DEVELOPMENT OF A THREE-PHASE THREE-LEVEL INVERTER FOR AN ELECTRIC VEHICLE

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Abstract

The development of variable speed AC induction motor drive systems for electric vehicles has been carried out at the University of Canterbury for more than 20 years. A three-phase three-level IGBT inverter has been developed for the University of Canterbury electric vehicle propulsion system. This paper deals with the three-phase three-level inverter switching device selection and inverter construction details. Experimental testing has been undertaken to examine the operating characteristics of the completed three-phase three-level inverter driving one of the electric vehicle motors.

1. INTRODUCTION

This is a follow up paper, where the original single-phase three-level inverter design incorporating a laminated busbar structure and gate drivers [1] has been extended to a three-phase three-level inverter for an electric vehicle. Initially, one three-level IGBT inverter leg was constructed and tested to demonstrate its operation. The design was based on the philosophy that two new three-level inverters will separately control two AC induction motors that have a normal rated power of 2.2kW at 50Hz. Each inverter operates from a nominal 240V DC power supply formed by twenty 12V lead acid batteries.

Improvements in the performance of motor drives have been directly related to the availability of power semiconductor devices with better electrical characteristics [2], so choosing the semiconductor switches for an electrical vehicle propulsion system is important. Computer simulations based on the electric vehicle motor parameters have been carried out to investigate the performance and determine the switching device ratings for the three-level inverter. The inverter design incorporates a laminated busbar structure consisting of alternate copper plates and insulating layers. The advantages of this mechanical construction are that overvoltages can be reduced by reducing the stray inductance, and snubber circuits are therefore unnecessary.

This paper presents the selection of the switching devices and clamping diodes used in the inverter, and details the construction of the completed inverter, mounted in its purpose built enclosure. Experimental tests with a motor load at full voltage, and maximum rated current have been carried out to evaluate the performance of the three-level inverter. The results show that the inverter line-to-line output voltage has five voltage levels and closely approximates a sinusoid. As a result the output load currents also have low level harmonic components.

2. SWITCHING DEVICE SELECTION

In the electric vehicle each three-level inverter will operate from a nominal DC voltage of 240V and drive an AC induction motor. Simulations of the steady-state operation of a three-level inverter driving an induction motor model were carried out to investigate the performance of the motor drive system. The power switching component ratings and overall inverter specifications are determined from an analysis of these simulation results.

Figure 1 presents the simulation results showing the waveforms of the inverter output line-to-line voltage and three-phase currents under steady-state operation with a motor load at the nominal fundamental frequency of 50Hz. It can be seen that inverter line-to-line output voltage has five voltage levels, and the motor current is very close to a sinusoidal waveform.

As shown in Figure 1, the steady-state RMS value of the per-phase inverter output current is about 50A when the inverter operates with a maximum motor overload at a frequency of 50Hz. To account for overload current transient conditions, the current rating of the switching device should be at least 1.5 times the value of the steady-state current [2]. Thus the overload rating of the switching device should be at least $75A_{RMS}$. Therefore, each switch should have at least a peak current rating of about 110A.

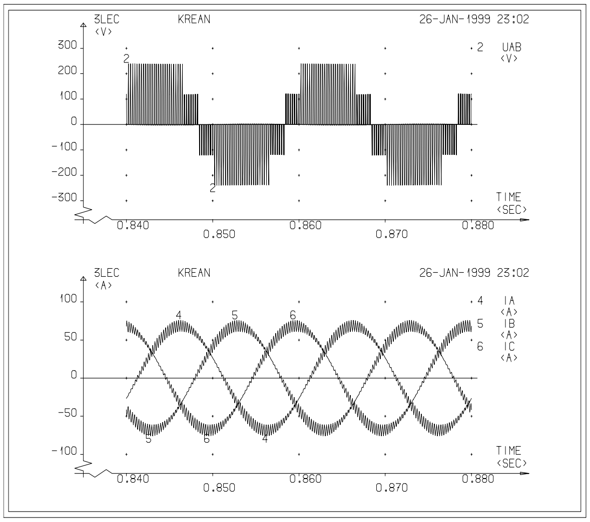

Figure 1 Motor line-to-line voltage and phase current waveforms for fundamental frequency of 50Hz

The three-level inverter operates from a nominal 240V DC power supply, with the neutral tied to the mid-point of the battery bank. According to the simulation results, the voltage stress experienced by each switching device is limited to half the total DC bus voltage or 120V. To allow an adequate voltage margin for inductive di/dt voltage spikes, switching devices and clamping diodes with at least a blocking voltage rating of 200V need to be selected.

IGBTs are the modern efficient switching elements for medium power inverter applications [3]. Typically the closest available IGBT devices have a current rating of 150A. At this current rating, the blocking voltage rating of the device is usually 600V or 1200V. So IGBT devices with the rating of 150A, 600V were selected for the switching elements of the inverter.

Six-pack 600V/50A Siemens IGBT modules (BSM50GD60DN2), originally designed for two-level three-phase full-bridge inverter applications, are selected as the switching elements of the inverter due to their low cost. The top and bottom three IGBTs in each module are paralleled to obtain the required 150A rating. Ultra-fast-recovery diodes, RURG8060, are used in the inverter as the clamping diodes. These diodes have a soft recovery characteristic and low forward voltage drop that satisfies operating requirements and reduces the power loss. The RURG8060 blocking voltage is 600V, and the average rectified forward current rating is 80A, with a repetitive peak surge current of 160A.

Figure 2 shows one phase of the three-level inverter. Two six-pack IGBT modules and two external clamping diodes in the inverter leg form four paralleled IGBT groups. The power connections are symmetrical and of low inductance. The positive DC input is connected to the collectors of the top IGBT module, and the negative DC input is connected to the emitters of the bottom IGBT module. The gates of the three paralleled IGBTs in each group are driven by a single gate drive signal via resistor R.

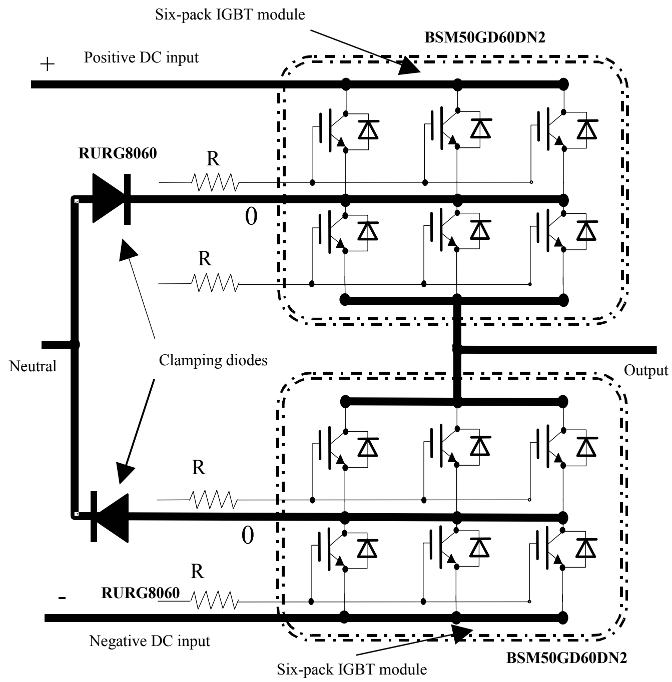

Figure 2 One-inverter leg using six-pack IGBT modules

For the selected IGBT module, the temperature coefficient of $V_{CE(sat)}$ goes from a bipolar-like negative at low current to a MOSFET-like positive coefficient as current increases above its rated value [4]. At high current levels the behaviour is similar to the power-MOSFET and current balance between devices improves when the temperature difference increases. Therefore the minor differences occurring between the $V_{CE(sat)}$ of parallel dies are automatically balanced with small temperature variations.

3. INVERTER CONSTRUCTION

During operation of the inverter, energy is stored in the stray inductance of the power circuit during conduction.

At turn-off, this energy is released and voltage spikes are generated. These over-voltages will generally be caused when stray inductance in the power supply busbars experiences large values of di/dt. If the voltage spikes exceed the reverse biased safe operating area curve of the IGBT, the switch can be destroyed. It is essential to minimise stray inductance in the busbars. This has the added benefit of reducing stray magnetic flux and electromagnetic interference [5].

To reduce the stray inductance, a laminated busbar, that consists of five-layer alternate copper plates and insulating layers, is used in the inverter [1]. Snubber circuits are unnecessary with this low stray inductance design technique. In the electric vehicle the batteries are in the front of the vehicle and the inverters are installed in the rear. Therefore relatively long battery cables with significant inductance are needed. Two busbar capacitors of 470μF per phase are used to offset the inductance of these relatively long battery cables. The bus capacitors are positioned vertically on the topside of the five-layer busbar.

As shown in the photograph Figure 3, the IGBT modules and clamping diodes were mounted onto the large finned aluminium heatsink. To promote an even temperature distribution and avoid hot spots, care was taken to ensure that these devices were evenly spaced on the top of the heatsink. A thermally conductive silicon paste was applied to the contact surfaces, and all mounting bolts securing the power devices were tightened to ensure a good thermal contact to the mounting surface of the heatsink.

Two-ounce single sided copper printed circuit boards (PCBs) were used to construct the laminated five-layer busbar structure. Single sided PCBs are necessary as the bus structure is built up at one layer at a time since solder connections were made to the IGBTs pins. The insulation is provided by the fibreglass boards. These PCBs electrically link the power devices and carry current. The cross sectional areas of the boards accommodated within the existing enclosure are designed to be as large as possible to handle the high currents and minimise the conductor losses and temperature rise. Three 80mm (approximately 3150mils) wide PCBs in the middle of the five-layer busbar structure run the length of the inverter as the main DC busbars. A two-ounce, 100mils wide copper track allows a current of 6.5A for a temperature rise of 10ºC above ambient. Therefore, the 80mm-wide two-ounce copper PCB should be capable of carrying a current of 205A and still only have a temperature rise of 10ºC above ambient. This means that the PCBs are capable of handling the required peak motor current. During testing it was observed that there was no significant temperature rise of the copper tracks when the nominal current was flowing in the inverter.

This laminated five-layer busbar permits a compact and clearly arranged mechanical construction. The main advantage of this construction is that overvoltages can be reduced by minimising stray inductance. This has the added benefit of reducing stray magnetic flux and electromagnetic interference.

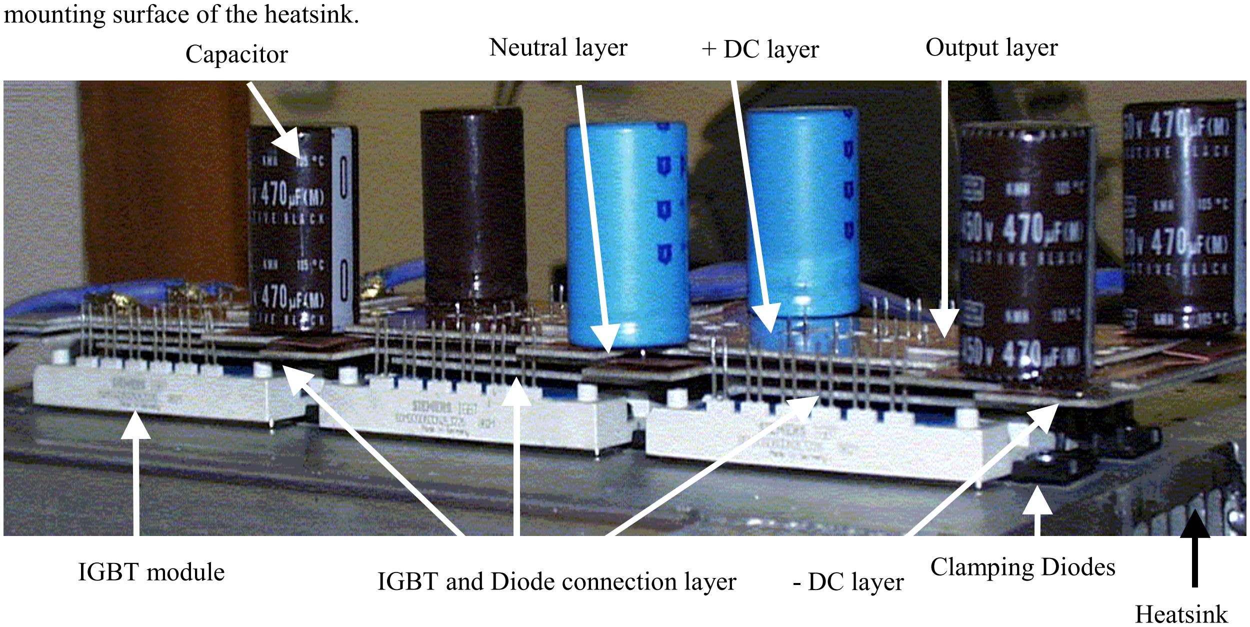

Figure 3 Photograph showing the inverter viewed from left side with sidewalls and gate drive boards removed

4. INVERTER TESTS

Experimental tests were carried out to evaluate the performance of the three-level inverter as a motor speed controller for the electric vehicle. A discrete open-loop subharmonic PWM controller was designed for use in these tests. The operates at a fixed frequency of 4kHz and a fixed modulation ratio.

The inverter was operated and tested at three frequencies, 50Hz, 30Hz and 70Hz from a ±120V DC bus. The switching frequency is set to 4kHz for all tests. To keep the air gap flux constant, the inverter line-to-line voltage was adjusted to be proportional to the frequency. Load torque was increased by successively adding weights to a friction brake, which the motor was coupled to. Figure 4 shows the torque and current characteristics of the motor when operated from the inverter at the three different frequencies. The motor load was increased in a number of steps until the motor current was at its nominal rated value of 25A. These test results show that the inverter is capable of delivering rated current at rated torque for a range of fundamental frequencies.

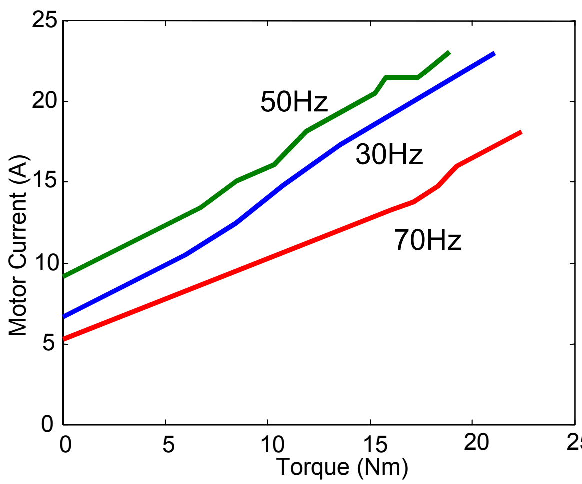

Figure 4 Motor current-torque characteristic.

Figure 5 shows the waveforms of the inverter line-to-line output voltage and phase A current at a fundamental frequency of 50Hz. The waveforms of the phase B and phase C currents are similar to that of the phase A current and being mutually 120 degree apart in phase. The motor was loaded by suspending weights of 5kg and the value of the motor torque was up to 18.9Nm with full load. Motor speeds were measured, and they are 1500rpm at a frequency of 50Hz with full load.

It can be seen that the line-to-line output voltages, or motor voltage, have five voltage levels of +240V, +120V, 0, -120V and –240V. There is just a small voltage overshoot of less than 5V in the line-to-line output voltage. The output currents are sufficiently close to being sinusoidal and the harmonic components are small. The maximum peak value of the current is about 33A at a frequency of 50Hz. These tests show the inverter is capable of delivering rated current at rated torque for a range of fundamental frequencies.

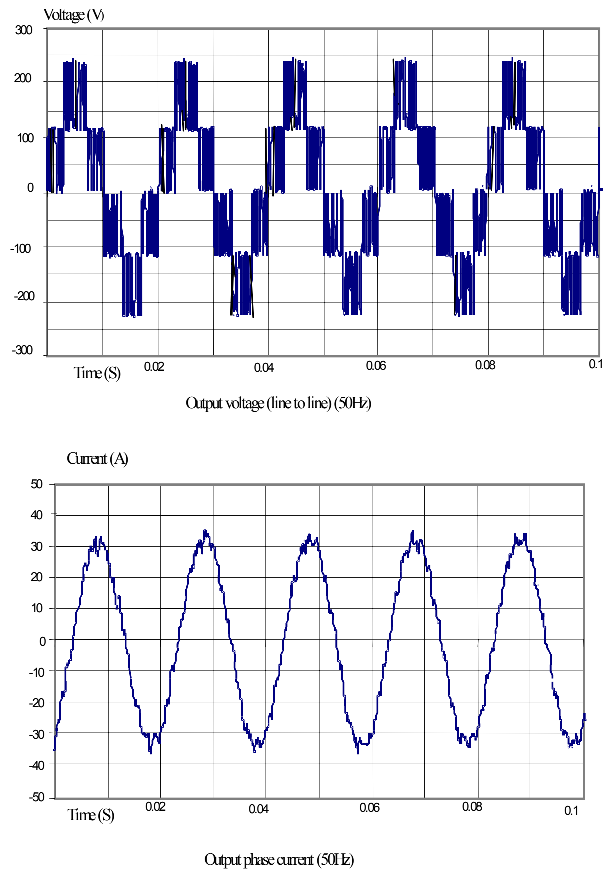

Figure 5 Output voltage (line-to-line) and phase current at a frequency of 50Hz**.**

5. CONCLUSION

A three-phase three-level IGBT inverter for an electric vehicle has been developed. Six-pack 600V/50A IGBT modules were selected as the main switching elements for the inverter. By paralleling three IGBTs together in each module the required current rating of 150A was obtained. The laminated five-layer busbar structure of the inverter permits a compact and clearly arranged mechanical construction. Tests were performed with an induction motor load at full voltage, and maximum rated current and torque. The results showed that the inverter is capable of reliable and efficient operation over a range of frequencies.

6. REFERENCES

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