Traction Inverter Systems with SiC Power Modules for Railway Vehicles

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1. Introduction [1] [2] [3]

After the adoption of the Kyoto Protocol in 1997, various measures against the global warming have been promoted. In 2018, the UN adopted the Sustainable Development Goals (SDGs) to mitigate social issues from a broader perspective. Under such circumstances, Mitsubishi Electric Corporation (MELCO) has been working to help build a sustainable, safe, secure, comfortable, and affluent society by using technologies that we have cultivated in the railway sector. Regarding the effective use of energy, in February 2012, we carried out a test to evaluate the performance of traction inverter systems using the hybrid SiC power module on Tokyo Metro's line No. 1, for the first time in the world. For such power modules, silicon (Si) is used for the insulated gate bipolar transistors (IGBTs), and SiC is used for the diodes. Since then, we have applied many SiC technologies to traction inverter systems for the Japanese and overseas markets. The application of SiC power modules has helped reduce the energy consumption of entire main circuit systems, for example, by expanding the range of power regenerative brakes and reducing the loss in motors through high-frequency switching. In February 2016, our propulsion control units, the world's first to use full-SiC power modules, received the Excellent Energy-Saving Device Award from the Japanese Minister of Economy, Trade and Industry. In such power modules, SiCs are used for both metal-oxide-semiconductor field-effect transistors (MOSFETs) and diodes.

To continuously contribute to the energy-saving goals of the SDGs in the future, we have developed smaller and lighter traction inverter systems by applying the latest SiC power modules that can act flexibly for the customer requirements as to the main circuit system.

Recently, the world-standard type of power module is the LV100 package, which is suitable for a parallel drive. Although various manufacturers have been commercializing LV100 Si power modules, MELCO commercialized LV100 full-SiC power modules for the first time in the world.[1] The full-SiC power module reduces about 80% of the switching loss in comparison to the Si power module, which helps reduce the energy consumed by the main circuit system. Yet, the application of the world-standard package also enables the size and weight of the traction inverter system to reduce. Thus, the optimum design can be chosen depending on the configuration and capacity of various types of traction inverter systems for railway vehicles.

This paper describes the advantages of the traction inverter systems with the latest SiC power modules for railway vehicles and its energy-saving effects in real operation.

2. Traction Inverter Systems with LV100 full-SiC Power Modules

2.1 Traction inverter systems

Table 1 describes the main specifications of a traction inverter system with LV100 full-SiC power modules, and Figure 1 shows its appearance. Assuming systems for conventional lines in Japan, one traction inverter system drives four induction motors of up to 220 kW connected in parallel as the specifications.

A traction inverter system consists of a line breaker circuit, power unit, and gate control unit. The LV100 SiC power module enables the cooler to be compact and the

Table 1 Main specifications of a traction inverter system with LV100 full-SiC power modules

Item	Specification
Input (overhead line) voltage	1,500 VDC
Main circuit method	2-level voltage source PWM inverter
Motor drive capacity	Maximum rating of 220 kW × 4 units
Cooling method	Self-cooling by moving air

Fig. 1 Traction inverter system with LV100 full-SiC power modules

[1] As of May 11, 2017, researched by Mitsubishi Electric Corporation

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power units to be high-density packaging, such as a filter capacitor and laminated busbar configurated with the SiC power module. This achievement reduces about 60% of the volume and 50% of the mass in comparison to the conventional Si power module application.

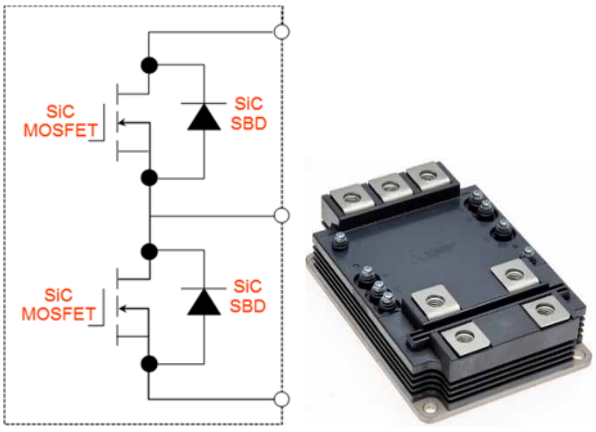
2.2 Advantages of LV100 full-SiC power modules[4]

Figure 2 shows the circuit diagram of the LV100 full-SiC power module and its appearance. The power module in the LV100 type consists of the circuit for the one arm of the two-level inverter. In general, Si power modules, the Si-IGBTs, and flywheels consist of silicon diode (Si-Di) devices while, for full-SiC power modules, they consist of SiC-MOSFETs and SiC Schottky Barrier Diodes (SiC-SBDs).

MELCO has commercialized Si and hybrid SiC power modules that are compatible with full-SiC power modules as our LV100 power modules, adding to full-SiC power modules, and they allow the optimum devices to be selected based on the required specifications of railway vehicles.

The LV100 power module also has the terminal arrangement to make the parallel drive easier, which is the advantage to achieve optimization by altering the parallel numbers corresponding to the vehicle specification.

Table 2 describes the main specifications of an LV100 Si power module and LV100 full-SiC power module. In comparison to the Si power module, the full-SiC power module increases 25% of the current-carrying capacity and about 16% of tolerable junction temperature, as well as reduces 80% of the switching loss. The achievements enable the equivalent motor to the Si power one to drive in the smaller number of the terminal arrangement than the Si power.



SBD: Schottky Barrier Diode

(a) Circuit diagram (b) Appearance

Fig. 2 LV100 full-SiC power module

Table 2 Main specifications of LV100 power modules

Module type	Si module	SiC module
Drain-source voltage	3300 V	3300 V
Drain current	600 A	750 A
Maximum junction temperature	150°C	175°C
Switching section	Si-IGBT	SiC-MOSFET
Diode section	Si-Di	SiC-SBD
Outside dimensions	100×140 mm	100×140 mm

3. Application to the Odakyu 5000 Series

Odakyu Electric Railway (“Odakyu”) started operating the remodeled 1000 series in 2014. Mitsubishi Electric delivered traction inverter systems with 3.3-kV full-SiC power modules for the remodeled series for the first time in the world and demonstrated the energy-saving effects. In February 2016, we received the Excellent Energy-Saving Device Award from the Japanese Minister of Economy, Trade and Industry jointly with Odakyu.

In 2019, we delivered traction inverter systems with LV100 full-SiC power modules, as described in section 2, for the Odakyu 5000 series. This section mainly describes the case where traction inverter systems with LV100 full-SiC power modules for the 5000 series were used.

3.1 Specifications of the inverter system

Table 3 lists the specifications of vehicles of the 5000 series and remodeled 1000 series. The train set of the 5000 series is ten vehicles (5M5T), the same as the remodeled 1000 series. The newly manufactured series are to replace 8000 series vehicles and other types. As shown in Fig. 3, as the main circuit system, one variable voltage variable frequency (VVVF) traction inverter system controls four main motors.

Figure 4 shows the appearance of a VVVF traction inverter system. Traction inverter systems for the 5000 series are smaller and lighter: the volume was reduced by about 30% and the mass by about 20% compared to the traction inverter systems for the remodeled 1000 series.

Table 3 Specifications of Odakyu railway vehicles

Item	5000 series	Remodeled 1000 series
Electrical mode	1,500 VDC (overhead line method)	
Train set (MT ratio)	Ten vehicles (5 Motor cars 5 Trailer cars)	
Gauge	1067 mm	
Maximum speed	120 km/h	110 km/h
Acceleration	3.3 km/h/s (to a load factor of 250%)	
Deceleration	4.0 km/h/s	
Gear ratio	6.31	
Train set mass	308.7 tons/ train set	351.8 tons/ train set
Main-circuit control method	SiC voltage source VVVF inverter	

3.2 Results of running tests on a main line

MELCO conducted the performance confirmation test of the traction inverter systems for the 5000 series on an Odakyu main line. Figure 5 shows the power running test chart, and Fig. 6 shows the regeneration test chart. MELCO used the test result to evaluate the performance, such as the acceleration and deceleration of the various types of vehicles at powering and braking, as well as verify the noise of the traction inverter systems with the LV100 full-SiC power module. The modulation method based on our knowledge gained through developing the conventional traction inverter system with SiC power modules achieved the reduction of noises and to provide further comfortability for passengers onboarding.

Table 4 shows the results of analyzing the intensity of vehicles of the 5000 series and remodeled 1000 series in operation on lines in use. Although the running conditions vary, the intensity of the 5000 series is 0.0241 kWh/(km·ton), and that of the remodeled 1000 series is 0.0232 kWh/(km·ton), both the values being of a similar level. These values confirm that the main circuit system for the 5000 series saves roughly the same energy as that for the remodeled 1000 series, which reduces energy usage by about 40% compared with vehicles with the existing gate turn-off thyristors (GTOs).

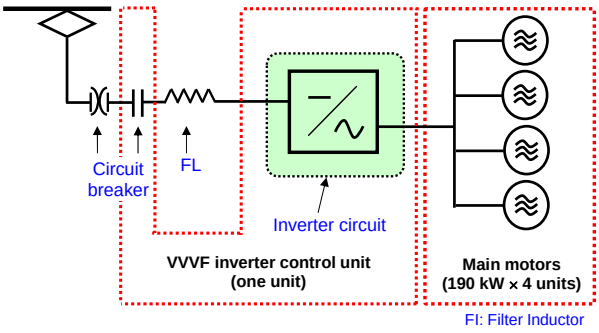


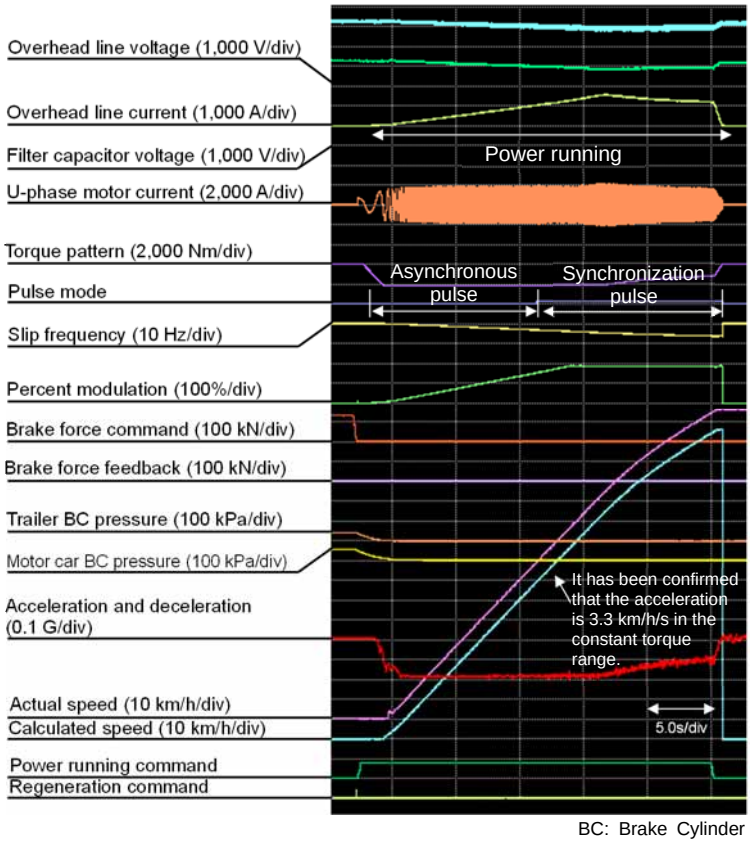
Fig. 3 5000 series main circuit system configuration

Fig. 4 VVVF traction inverter system for the 5000 series

4. Conclusion

This paper described the advantages of traction inverter systems with LV100 full-SiC power modules for railway vehicles and their application to the Odakyu 5000 series.

As manufacturers around the world must contribute to the SDGs, railway systems that have less environmental impact and that help save energy will play an important role. In the semiconductor device and



BC: Brake Cylinder

Fig. 5 Power running test chart

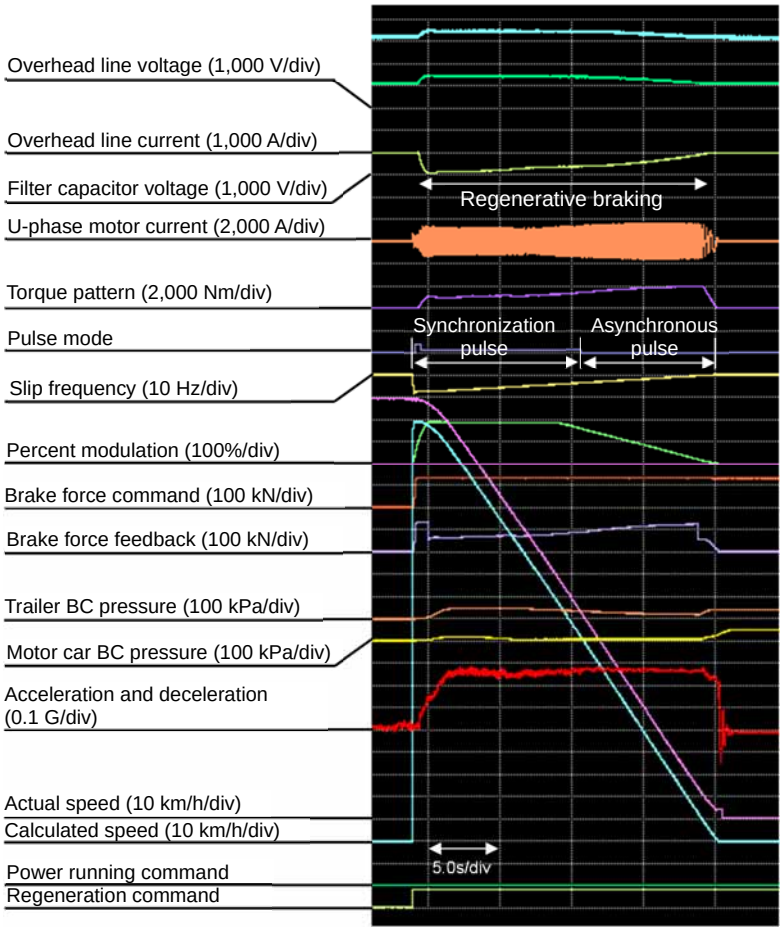


Fig. 6 Regeneration test chart

Table 4 Power analysis results of vehicles of the 5000 and remodeled 1000 series

5000 series

Train set with vehicle code 5051 (5M5T)

	Power running intensity (kWh/(km・vehicle))	Regenerative intensity (kWh/(km・vehicle))	Intensity (kwh/(km・vehicle))	Intensity (kwh/(km・ton))
Total of the train set	1.3330	0.5880	0.7450	**0.0241**

Remodeled 1000 series

Train set with vehicle code 1093 (5M5T)

	Power running intensity (kWh/(km・vehicle))	Regenerative intensity (kWh/(km・vehicle))	Intensity (kwh/(km・vehicle))	Intensity (kwh/(km・ton))
Total of the train set	1.5500	0.7340	0.8160	**0.0232**

power electronics sectors, which are likely to keep advancing, more energy saving systems will continue to get developed.

As the world's first manufacturer of SiC power modules for railway vehicles, Mitsubishi Electric will continue to develop and commercialize energy-saving equipment to help reduce environmental impact.

References

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