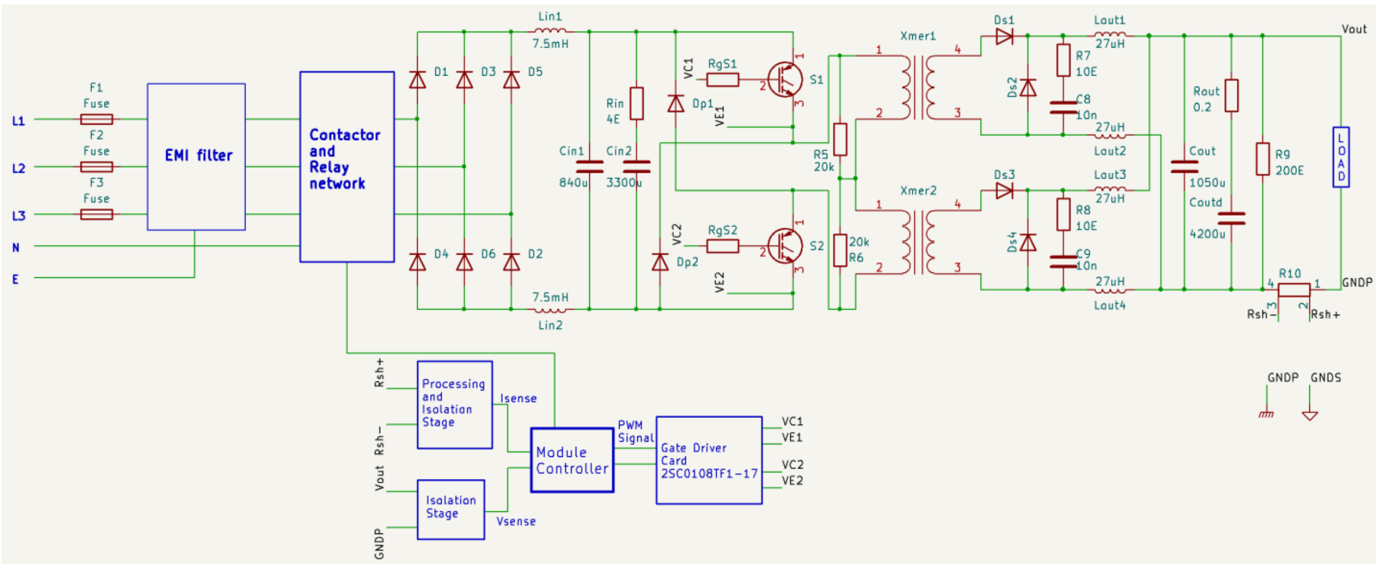

Figure 3: Schematic of 50 V, 150 A DC power module based on forward converter topology

The input source to this DC power module is 3-phase, 480 V, 50 Hz AC input. This input source is connected to diode bridge rectifier and input LC filter through circuit protections and EMI filter. After diode bridge rectifier, AC voltage is converted into DC voltage which then feeds to IGBT switches S1 and S2 as shown in Figure 3. These IGBTs are operated at 40 kHz switching frequency and both IGBTs turn on together thereby transferring power through transformer primary into the secondary side. The control signals for gate drive are generated by module controller. Module controller regulates the output voltage of power module against variation in input voltage and load current requirements. Two high frequency ferrite core transformers (Xmer1 and Xmer2) are employed with their primary windings connected in series to equally divide high input voltage across each transformer [15]-[17]. At the secondary side, rectifying diodes transfer energy into load through output filter. Secondary windings of transformer are connected in parallel through rectifier bridge to meet high output current requirement. Protection features such as output over voltage,

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over current/short circuit and over temperature are employed through module controller.

III. SIMULATION ANALYSIS

The 50 V, 150 A water-cooled DC power module has been implemented in OrCAD PSpice Cadence software [8], [18]-[19]. Various simulations have been carried out to validate the design and optimize critical components of the power module. To achieve an optimized design, multiple iterations of simulations were performed by adjusting component parameters such as inductor and capacitor values, switching frequency etc. The final schematic, incorporating these optimizations, is shown in Figure 4. The output voltage waveform and output voltage ripple from this schematic are shown in Figure 5 and Figure 6 respectively. These results confirm that the module meets the expected design criteria, with voltage ripple kept within acceptable limits to ensure smooth operation with RF amplifier.

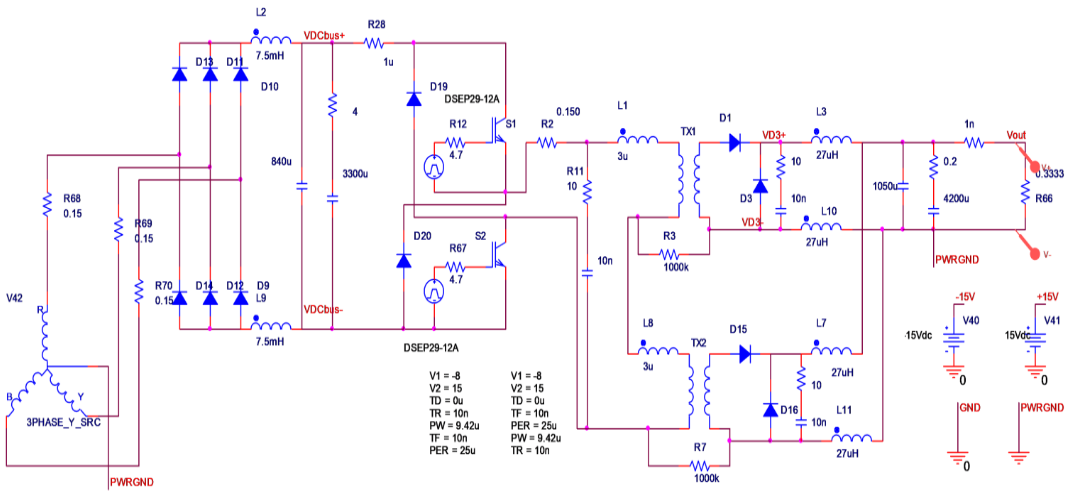

Figure 4: Simulation circuit of 50 V, 150 A water-cooled DC power module

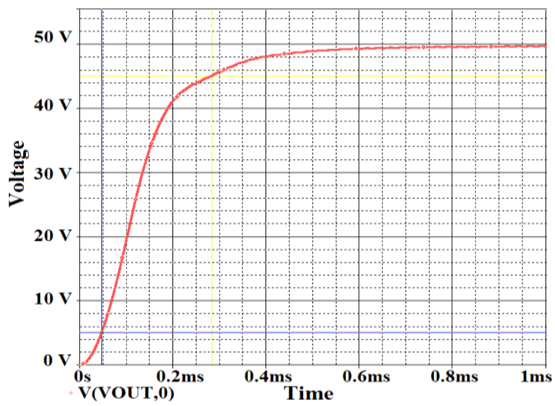

Figure 5: Output voltage waveform

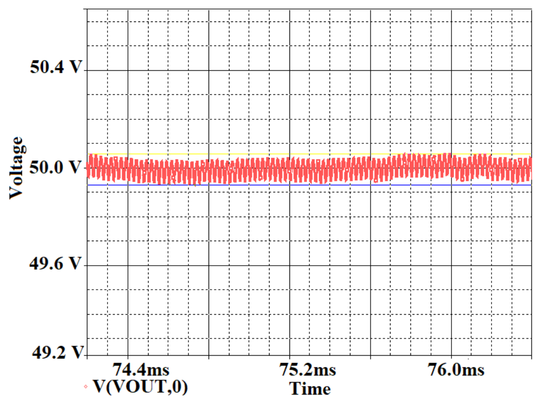

Figure 6: Output voltage ripple < 150 mV

IV. FAILURE MODE ANALYSIS

The failure mode analysis of the 50 V, 150 A water-cooled DC power module has been conducted by simulating faults of key power components [20]-[21]. It has been observed that two components i.e., semiconductor devices (IGBTs and diodes) and capacitors are more prone to failure during running conditions [22]-[25]. To achieve this, controlled failure conditions have been introduced in major components such as output filter capacitor, output rectifier diode, and IGBT switch etc. These simulations provide valuable insights into the transient responses of the power module under fault conditions, helping in the development of effective protection strategies.

4.1 Short circuit across output filter capacitor

The simulation circuit of 50 V, 150 A DC power module is shown in Figure 7 wherein intentional short circuit has been created across output filter capacitor (Cout) by closing the switch at t = 100 ms placed between terminals A and B. Such fault may arise due to aging of capacitor or external fault. Resulting output voltage waveform and output filter inductor current have been shown in Figure 8 and 9 respectively. In these simulations, gate pulse of IGBT was intentionally not withdrawn to analyze effect of shorted output capacitor on various components of DC power module.

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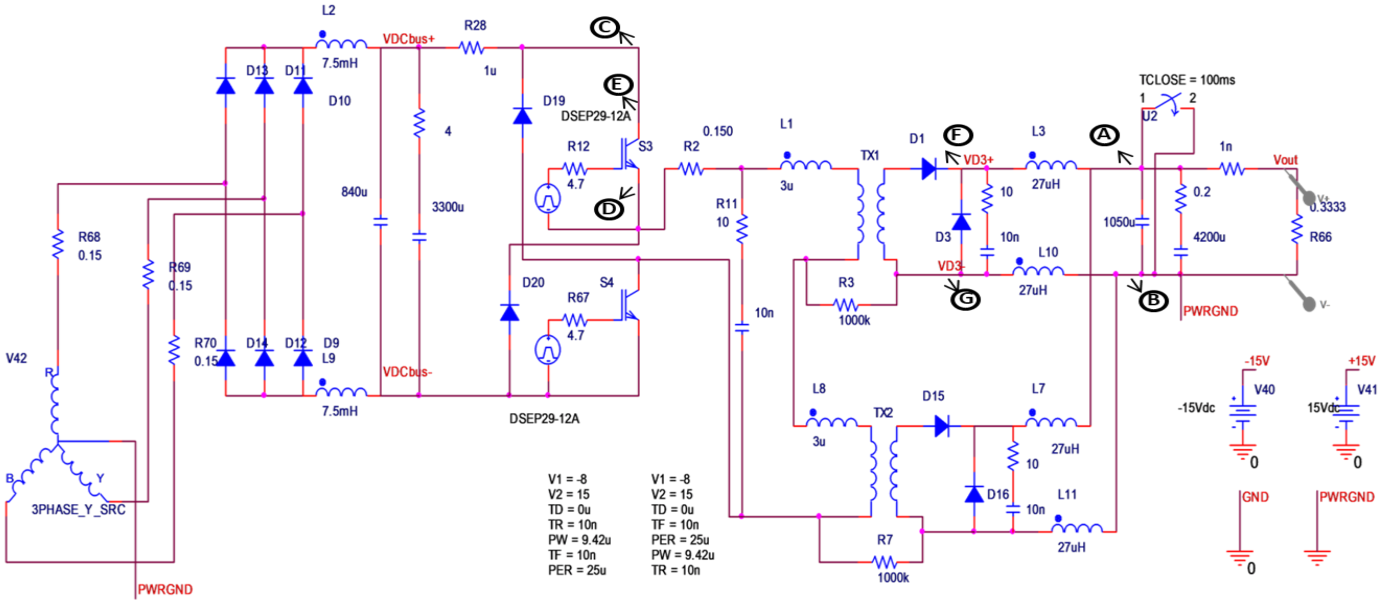

Figure 7: Simulation circuit for short circuit across output filter capacitor (Cout)

A short circuit across the output filter capacitor can cause a sudden and excessive surge in current and may cause component failure, overheating, or even permanent damage to the power module. It may significantly affect system availability. In such scenarios, fast fault detection and its suppression is critical to ensure system's operation for long hours. For this, the module controller has been programmed to quickly sense the current surge and issue withdrawal of gate pulse to IGBTs.

In next simulation, the gate pulses of IGBT switches were withdrawn within 10 µs of short circuit, which is the expected response time of module controller for this power module. Resulting output voltage waveform and current through output filter have been shown in Figure 10 and 11 respectively.

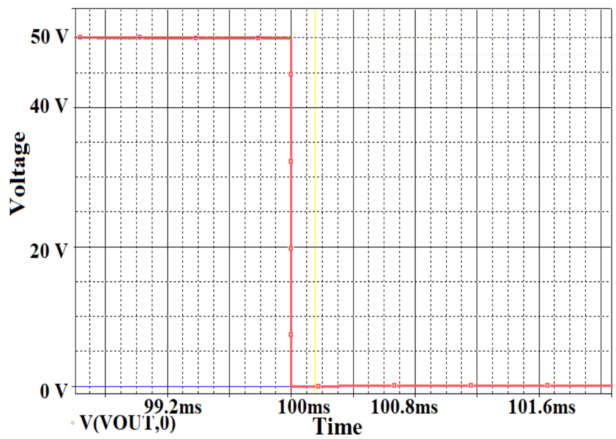

Figure 8: Output voltage waveform with Cout shorted

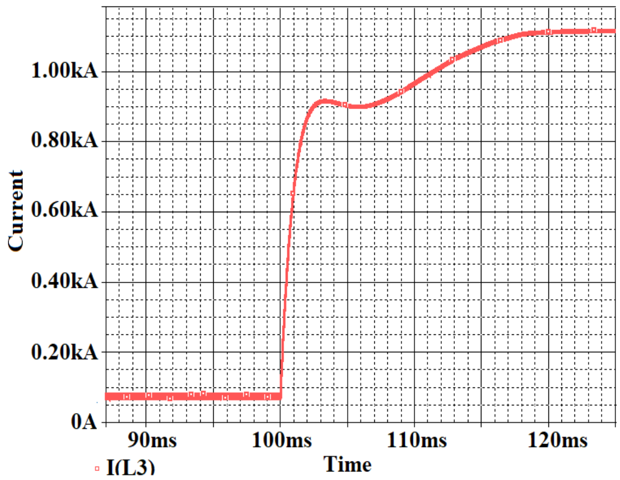

Figure 9: Output filter inductor current waveform with Cout shorted

From these results, it can be seen that with removal of gate drives after 10 µs, switching currents are well within their rated limit. By quickly removing the gate drives, the module controller effectively limits the duration of excessive current flow, thereby protecting the system from severe damage. All power components, windings, interconnections etc. are designed to withstand fault currents for more than 20 ms, within which secondary protection through input contactor will act. Furthermore, tertiary protection mechanisms such as fast acting fuses and circuit breakers provide additional safety measures, ensuring that faults are isolated from the system before they can cause irreversible damage. This multilevel protection strategy helps in maintaining system stability and preventing unexpected downtimes in the operation of the power module.

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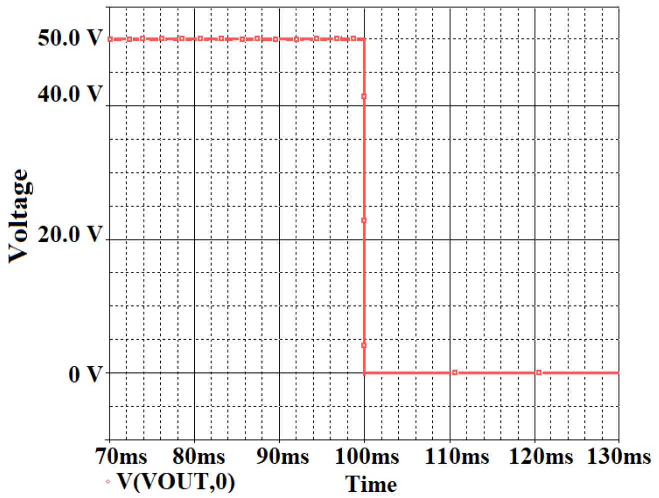

Figure 10: Output voltage waveform with Cout shorted and gate pulse withdrawn after 10us

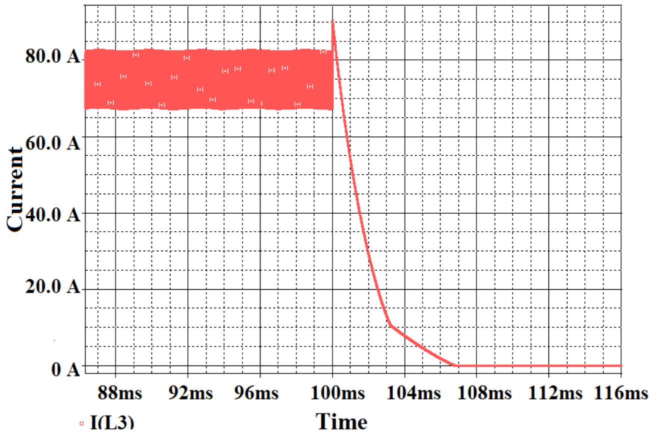

Figure 11: Output filter inductor current waveform and gate pulse withdrawn after 10us

4.2 Short circuit across IGBT switch

The simulation circuit of 50 V, 150 A DC power module is as shown in Figure 7 wherein intentional short circuit has been created across IGBT switch S1. Here a switch has been placed connecting terminals C and D in parallel to IGBT S1, which connects these terminals at t = 100 ms. The output voltage waveform, output filter inductor current and input AC source current have been shown in Figure 12 and 13 respectively. When an IGBT switch undergoes a short circuit, it results in an uncontrolled surge of current, which can severely damage the switch itself and other critical components of the circuit. The excessive current can lead to overheating, insulation breakdown, and in extreme cases, complete failure of the power module. In order to avoid short circuiting of IGBT switches, IGBT switches of considerably higher voltage and current ratings are chosen and employed in 50 V, 150 A DC power module. Further, fast acting fault detection and protection mechanisms have been integrated into the system.

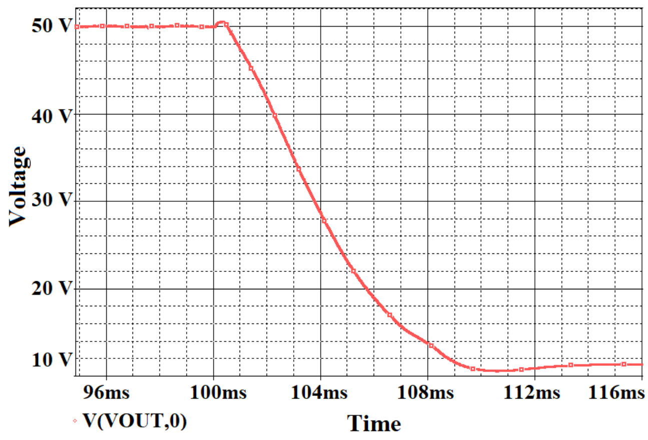

Figure 12: Output voltage waveform with S1 shorted

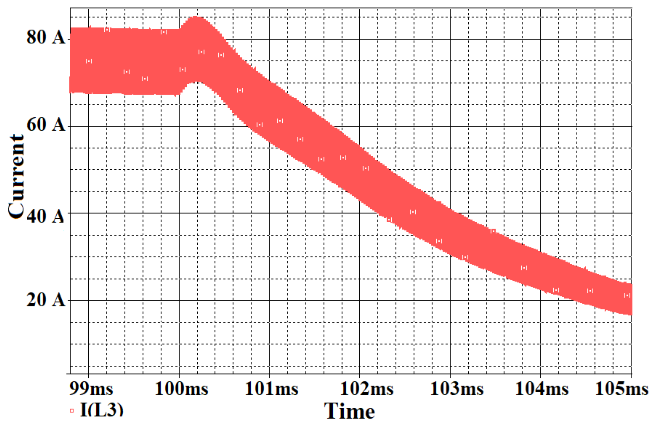

Figure 13: Output filter inductor current waveform with S1 shorted

The module controller is designed to continuously monitor the current flowing through the IGBT and respond to abnormal spikes by immediately withdrawing the gate drive pulses within 10 µs. There is provision of short circuit protection in the gate drivers as well. The voltage across IGBT switch (V_{CE}) is consistently monitored and whenever V_{CE} exceeds a set limit, gate drive signals to IGBTs are removed. Additionally, secondary protection mechanisms such as input mains contactor, fuses and circuit breakers are incorporated to act within milliseconds, preventing excessive stress on the power module. Moreover, thermal sensors are strategically placed to detect overheating caused by short circuits and trigger protective shutdowns if necessary. Another critical aspect of protecting the IGBT switches from short circuits is ensuring that the module operates within its designed electrical and thermal limits. Proper heat dissipation mechanisms, including water-cooled heat sinks, are used to keep the device temperature within safe operating levels. By implementing these proactive protection strategies, the system ensures high reliability and longevity of the power module, even under fault conditions.

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4.3 Open circuit across IGBT switch

To simulate effect on performance parameters if switch gets opened, simulations have been performed as per schematic shown in Figure 7. For this simulation, IGBT S1 has been opened by connecting a switch between terminals C and E which opens at t = 100 ms. Corresponding output voltage waveform and output filter inductor current have been shown in Figure 14 and 15 respectively. When the IGBT switch is open, power transfer to the load is disrupted, leading to a sudden drop in output voltage and fluctuations in current through the output filter inductor. This behavior can affect the stability of the DC power module and, consequently, the overall performance of the system. In practical implementations, such open circuit failures can occur due to gate drive failures, loose interconnections, or internal faults within the IGBT itself.

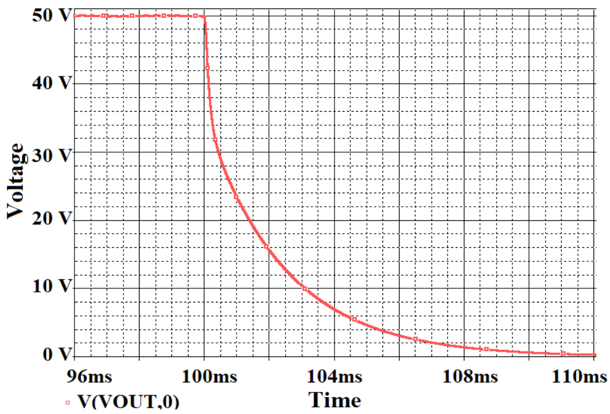

Figure 14: Output voltage waveform with S1 opened

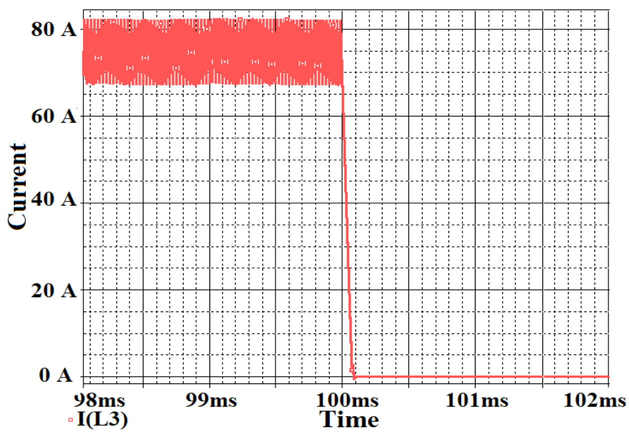

Figure 15: Output filter inductor current waveform with S1 opened

4.4 Short circuit across output rectifier diode

Another likely failure for this DC power module is short circuit across output rectifier diode. To simulate the effect parameters of DC power module in the event of short circuit across output rectifier diode, simulations have been performed. The simulation circuit of 50 V, 150 A DC power module is as shown in Figure 7. For simulating short circuit across output rectifier diode D3, a switch has been placed in parallel to D3, connecting terminals F and G. This switch is short circuited at t = 100 ms. Corresponding output voltage waveform and output filter inductor current have been shown in Figure 16 and 17 respectively. In these simulations, it is evident that because of short circuit across output diode there is substantial increase in current which can be detrimental for DC power module. In order to analyze performance of DC power module during short circuit, gate pulse of IGBT was not withdrawn intentionally in previous simulation. However, input contactor of power module has been installed in order to detect such sudden increase in current. In the event of short circuit, the input contactor of power module will be opened within 20 ms of short circuit. Furthermore, to ensure rapid action, an additional layer of protection is implemented in the power module. This includes programmable logic in the module controller that monitors current surges and takes necessary action in the event of observed current surge. As soon as output diode gets short circuited, resultant rise in current will be detected by module controller. The module controller will then generate command to withdraw IGBT gate drive pulses. This command will be transmitted to IGBT devices with certain delay of the order of few µs.

Upon receiving such command, gate driver will withdraw gate pulses to IGBT resulting in tripping off the DC power module. In this way, short circuit current can be interrupted in due time to maintain the integrity of DC power module. Such protection mechanisms help improve system resilience and minimize unnecessary shutdowns caused by transient anomalies. To simulate such event, gate drive pulses are removed after 10 µs of shorting instant in order to emulate action taken by module controller. Resulting output voltage waveform and current through output inductor L3 have been shown in Figure 18 and 19 respectively. From these results, it can be seen that voltage and currents of all power components are within safe limit in case of output diode short circuit when gate drives to module IGBTs are withdrawn within 10 µs.

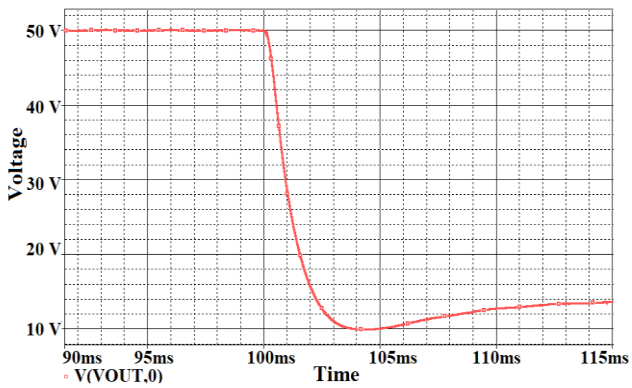

Figure 16: Output voltage waveform with D3 shorted

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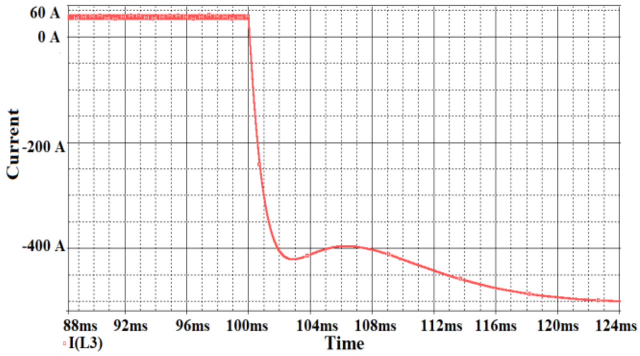

Figure 17: Output filter inductor current waveform with D3 shorted

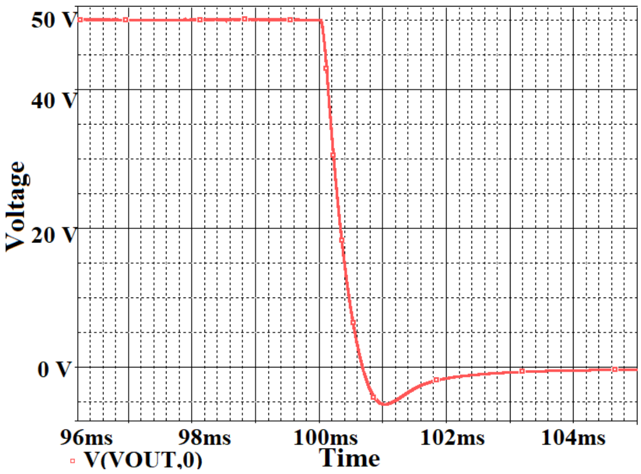

Figure 18: Output voltage waveform with D3 shorted and gate pulse withdrawn after 10 us

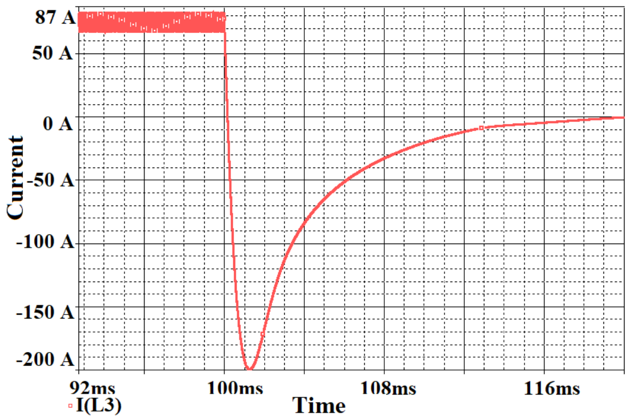

Figure 19: Output filter inductor current waveform with D3 shorted and gate pulse withdrawn after 10 us

V. THERMAL ABILITY OF WOUND COMPONENTS TO WITHSTAND SHORT CIRCUIT

The short circuit withstand capability of high frequency (HF) transformer windings and inductor windings, used in 50 V, 150 A DC power module has been calculated. The highest temperature attained by a winding after short circuit is given by:

$$T_1 = [T_0 + (a\Gamma^2 \times t) \times 10^{-3}]\ ^{o}C$$

Where,

To = Initial temperature in ^{o}C.

Γ = Short circuit current density of secondary in Amperes per square millimeter

a = Function of (T1 +T0)/2 as per IS-2026

T_1 = Highest temperature attained by a winding after short circuit

t = Short circuit withstand time

As per standard IS-2026, part-I, for dry type transformer with copper windings, T1 = 250 ^{o}C. To = temperature of transformer winding after 8 hours = 70 ^{o}C. So, (T1 + To)/2 = (250 + 70)/2 = 160 ^{o}C. At 160 ^{o}C, a = 7.8 from IS-2026. For self-cooled dry type transformer, current density is taken as 1.8 A/mm^2. Per unit impedance of HF transformer used in 50 V, 150 A DC power module = 5%, so short circuit current density (Γ) of HF transformer = 1.8 x 20 = 36 A/mm^2. So, from above equation, t = 17.8 seconds. Inductor windings can also tolerate the short circuit for nearly same time period. So, all wound components can tolerate short circuit up to 17.8 seconds. This is sufficiently large time for circuit protections to act and trip off the power module.

VI. SUMMARY AND DISCUSSION

In this work, failure mode analysis of 50 V, 150 A water-cooled DC power module based on two switch forward converter topology has been presented. The design of the DC power module is validated using simulations performed in OrCAD PSpice Cadence software. Various failure scenarios such as short circuits across output filter capacitors, IGBT switches, and rectifier diodes as well as open circuit of IGBT switches are analyzed to evaluate the system's robustness. In the case of short circuit across output filter capacitor, module controller withdraws gate drive pulse within 10 µs because of which switching currents are maintained well within their rated limits. Again, power components, windings, interconnections etc. are designed to withstand fault currents for more than 20 ms, within which secondary protection through input contactor will act. To prevent short circuit across IGBT switch, switches of considerably higher voltage and current ratings are chosen and employed in DC power module. Further, module controller continuously monitors the current flowing though IGBTs and responds in the case of fault. In case of open circuit across IGBT switch, sudden drop in output voltage is observed which will be detected by module controller and mains contactor of DC power module is turned OFF. In case of short circuit across output diode, there is significant increase in current which can be detrimental for DC power module. To cater to this fault, module controller along with input contactor takes action to turn off the power module.

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Various circuit protection features such as output over voltage, over current/short circuit and over temperature protection. Additional multi-tiered protection mechanisms, including input mains contactors, miniature circuit breakers (MCBs), and fuses, provide secondary and tertiary levels of fault protection. A thermal analysis of the transformer and inductor windings under short-circuit conditions is conducted to determine their withstand capability. It has been estimated that the windings can tolerate short circuits for approximately 17.8 seconds which is sufficient time for the circuit protections to respond and shut down the module. The failure mode analysis paves the path to increase availability of this power module as well as the availability of 50 V, 1950 A water-cooled DC power supply, wherein multiple numbers of such power modules will be connected in parallel. Additionally, active redundancy among 50 V, 150 A DC power modules will further increase the availability of 50 V, 1950 A water-cooled DC power supply.

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