

Development of Low-loss Inverters for Electric Vehicle (EV) Motors

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The reduction of emissions of carbon dioxide (CO₂) is presently an urgent task given that such emissions are playing a large part in global warming. Improved fuel consumption technologies have been developed and stringent emissions rules have been applied in relation to automobiles as environmental awareness has increased. Ever since it started to produce a series of motors and inverters for hybrid compact trucks in May 2006, Mitsubishi Heavy Industries, Ltd. (MHI) has been contributing to the production of environmentally friendly automobiles that comply with automobile emissions control. This paper reports MHI's new development of an inverter with a control system that changes the switching frequencies to reduce power module loss which in turn drives the motor more efficiently.

1. Introduction

Reducing CO₂ emissions is mandatory, as they have a significant impact on global warming. Since automobiles account for a high percentage of total CO₂ emissions, the automobile industry has been keen to promote the spread of hybrid cars and electric vehicles.

MHI began producing a series of motors and inverters for hybrid compact trucks in May 2006 by way of developing environmentally friendly vehicles that comply with emissions control. With more hybrid trucks expected to be marketed, MHI must produce efficient vehicle motors that will improve fuel consumption while contributing to environment preservation.

This paper describes a newly developed control system that reduces inverter loss as a measure to drive motors more efficiently.

2. Basic inverter control system

Electric vehicles (EVs) generally use interior permanent magnetic synchronous (IPM) motors, which control the electric current in response to the torque commands. **Figure 1** shows a schematic block diagram of the control system.

The current detected by the three-phase current sensor is coordinate-transformed from triple-phase to *d*- and *q*-axes so that the current feedback control takes place in the *d*-*q* axes coordinate system. Since the *d*-*q* axes form a rotating coordinate system, the current vector control occurs while dividing the current into torque and field-weakening components.

Since the induction voltage is higher than the power line voltage in the high-speed region, the current would normally be unable to flow. To avoid this, field-weakening control

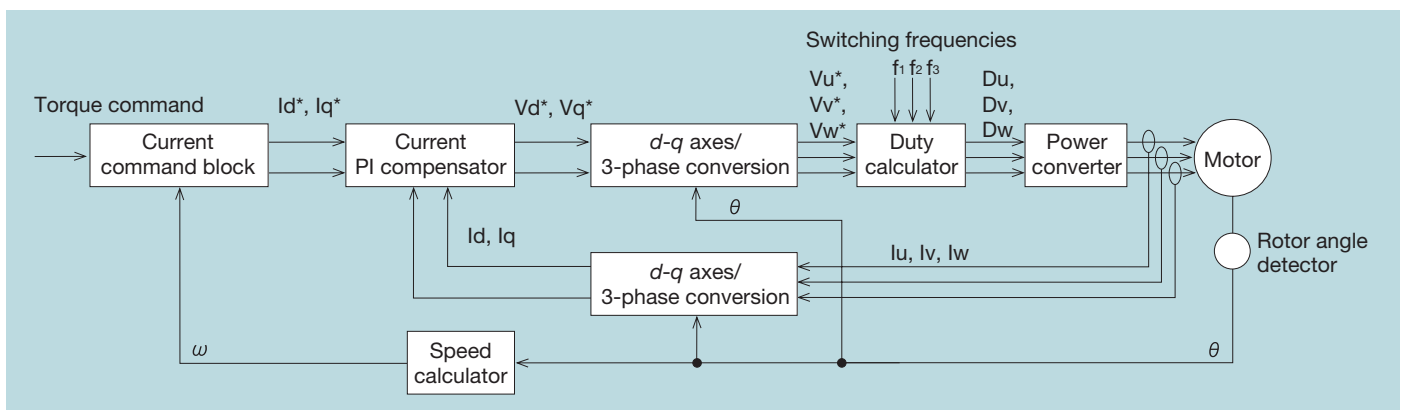


Fig. 1 Schematic block diagram of the motor and inverter control

The current is controlled by controlling the torque commands by switching frequency.

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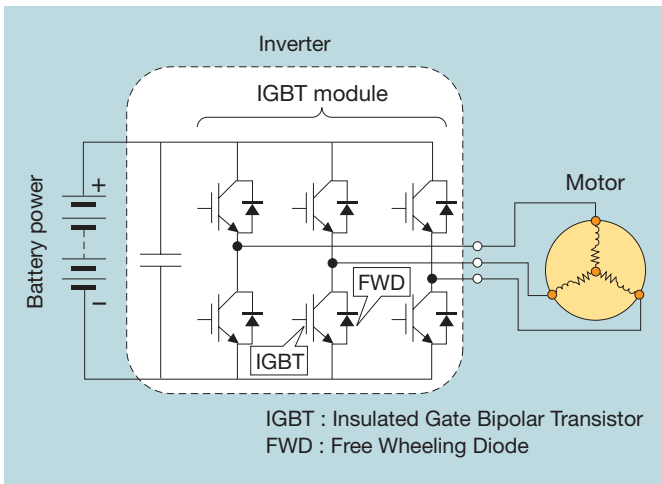


Fig. 2 The basic hardware configuration
The IGBT is PWM-controlled to drive the motor.

generally occurs where a negative d -axis current flows and weakens the magnetic flux in the direction of the d -axis, so as to suppress the induction voltage.

Figure 2 shows the basic hardware configuration for the IPM motor system. The inverter must be compact and highly efficient, as it has to be mounted on a car. Since driving an EV motor requires a large current, the heat generated by the insulated gate bipolar transistor (IGBT) module, which is the power module in the inverter, has been a stumbling block to achieving both compactness and high efficiency. **Figure 3** classifies the causes of IGBT module heat generation (total loss).

The IGBT switching loss and FWD reverse recovery loss increase with the switching frequency while the total loss increases as the current increases. In other words, a higher switching frequency and current both induce more power module loss and heat generation. Coping with heat generation requires a larger power module and a cooling system. Attempting to suppress the current would compromise the performance. To solve this problem, MHI have adopted a control system that changes the switching frequencies.

3. Low-loss motor control system

When driving a motor at a high speed, the pulse width modulation (PWM) control system has to be set to a high switching frequency to ensure controllability in response to the increase in the sinusoidal frequency of the motor current. By contrast, in a low-speed region where a high electric current flows, the motor does not require a high switching frequency. Despite a short drive time in the high-speed range, driving an EV motor requires that the switching frequency always be compatible with the high-speed region. The resulting switching loss reduces the efficiency significantly. To solve this problem, MHI divided the switching frequencies into three steps for the low-, intermediate-, and high-speed regions, as shown in **Fig. 4**.



Fig. 3 Total power module losses
The causes of power module loss are classified into four categories.

Changing the switching frequencies helps to minimize the heat generation and loss in the low-speed region, as shown in **Fig. 4**. The resulting significant reduction in heat and loss enables the construction of a smaller power module and cooling system, which in turn allows a compact inverter.

Nevertheless, this method has a problem: torque shock and abnormal noise are generated when the switching frequencies change. The difference in the switching frequencies causes a delay in the current control system.

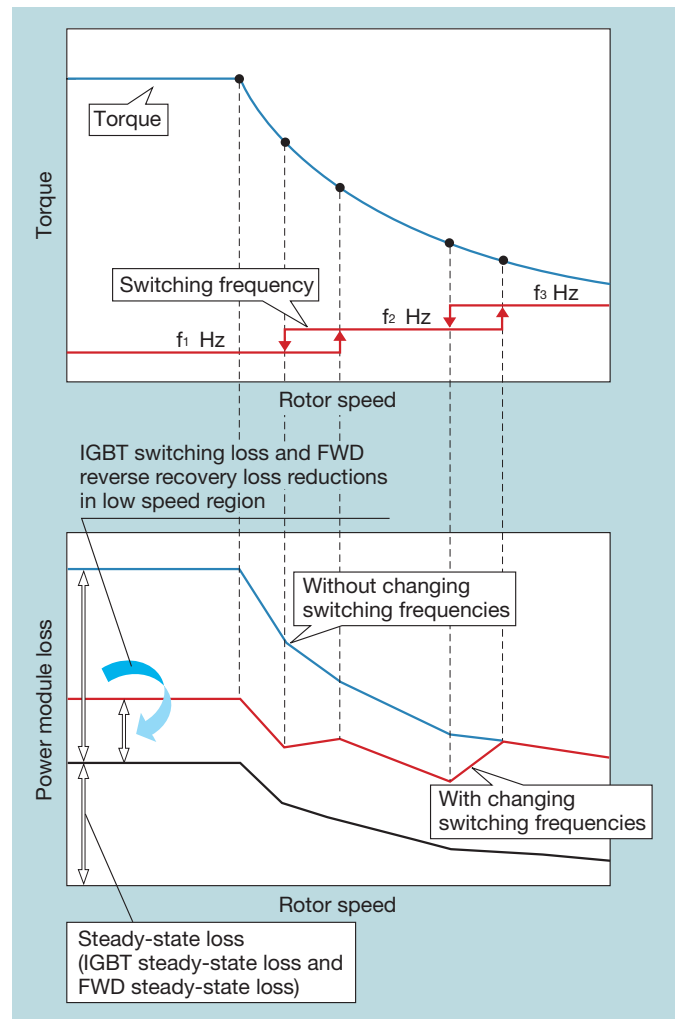


Fig. 4 Changing regions of the switching frequencies and power module loss

The top diagram is the N-T diagram and shows the changing regions of the switching frequencies. The bottom diagram indicates the effect on reducing power module loss.

The resulting fluctuation in the motor voltage and current leads to torque shock and abnormal noise.

MHI have developed a current-control software program to cope with this delay, one that successfully suppresses the torque shock and abnormal noise.

4. Improving reliability

4.1 Reliability evaluation

To evaluate the reliability of the product, each part and component of the major constituent parts (power modules) of the inverter are tested in terms of performance, temperature, and vibration to ensure that the vehicle-mount criteria are satisfied. In addition to the performance tests, the inverters must pass various car-mount tests concerning electrical characteristics, thermal environment, mechanical strength (vibration and impact), electromagnetic interference, and immunity (electromagnetic compatibility (EMC)).

MHI obtained certification for the quality management system ISO/TS16949, for the EV motors and inverters products in March 2008. The product design and production quality management system (QMS) comply with accredited ISO/TS16949 of product quality.

4.2 Improving software reliability

Inverter software programs for control have been designed for each vehicle. From the viewpoint of parts standardization and reuse, the functions of these software programs have been reorganized.

The inverter software programs are roughly classified into core (the core software responsible for control calculation), hardware-dependent, and vehicle-compatible (I/O compatible) software. From the core software programs, which account for almost 40% of all of the software, representative programs are selected based on the contents and actual implementation as common software programs.

The programs are also reorganized in line with the series models of the inverter hardware products. Additional design

is necessary only when a customer requires anything other than the standard MHI I/O system, which reduces the time needed for software design, while improving the reliability of the software.

5. Conclusion

This paper has outlined the development of low-loss inverters for EV motors and ways to improve product reliability.

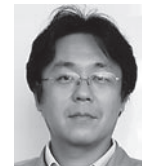
The development of various hybrid and electric vehicles, as environmentally friendly vehicles, has been given high priority worldwide. Electric motors will surely require attention as the engines for such vehicles. MHI is involved in the development of high-efficiency EV motors, with the aim of developing inexpensive, high-performance motor systems while improving, for instance, the regeneration rate of regenerative energy.

Reference

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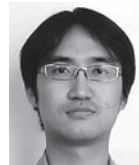
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