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Mitsubishi Electric

ADVANCE

The Latest Energy System Products for Overseas Markets

MITSUBISHI ELECTRIC
Changes for the Better

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The Latest Energy System Products for Overseas Markets

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CONTENTS

Technical Reports

Precis

Mitsubishi Electric Corporation uses its reliable technologies to support electric power systems as important infrastructure toward supporting our society and economic activities. This paper describes the following technologies, along with use examples in Japan and overseas: preventive maintenance technologies that contribute to improving the reliability of generators; cubicle-type gas-insulated switchgears for offshore wind turbines; and power system stabilization technologies and asset management systems for supplying generated electric power to required places in a stable way. This paper also describes the application of natural air-cooling-type traction transformers that are installed in trains in Japan and overseas and help save energy, simplify maintenance, and reduce noise.

Preventive Maintenance Technology for Enhancing Generator Reliability

Authors: *Kazuaki Ogura** and *Go Kajiwara**

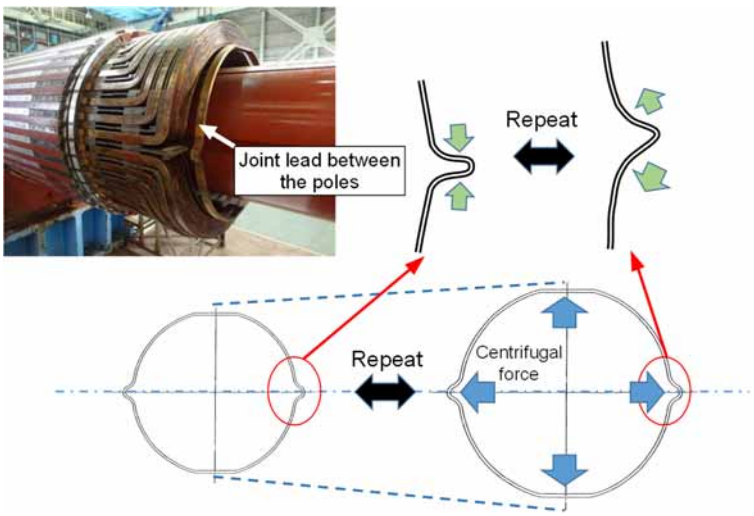
1. Introduction

In recent years, power generation systems using renewable energy have been steadily increasing. The role of thermal power plants is expected to change from conventional base-load operation to peak-load operation depending on the power demand. During peak-load operation, generators are operated only for the necessary hours in one day (daily start and stop (DSS)), increasing the number of starts and stops of turbine generators. This in turn increases the number of repeated stress due to centrifugal force acting on each section of the rotor parts in the generators, inevitably increasing the risk of low cycle fatigue failure. Accordingly, to ensure the high reliability of generators in long-term operation in the future, we have been developing technologies for accurately evaluating lifetime using the latest analysis techniques. This paper also introduces a new non-destructive testing (NDT) technology for rotor parts and proposal to add value to preventive maintenance work.[1]

2. DSS Operation of Generators and Low Cycle Fatigue Failure of Rotor Parts

In daily start and stop (DSS) operation, a turbine generator is operated only in a certain time of a day for adjustment of power supply, and the start and stop cycle is repeated approximately once a day. By continuing this operation, the number of starts and stops will reach 1,000 in several years. While generators are operating, centrifugal forces and thermal stresses due to the increase in temperature occur at each section of the rotors. Even if the stress amplitude of rotor parts is lower than the yield point of the materials, there is a possibility that the parts are damaged because of repeated stress. Generally, low cycle fatigue failure occurs at around 10^4 cycles. The threshold of failure is determined by the number of repetitions and the magnitude of stress amplitude, and if the stress amplitude is large, failure may occur after only several thousand cycles.

Figure 1 shows an example of repeated stress occurring at the rotor parts during stoppage and operation. Because the joint lead between the poles has a circular structure, circumferential tensile force occurs due to its own centrifugal force during operation. In addition, because the structure absorbs deformation at some sections, stress concentrates at the sections as shown in Fig. 2(a). The parts will not suddenly break when the generator is operated under these conditions. On the other hand, if the number of starts and stops increases under high stress amplitude, failure may occur in susceptible sections. As shown in Fig. 2(b), the section where stress concentrates in the simulation often matches the section that actually broke. Accordingly, when the number of starts and stops of a generator increases, it is important to calculate accurately the stress amplitude at



(a) During stoppage (b) During operation

Fig. 1 Repeated stress occurring at rotor parts due to start and stop

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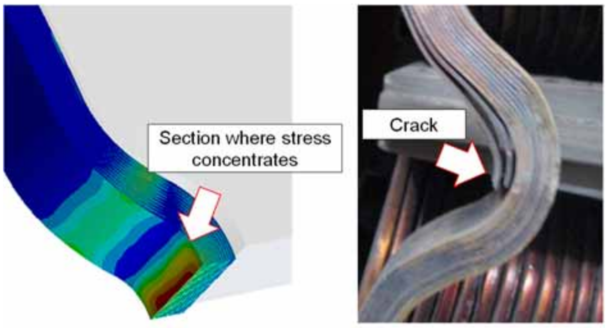


(a) Analysis result (b) Breakage

Fig. 2 Breakage of a rotor part due to low cycle fatigue

the sections where stress is concentrated to evaluate the strength against low cycle fatigue.

3. Large-Scale 3D Analysis Technique for Rotor Parts

3.1 Structure of the end of a generator rotor

Figure 3 illustrates the cross-section of a turbine generator rotor. A rotor mainly consists of rotor coils, rotor shaft (shaft/teeth), and wedges. The coils and wedges are stored in the slots in the axial direction of the shaft as its structure. During operation, the coils' centrifugal force is retained by the teeth via the wedges, causing tensile force to act on the teeth and wedges. When the generator stops, this tensile force is unloaded, and so stress amplitude occurs due to starts and stops. Figure 4 illustrates the structure of the end of a rotor. The retaining rings retain the centrifugal force of the rotor end coils. They are structurally engaged with the shaft and end plates strongly enough by shrinkage fitting such that they will not separate during operation. Therefore, while the generator is not operating, compressive force due to the shrinkage fitting acts on the sections where the retaining rings are coupled with the shaft and end plates. While the generator is operating, tensile force acts due to centrifugal force. In other words, due to start and stop, stress amplitude occurs at the rotor end teeth, end plates, and retaining rings.

In recent years, thanks to the improved performance of computers, the calculation time for models of complicated structures involving many elements has been remarkably reduced. Practical-level structural analysis of a 3D model of a whole rotor end structure including retaining rings, rotor coils, and other components is now possible. Thanks to this improvement, by re-evaluating verification tests performed in the past and evaluation by comparison with actual generator rotor appearance, it is possible to evaluate with higher accuracy the aforementioned local stress at each section of a complexly shaped rotor, which affects the low cycle fatigue lifetime, thus enabling higher-accuracy lifetime evaluation of each part.

3.2 3D analysis results and their appropriateness

Figure 5 shows the structural analysis model of a rotor end. Figure 6 shows the stress amplitude values (difference in stress between the generator under operation and standstill) at each section at the rotor end per start and stop of a generator. The stress concentrates on the sections marked by arrows and they match the sections with a high breakage risk due to low cycle fatigue caused by repeated starts and stops. The stress at the rotor end teeth, end plates, and retaining rings is distributed in the circumferential direction and the tendency in the axial direction is also different from the results of conventional 2D analysis. These results exceed the stress amplitude values assumed initially. This new knowledge obtained by the 3D analysis shows that the allowable number of starts and stops regarding low cycle fatigue fracture for actual equipment is less

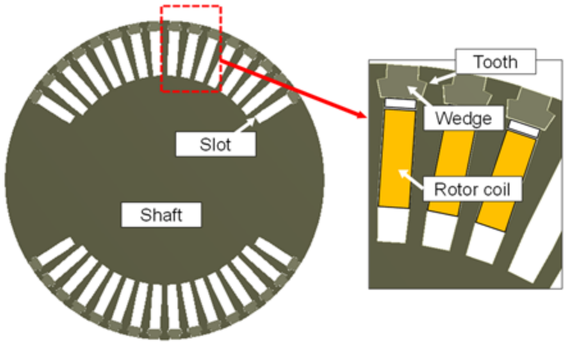


Fig. 3 Cross-section of a rotor

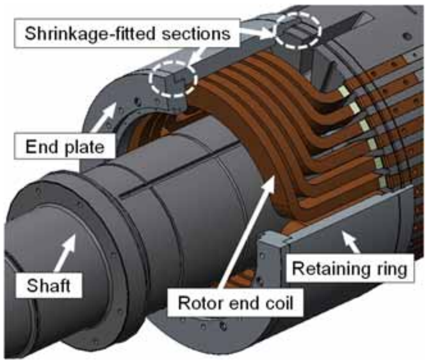


Fig. 4 Rotor end structure

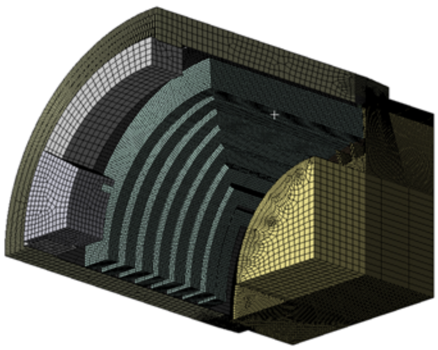


Fig. 5 Structural analysis model for a rotor end (1/4 of the circumference)

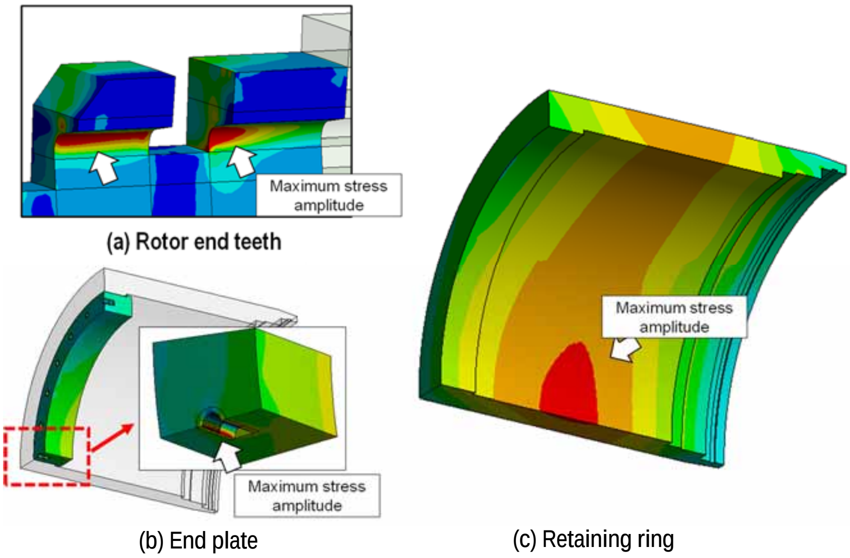


Fig. 6 Stress amplitude at the rotor end when a generator is operating and not operating

than the assumed number. In conventional analysis, the rotor end was assumed to be symmetric in the circumferential direction. However, these results have revealed that slight structural asymmetries in actual equipment cannot be ignored when evaluating low cycle fatigue lifetime.

Evaluation by comparison with existing data has confirmed that the estimation of the aforementioned 3D analysis is accurate enough for designing. In order to add value when proposing preventive maintenance work, an actual rotor was used to measure the stress at each section to re-check the accuracy of the stress calculation. Figure 7 shows the measured stress on the rotor wedge and retaining ring as examples. The values in Fig. 7 have been normalized by regarding the largest measured value for each rotor wedge and retaining ring as one. In both cases, the measured values closely match the calculated ones including differences in the circumferential and axial directions, confirming the validity of the current analysis technique including boundary conditions. Regarding fatigue characteristics of the materials, test samples imitating actual equipment were used to collect data separately, enabling highly accurate evaluation of fatigue lifetime.

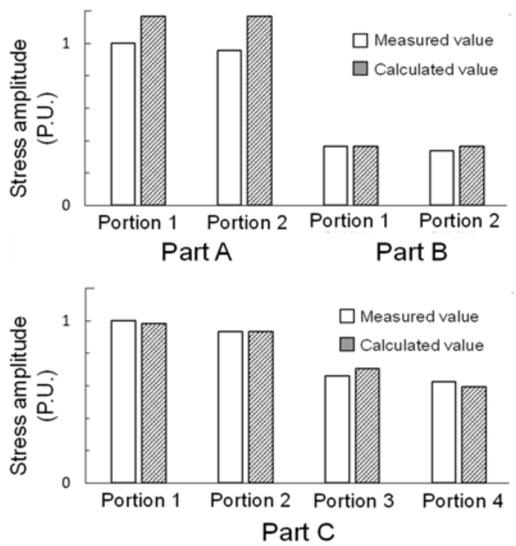


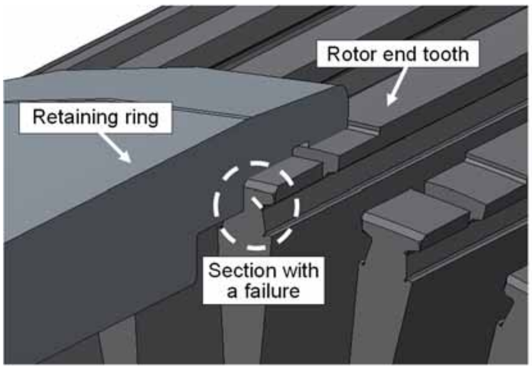
Fig. 7 Measurement results of stress on the rotor wedge and retaining ring

4. Preventive Maintenance Technologies to Create Benefits for Customers

4.1 Non-destructive testing (NDT) technology for rotor parts

The risk of breakage can be predicted by using the 3D analysis described in the previous chapter and then comparing the results with actual generator operation conditions. However, performing lifetime evaluation for all generators manufactured in the past is not practical in terms of cost. Under current conditions in which periodic inspection periods are becoming shorter and performed less frequently, it is necessary to develop inspection technologies to detect damage to rotors quickly and without fail when inspecting actual equipment.

Failures that are caused by low cycle fatigue as a result of starting and stopping generators may develop even under smaller loads compared to that before the failures are formed, resulting in breakage. Around rotor parts, centrifugal force acts during operation and very small repeated stress successively occurs due to shaft vibration. Therefore, it is not acceptable to continue operating such generators with a remaining failure for safety reasons. In such a case, it is important to detect an initial crack at an early stage. Conventionally, to detect an initial crack in rotor parts, liquid penetrant inspections are required; for example, if a failure develops at a rotor end tooth as shown in Fig. 8, it is



(a) Section with a failure on a rotor end tooth

(b) Penetrant test

Fig. 8 Penetrant inspection of a rotor end tooth

hidden in the retaining ring due to the structure and cannot be directly inspected. To inspect this section, the rotor needs to be pulled out from the generator and then disassembled into each part, which takes a long time and is unacceptable to customers.

Currently, we have been developing a technology to shorten the inspection procedure. Figure 9 outlines the new technology that ultrasound is used to detect a failure in a tooth inside a retaining ring from the surface of the ring. This technology enables inspections to be conducted without disassembling the rotor end parts. In other words, the technology can greatly shorten the conventional inspection processes. It also allows detailed inspections of rotor parts, which used to be impossible in conventional periodic inspection periods, to be included at predetermined periods without problems, thus increasing the opportunities for detailed inspections of rotor parts. We are planning to apply the same technology to inspect each rotor part in the future. We will continue our development efforts to ensure that breakage risks can be detected at an early stage and serious accidents can be prevented without decreasing the availability of thermal power plants.

4.2 Proposal to add value to preventive maintenance work

Accurate evaluation of the fatigue lifetime of each rotor part can enhance the reliability of long-term operation of generators by proposing appropriate timings for inspection and parts replacement. Also, optimizing the strength design standards at the part level can improve the efficiency of generators and reduce costs. As a concrete example, the results obtained this time were incorporated into the design of the cross section of a rotor to optimize its form, which improved the efficiency of the generators by 0.02%. Higher efficiency of generators reduces CO_2 emissions and environmental impact, and also increases the profitability of generation plants by reducing the cost per unit output.

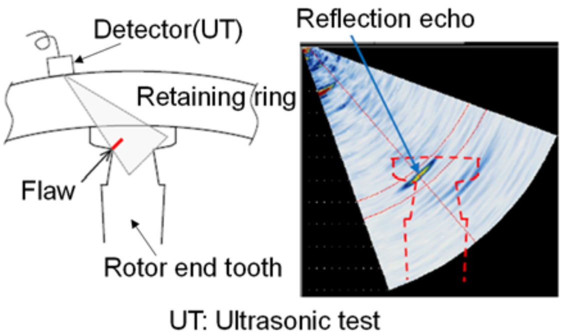


Fig. 9 Ultrasonic test of a rotor end tooth

5. Conclusion

The operation environment of thermal power plants has been changing. For turbine generators in particular, preventive maintenance technologies for rotor parts are becoming more important. Therefore, we have improved the technologies used to evaluate the lifetime of rotor parts by combining the latest analysis techniques with verification using actual equipment and the results of testing of materials. In addition, we have been developing a new inspection technology to detect breakage in rotor parts quickly and without fail in order to shorten periodic inspection periods and improve the availability of generators.

We will use these technologies to propose appropriate maintenance frequencies along with elemental technologies that add value to preventive maintenance work, thus contributing to the reliability of generators in long-term operation and improving profitability.

Reference

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Asset Management System for Electrical Distribution & Transmission Lines of Business

Authors: *Shunji Mori** and *Taichi Ide**

1. Introduction

Due to energy network price controls, electric power companies must provide appropriate explanations for asset investments as energy network costs. However, many assets that were introduced during the period of high economic growth and the bubble economy are aging, which will increase maintenance costs. In addition, experienced engineers are growing older and the labor force is shrinking. Suppressing maintenance costs while increasing the number of workers is mutually contradictory, and so investments for maintaining necessary assets in order to stabilize electric power systems must be properly explained. Therefore, instead of conventional time-based maintenance (TBM) in which aged assets are replaced and refurbished, risk-based maintenance (RBM) is needed. In RBM, the conditions and risks of assets are identified and investments in asset maintenance are planned and made accordingly. This paper describes Mitsubishi Electric Corporation's asset management system and its functions.

2. Work on Asset Management

As international asset management standards, the ISO55000 series were issued in 2014. In these series, all elements from an organization's plans and goals (vision) to its policies, strategies, and plans of actual worksites are regarded as a single flow (hereafter, "Line of Sight") and a framework in which all stakeholders from top management to operators at worksites needs to be established (Fig. 1).

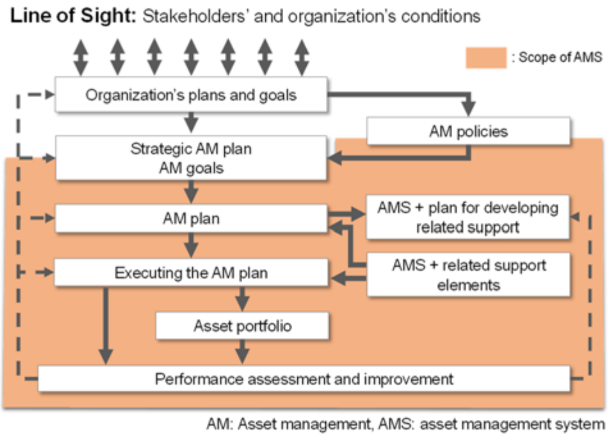

Fig. 1 Relationship among elements of the asset management system (1)

In addition, based on the concept of the ISO55000 series, IEC/TC123 (Management of network assets in power systems), which focuses on asset management of electrical distribution facilities, was established in October 2016 under the leadership of Japan. This group has been considering medium- and long-term strategies, life cycle costs, and standardization of risk analysis and other operations.

Furthermore, the Electric Technology Research Association in Japan started literature research in FY2018 on the theme of "A study on improving the maintenance of substation facilities and asset management."

In line with this trend, Mitsubishi Electric strives to assess and quantify risk based on asset conditions, and to apply developed plans to actual worksites.

3. Overview of Mitsubishi Electric's Asset Management System

As described above, in view of the need for asset management in Japan and overseas, Mitsubishi Electric offers an asset management system for the electrical distribution and transmission lines of business. Table 1 lists the requirements, Table 2 lists the functions to be provided, and Fig. 2 shows the functional composition that was determined based on recent trends and problems in the electrical distribution and transmission lines of business.

3.1 EAM

For customers who have various types of assets, Mitsubishi Electric has been offering products with functions that can be commonly used in maintenance operations and integrated asset database management platforms.

3.1.1 DiaPassage

Mitsubishi Electric has been providing customers in the societal infrastructure industry with DiaPassage,

Table 1 Asset management requirements

No	Asset management requirements
1	Risk assessment and quantification based on asset conditions
2	Formation of asset replacement and refurbishment plans based on the risk assessments and objective evaluations
3	Application of the plans to actual worksites considering Line of Sight

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Table 2 Functions of MELCO's asset management system

Function		Details
EAM	Asset maintenance and management	Centrally manages the asset lists and records of a company.
	Inspection plan management	Manages inspection plans.
	Support of construction and operations and management of actual results	Assigns workers and equipment according to the plans and manages operations.
APM	Asset condition check	Calculates and estimates the rank of asset deterioration based on inspection data and other data.
	Function for calculating consequence of failures	Calculates the influences of line failures based on line data.
	Risk assessment	Calculates risks using risk matrices using the asset conditions and consequence of failures as input data.
AIPM	Predictive analytics	Calculates the optimal intervention dates for each asset in consideration of economic efficiency and risks.
	Investment planning support	Supports the formation of medium- and long-term investments plans based on the inspection plans.
	Optimization	Evaluates the planned investments. Computes a plan that maximizes the value for the entire group of investments (hereafter, "portfolio").
	Value framework	Helps align your decision making to goals and priorities

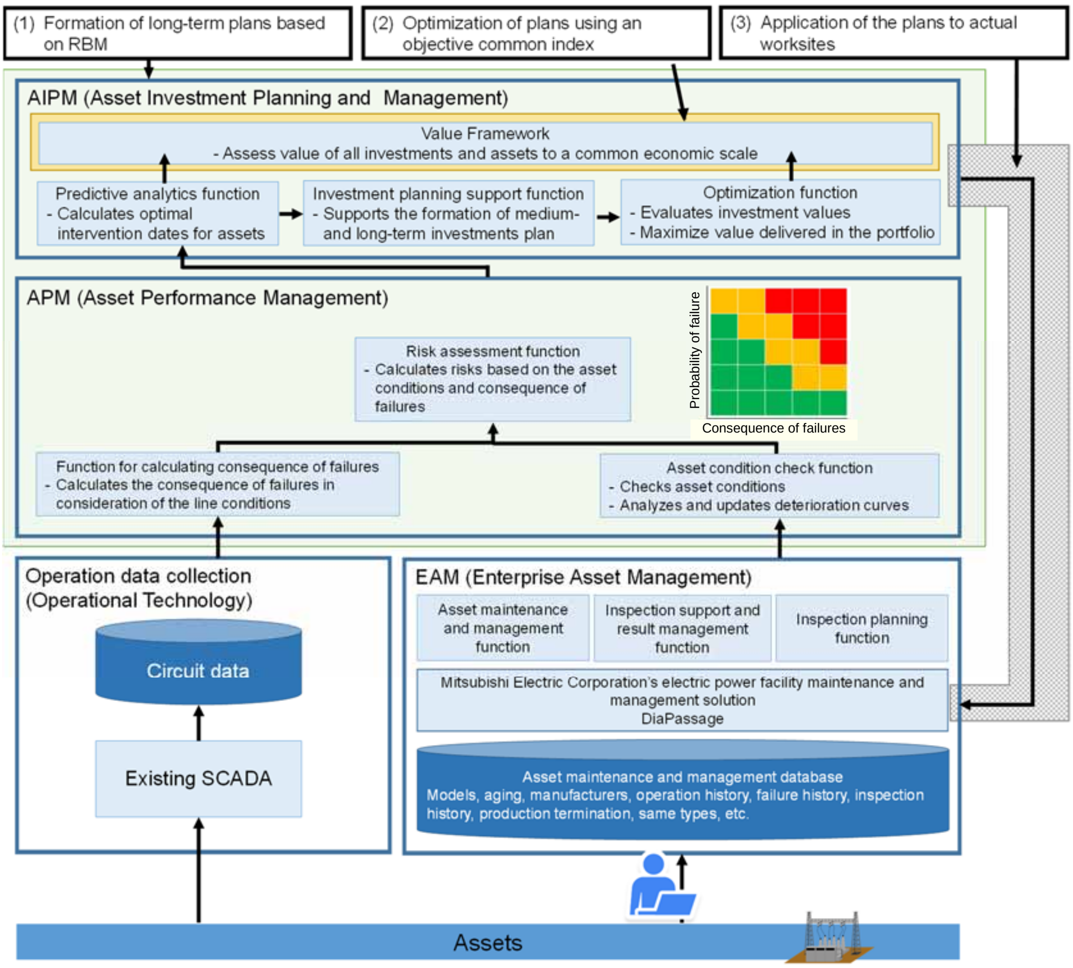

Fig. 2 Overview of MELCO's asset management system

which is an integrated asset database management platform. The asset maintenance and management functions of DiaPassage allow customers to centrally manage asset specifications, drawings, patrol and inspection records, accident history, and information on equipment of the same types as those that caused accidents, thus supporting asset maintenance operations at actual worksites. DiaPassage also manages operations based on maintenance plans.

3.2 APM (2)

Mitsubishi Electric's APM has asset condition check and risk assessment functions and a function for calculating the consequence of failures. APM calculates

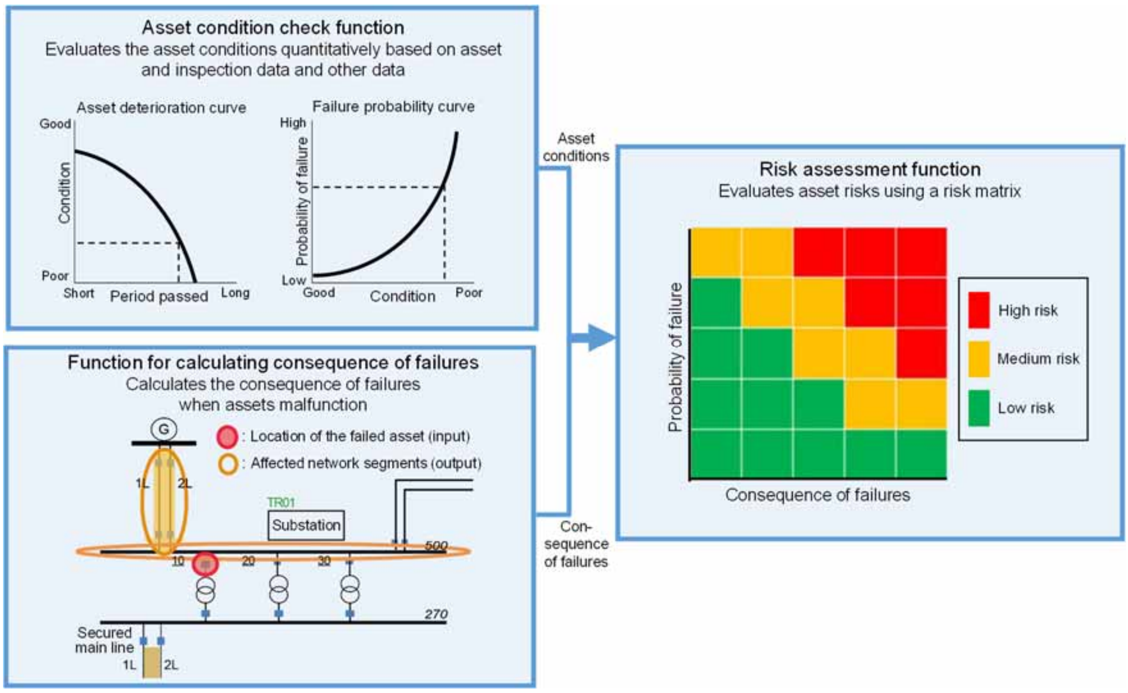

Fig. 3 Structure of MELCO's APM

risks based on the asset conditions and consequence of failures that were calculated by these functions (Fig. 3). In addition, Mitsubishi Electric has been incorporating international standards into APM in system development.

3.2.1 Asset condition check function

The asset condition check function evaluates asset conditions quantitatively based on the asset and inspection data and other data sent from the EAM function. "Asset condition" refers to the degree of deterioration of assets and the probability of failure. The degree of deterioration of an asset is calculated by applying methodologies used in Japan. Mitsubishi Electric has developed a technique to exclude variations caused by differences in individual skills when judging the rank of deterioration of assets based on inspection data, which is the original data for quantification. The relationship between inspection data and deterioration rank is statistically judged and the transition of deterioration ranks is estimated based on the inspection data.

3.2.2 Function for calculating consequence of failures

This function calculates the consequence of failures on assets. Various calculation methods have been proposed. Mitsubishi Electric supports the calculation of the consequence of failures proposed in such methods and has developed its proprietary function for calculating the consequence of failures on circuits. If assets on circuits stop working due to a malfunction or other reason, influences on the surrounding circuits and demand side are quantified in order to judge the consequence of the failure (Fig. 4). This function quantifies the influences of

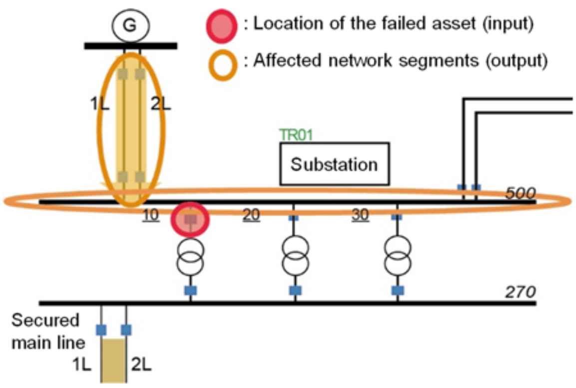

Fig. 4 Consequence of failure calculation

failures on circuits and determines the magnitude of the consequence of a failure for each asset.

3.2.3 Risk assessment function

The risk assessment function assesses risks for each asset based on the asset conditions and consequence of failures calculated by the other functions. A risk matrix is used for risk assessments and the products of the probability of failures and the consequence of failures are used to assess the magnitude of the risks. It can be assumed that assets with high risks need to be handled with priority, while assets with low risks can be handled later. This function is used for assessing risk based on the condition judgment for each asset and the consequence of failures. In addition, when risks are calculated based on various types of consequence of failures, they are converted into a common index (Fig. 5).

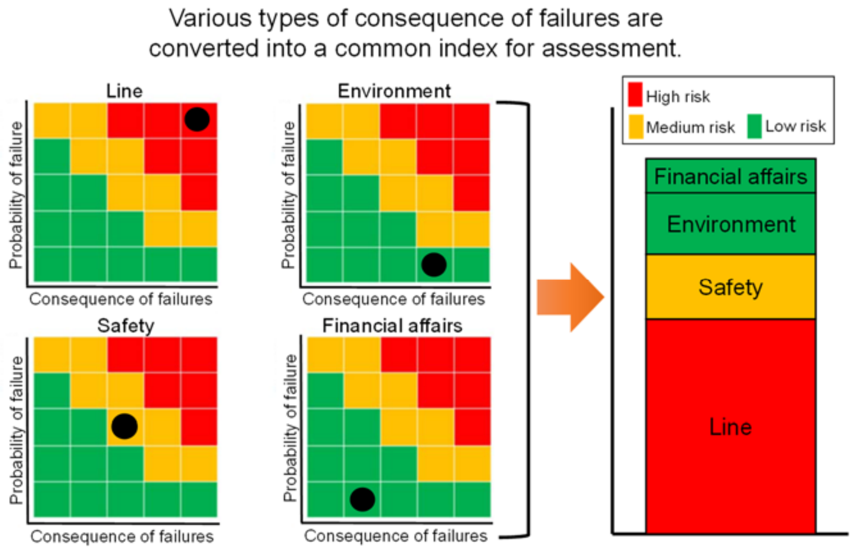

Fig. 5 Concept of risk evaluation

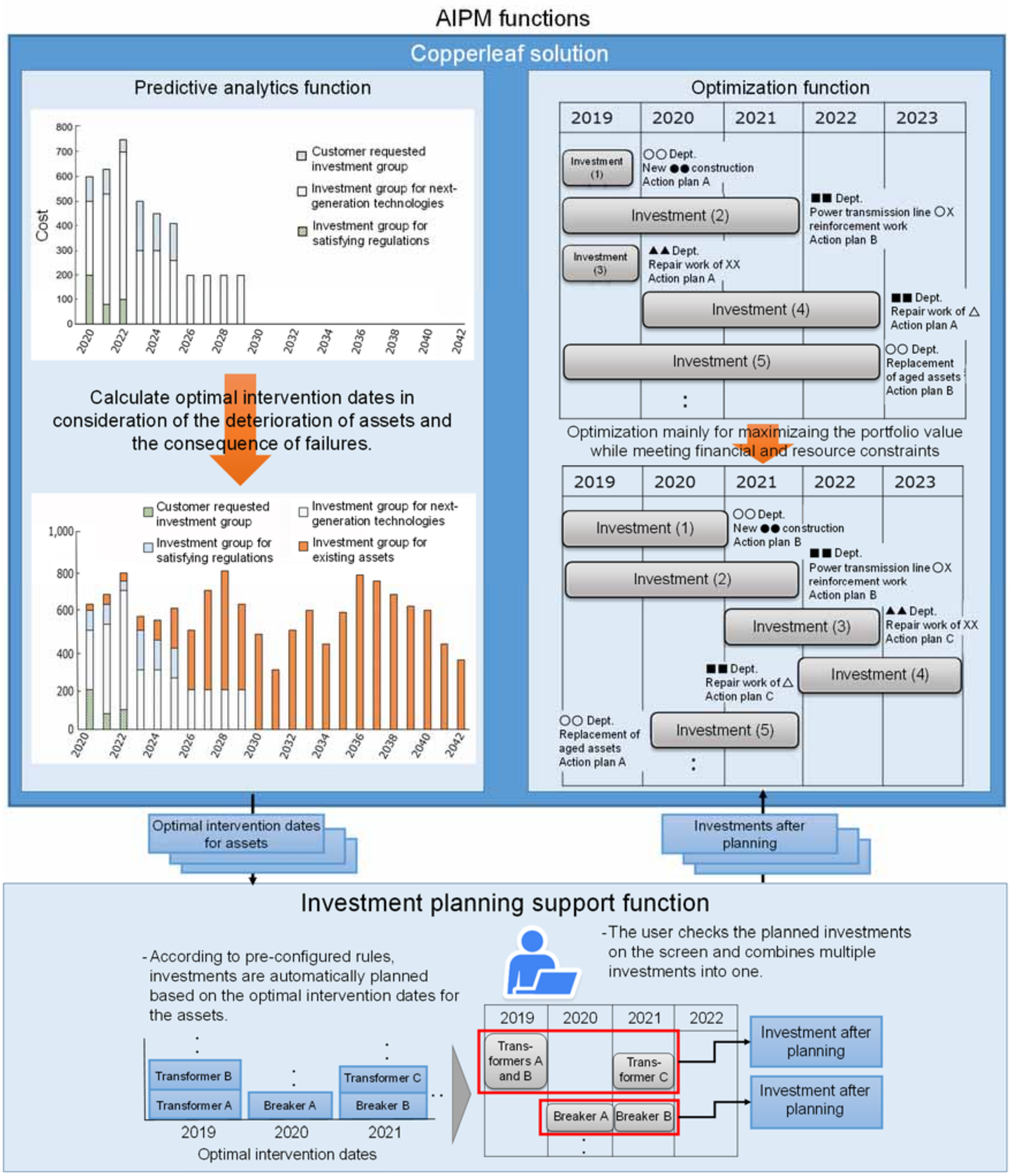

Fig. 6 Structure of MELCO's AIPM

3.3 AIPM

AIPM consists of predictive analytics, construction planning support, and optimization functions. AIPM plans investments based on the risks of assets and optimizes the investment groups in the portfolio to deliver the greatest value. Mitsubishi Electric has concluded a partnership contract with Copperleaf Technologies Inc., is the leader in the AIPM industry worldwide. The combination of the Copperleaf solution and products of Mitsubishi Electric has resulted in an AIPM tailored to the electrical distribution and transmission lines of business in Japan (Fig. 6).

The Copperleaf solution quantifies various types of value indexes (e.g., the value of avoiding power outage risks and the value of improving operation efficiency) with reference to a common value index (hereafter, "value"), which enables optimization to maximize value and achieve organizational goals. This not only manages risk, but also maximizes financial and non-financial benefits.

3.3.1 Predictive analytics function

The predictive analytics function calculates the optimal intervention date for each asset using the asset conditions and the consequence of the failures that were calculated in section 3.2 as input data. The value calculated by this function based on the risks calculated by the asset condition check function refers to a risk reduction amount. The calculation is repeated to year N in the future to obtain the optimal intervention date that maximizes the value. This function clarifies the asset conditions and risks over the long term (Fig. 7).

3.3.2 Investment planning support function

The investment planning support function assists users in drawing up efficient construction plans based on target asset information obtained by the predictive analytics. For example, in the electrical distribution and transmission lines of business, there is the concept of "bundled work." This means, when there is another asset that will be worked on in the near future near a target asset, working on the two assets at the same time. Construction plans that take into account bundled work can reduce the costs and number of power outages.

3.3.3 Optimization function

The portfolio optimization function computes an investment plan that maximizes the portfolio value. Two possible alternatives can be specified to address a problem with an existing asset (e.g., replacement, refurbishment, and removal) and introduction of a new asset. This function can optimize these two types to maximize the value. For example, regarding an investment for replacing an existing asset, the risk of a power supply problem is reduced by replacing the asset, whereas for an investment for introducing a new asset, the value of the safety and operation efficiency increases. The advantages of such different types of investments are evaluated as values.

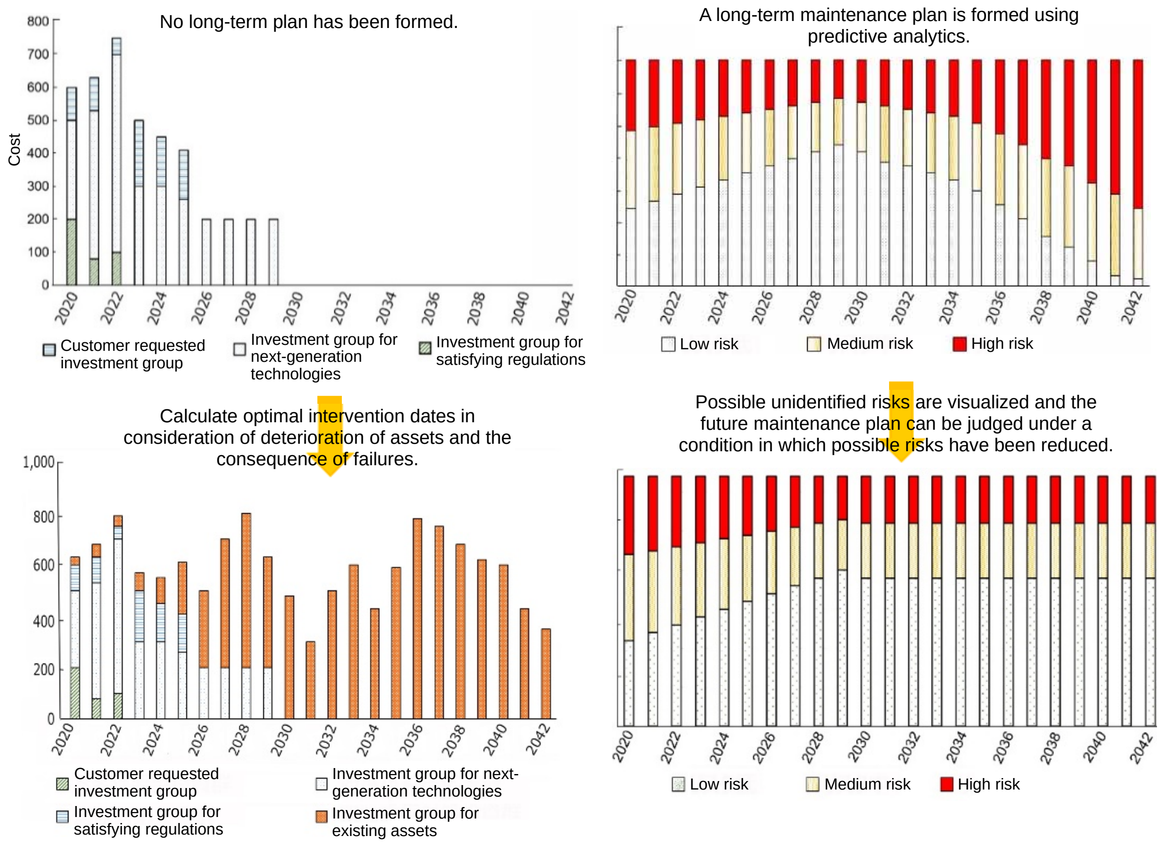

Fig. 7 "Predictive Analytics" using asset risk

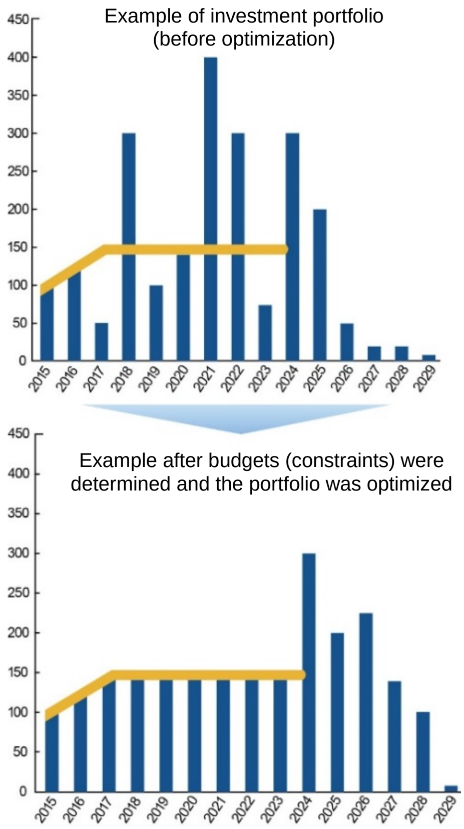

Fig. 8 Example of portfolio optimization

In addition, as shown in Fig. 8, when the investments are added, the investment costs and resources (operators) vary from year to year. Investments plans must meet financial and resource constraints, optimizing the portfolio will yield an investment plan with maximum value while satisfying all constraints.

4. Conclusion

This paper outlined Mitsubishi Electric's asset management system for the electrical distribution and transmission lines of business, and explained how the functions satisfy the asset management requirements.

Mitsubishi Electric will continue to focus on the trend of international standards and contribute to improving the levels and efficiency of asset management for the electrical distribution and transmission lines of business by refining and improving APM and AIPM using asset operation data.

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(2) IEC White Paper: Strategic asset management of power networks

Stabilizing the Power System in the US by Using FACTS Devices

Authors: *Fuminori Nakamura** and *Akihiro Matsuda**

1. Introduction

Since the mid 1990s, electric power companies in the US have been concerned about voltage stability and restrictions on reactive power as a result of the deregulation on electric power systems and the separation of electrical power production from power distribution and transmission.

Figure 1 shows the retirement of power supplies by energy type from 2008 to 2020 in the US. In recent years, to reduce carbon emissions, aged thermal coal generation plants have been retired successively and the use of renewable energy resources as an alternative energy has been increasing.(1) Due to these changes, inverter-connected renewable energy resources are being interconnected to systems that have already been weakened by the decrease of thermal power plants that use synchronous generators, thus worsening the voltage stability of the electric power systems.

Constructing new grid systems to stabilize the voltage of such electric power systems is very expensive. In addition, mechanically-switched capacitor banks are not effective for problems with dynamic system stability including system faults due to operation delays, discrete control levels, and restrictions on the service life based on the number of opening and closing times. Therefore, static var compensators (SVCs) and static synchronous compensators (STATCOMs), which are the main types of flexible AC transmission systems (FACTSs), have been widely applied to improve the voltage stability of electric power systems because they can control reactive power in both the steady and dynamic states at high speed. This paper introduces the characteristics of SVCs and STATCOMs along with case examples.

2. Characteristics of SVCs and STATCOMs

Adopting SVCs and STATCOMs (FACTS devices) increases the power transmission capacity of existing systems and contributes to stabilizing the system voltage. Therefore, for electric power companies, they are highly cost-effective solutions for a wide variety of requirements of electric power systems. Table 1 compares the characteristics of a general SVC and STATCOM.

SVCs have thyristors as switching elements. Thyristors are line-commutated and currents are commuted by the system voltage. An SVC mainly consists of a thyristor-controlled reactor (TCR), thyristor-switched capacitor (TSC), and harmonic filter. Because the currents output from TCRs contain harmonics, harmonic filters are required. The current that an SVC can output decreases in proportion to the decrease in the system voltage because the inductance and capacitance of the TCR, TSC, and harmonic filter are fixed values.

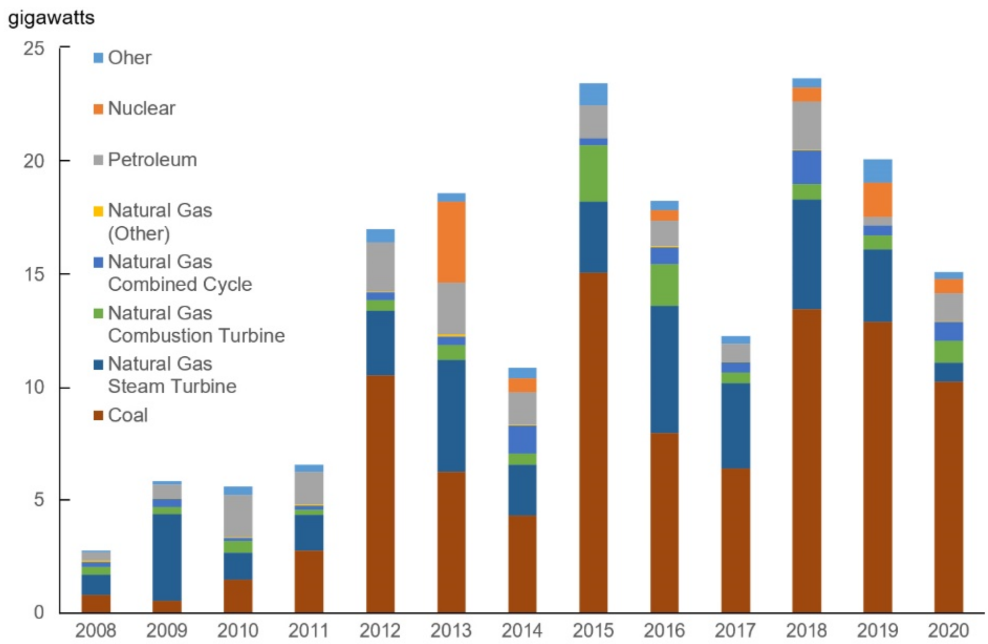
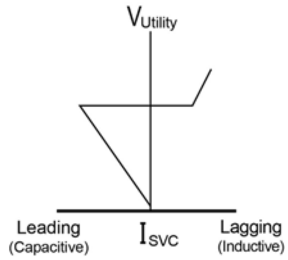
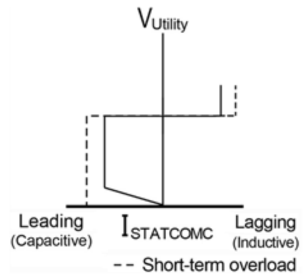
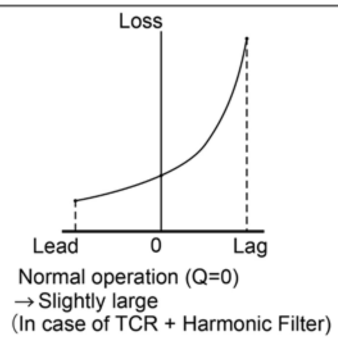
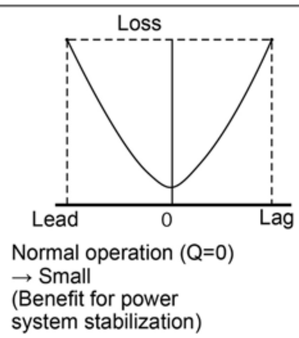


Fig. 1 Retirement of utility-scale electric generating capacity in the US(1)

*Transmission & Distribution Systems Center

Table 1 Characteristics of SVC and STATCOM

	SVC	STATCOM
Output current characteristics		
Harmonics	Large (As a result of TCR firing control)	Small (As a result of multiple converters)
Loss characteristics		
Footprint	Large (Harmonic filter is necessary)	Small

On the other hand, for STATCOMs, gate commutated turn-off (GCT) thyristors and insulated gate bipolar transistors (IGBTs) are used as switching elements. These self-commutated switching elements can be turned on and off independently from the power system voltage. The harmonics generated by STATCOMs are small in general and no harmonic filter is required; therefore, the footprints of STATCOMs are smaller than those of SVCs. In addition, currents that STATCOMs can output are steady regardless of a decrease in system voltage. Therefore, the STATCOMs' reactive power compensation characteristics when the voltage drops are superior to those of SVCs.

Mitsubishi Electric Corporation and Mitsubishi Electric Power Product Inc. (MEPPI) have installed many SVCs and STATCOMs in electric power systems in North America. The following section describes case examples.

3. Case examples of FACTS

3.1 SVC

In May 2016, Indianapolis Power & Light Company (IPL) started operation of our SVC (+300/−100 MVar) at the Southwest S/S.

The SVC was installed to solve fault induced delayed voltage recovery (FIDVR) due to faults on the 138-kV system. The US Environmental Protection Agency (EPA) ordered IPL to retire most of its thermal coal generation plants on the 138-kV system or replace them with natural gas power plants by 2016. As a result, many thermal coal generation plants were retired in 2016 and 2017 and the operation of new combined cycle natural gas power plants began in 2017. However, system analysis revealed that the voltage behavior after system faults would not be within design criteria and system loads would drop by FIDVR. Although application of a switched shunt capacitor (300 MVA) was first considered as a countermeasure, it could not be confirmed that it would meet the criteria for FIDVR. Therefore, application of quick-response FACTS was considered. It was confirmed that applying an SVC (+300/−100 MVar) or STATCOM (+250/−100 MVar, short-term overload: 125%) would meet the system contingency criteria as a countermeasure against FIDVR; an SVC was selected because there was plenty of space, there was a margin on the system side for harmonics, and an SVC cost less.

Figure 2 is a one-line diagram of the Southwest SVC delivered by Mitsubishi Electric. It consists of a TCR (0 to −200 MVA), TSC (+200 MVA), and harmonic filter (5th and 7th, 100 MVA).(2)

3.2 STATCOM

In June 2017, Dominion Energy (DE) started operation of our STATCOM (+/−125 MVar) at the Colington Substation (S/S).

This STATCOM was installed to solve FIDVR due to faults on the 115-kV system. The Colington S/S is located in an area consisting of a string of barrier islands of more than 200 miles (approximately 320 km) and it is on the end system side. The climate of the area is subtropical and the population increases approximately three- or five-fold in summer because it is a popular tourist destination. Therefore, FIDVR may occur due to the increase in air-conditioning loads in summer.

According to the guidelines of the Potomac-Jersey-Maryland (PJM) system, the electric power system must recover the system voltage to 70% within 2.5 seconds after a system fault of N-1-1 (when one line is out of service, another one transmission line fault occurs).

At the Colington S/S, as a countermeasure against FIDVR, an SVC (+167/−30 MVar) manufactured by another company had been used since 1997. Because it had been operating for approximately 20 years, replacement was planned in view of the following factors: operational reliability considering replacement parts, salt damage to the outdoor equipment, and restrictions on the stabilization performance. Because the power system was particularly weak, importance was placed on reducing the influence of harmonics on the system and so a STATCOM was selected. The rating was +/−125 MVar (short-term overload: 125%).

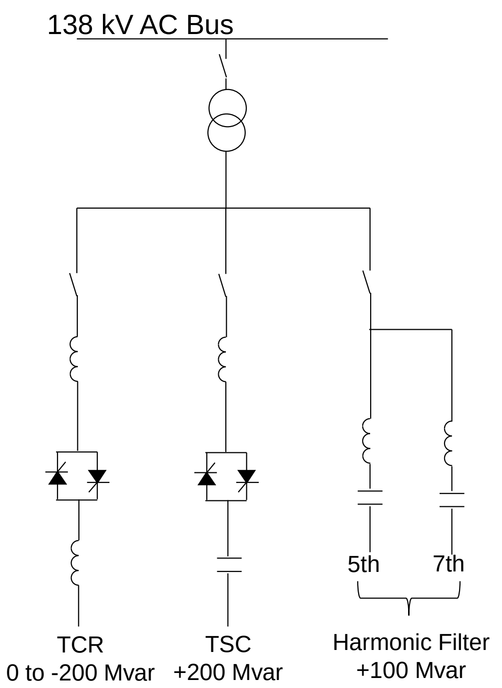


Fig. 2 Southwest SVC one-line diagram

The Colington STATCOM is a modular multilevel converter (MMC) type STATCOM, which is our first model. Figure 3 illustrates the configuration of the STATCOM. Figure 4 is a photograph of the outdoor equipment. Figure 5 shows a photograph of the valves. In the MMC type, small converters called sub-modules (SMs) are connected in series as shown in Fig. 3. As switching elements, IGBTs (manufactured by Mitsubishi Electric) are used. In addition, each SM has a bypass switch (manufactured by Mitsubishi Electric) that is closed when the SM fails and therefore each SM has redundancy.[3]

Before shipping the product, the control system of the STATCOM was connected to a real-time simulator to test its control performance as factory testing.

Figure 6 shows part of the waveforms obtained in

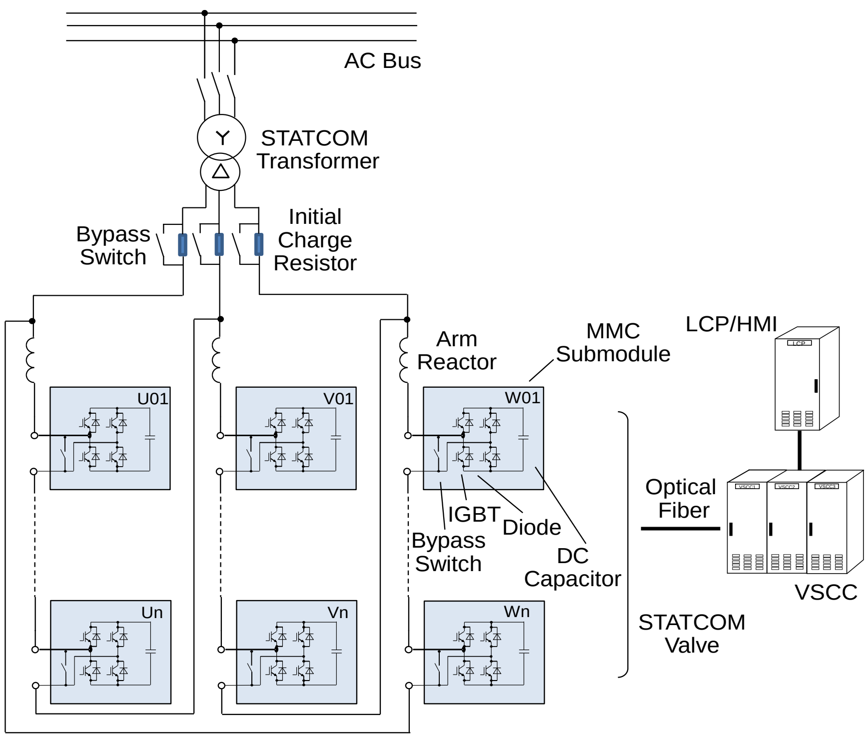


Fig. 3 Colington STATCOM system configuration

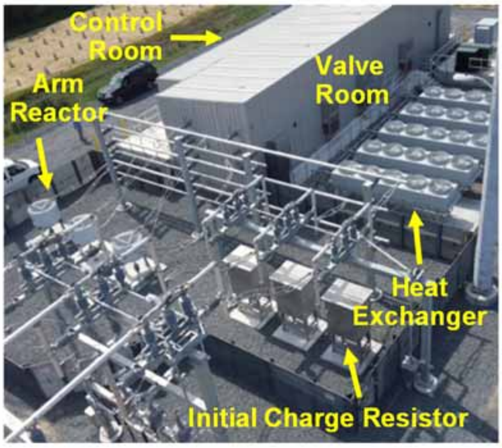


Fig. 4 STATCOM outdoor equipment

Fig. 5 STATCOM valve

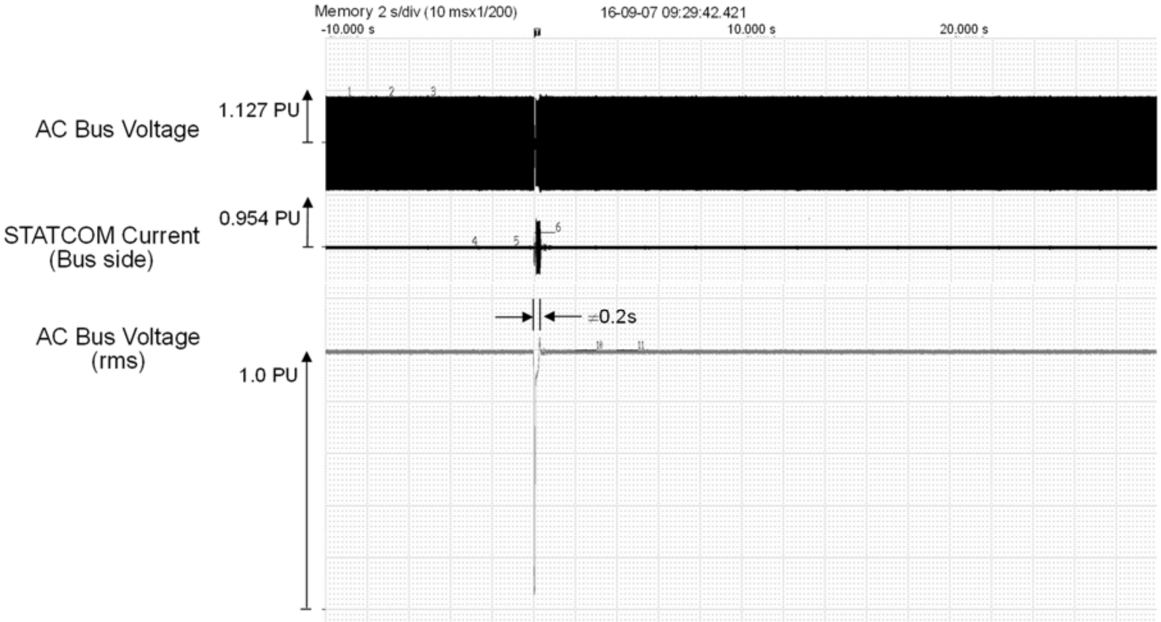


Fig. 6 An example waveform of the real-time simulator test

the test when a three-line ground fault was simulated. The test conditions were as follows: an induction motor with 0.6 pu (STATCOM's capacity) was connected as a load; and without the STATCOM, approximately 20-second FIDVR would occur under the test conditions. On the other hand, as shown in Fig. 6, with the STATCOM, the system voltage returns to 1.0 pu in approximately 0.2 second due to its reactive power control. This result shows that the STATCOM has the required performance.

4. Conclusion

FACTS devices such as SVCs and STATCOMs have been introduced to stabilize electric power systems. Mitsubishi Electric and MEPPI have installed many SVCs and STATCOMs in power systems in North America. This paper introduced some case examples. We will promote the FACTS business in the world including Japan, Europe, the Middle East, and Asia in the future as well.

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Natural Air Cooling for Traction Transformer

Authors: *Shiki Hayamizu*, Toshihiro Noda** and *Koki Shinjo**

1. Introduction [1] [2]

The main type of traction transformers installed on recent AC electric trains on narrow-gauge lines is the natural air cooling type, which uses natural wind during traveling and eliminates the need for blowers. Its characteristics are different from those of the conventional forced air cooling type and so its design requires careful consideration.

This paper describes natural air cooling type transformers that have been contributing to reducing energy requirements, maintenance, and noise, and their expansion and application in both Japan and overseas.

2. Natural Air Cooling Type

2.1 Cooling of traction transformers

Traction transformers are important equipment that supplies electricity drawn from the overhead lines to all devices on the train. They supply electric power to the main circuits that drive the train and to the auxiliary circuits to operate the air conditioning systems and other devices.

On general traction transformers, blowers are used to forcibly send wind to the coolers for cooling. Meanwhile, on natural air cooling type transformers, wind caused by the traveling train is drawn into the coolers and used to cool the traction transformers and thus no blowers are required.

Figure 1 illustrates a natural air cooling type transformer and Fig. 2 shows its appearance.

2.2 Characteristics of natural air cooling type transformers

Natural air cooling type transformers that do not require blowers have the following characteristics.

(1) Energy-saving (no electric power for operating blowers is required)
(2) Reduced maintenance (maintenance of blowers and cleaning of coolers are unnecessary)
(3) Low noise (no operation noise of blowers)

2.3 Notes on cooling designing

When designing the cooling of natural air cooling type transformers, the following points are considered.

2.3.1 Relationship between travel speed and cooling wind velocity

One characteristic of cooling of the natural air cooling type is that the velocity of wind caused by the traveling train depends on the travel speed and so the cooling capacity changes all the time.

The cooling is designed based on the relationship between travel speed and cooling wind velocity determined from past tests.

2.3.2 Calculation of cooling capacity and capacity of traction transformers

Considering that the cooling capacity varies as a function of travel speed, temperature simulations are performed on designated lines and for designated travel patterns to determine the rated capacity.

2.3.3 Arrangement of traction transformers

The cooler of a natural air cooling type transformer needs to be installed on the side of a train if possible as shown in Fig. 1, and appropriate spaces need to be secured between the cooler and devices installed in front and to the rear of the cooler such that wind caused by the traveling train is easily drawn into it.

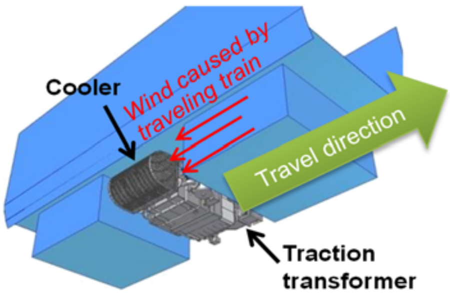


Fig. 1 Image of natural air cooling type transformer

Fig. 2 Natural air cooling type transformer for type E657 train (JR-East)

*Transmission & Distribution Systems Center

For trains for which the bottoms of the floors are completely covered, in order to draw in wind caused by the traveling train, the coolers need to be located outside of the side covers in the configuration. We have adopted an air intake structure. In this structure, inclined covers are used in front and to the rear of a cooler to draw more wind caused by the traveling train into the cooler. Figure 3 shows examples of the cooling air calculation.

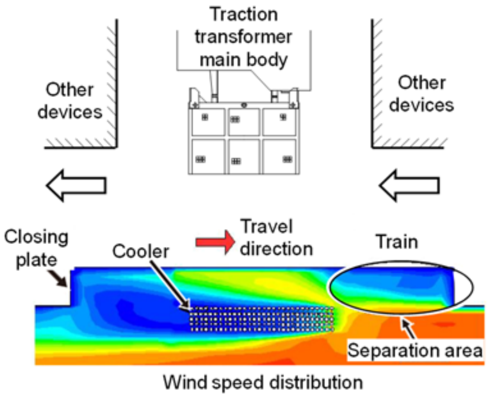
2.3.4 Protection of coolers

As described in section 2.3.3, natural air cooling type coolers need to be located close to the sides of the train to draw in wind caused by the traveling train, while taking into consideration stones and other flying objects.

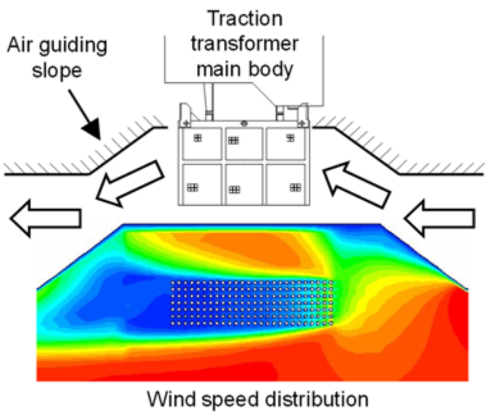
3. Use in Japan

Natural air cooling type transformers having the characteristics described in section 2.2 have been widely used for narrow-gauge line trains in Japan because their characteristics are highly evaluated. We delivered 814 natural air cooling type transformers from the first one in 1980 to February 2021 (Fig. 2 and Fig. 4).

During use for more than 40 years, there have been no malfunctions due to cooling by natural air cooling type transformers, and so our transformers are regarded as highly reliable. Regarding maintenance, too, it has been demonstrated that no cleaning is required.



(a) Existing structure



(b) Air intake structure

Fig. 3 Examples of calculation for cooling air

4. Expansion and Application to Asia

Regarding expansion of the market to Asia, we proposed the natural air cooling type to India where there is high demand for railway services. In India, air pollution is serious and awareness of energy-saving (e.g., reducing exhaust gas emissions) and the environment has been rising. In recent years, in particular, there is strong demand to reduce the energy consumed by the trains themselves in addition to reducing energy for train maintenance.

Furthermore, trains operate in an environment containing a lot of dust, feathers, and oily dirt and so cleaning and maintenance of general forced air cooling type transformers is costly. Although the natural air cooling type is an appropriate method for dealing with such problems, it has not been widely recognized in the Indian market. Accordingly, we explained to customers the technologies and track records of the natural air cooling type, the difference in energy consumption between the natural air cooling type and the existing type, and the noise reduction ratio. As a result, the natural air cooling type was introduced to Delhi metro trains in 2016 (Fig. 5).

After being used for one year, the transformers on actual trains were subjected to a temperature rise test and the conditions were checked. Figure 6 compares the results of oil temperature measurement on actual trains and simulation results. The oil temperatures are within the allowable range (less than 100C) and equal to the simulation results, thus verifying the design (Fig. 7).

Figure 8 shows the results of checking the condition of the natural air cooling type coolers. The same as in Japan, it was confirmed that no dust, feathers, or oily dirt had attached and the coolers were in good condition.

Fig. 4 Natural air cooling type transformer for type 683 train (JR-West)

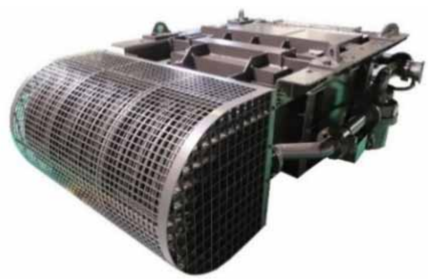


Fig. 5 Natural air cooling type transformer for the RS13 train (India Delhi metro)

These results demonstrate that even in a severe environment like in India, natural air cooling type coolers can be used without problems.

5. Expansion and Application to Europe

5.1 Rooftop natural air cooling type coolers

To expand the product to other overseas markets, we proposed the natural air cooling type in the European market. Although the service environment in Europe is similar to that in Japan, traction transformers are installed in different locations. In Japan, they are installed under the train floor in general, whereas in Europe traction transformers and other electrical components are installed on the train roof because station platforms are low and barrier-free low-floor trains are used. Consequently, natural air cooling type coolers are also installed on train roofs.

When these coolers are installed on the open train roof instead of in closed sections under the train floor, more wind caused by the traveling train can be drawn in. However, we had no experience of installing the natural air cooling type cooler on the roof and did not know the relationship between train speed and wind while traveling. Accordingly, we performed fluid analysis simulating train conditions to check the conditions of rooftop wind caused by the traveling train.

Figure 9 shows an example of the calculation. The results show that more wind can be drawn in while the train is traveling compared to underfloor installation, and that the flow pattern is also different. Therefore, we designed and developed light-weight rooftop natural air cooling type coolers suitable for installation on the train roof.

5.2 New business with SNCF

SNCF has been procuring new trains for its TGV high-speed trains and commuter trains. For environmental reasons and to use utilize resources effectively, it has been actively updating older trains; it replaces only the electrical components while reusing the bodies of such trains. Accordingly, for its T4 tram trains (Fig. 10), energy-saving, lower noise, and reduced life cycle costs were demanded.

The rooftop natural air cooling type transformers developed by Mitsubishi Electric Corporation matched the requirements of SNCF and were selected because our traction transformer technologies were highly

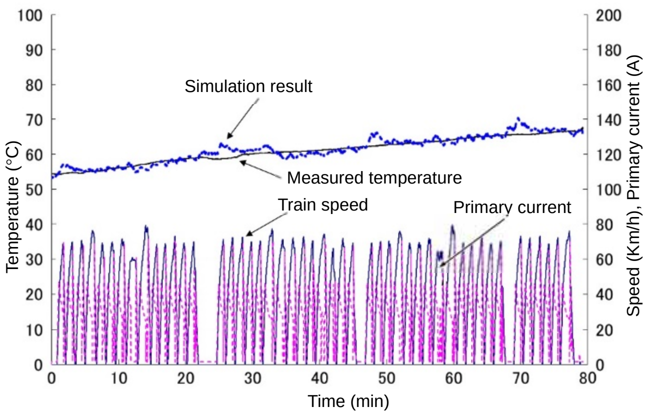


Fig. 6 Comparison of oil temperature between measurement and simulation

Fig. 8 Condition of cooler after one year of operation on the RS13 train (India Delhi metro)

Fig. 7 Measurement on main line

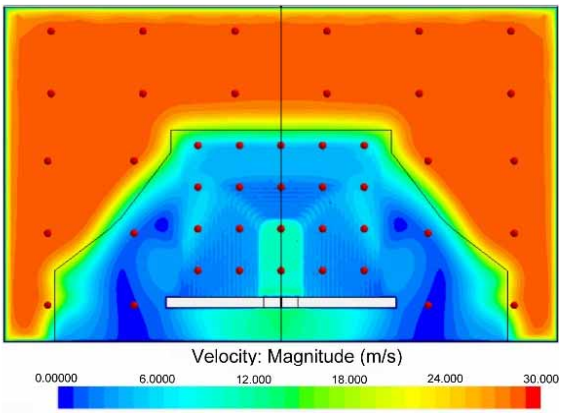


Fig. 9 Example of calculation for rooftop-type natural air cooler

Fig. 10 Type T4 tram train

Table 1 Comparison of existing transformer and natural air cooling transformer on the Type T4 tram train (Comparison of same capacity, impedance, and mass)

Item	Existing transformer	Our transformer
Size (Longitudinal direction)	2,493 mm	2,125 mm
Reliability	Malfunction once every five years	Almost no malfunction in 30 years
Noise level	80 dB(A)	67 dB(A)
Maintenance	• Parts maintenance • Replacement of blower motor bearing • Cleaning of coolers, etc.	• Bearing replacement not required • Cleaning of coolers not required
Loss (efficiency) @ rating	27.3 kW (96.2%)	14 kW (98.0%)
Mass	2150 kg	2150 kg

regarded; we became the first Japanese manufacturer to do business with SNCF. Table 1 compares the existing transformer and our natural air cooling type transformer for T4 tram trains.

In update work, the interfaces with trains needed to be completely matched while maintaining the superiority over the existing type. In addition, because the train conditions and the positional relationship of the rooftop natural air cooling type transformers with other devices could not be changed, we designed and manufactured them while carefully considering the wind conditions caused by the traveling train in the surroundings.

One year has passed since this prototype transformer entered operation and the trains are running in good condition without problems.

Currently, we are manufacturing traction transformers using technologies for rooftop wind caused by the traveling train for trains operating near Paris. We will continue working to expand the technologies in the future.

6. Conclusion

As environmental awareness grows, railway services are becoming more important as an eco-friendly means of transportation, and our natural air cooling type transformers have been highly valued by our customers.

We will continue working to expand the application of environment-friendly natural air cooling type transformers and contribute to society.

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