# Railway Static Power Conditioner for Shin-Kurobe Substation of Hokuriku Shinkansen

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**ABSTRACT**

Fuji Electric has delivered a railway static power conditioner (RPC) to Shin-Kurobe Substation, located between Nagano and Kanazawa on the Hokuriku Shinkansen Line. This equipment is composed of an inverter and an inverter transformer. While the trains run, it compensates for the unbalanced load in 3 phases and voltage fluctuation by interchanging power between two circuits in the direction of Nagano and Kanazawa. It also compensates for the harmonic current generated by trains. We developed a high-capacity downsized inverter by engaging a water-cooling system and equalizing the current sharing of insulated gate bipolar transistors (IGBTs). We adopted a gapless transformer for the inverter transformer to achieve low-noise level and high reliability.

## 1. Introduction

As part of the Projected Shinkansen Line Plan, the Hokuriku Shinkansen started service between Nagano and Kanazawa from March 14, 2015, following the section that had already opened between Takasaki and Nagano. The route map of the Hokuriku Shinkansen is shown in Fig. 1.

Six substations have been built between Nagano and Kanazawa: Shin-Nagano, Shin-Joetsu, Shin-Kurobe, Shin-Takaoka, Shin-Hakusan and Hakusan Depot. Among these, the Shin-Kurobe Substation has the smallest short-circuit withstand capability and the longest feeding section, so that it is subject to fluctuations in the receiving voltage. To suppress these fluctuations, Fuji Electric has delivered a railway static power conditioner (RPC).

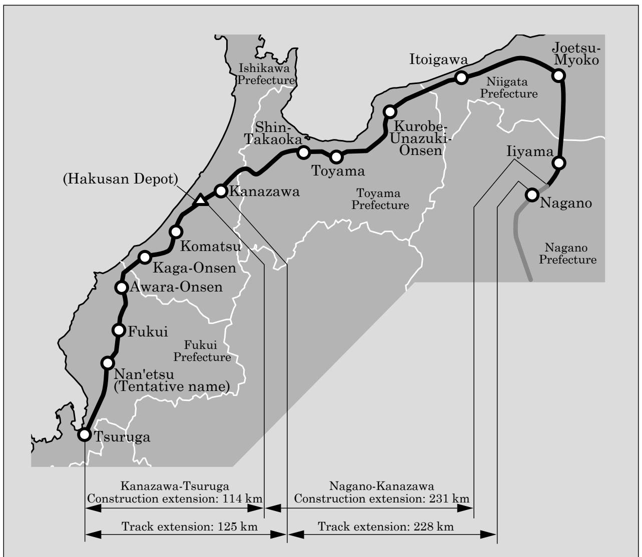


Fig.1 Route map of the Hokuriku Shinkansen

This RPC has adopted inverters and inverter transformers based on the latest power electronics technologies and the leading-edge control technologies have been applied. This paper describes an overview of the RPC and its control technologies.

## 2. Overview of Railway Static Power Conditioner (RPC)

### 2.1 Concept of power interchange

The concept of power interchange is shown in Fig. 2. The AC substation for the Shinkansen uses a Scott connection transformer and a roof-delta connection transformer to step down the voltage for 2 feeder lines of single-phase 60 kV AC and feeds the power to the main phase and teaser respectively. When the voltages on these 2 lines become unbalanced due to train run, the voltage on the 3-phase side also becomes un-

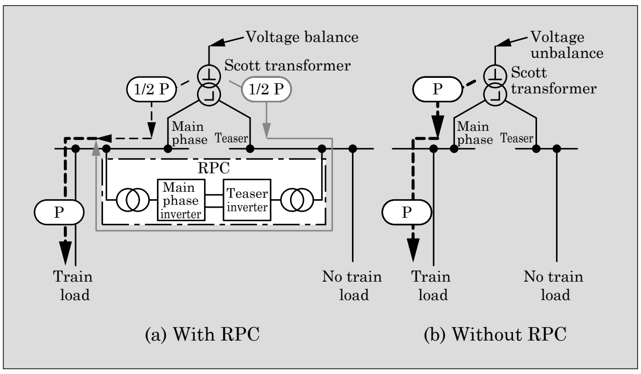


Fig.2 Concept of power interchange

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balanced in 3 phases, resulting in a large voltage fluctuation at a specific phase. To prevent this, we use an RPC and connect a power converter to the buses of the 2 single-phase lines on the feeding side of the feeding transformer to interchange effective power between circuits and compensate reactive power for power feeding simultaneously. This compensates for the unbalanced voltage in 3 phases and voltage fluctuation, as well as harmonic current of high voltage generated by trains. If the power cannot be interchanged due to the substation equipment configuration, the RPC can be operated as a static var compensator (SVC).

### 2.2 Configuration and specifications of the RPC

The single-line diagram for the Shin-Kurobe Substation is shown in Fig. 3. The Shin-Kurobe Substation is comprised of two 154 kV receiving lines, 4 feeder lines and the RPC. When the loads do not match between the directions of Nagano and Kanazawa, the RPC makes the feeding powers of the main phase and teaser match within the range of the capacity of the RPC to balance the receiving voltages.

Figure 4 shows the basic configuration of the RPC

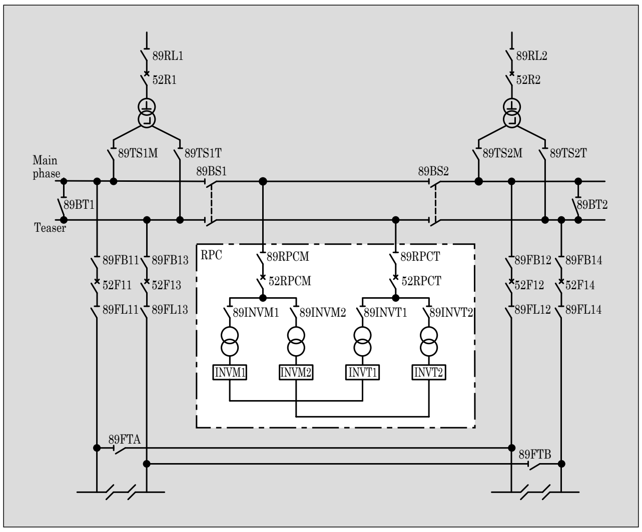



Fig.3 Single-line diagram for Shin-Kurobe Substation

Table 1 Major specifications of the RPC

| Item | Specification |
|---|---|
| Rated capacity | 15 MVA (7.5 MVA × 2 phases) × 2 banks |
| | RPC: 15 MVA (7.5 MVA × 2 banks)<br>SVC: 30 MVA (15 MVA × 2 banks) |
| Frequency | 60 Hz |
| Rated voltage | 60 kV |
| Inverter output voltage | 2,460 V |
| DC voltage | 2,200 V × 2 |
| Bank configuration | 7.5 MVA (3-level inverter × Parallel quad) × 2 phases |
| Carrier frequency | 540 Hz (9-pulse sine wave PWM) |
| Equivalent carrier frequency | 4,320 Hz (Quad × 2) |
| DC capacitor capacity | 24.3 mF × 2 banks |
| Cooling | Pure water circulation + Antifreezing solution circulation + Wind-cooling |
| Control | Effective power interchange control/reactive power compensation control (RPC mode)<br>Reactive power compensation control (SVC-Q mode)<br>Feeding voltage constant control (SVC-V mode)<br>Harmonic compensation (3rd, 5th, 7th and 9th harmonics compensation with a function to stop compensation during resonance) |

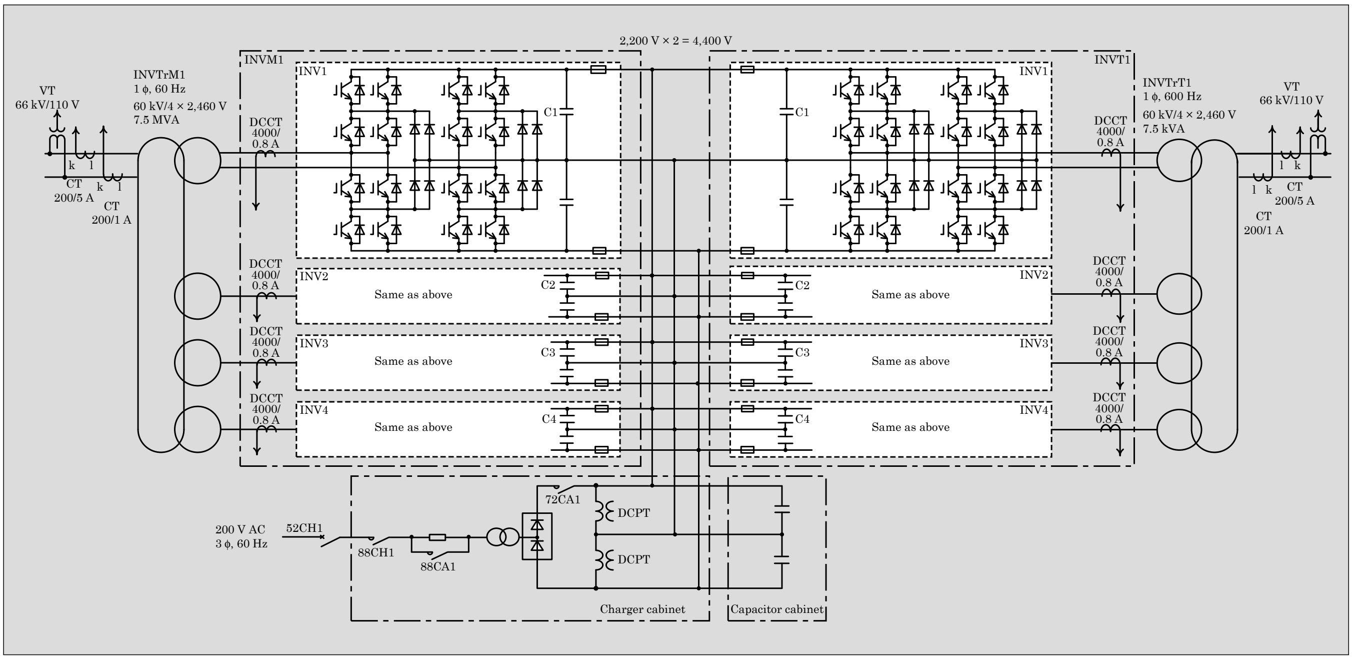
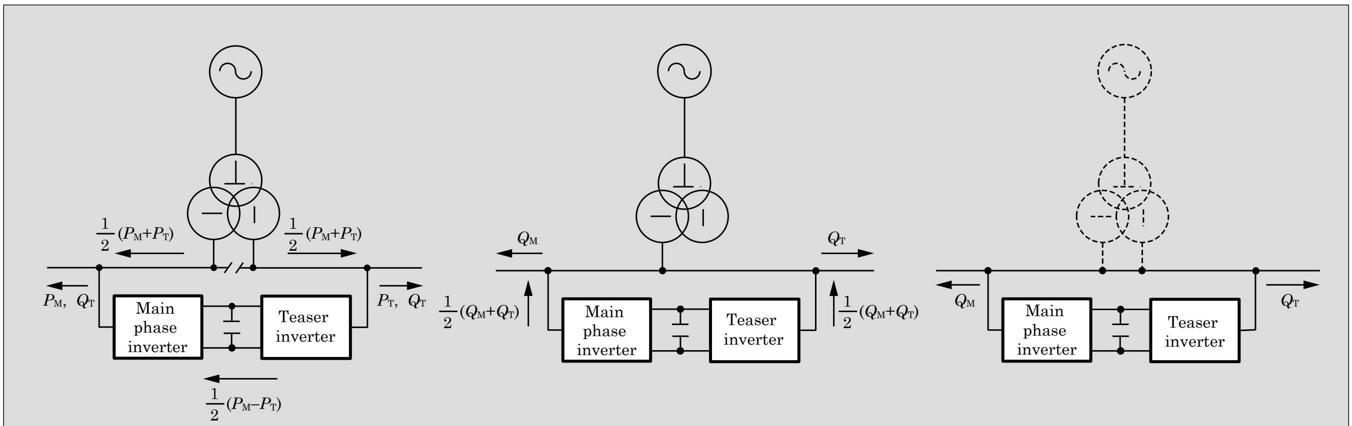



Fig.4 Basic configuration of RPC



(a) RPC mode (b) SVC-Q mode (Reactive power compensation control) (c) SVC-V mode (Feeding voltage constant control)

Fig.5 Operation modes of the RPC

at the Shin-Kurobe Substation. The RPC connects the 2 sets of single-phase inverters on the main phase side and teaser side from the feeding buses of the main phase and teaser respectively in the DC current section via circuit breakers and inverter transformers. This makes a configuration in which the AC currents of the main phase and teaser are interchanged through the use of DC currents. The RPC includes 2 sets of a 7.5 MVA system, making for a total capacity of 15 MVA. Table 1 lists the major specifications of the RPC.

### 2.3 RPC operation

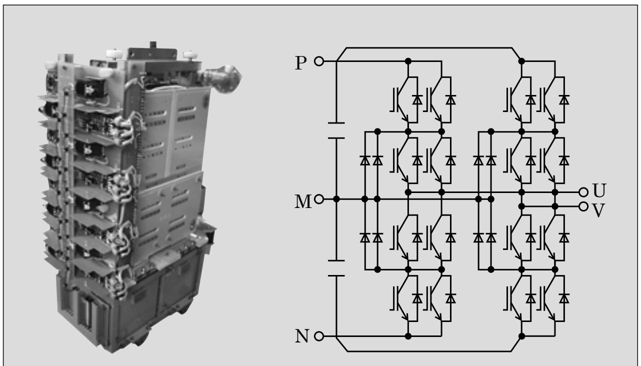
The operation modes of the RPC are shown in Fig. 5. Normally, the RPC is operated in the RPC mode shown in Fig. 5 (a). When the effective powers under the load of the feeding side are different between the main phase and teaser, the active power of half the difference is interchanged through the RPC. This equalizes the effective powers of the main phase and teaser on the secondary side of the Scott connection transformer and balances the 3-phase effective power on the primary side of the transformer. If the main phase and teaser are not switched directly in the substation, the RPC is operated in the SVC-Q mode (Reactive power compensation control) shown in Fig. 5 (b). If the facility is not operated as a substation for some reason, the RPC is operated in the SVC-V mode (Feeding voltage constant control) shown in Fig. 5 (c). The details of the controls are described in Chapter 5.

## 3. Inverter System

The appearance of the inverter system is shown in Fig. 6. The inverter system is composed of 2 cabinets, each of which is mounted with four 3-level single-phase inverter units, and one cabinet of a capacitor bank.

The appearance and circuit diagram of the inverter unit are shown in Fig. 7.

Fig.6 Inverter system



(a) Appearance (b) Circuit diagram

Fig.7 Inverter unit

### 3.1 Inverter unit

The inverter unit we developed was designed to increase capacity through the parallel connection of 2 modular insulated gate bipolar transistors (IGBT) rated at 4.5 kV, 1.2 kA. One unit has a capacity of 3.3 MVA. The key development points are described in the following points.

(1) Equalizing the current sharing of IGBT

To obtain the maximum performance of the parallel-connected IGBTs, equalizing the current sharing

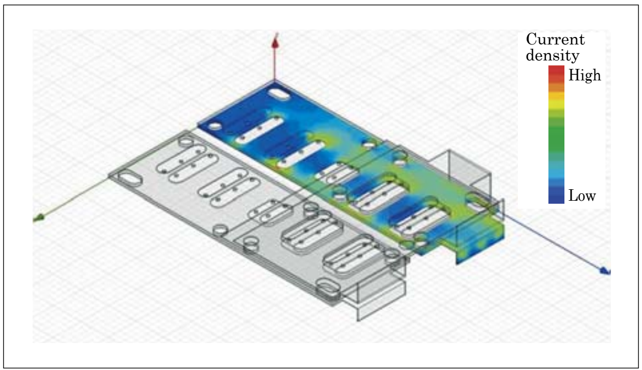



Fig.8 Sample result of 3D magnetic field analysis

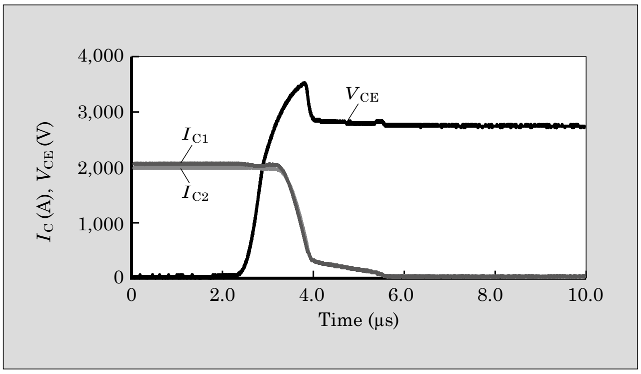



Fig.9 Turn-off waveforms of 2 parallel-connected IGBTs

of each IGBT is necessary. We designed a proper layout of the parts including DC capacitors and adopted laminated bus bars for the main circuit line to ensure low inductance. We calculated the current density, inductance and generated loss from bus bars through 3D magnetic field analysis to determine the configuration of the laminated bus bar. In this analysis, we conducted circuit simulation to calculate the frequency components of the current flowing through each bus bar in each switching mode of a pulse width modulation (PWM) inverter and evaluate the current density distribution for each frequency component. Figure 8 shows a sample result of the 3D magnetic field analysis. The result showed that there are some sections with high current density. In a continuous current flowing test using an actual machine, we evaluated the temperature increase of such sections and confirmed that the temperature was lower than the allowable level of the bus bars.

(2) IGBT cooling method

We used a water-cooling method for the unit to cool the IGBT effectively and improve its availability. Moreover, to allow further unit downsizing, we developed a low-profile heat sink that does not use a water-cooling hose for cooling the IGBT. During the development of this cooling mechanism, we conducted long-term corrosion verification using a water-cooling model to ensure reliability.

The characteristics of IGBT change depending on the temperature. In order to equalize the current sharing and loss of 2 parallel-connected IGBTs, we devised a layout of 2 IGBTs in the heat sink to make their case temperatures be the same.

(3) Unit structure

We designed the unit structure to allow the unit to be drawn out easily from the cabinet without a need for a lifter. This has improved workability and safety during unit replacement, maintenance and inspection.

### 3.2 Inverter unit evaluation

We evaluated switching loss by conducting a switching test and measured the current shared between the parallel elements. We confirmed that the current shared between 2 parallel elements was almost equal and the current unbalance ratio was 10% or lower. In the field check of the cutoff performance of the unit that considered system overcurrent under abnormal conditions such as system disturbance, the jumping voltage at turn-off was about 3,500 V, even when a current of about 4 times the rated peak current of the system (4,000 A) was cut off. This voltage is sufficiently below the allowable voltage of the IGBT (4,500 V) so that the system can be stopped safely if an abnormality occurs. Figure 9 shows the turn-off waveforms of the IGBT under this condition.

## 4. Inverter Transformer

The inverter transformer is designed to have a multi-output structure. The appearance is shown in Fig. 10 and the major specifications are listed in Table 2.

In order to reduce the noise of the inverter trans-

Fig.10 Inverter transformer

Table 2 Major specifications of the inverter transformer

| Item | Specification |
|---|---|
| Rated capacity | 7.5 MVA |
| Rated voltage | 60 kV/2,460 V × Quad |
| Rated frequency | 60 Hz |
| Number of phases | Single phase |
| Cooling method | Oil immersed self-cooled |
| Boundary noise | 50 dBA |
| Number of transformers | 4 units (2 phases × 2 banks) |

former, we adopted a gapless type core to achieve a similar structure to normal transformers and created a double-layered tank structure. The noise at the site boundary has been reduced to 50 dBA.

Since the inverter transformer is excited by an inverter through the application of square waves, the duty on the core is more severe than sine wave excitation. To address the issue, we studied the no-load loss characteristics, saturation characteristics, no-load current characteristics, DC-biased magnetic characteristics and other characteristics of sine wave excitation and inverter excitation respectively to determine the optimum magnetic flux density, in order to reduce the noise, improve the reliability and miniaturize the system.

Furthermore, we designed a cooling mechanism by allowing for the loss increase during operation under the PWM control of the inverter.

## 5. Control Technologies

Figure 11 shows the block diagram for control logic of the RPC mode. In the RPC mode, the effective powers and reactive powers of the substation outputs of the main phase and teaser are calculated from the feeding voltage and feeding current of the substation. The RPC interchanges half the difference in the effective powers between the main phase and teaser to equalize the effective power outputs of the main phase and teaser of the Scott transformer. On the other hand, reactive power compensation is conducted individually for the main phase and teaser. The RPC outputs a reactive power that has reverse polarity of the reactive power of the substation output to counteract the reactive power output of the Scott transformer. When the composition capacity of the effective power interchange amount (reference) and the reactive power compensation amount (reference) of the RPC is within the rated capacity of the RPC, the current received by the Scott transformer is balanced in 3 phases with a power factor of 1. When the composition capacity exceeds the rated capacity of the RPC, the RPC limits the effective power interchange amount and reactive power compensation amount in the same proportion (equal ratio limitation) so that the output of the RPC does not exceed the rated capacity.

Figure 12 shows the block diagram for control logic of the SVC-Q mode. The SVC-Q mode calculates the reactive power of the substation output from the voltage and current of the feeding phase sent from the substation. The RPC outputs a reactive power that has reverse polarity of the calculated reactive power to perform reactive power compensation.

In the RPC mode and SVC-Q mode, the surplus capacity from the output of fundamental frequency components (used for the effective power interchange and reactive power compensation) is used for harmonic compensation. As shown in Fig. 11 and Fig. 12, Fourier transform is applied to the detected current sent from the substation to extract harmonics of the 3rd, 5th, 7th and 9th components to be compensated, and then Fourier inverse transform is applied to the extracted components to generate harmonic current references. If the resonance frequency generated from the stray capacitance between the feeder line and ground and the inductance of the feeder line is close to the harmonic number to be compensated, the harmonic may be amplified. Therefore, we provided a function that determines the amplification of harmonic when any Fourier-transformed component exceeds the judgment value, and stops the harmonic compensation of that component. This function ensures stable operation without amplifying harmonics even when the resonance frequency becomes close to the harmonic num-

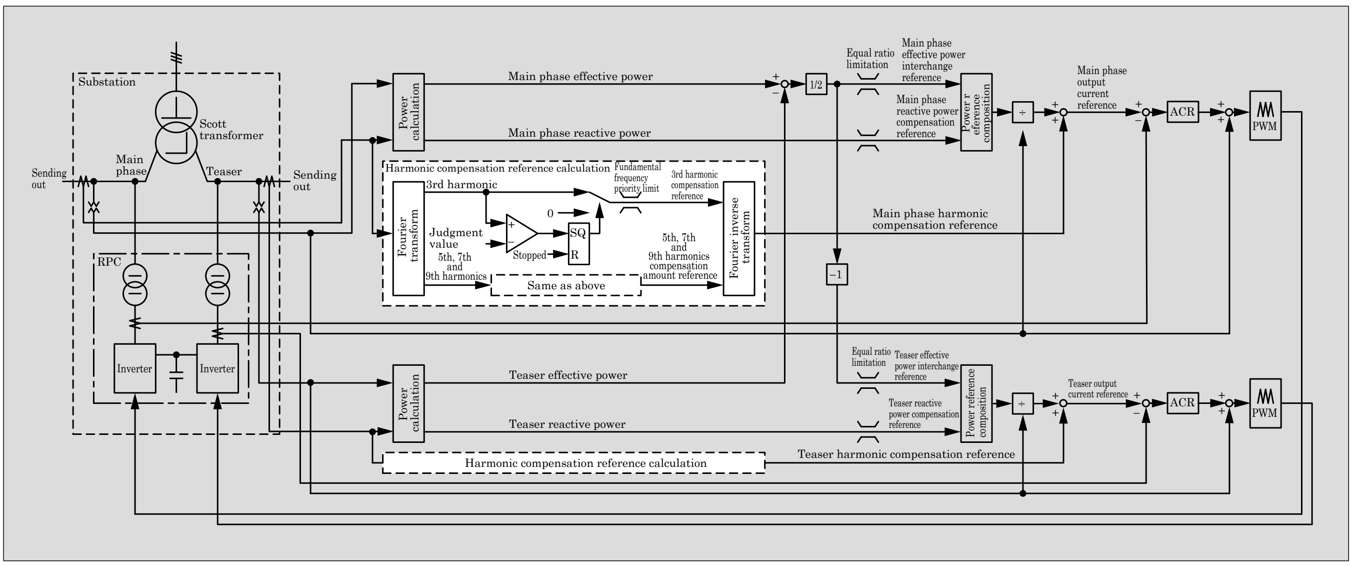


Fig.11 Block diagram for control logic of RPC mode

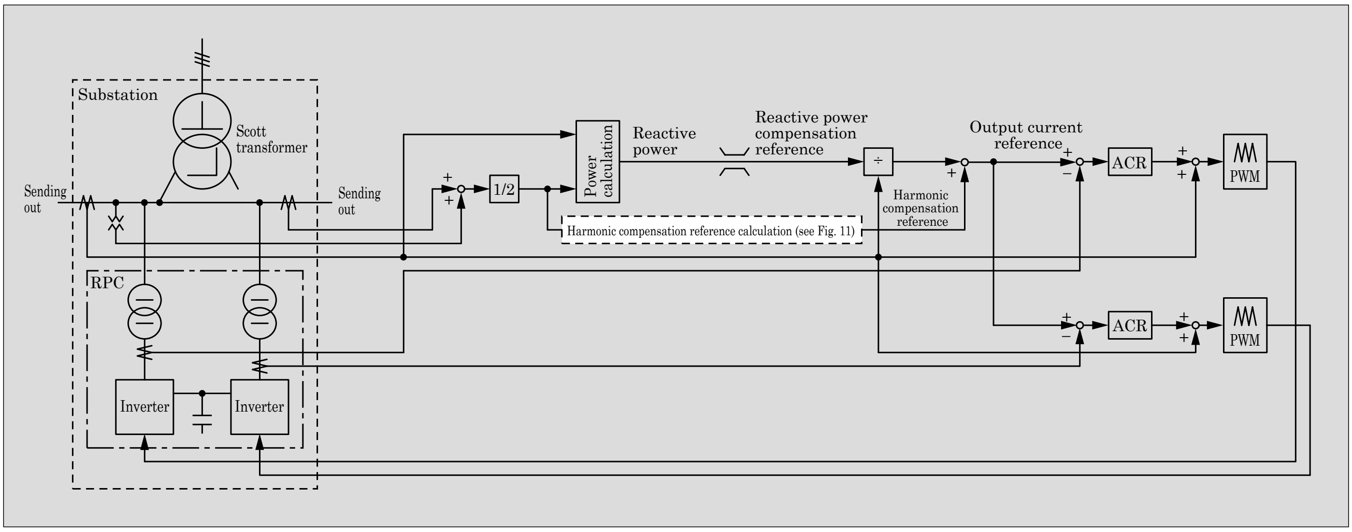



Fig.12 Block diagram for control logic of SVC-Q mode

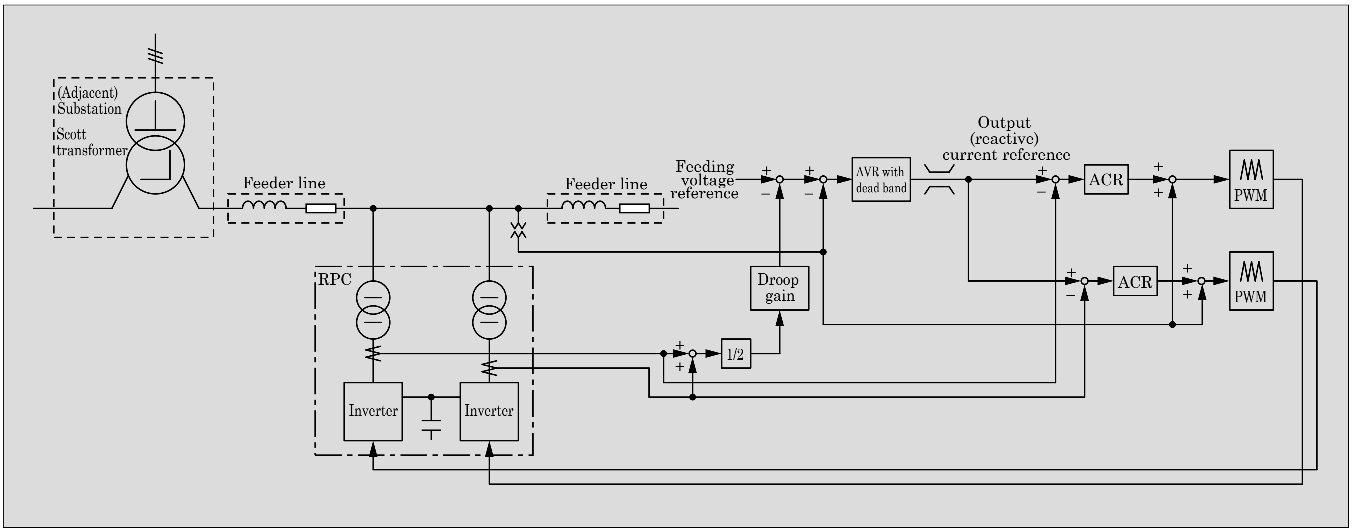



Fig.13 Block diagram for control logic of SVC-V mode

ber to be compensated due to the change in the impedance of the feeder line or the stray capacitance between the wire and ground caused by the configuration switching of the feeding system or weather conditions.

Figure 13 shows the block diagram for control logic of the SVC-V mode. In the SVC-V mode, the RPC is not connected directly in the substation but connected to a certain point in the feeding system. Consequently, it does not provide effective power interchange or reactive power compensation but controls the voltage of the connection point. The voltage is controlled through the adjustment of the reactive power output so that the voltage of the connection point is kept within the set range. Because we only need to keep the feeding voltage within a certain range, we set a dead band for the voltage control to suppress the reactive power output and reduce system loss. Since the RPCs in 2 banks individually detect the voltage of the connection point for voltage control, a compensation loop has been provided to equalize the reactive power outputs between the 2 banks.

## 6. Postscript

This paper described an overview of the RPC delivered to the Shin-Kurobe Substation of the Hokuriku Shinkansen and its control technologies. With the inauguration of the Hokuriku Shinkansen, this RPC started operating smoothly. Fuji Electric continues to promote the development of high-performance power converters based on power electronics technologies.

In closing, we would like to express our deep gratitude to Japan Railway Construction, Transport and Technology Agency and other parties concerned for the guidance and cooperation they gave in the development and operation of the RPC.

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