Special feature article

Future Power Electronics Applications for Railway Vehicle Traction

Keiichiro Kondo
Professor, Division of Artificial Systems Science, Chiba University Graduate School of Engineering

Profile

March 1991 Graduated from Faculty of Electrical Engineering, Department of Science and Technology, Waseda University
April 1991 Research and development in railway rolling stock traction circuit systems at Railway Technical Research Institute in 1991
January 2007 Associate Professor, Department of Engineering, Graduate School of Chiba University
April 2015 Professor, Chiba University Graduate School of Engineering (Division of Artificial Systems Science, Electrical and Electronics Course)

1 Introduction

Railways are able to couple many large cars and run them at speeds of hundreds of kilometers per hour due to being supported (support), guided (turning), and driven (running/stopping) by steel rail and wheel systems. Much energy is thus needed to move railway rolling stock. Railways initially utilized steam locomotives, but use of electric energy started in the early 20th century, and that soon came to be applied to railways as well. This probably came about because much electricity could be transmitted easily by overhead contact lines and pantograph systems, even with the technology of the time, as routes of travel could be secured with high accuracy as a result of the direction of travel being restricted by rails and wheels.

In other words, because railway rolling stock is a steel rail and wheel system, just the amount of electricity needed could be supplied when needed, large but light rolling stock achieved, and high-speed/high-volume transport with high energy efficiency achieved. On the other hand, the route traveled can be selected freely with automobiles, so they need to be autonomous in terms of energy. For that reason, a system where fossil fuel is stored onboard and the vehicle is driven by an internal combustion engine developed. However, automobiles too came to run on electricity again in the 21st century. I say "again" because there was technology at the dawn of the age of the automobile where batteries and motors could sufficiently compete against not-yet-mature internal combustion engine technology. Also, the history of the advancement of electric railways and the recent trend of electrification of automobiles demonstrate that electric drive systems are technically superior. In order for electric drive systems to be feasible, technology to convert electric energy to mechanical energy is naturally needed. With electric railways, the devices and functions to achieve that are collectively called traction circuit systems. In traction circuit systems up to now, direct current electric motor drive systems advancing to low-maintenance and highly efficient alternating current electric motor drive systems and improving their performance were focused on. As a result, traction circuit devices were able to achieve high efficiency, high performance, and high functionality. However, there is little room left recently for improving on traction circuit system technology alone. In technology for energy saving, for example, it is thought that the need is growing for considering technology for energy saving from a perspective of controlling a train's operating energy, such as utilizing regenerative energy or considering the operating method of the train itself. Also, with the advance in technology behind power storage accompanying electrification of automobiles, there have been movements to apply this to railway rolling stock driving as well. This suggests that the time has come to reconsider the how energy is supplied to rolling stock too, such as the aforementioned assumptions of electric driving. In other words, I feel that the time has come to think from a perspective of technologies enabling use of electric energy in electric railway systems in addition to improving performance of traction system technology itself. In this article, I will give an outlook on future traction circuit systems technology while giving an overview of the history of rolling stock traction circuit system technology advancement.

2 Changes in Traction Circuit Device Technology for Railway Rolling Stock

Variable speed control was achieved by DC traction motors controlling their voltage by means of connection of motors and voltage sharing resistance, which are technologies that were available in the 19th century. For that reason, DC motors have been used as motors for driving rolling stock from the early days of electric trains. However, the need for commutator and brush maintenance and the risk of flashover have been raised as issues intrinsic of DC motors. And with rheostatic control, contactor maintenance is also needed. Use of induction motor driving was sought after as a means of overcoming those issues. As shown in Fig. 1, 4.5 kV dielectric strength gate turn-off thyristors (GTOs) were developed in the late 1980s, and inverters for rolling stock in 1.5 kV electrified sections came into practical use. With that, use of inverter motor driving spread in earnest for rolling stock in Japan.

Inverter technology using GTOs also contributed to Shinkansen pulse-width modulation (PWM) rectification circuits coming into practical use. With this, regenerative braking came into practical use for the Shinkansen, and both lighter rolling stock and higher speeds—something impossible without trade-off with dynamic braking—were achieved. GTOs require di/dt control to prevent device overvoltage and current concentration when turned off. For that reason, anode reactors, snubber circuits, and the like are needed. Switching time of a GTO itself is long and switching loss large, so reduction of those was needed. As a solution to that problem, insulated-gate bipolar transistors (IGBTs) with short switching time gained higher dielectric strength in the late 1990s, and those came to be used in power conversion circuits for driving rolling stock. IGBTs themselves had reduced switching loss, and they achieved major size and weight reduction and better efficiency than GTOs due to their not requiring snubber circuits and gate circuits having low loss and being compact and light due to voltage driving. Recently, 3.3 kV dielectric strength metal-oxide-semiconductor field-effect transistors (MOSFETs) and Schottky diodes (SBDs) using silicon carbide (SiC) have also appeared. Application of such inverters for driving rolling stock has started, and greater size and weight reduction compared with conventional inverters using IGBTs has been achieved.

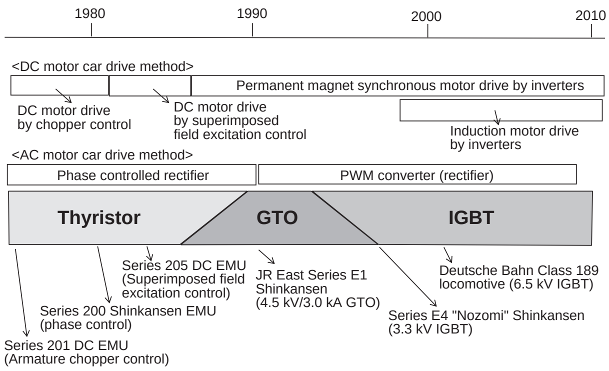

Fig. 1 Changes in Power Semiconductor Switching Device and Traction Circuit Technologies

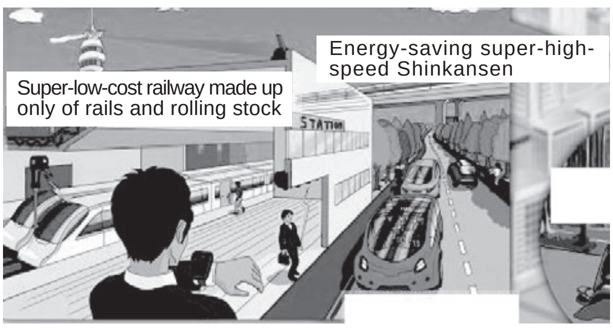

Fig. 2 Future Form of Railways in Institute of Electrical Engineers of Japan Roadmap for Industrial Applications "Future Society Supported by Industrial Application Technologies"[1)]

In this way, technical innovation has progressed in application of power electronics to driving railway rolling stock through performance enhancement and capacity increase of power semiconductor switching elements.

3 Circumstances Surrounding Traction Circuit Technology

Traction circuit systems are an underlying technology that rolling stock systems are composed of. And rolling stock is technology behind electric railway systems, a mode of transport. I would thus like to cover the ideal form of those railway systems and rolling stock systems along with traction circuit technologies from a perspective of the roles demanded of traction circuit systems. The roadmap for industrial applications by the Institute of Electrical Engineers of Japan indicates that energy-saving high-speed railways and maintenance-free railways made up only of rails and rolling stock will appear in the future, as is shown in Fig. 2.[1)] This symbolizes improving the advantage in energy saving and making wayside equipment related to power supply and train protection simple. Those will probably not be achieved until far in the future, but with the method shown in detail below, this could actually be an achievable dream.

Looking at electric railway systems from the perspective of electric power use, the ideal form of an electric railway[2)] is assumed to be one that is energy-saving and where peak power is leveled and maintenance reduction can be expected. Electric railways are energy-saving to start with, but they drive inertial load, so the electric power system must supply peak power at acceleration many times greater than average power. Even within an electric railway system (feed system), transmission of much electric power (current) causes voltage drop due to factors such as feed system resistance, leading to decreased acceleration performance

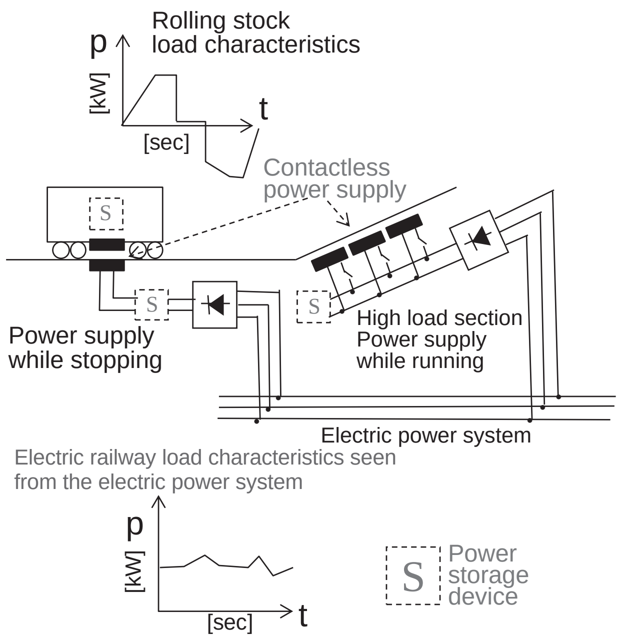

Fig. 3 Load of Future Electric Railways[2)]

of the train. Also, electric power greater than that at powered running is sent to the overhead contact lines when regenerating. If the electric power is for an AC electric railway, it is returned to the electric power system, causing high peak power similar to that at powered running. With DC electric railways, substation rectifiers are ordinarily diode rectifiers, so regenerative power is not returned to the electric power system. For that reason, the problem comes up of regenerative energy not necessarily being used effectively if a train in powered running is not in the vicinity of the train regenerating. Possible methods to counter those issues include appropriately placing high-performance secondary batteries and electric double-layer capacitors (EDLCs) at the wayside and onboard trains. Remarkable technical advances have been seen with those power elements for electric and hybrid electric vehicles. By doing so, we can expect cuts in peak power as seen from the electric power system, effective use of regenerative energy, and stabilization of feed system. Moreover, emergency operation to move a train to the nearest station even if the electric power system or feed system fails becomes possible, and improved safety and reliability of electric railways can be expected. And if the power storage device is equipped onboard, constant power supply from overhead contact lines as is required now will be unnecessary. By applying contactless current collection technologies that have been studied for automobiles in recent years, intermittent power supply systems requiring little maintenance can be achieved. And by appropriately controlling those power storage devices and power supply devices by having them communicate with each other, the effects of setting up the equipment may be maximized. Such an ultimate form of electric railway will be able to save energy and cut peak power while simplifying wayside equipment as much as possible. A traction circuit systems will need to have functions to appropriately distribute energy by converting energy supplied from the wayside to both energy stored onboard and motive energy instead of just motive energy at that time. Also, maximum utilization of regenerative energy is required. In other words, a traction circuit system is expected to have energy management functions, not just energy conversion functions.

4 Future Traction Circuit Technologies

Rolling stock systems that include the aforementioned traction circuit technologies as a subsystem and electric railway systems that include those rolling stock systems as a subsystem need to be energy-saving, cut peak power, and be maintenance-free, as noted above, while maintaining current levels of safety and convenience. The following are traction circuit system technologies that may contribute to achieving that goal.

As mentioned in Chapter 2, technologies that came about with changes in traction circuit technologies are inverters that bring about large reduction in resistance loss by MOSFET and SBD using SiC (SiC-MOSFET and SiC-SBD), and those have started to be used on JR East series 235 EMUs[3]. This technology works to make traction circuit systems themselves more efficient and promotes making power conversion circuits smaller and lighter. Making power conversion circuits more efficient smaller and lighter is an important element when considering that more power converters will be needed to enable onboard power storage control. However, there are still issues that have to be overcome in terms of both cost and technology, such as SiC devices still having poor yield and MOSFET having high sensitivity to conduction loss of gate voltage. As for SiC devices, making use of the benefit of their being easy to given high dielectric strength, application to technologies for directly receiving extra-high voltage without going through a transformer in AC motor cars[4] and the like too is effective. Shinkansen traction circuit systems can be expected to be made smaller and lighter if those can be achieved. This also will contribute to vibration and noise reduction as well as energy saving in high-speed vehicles.

Working to be energy-saving by increasing regenerative energy is effective in order for an electric railway like mentioned in Chapter 3 to achieve ideal load. In technology to do so, proving tests and the like have been reported for methods of using GPS to detect train location and speed so as to stop trains from high speed using just regenerative brakes as much as possible and to support energy-saving operation has been reported.[5] With this technique, a function to propose energy-saving driving operations to crews is achieved as an external function for train protection. The ability to achieve the function at relatively low cost because driver operations are not directly interfered with is revolutionary. Moreover, attempts to set brake notching where only regenerative brakes are acted on and make maximum use of motive energy[6] have been reported as a method where energy saving can be expected in a simple manner.

Improving regenerative brake output contributes to energy saving, but peak power becomes larger. Power storage elements, however, overcome these contradictory phenomena. Even in the area of railway rolling stock driving, full-scale application of high-performance secondary batteries has started and entered the practical use phase. Specifically, JR East's EV-E301 EMUs are equipped with lithium-ion batteries, and those are charged in electrified sections and used for autonomous running in non-electrified sections.[7] If such rolling stock is used in electrified sections, the load of the rolling stock can be leveled. As previously noted, such a system requires the traction circuit to be smaller and lighter and have high performance. In addition, control technology for trading off the contradictory phenomena of appropriate energy management of power storage devices and the effect of cutting peak power of overhead contract line power becomes important. Research is being conducted in the technologies behind this, specifically, control technology to keep power storage device energy within a specified range while cutting the peak use of overhead contact line power as much as possible in catenary and battery-powered hybrid railcars that use EDLCs and other power storage devices and overhead contact lines as shown in Fig. 5.

In this way, we can say that R&D in elemental technologies of traction circuit systems brings the ideal electric railway system to reality step-by-step.

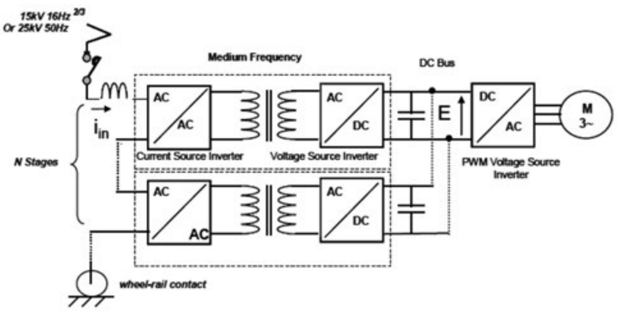

Fig. 4 Example of Traction Circuit System for AC Motor Cars that Receive Power from Overhead Lines Without Going Through Transformers[4)]

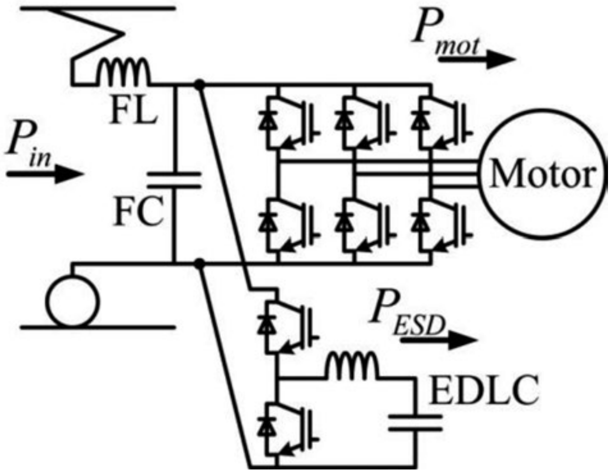

Fig. 5 Example of Traction System for Catenary and Battery-powered Hybrid Railcars[8)]

5 Conclusion

On a personal note, about 25 years ago when working at the Electric Car Laboratory of the Railway Technical Research Institute, induction motor driving came into practical use, as did regenerative braking for the Shinkansen. Traction circuit technology at last was induction motor driving, and I remember we were afraid that there would be nothing left for us to do in this area. However, examining future traction circuit technology now, I feel that technical progress never ends and that advancing technology is an endeavor that continues to build human wisdom. As noted in Chapter 2, power electronics technology has brought about innovation in traction circuit technology. Up to now, we had focused on increasing the performance of traction circuit devices themselves. Of course, technical advancement of traction circuit devices, such as making them smaller and lighter, more reliable, and low-maintenance, will continue to be imperative. But in addition to that, advancing system technology to contribute to energy saving, low maintenance, and increased reliability of electric railway systems with traction circuit devices as an underlying technology as covered in Chapter 3 also is important. The specific scheme for that is as laid out in Chapter 4. High dielectric strength GTOs have allowed induction motors to be applied as motors for driving electric railway rolling stock. Moreover, regenerative braking for the Shinkansen has been achieved and higher speeds reached. SiC and power storage devices as well as highly efficient motors such as permanent magnet synchronous motors not covered here due to space constrains contribute to increase performance of traction circuit systems and at the same time are starting to bring about improvements to the functionality of those. From the standpoint of bringing about innovation in railways, this is a technical field where further advancement is expected.

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