Fault tolerant single-phase capacitor start capacitor run induction motor powered with cascaded multilevel quasi impedance source inverter

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Abstract: In this study, the performance of fault tolerant single-phase capacitor start capacitor run induction motor powered using seven-level quasi-impedance source inverter (qZSI) is analysed. The seven-level inverter consists of three units of qZSI connected in cascade. When one of the qZSI module fails (due to semiconductor failure), the resultant rms voltage applied to the motor will be reduced by one-third. This leads to reduction in both mechanical speed and electromagnetic torque of the motor. To restore the performance of the motor to pre-fault condition, the voltage deficit must be compensated. In conventional CHB inverter, it is not possible to achieve the pre-fault voltage. However, in qZSI, it is possible to achieve required voltage boost by application of shoot through duty cycle. Here, voltage of other two healthy operating modules can be boosted to reach pre-fault inverter output voltage during post-fault condition. The maximum voltage boost achievable is limited by the maximum shoot-through duty cycle which is related with modulation index. To verify the concept, simulation results of single-phase capacitor-start capacitor-run induction motor with or without proposed control algorithm are discussed. Experimental results for the proposed algorithm with RL load are discussed.

1 Introduction

Domestic loads connected to the utility grid consist of lighting loads, heating loads and induction motors. Usually different types of single-phase motors are used in the household products like fans, coolers, heaters, washing machines, pumps etc. [1, 2]. In single-phase motor, special arrangement of auxiliary winding is provided to allow starting of the motor. Once the motor reaches the specified speed, part of auxiliary winding or entire auxiliary winding is disconnected by operation of centrifugal switch. In single-phase capacitor-start capacitor-run induction motor, there are two capacitors in the auxiliary windings. Starting capacitor is disconnected once the desired speed is achieved [3–5].

In islanded mode operations like cargo ships, fishing boats, forest agriculture land, the single-phase motors are supplied by the single-phase inverters and multilevel inverters to run the machines. Single converter operation of the loads is widely discussed using frequency control method [6, 7]. However, they are facing the serious drawback during the fault or failure of the converter components because the customer cannot install the extra converter. To overcome this problem, the single-phase motor loads are fed with the multilevel inverters to achieve continuity of loading operation [8, 9].

Quasi-impedance source inverter (qZSI) is proposed in [10], to achieve the buck, boost and buck–boost operation of the input voltage. Recently, solar-powered motor drives are quite popular for standalone systems. To operate the photovoltaic panels at maximum power point, an extra DC–DC converter is required for getting the desired DC bus voltage [11, 12]. Maximum power point operation of qZSI module is achieved. This converter can be used for powering the motor drive from the power generated by solar panel. Cascaded qZSI is also reported in the literature for grid synchronisation [13–15]. Multilevel inverters have advantages of lower switch ratings, voltage stress and dV/dt leading to reduction in electromagnetic interference. However, they also have disadvantages of higher component count and require more than

one isolated dc supplies. Hence for achieving higher power rating of converters, multilevel inverters are quite popular [11, 12].

Failure of semiconductors switches in cascaded bridge module in the multilevel inverter leads to reduction of power fed to the motor and torque profile deviates from the desired value. Also there will be reduction in the rms voltage of the multilevel inverter. This deficit due to bridge failure must be compensated by the other healthy operating modules [16]. In [17], the author proposed the additional module to compensate the extra required voltage. Popescu *et al.* [18] discussed the detailed study and operation of the asynchronous single-phase permanent magnet machines. In [19], the fault of the transistor is discussed and the detecting algorithm which gives lesser voltage and complex controller design is proposed. It also increases the voltage and current stresses on the transistors. In the presented paper, novel voltage control algorithm which detects the module failure and compensate the dc bus voltage of healthy modules so that the motor drive achieves the pre-fault operation.

This paper is organised as follows. Section 2 deals with operating principle of the cascaded qZSI and system description. Section 3 presents the detailed control algorithm during fault and after fault in the proposed system. Detailed simulation results are discussed in Section 4 which validates the proposed control algorithm for single-phase induction motor. The experimental prototype is developed for 1 kW cascaded qZSI and tested for RL load. Experimental results are discussed in Section 5. It is followed by the conclusion.

2 System description

The system consists of seven-level qZSI powering the single-phase induction motor as shown in Fig. 1. Single-phase induction motor is capacitor-start capacitor-run type. The centrifugal switch disconnects the starting capacitor once the motor reaches a pre-defined speed. Run capacitor always remain connected in the auxiliary winding and draws current from the power supply to improve the power factor of the drive. The purpose of starting
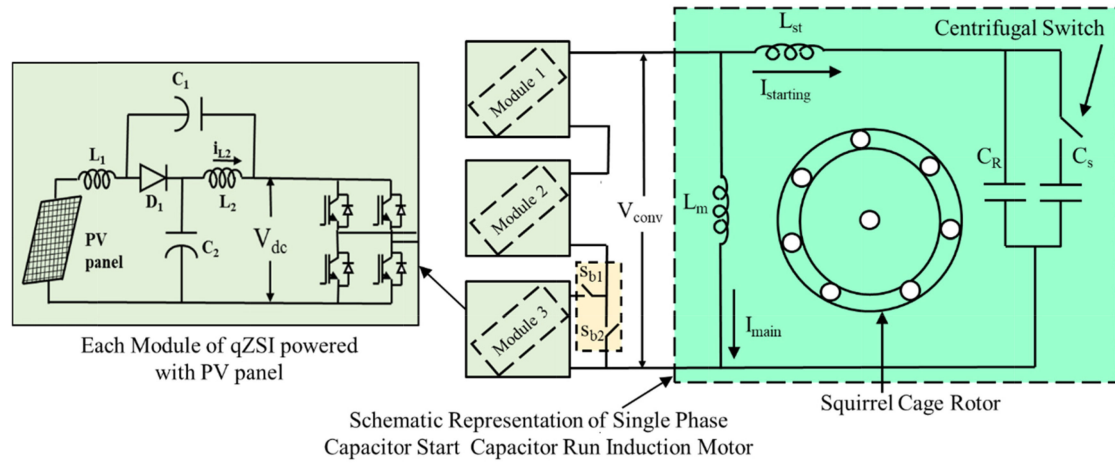
Fig. 1 *Single phase capacitor – start capacitor – run induction motor powered with multilevel qZSI (provided with bypass switches – S_{b1}, S_{b2})*

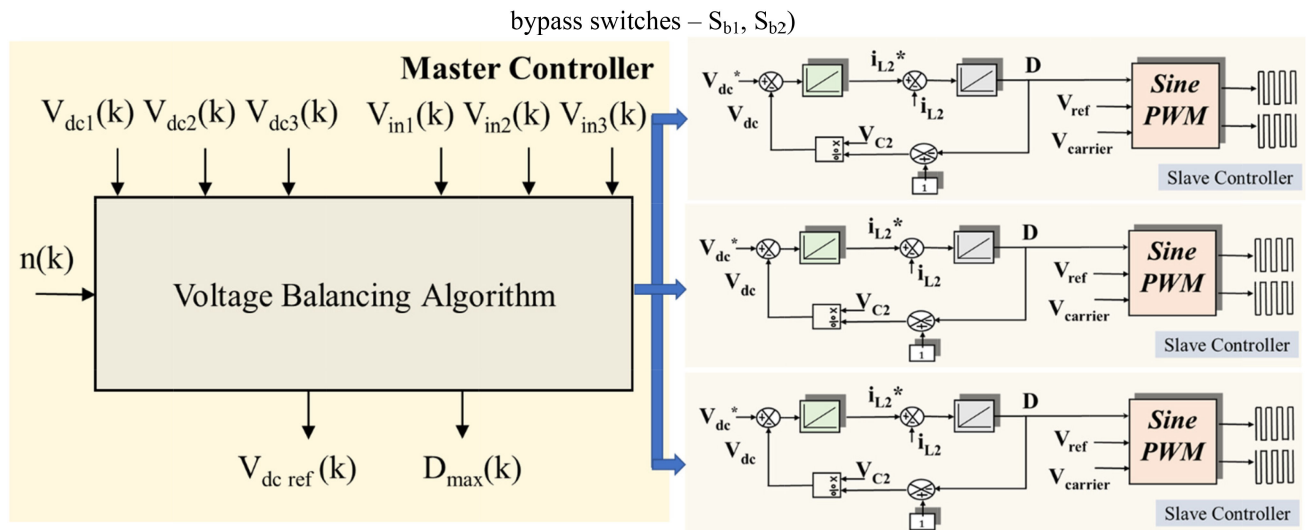bypass switches – S_{b1}, S_{b2})

Fig. 2 *Control algorithm for voltage balancing of each qZSI (with and without fault)*

capacitor is to help in starting process along with run capacitor whereas the run capacitor improves the power factor of the motor during running condition [2].

To achieve seven-level inverter output voltage, three modules of qZSI are connected in cascade. Phase-shifted carrier pulse-width modulation (PSCPWM) is implemented for controlling the qZSI modules. Carrier signal of each module is displaced by 60° with respect to each other [11].

3 Control algorithm

The proposed control algorithm is shown in Fig. 2. It consists of two types of controllers. Master controller is the central controller whereas slave controller is placed individually with each module.

Master controller receives input voltage, dc bus voltage, and fault status of each module. In case of a failure, the fault status becomes low and the output voltage of the inverter becomes zero. Due to this, the required motor input voltage becomes low. However, the proposed control algorithm increases the dc bus voltage of each healthy module. This new dc bus voltage reference should be achieved by healthy module. To check this, input voltage is sensed into the system and the maximum dc bus voltage possible is calculated using

$$V_{dc\_max} = \frac{V_{in}}{1 - D_{max}} \qquad (1)$$

where D_{max} is the maximum shoot-through duty cycle.

Slave controller receives the dc bus voltage reference and maximum shoot-through duty cycle from the master controller. It

consists of two cascaded PI control loops. The first control loop gives the inductor current reference and the second control loop gives the shoot-through duty cycle required to achieve the desired dc bus voltage. The maximum shoot-through duty cycle is constrained by the relation

$$D_{max} = 1 - m \qquad (2)$$

In addition to conventional sine-triangle comparison, shoot-through pulses must also be considered. To achieve, comparison of carrier signal with $1 - D$ and $D - 1$ is done and resulting pulses are obtained. Logical OR operation is performed between these shoot-through pulses and conventional PWM generated pulses.

4 Simulation results

Single-phase induction motor is rated for 1 HP, 230 V, 50 Hz. Synchronous speed of the motor is 1500 rpm. For a rated voltage of 230 V, modulation index is selected to be 0.75 and maximum shoot-through duty cycle of 0.25. For modulation index of 0.75, the dc bus voltage required is 450 V. This means dc bus voltage of each module during pre-fault condition should be 150 V. For post-fault condition, the dc bus voltage must be 225 V. The parameter or component specification is given in Table 1.

To demonstrate the robustness of the proposed control algorithm, module failure is emulated by opening the series bypass switch and closing the shunt bypass switch. Response of the system is shown in Fig. 3.

Induction motor is started at no-load to allow fast acceleration. At starting, the motor input current is higher than the rated current. Since the motor is capacitor-start capacitor-run, once the motor

Table 1 Component/Parameter specification of system

Parameter/Component	Specification
V_{in} (each module), V	120
pre-fault DC bus voltage, V	150
post-fault DC bus voltage, V	225
load voltage (RMS), V	230
modulation index	0.75
shoot-through duty limit, D_{max}	0.25
switching frequency, kHz	5
$L_1 = L_2$, mH	1.8
$C_1 = C_2$, mF	3.0
single phase capacitor start capacitor run induction motor	1 HP, 1500 rpm
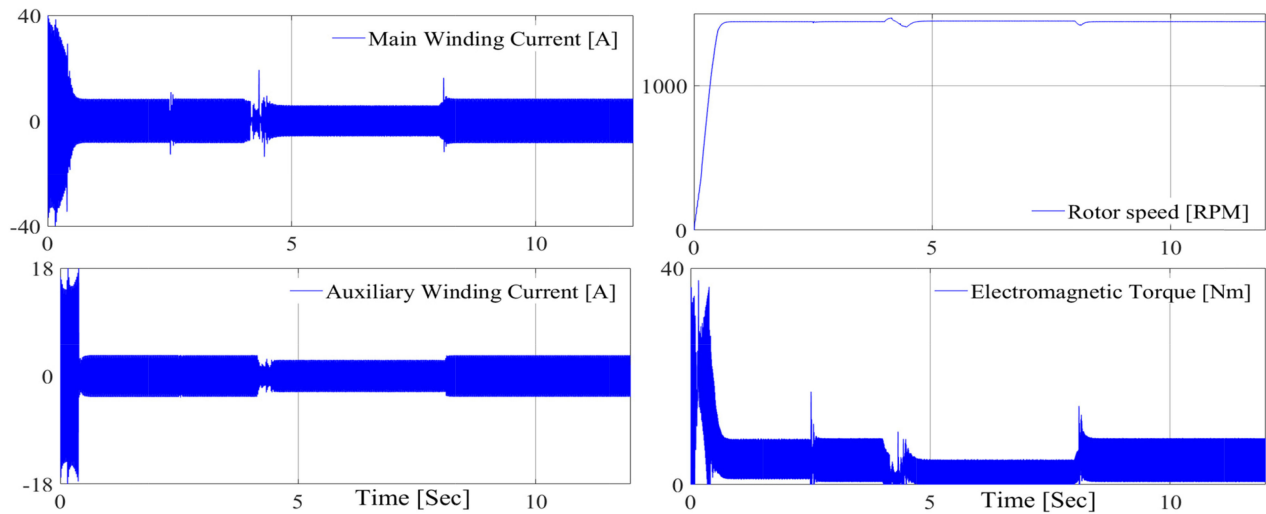
Fig. 3 *Single-phase capacitor start capacitor run induction motor with fault at t = 2.5 s*
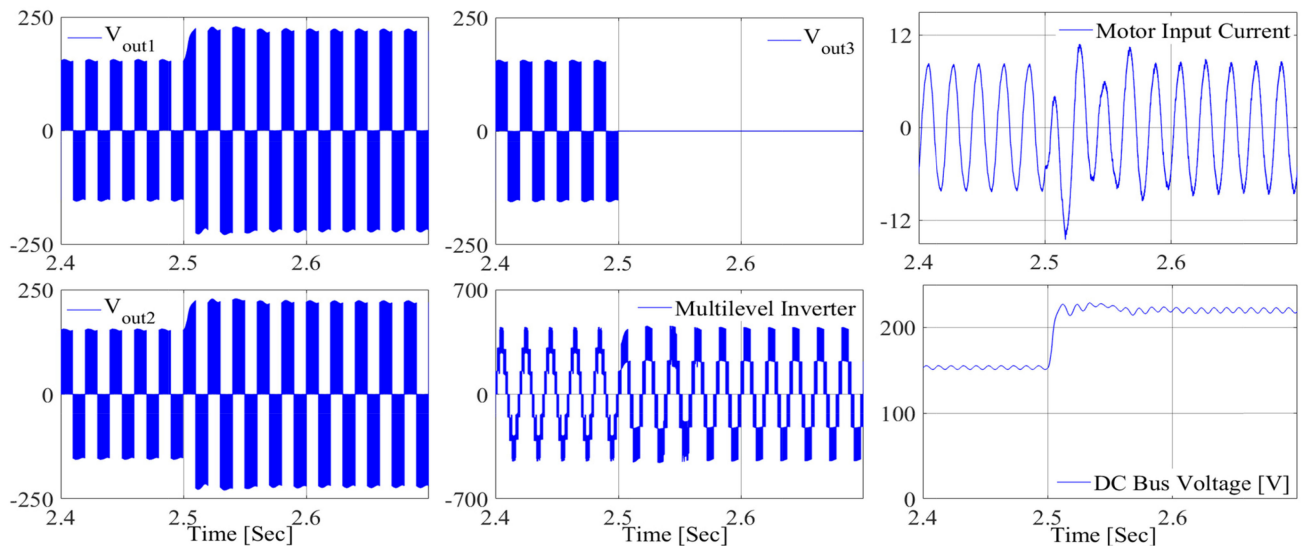
Fig. 4 *Transient response of multilevel during fault and post-fault condition*

speed becomes higher than 75% of the synchronous speed, the starting capacitor is disconnected by the centrifugal switch. As the motor approaches near the rated speed reference, the motor current decreases. At $t = 0.5$ s, the load torque of 5 N m is applied to the motor. Once the motor reaches near reference speed, the motor current will be in correspondence with the load torque reference. At $t = 2.5$ s, module failure occurs is emulated and the number of levels in the multilevel inverter voltage are reduced from seven to five as shown in Fig. 4. Due to this, reduction in rms voltage of inverter output voltage occurs. However, with the proposed algorithm, reduction in rms volt age is countered by increasing the dc bus voltage of each healthy module. Due to this, rms voltage is

restored to pre-fault value. Since electrical transients are faster than mechanical transients, small transients in the motor output parameters are observed at $t = 2.5$ s. No drop in mechanical speed or electromagnetic torque is observed during post-fault operation.

At $t = 4$ s, the load torque is reduced from 5 to 2.5 N m. From motor performance characteristics, drop in the load torque is accompanied by momentary increase in the motor's speed. At this condition, the control algorithm controls the speed of the motor and it is brought back to the desired speed. Similarly, at $t = 8$ s, motor load torque is increased from 2.5 to 5 N m. Even here, motor speed decreases momentarily but restored back to the reference speed as shown in Fig. 3.
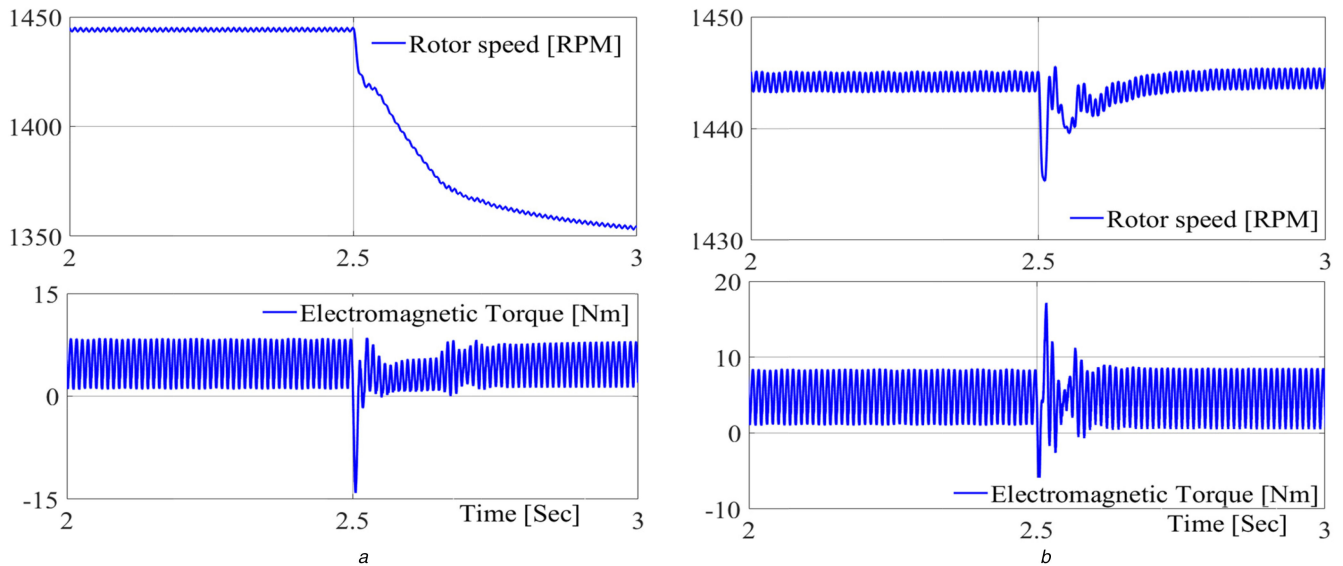
Fig. 5 *Motor performance comparison with conventional and proposed control algorithm*
(a) Response with conventional control algorithm, *(b)* Response with proposed control algorithm

Table 2 List of components for control implementation

Purpose	Part No.
FPGA	VIR EX 5 – xc5vlx50t
ADC	PMOD AD1
DAC	PMOD DA4
voltage sensor	LV 25P
current sensor	LA 55P
gate driver board	GDA2A2S1

For purpose of comparison, Fig. 5 shows the performance of the single-phase induction motor with and without the proposed voltage boosting algorithm. In case of conventional control algorithm, the motor response is shown in Fig. 5a where motor speed and electromagnetic torque decreases due to module failure. Fig. 5b shows the response with proposed algorithm where the desired speed is restored to pre-fault value.

5 Hardware results

For experimental verification of the control algorithm, parameters given in Table 1 are used for hardware implementation. Seven-level qZSI is implemented by connecting three qZSI modules in cascade. Multilevel qZSI is connected to RL load for the purpose of evaluation of algorithm effectiveness. Closed-loop control of qZSI is implemented with field-programmable gate array (FPGA). The components used in the implementation are given in Table 2.

Fig. 6 shows the response of qZSI module when dc bus voltage reference is varied. The changes in dc bus voltage reference are also reflected in inductor current reference due to cascaded control strategy. Fig. 7 shows the response of the system when module failure is emulated. It should be observe that the number of levels in the output voltage is reduced from seven to five, but the control algorithm boosts the dc bus voltage of remaining two healthy modules. Due to this, the power drawn from each input dc power supply is also increased.

6 Conclusion

The paper discusses the impact of module failure in seven-level qZSI powered single phase induction motor. Deterioration in motor performance due to reduction in rms voltage is discussed. To overcome this issue, control algorithm is proposed. Here, dc bus voltage of each healthy module is boosted to compensate for the deficit in rms voltage reduction. With this control algorithm, improvement in the motor response is discussed in the paper. Simulation results that validate the performance of the single-phase motor are presented and discussed. Response of the system for
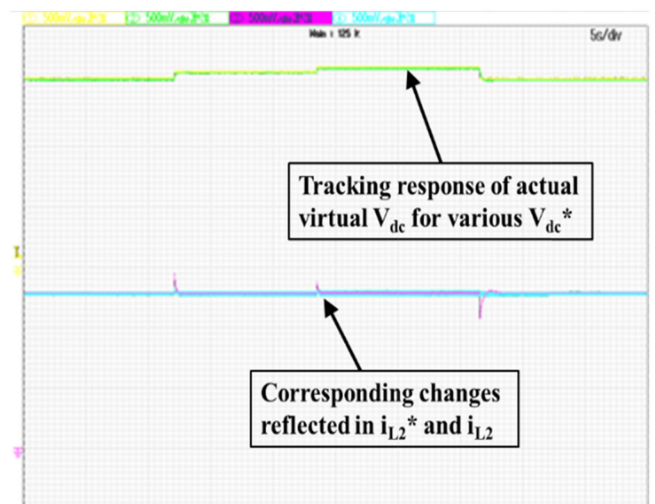

Fig. 6 *Tracking performance of qZSI module*

varying load torque is discussed. Experimental results for validation of the proposed control algorithm for seven-level qZSI connected to RL load are presented. Future work includes implementation of proposed control algorithm to single-phase induction motor.
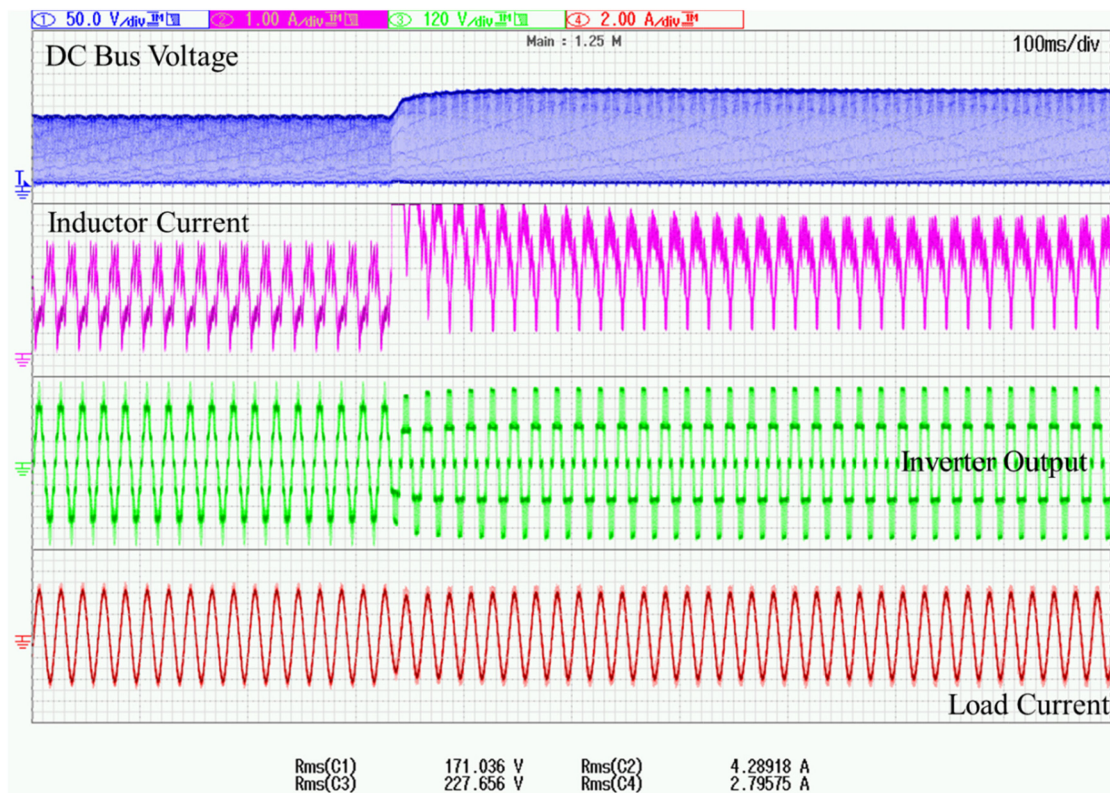
7 Acknowledgment

Fig. 7 *Response of multilevel qZSI during module failure when connected to RL load*

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