Carbon Neutrality Initiatives by Reduction of Operating Power of Railway Vehicles

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1. Introduction

Developed nations have committed to realizing carbon neutrality by 2050 in an effort to combat climate change as people become more vested interest in decarbonization throughout the world. Japan is already engaged in active efforts to reach the ambitious goal it set to reduce greenhouse gas emissions 46% by 2030 compared to 2013 levels.

Railways give hope to these initiatives as a highly efficient transport system with a low environmental impact. Development is already advancing technologies toward a greater modal shift from automotive and air travel to railway transport as well as greater railway energy-savings and decarbonization(1). Mitsubishi Electric has pioneered efforts to realize carbon neutrality through the sophisticated technologies it has amassed in its transportation systems business with the hope to bring about a sustainable society offering safety, comfort, and prosperity.

Trains make up roughly 70% of the CO_2 emissions produced by railway operators. The reduction of these emissions is essential to realize carbon neutrality in the railway industry. As a few measures to save energy during the operation of train systems, Mitsubishi Electric introduced silicon carbide (SiC) applied drive control equipment and highly efficient totally enclosed electric motors to the main circuit system. These innovations improve efficiency during operation and drastically increase regenerative electricity to save energy. We also developed a Station Energy Saving Inverter (S-EIV) to more effectively utilize the surplus regenerative energy produced by each train.

Both the expansion of these efforts as well as initiatives linking each subsystem configuring the railways system based on an in-depth analysis of mechanical and electrical systems is necessary to further reduce CO_2 emissions in the future. Mitsubishi Electric uses the data aggregated from the onboard electrical equipment to link data between the station and onboard systems in an effort to spearhead more effective energy savings.

This paper describes adjustments to substation transmission voltages to improve utilization of the regenerative energy as well as other initiatives to realize carbon neutrality in the railway industry. These initiatives employ technologies to save energy in onboard systems, to realize high efficiency through the adoption of innovative circuit systems as well as improve the efficiency of devices throughout the Train Control and Management System (TCMS) configuration, and those to save energy by linking stations and trains.

2. Energy-saving Technologies for Onboard Systems

Onboard systems include energy-saving technologies from the main circuit systems directly tied to the drive control of trains and Auxiliary Power Supply System to methods that reduce the equipment in operation under light-load conditions in order to drive trains in the high efficiency regions as well as analyses of vast run curve data from actual trains. These technologies give hope to realize approaches that create optimal energy-saving services according to each section of railway line.

2.1 Greater energy savings through technological innovations of main circuit systems

Mitsubishi Electric pioneered, commercialized and integrated a high-efficiency, totally enclosed Induction Motor and an Insulated Gate Bipolar Transistor (IGBT) hybrid SiC power module with an inverter system that adopts a Sic-Diode as the flywheel diode—a first in the world*1—into an energy-saving main circuit system for use on commercial lines in February 2012. This system contributes to greater energy savings throughout the entire circuit system by expanding the effective region of Power Regenerative Brake and reducing motor loss through high-frequency switching.

In addition, Mitsubishi Electric developed the first high-efficiency Synchronous Reluctance Motor (SynRM; Fig. 1) in the world*2 for railways and a Synchronous reluctance motor and inverter Traction drive System (SynTRACS). Railways use SynRM as drive motors due to the lower losses and higher efficiency characteristics than Induction Motors (IM). Permanent Magnet Synchronous Motors (PMSM) offer one option for a high-efficiency train motor, but the magnets embedded into the rotor of PMSM are powerful rare-earth magnets. However, rare earth elements will become harder to acquire in the future. Each motor requires an open magnetic contact in case of problems because the motors produce electromotive force when coasting, which makes the circuit configuration more complex and comes with other such challenges.

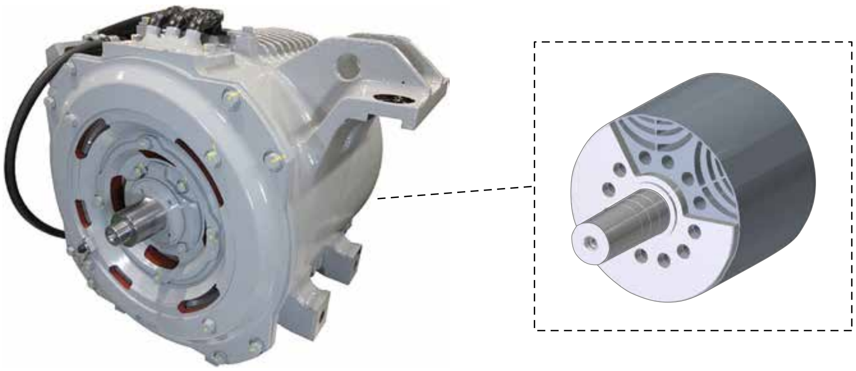


Fig. 1 Image of SynRM for rolling stock and the rotor inside the motor

SynTRACS consists of a SynRM and SiC inverter to realize the highest efficiency in the world without using rare-earth elements. The maximum motor output is 450 kW and reduces the losses generated in each motor by 50% compared to conventional high-efficiency IM. As described in Section 2.1.2, SynTRACS can even reduce power consumption by 18.1% throughout the entire propulsion control system compared to standard IM systems based on evaluations of the effective energy savings on commercial railways(2). As illustrated above, the SynTRACS system will contribute to even greater energy savings on railways in the future.

*1 Based on our research as of September 27, 2012.

*2 Based on our research as of November 10, 2022.

2.1.1 SynTRACS technical characteristics

PMSM have rare-earth magnets embedded in the rotor and produce electromotive force as described before. On the other hand, SynRM do not produce electromotive force while coasting and do not require the same measures be taken while coasting as IM systems because the rotor consists of an iron core just like IM. Most trains coast after accelerating to a certain speed after departing a station until braking to stop the train at the next station because rolling stock have a large amount of inertia and minimal running resistance. IM systems are seen as advantageous from the perspective of inducted voltage measures while coasting as well as mitigation of the losses produced due to changing magnetic flux in the motor under drive. However, IM systems require the flow of current in the rotor conductors, which produces cooper losses due to the winding resistance when current is flowing in the rotor. Therefore, in principle, synchronous motor systems is more advantageous from an efficiency standpoint. SynRM combines the benefits of IM with the high-efficiency characteristics of synchronous motors.

Generally, PMSM produce rotational force using the torque produced through the rare-earth magnets and reluctance torque produced by the rotor geometry. SynRM do come with many challenges in realizing larger capacity and high-torque variable speed control as a drive motor for railway applications because only reluctance torque produces the rotational force. Mitsubishi resolved these challenges in two ways: (1) optimization of the iron core geometry of the rotor and (2) utilization of the SiC inverter characteristics. Figure 2 presents the rotational principles of SynRM.

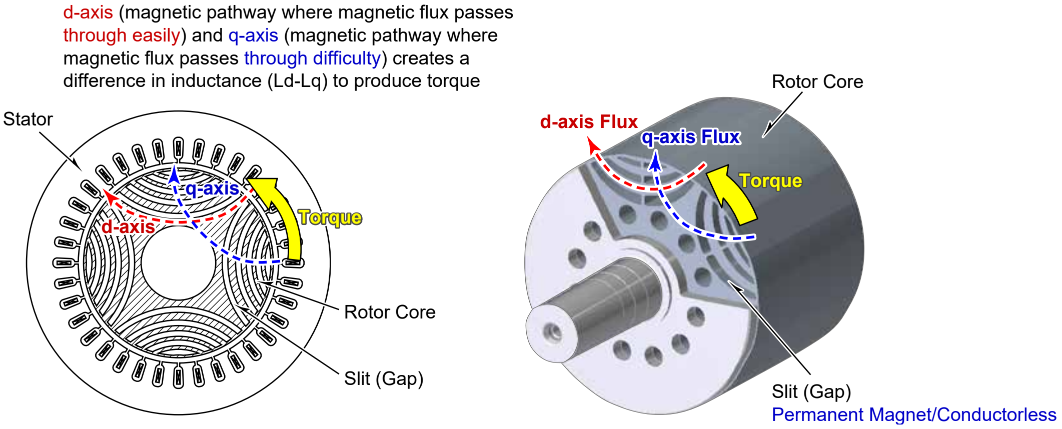


Fig. 2 Rotation principle of SynRM and image of rotor

2.1.2 Validation of the effectiveness in saving energy through SynTRACS

The SynTRACS was installed on a 13000 series train running on the Tokyo Metro Hibiya Line to conduct a running test and evaluate the energy savings during commercial operation in December 2021. Over a month and a half of commercial operations, Tokyo Metro measured the power consumption of its trains equipped with SynTRACS. The trains traveled a cumulative distance of 11,157 km with a power consumption intensity of 0.88 kWh/(train per kilometer). To verify the energy-saving benefits of SynTRACS, these results were compared to the power consumption intensity of typical IM systems. Table 1 shows this comparison after converting the different weights of the trains equipped with each system. The validation results comparing the SynTRACS system against the typical IM system indicate 18.1% better power consumption.

Table 1 Comparison of SynTRACS and conventional IM systems for consumption rate

	Train weight (t) (per train)	Intensity consumption (train per kilometer)		
		Motor	Regenerative	Actual consumption
SynTRACS 13000 series test-loaded trains (after train weight conversion)	33.31	1.58	0.81	0.77
Conventional IM System 9000 series large scale renewal construction trains	29.25	1.87	0.93	0.94

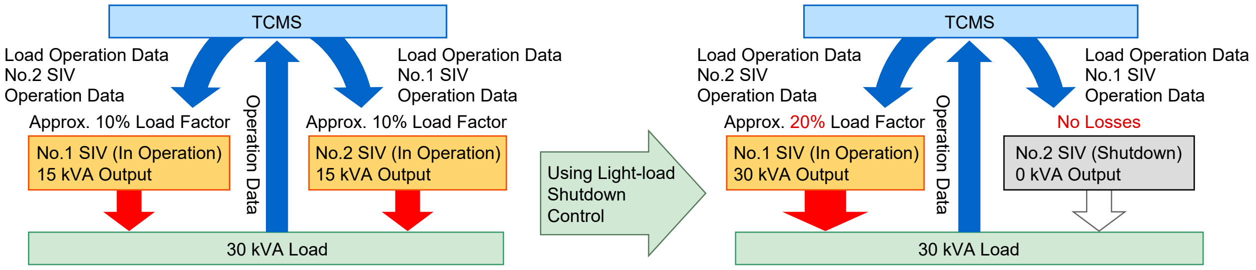
18.1% better

In addition, a simplified cooling structure that utilizes the high-efficiency characteristics of the SynRM not only reduced weight (-7.1%) but also increase capacity (+11%) compared to typical IM systems. Moreover, SynRM does not require the open contact necessary in PMSM systems in case of failures between the built-in inverter and motor in the event of any abnormalities, which simplifies the system.

2.2 Greater energy savings through formation control using TCMS

The load factor impacts the efficiency of the auxiliary power system (SIV system), decreasing equipment efficiency compared to the standard efficiency at a light load. To overcome this problem, each train formation that includes multiple SIV for parallel synchronous operations (control aligning the amplitude and phase of the three-phase output voltage) can take advantage of the ability to start and stop using an uninterruptible power supply. This system adjusts the SIV drive units in operation according to the load factor for the entire formation to realize a high-efficiency drive region during light loads.

More specifically, this control method reduces the number of SIV drive systems at a light load to increase the load factor of the SIV systems while the train is in service in order to enhance SIV system efficiency as a train formation (Fig. 3/Fig. 4). The SIV systems that have been shut down only take roughly one second to recover synchronous operations and adapt to rapid load fluctuations. The use of operational data from other SIV systems and loading equipment in TCMS (HVAC heating and cooling load/operational status of air compressors) enables the precision of in-operation/shutdown control.



Each SIV outputs 15 kVA when the formation load is 30 kVA.
The load factor is 10% with an efficiency of roughly 91%
when the SIV system capacity is 150 kVA.

The SIV load factor is 20% with roughly 95% efficiency, an
improvement of 4 points, because a single SIV supplies
power for a formation load of 30 kVA.

Fig. 3 Improved equipment efficiency through light-load deactivation control of SIV measures in the train

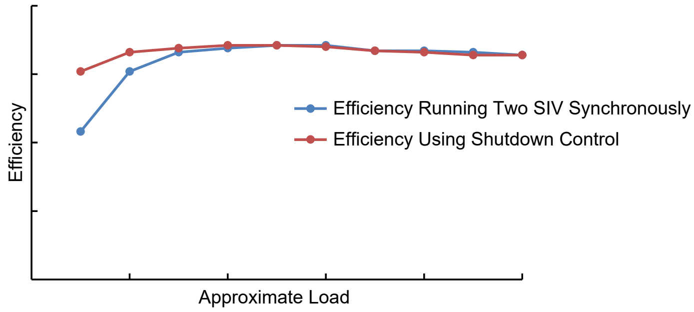


Fig. 4 Comparison of efficiency when two SIV units are operated in parallel and in idle control

2.3 Speed profile optimization for energy saving

The optimization of train speed profile to effectively use coasting and other drive conditions is known to greatly reduce power consumption, even with the same travel time between stations. Mitsubishi Electric has optimized ATO speed profile as well and demonstrated the tremendous energy-savings on real train lines(3). Train operators do require results tied to data to make decisions on whether to invest in revising train speed profile in order to save energy, but the collection and analysis of this data involves a significant undertaking. However, the aggregation and analysis of a huge volume of data has become much easier now that onboard data collection is possible using cloud computing. Mitsubishi Electric gained the following two insights as a result of visualizing and analyzing onboard data for numerous trains operating during actual train services.

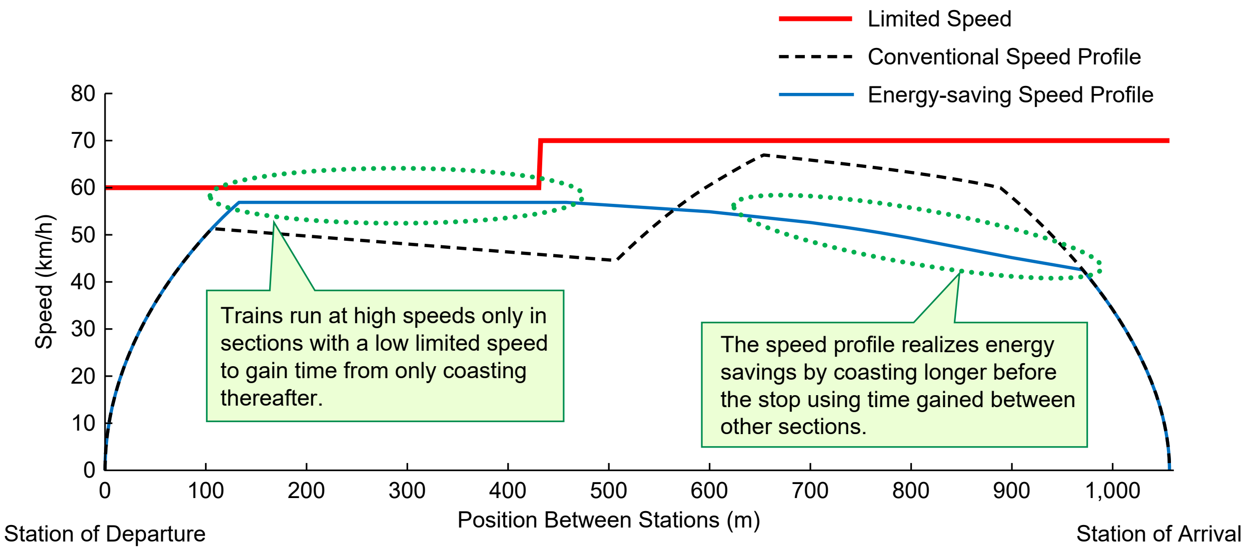
(1) Some cases selected the ATO recovery mode (mode to reduce the travel time as much as possible within speed limits) even without delayed services.

(2) There was some room to improve these train speed profile, especially as there were excessive acceleration between some stations.

To reduce the travel time by two seconds in the recovery mode outlined in (1), power consumption increases at least 10% between some stations. A revision of standard service and recovery speed profile should resolve this problem. As illustrated by Fig. 5, the speed profile optimizations intended to save energy during operation does demonstrate a 15% improvement to the power consumption between stations. The visualization of onboard data in this way can properly select effective measures using minimal effort.

3. Energy-saving Technologies Using Links Between Wayside and Onboard Equipment

Section 2 has described the energy-saving technologies of the onboard systems. A better usage rate of regenerative energy produced during braking in addition to the higher onboard equipment efficiency have been measures to reduce power consumption. It is essential to understand and adapt to the level of regenerative energy, which is influenced by factors that include the train load and voltage fluctuations in the overhead lines. Under minimal load, trains cannot always sufficiently use all of the regenerative energy produced during service operations either. That is why we are considering ways for station systems to effectively use surplus regenerative energy.



	Time to Reach Next Station (s)	Power Consumption (kWh)
Conventional Speed Profile	88.0	12.5
Energy-saving Speed Profile		10.6 (15% Reduction)

Fig. 5. Example of energy conservation promotion through optimization of speed profile

3.1 Higher usage rate of regenerative energy by modifying substation transmission voltage and narrowing regenerative train voltage

The effective use of regenerative energy requires awareness about the state of mechanical and electrical systems and substations. If multiple trains are running in the same feeder section, it is difficult to grasp the power exchange between trains using only measurements done at substations. The use of overhead line voltage and other measurable train data (onboard data) identifies the power conditions and enables optimization throughout all mechanical and electrical systems. This section describes the transmission voltage substations and effective use of regenerative energy based on onboard data analysis.

Figure 6 presents a schematic diagram of the power exchange between the overhead line voltage, motor trains and regenerative trains. When the transmission voltage from substations is high, the overhead line voltage raises above the constant voltage during regeneration. To avoid any excessive rise in voltage in the regenerative trains, the system narrows the regenerative current to reduce the regenerative energy. At the same time, the power supplied to the motor trains from the regenerative trains decreases, which proportionately increases the power supplied by the substation. In other words, the narrowing characteristics of the overhead line voltage and regenerative trains vary the regenerative energy. The analysis of the overhead line voltage, regenerative energy, and other data collected from the trains makes evaluations of measures to reduce the drive power and the effectiveness of those measures throughout all mechanical and electrical systems possible.

One measure to reduce drive power decreases the transmission voltage of the substation and increases the regenerative narrowing voltage to expand the range of the regenerative energy supply from the regenerative trains, which should improve the regenerative power usage rate. However, a drop in the transmission voltage from the substation decrease the overhead line voltage, which can lower train performance and increase motoring time. As an onboard function, such a measure limits the input current to mitigate the formation output if the overhead line voltage falls below a designated value during drive. When the overhead line voltage falls, the overhead line current increases to sustain the drive performance of the train, which could also increase power loss in the overhead lines. This measure must avoid any unnecessary drop in the overhead line voltage and adapt to the current conditions of the train by closely monitoring onboard data about the amount of transmission voltage drop of the substation.

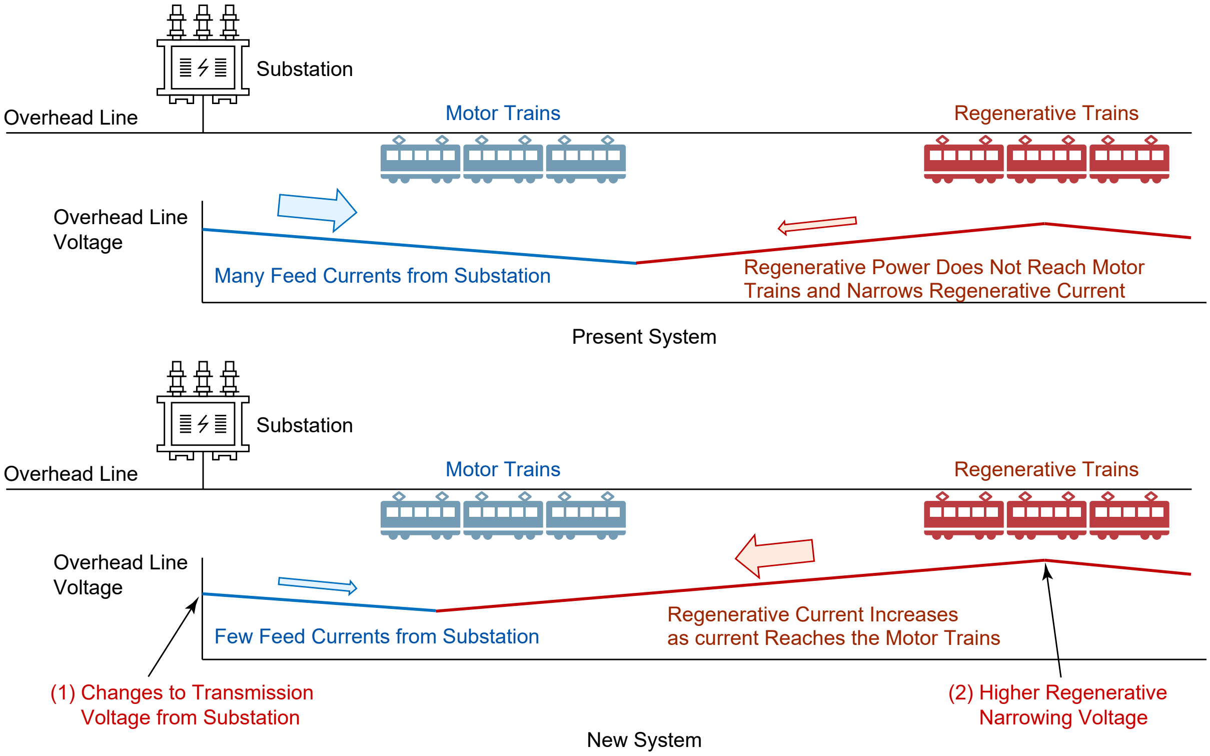


Fig. 6. Schematic diagram of overhead line voltage and power transfer between power and regenerative vehicles

3.2 Effective use of surplus regenerative energy using S-EIV

We are also working to use onboard data to assess S-EIV sites, which save energy through the use of surplus regenerative energy. This technology analyzes the drive power and pantograph voltage of the train from onboard data to visualize any surplus regenerative energy to evaluate sections between stations that have a large amount of regenerative narrowing power for selection as candidates for S-EIV stations.

An ideal system would collect and analyze onboard data from every train running on these section of track, but current evaluations only make considerations after analyzing data acquired from a certain percentage of every train because the data for every train cannot be. The results indicate that this measure can identify surplus power trends on each section between stations, even with only about 25% of the data. In the future, we hope to improve the accuracy of assessments by gradually increasing the number of trains included for data collection.

These reviews select potential installation sites, and then quantitatively identify the effective energy savings. The actual measurement equipment consists of a Direct Current Potential Transformer (DCPT) and effective nest measurement units that can be installed outdoors. The DCPT, S-EIV calculation and monitoring control units use the same equipment as the actual system to provide real measurements in a configuration equivalent to the actual S-EIV system. We estimate the annual amount of regenerative energy by taking actual measurements for at least nine days to calculate the average on weekdays and holidays as well as the monthly average, which is multiplied by a seasonal coefficient. The smooth adoption of S-EIV systems more quickly realizes carbon neutrality because actual measurements can evaluate the effective energy savings before implementing the actual system.

4. Conclusion

This paper has described various technologies to reduce the power used in train services that make up 70% of CO_2 emissions by railway operators as an initiative to realize carbon neutrality. As onboard systems for rolling stock, the SynTRACS development to realize the highest efficiency in the world in addition to SiC applied drive control has shown 18.1% lower power consumption than traditional IM systems in commercial operations. Moreover, auxiliary power systems can realize high-efficient train services by adjusting the number of SIV drive units in operation according to the load factor for all of the formations during parallel synchronous operations.

To optimize not only the onboard systems but also the wayside mechanical and electrical systems, this paper has looked at the use of onboard data to optimize the transmission voltage of substations and effective use of regenerative energy via an ideal placement of station energy-saving inverters.

In the future, comprehensive identification and analysis of current mechanical and electrical systems is essential to efforts that are working to establish links between systems in order to further reduce CO_2 emissions. Mitsubishi Electric will continue to contribute to the realization of carbon neutrality in the railway industry by expanding measures to further heighten effective energy savings using data collected from electronics onboard trains.

References

(1) Ministry of Land, Infrastructure, Transport and Tourism: Vision for Achieving Carbon Neutrality in the Railway Industry (2023; Only Japanese)
(2) Tomomatsu, A., et al.: Synchronous reluctance Motor System Development, 59th Japan Railway Cybernetics established and Symposium, 503 (2022; Only Japanese)
(3) Kaneko, S.: ATO Control Enhancements to Improve Energy Savings and Shutdown Accuracy, JREA, 59, No. 5 (2016; Only Japanese)