Self-Commutated Static Var Generator at Shintakatsuka Substation

A. Iizuka, M. Kishida
Central Japan Railway Company

Y. Mochinaga, T. Uzuka
Railway Technical
Research Institute

K. Hirakawa, F. Aoyama, T. Masuyama
Toshiba Corporation
Toshiba-cho 1, Fuchu
Tokyo 183, Japan
TEL 0423-33-2316
FAX 0423-40-8049

Abstract: This paper reports the outline of the 48 MVA self-commutated static var generator (SVG) installed in Central Japan Railway Company's Shintakatsuka substation and also summarizes the result of a performance verification test. As the number of passengers using the Tokaido Shinkansen bullet train increases year by year, there is a corresponding increase in the service load including stepped-up operation of trains and their increased speed. The SVG is designed to suppress voltage fluctuations and imbalance caused by load variations of trains and, thereby, to alleviate effects on other consumers on the same power system. We conducted a verification test on the SVG using an actual train load. This verification test found that the SVG can reliably compensate for reactive power and negative-phase-sequence current of magnitudes within a rated capacity, thus providing a satisfactory voltage variation suppression effect.

Introduction

There have been growing calls for higher stability and quality of electric power supply amid increasing power demand in recent years. Electric railway systems are also required to minimize voltage fluctuation and imbalance.

Recent advances in power electronics technology have enabled a substantial increase in the rating of power converting semiconductor devices having a self-extinguishing capability, such as GTO thyristors, which, in turn, has allowed practical use of large-capacity PWM inverters.

This PWM inverter is already in actual service as an SVG, whose capability to regulate reactive power and negative-phase-sequence current at high speed by PWM control of the GTO thyristors has been proven in service experience.

It is generally known that reactive power and negative-phase-sequence current cause variations and imbalance of power system voltage. We adopt a control system that is based on an instantaneous real and reactive power theory to detect and compensate for such disturbance components. We have recently installed an SVG for a Shinkansen superexpress train feeding circuit in the Central Japan Railway Company's Shintakatsuka substation. The outline of this equipment and the results of its performance verification test are described in this paper.

Objective

Where a substation has a small power supply short-circuit capacity, when two or more trains draw a large amount of load in the same substation section, the voltage variation of received power becomes large affecting other consumers connected to the same power system. Substations for feeding Shinkansen convert 3-phase AC voltage to single-phase AC voltage by Scott-connected transformers before supplying electricity. Trains collect this single-phase AC voltage through a pantograph and rectify it to drive a motor for propulsion. The Scott-connected transformer has a characteristic that when its two windings are applied with the same amount of load, the 3-phase AC currents on the primary side are balanced completely, but that when the two winding loads are not balanced, as in Shinkansen, the 3-phase AC current on the primary side becomes imbalanced, causing a voltage drop. The voltage drop is generally controlled by a shunt capacitor, which, however, cannot suppress variations of reactive power.

Considering the fact that the train load of the Shinkansen is basically an imbalanced load and that the imbalance components in the load will further increase as a growing number of regenerative cars are currently being introduced, we adopted a system incorporating an SVG to suppress the imbalance components and reactive power contained in load, thereby controlling voltage variations of received power.

System Configuration

Figure 1 shows a system configuration. The SVG system is installed in parallel with the feeding circuit and comprises a transformer to step down a received voltage of 154 kV to 33 kV, three 16-MVA GTO inverters, and a 6-MVA shunt capacitor. The transformer for stepping down to 33 kV makes savings in terms of economy and space of the SVG system. The use of the 6-MVA shunt capacitor that compensates for the

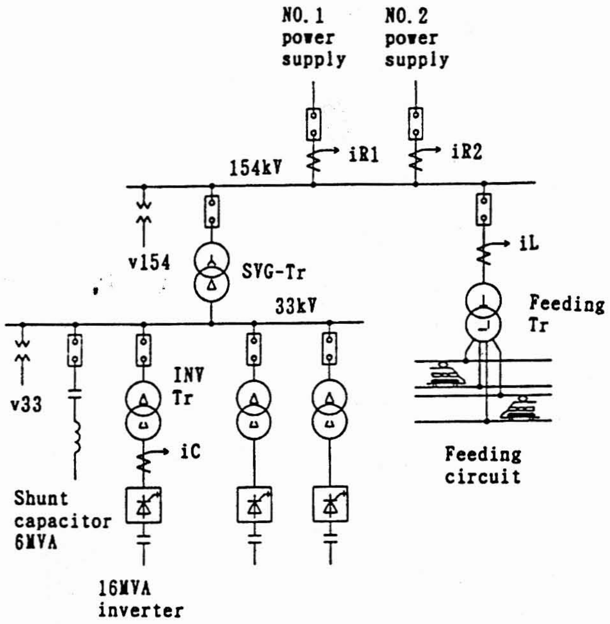


Figure 1 System configuration

reactive power consumed by the train load reduces the capacity and size of the SVG system itself. In this system, the GTO inverters are divided into three groups and are controlled independently so that the system can remain operational even when one or two GTO inverters should fail, thus enhancing reliability.

Control of SVG

Figure 2 shows the control block diagram. It is known that voltage variation results from reactive power and negative-phase-sequence current generated by a load. To control these, the SVG performs the following control:

(1) Detection of Reactive and Negative-Phase-Sequence Components of Load Current

The load current component detection block of Figure 2 detects a load reactive power Q_L and a negative-phase-sequence power p_{LN}, q_{LN}. Detection of Q_L, p_{LN} and q_{LN} is done by the generalized theory of the instantaneous reactive power in three-phase circuits[1]. Then, current values i_{LQ}*, i_{LN}* equivalent to Q_L and p_{LN}, q_{LN} are determined.

(2) Calculation of Current Reference

The current reference calculation block of Figure 2 combines i_{LQ}* and i_{LN}* of the load current and calculates an instantaneous real power and an instantaneous imaginary power of the combined current. The calculated values are adjusted by an output limit control factor (described later), APC factor (described later), number of operating inverters N_I and shunt capacitor Qc to determine the current reference i*.

(3) DC Voltage Control

The DC voltage control regulates the voltage of the DC capacitor to coincide with the reference voltage. The DC voltage command value is converted into a current i_{AVR}*, which is then added to the current reference i* for feedback control.

(4) Current Control

The current control circuit controls an output reference Ec so that the output current Ic of the GTO inverter agrees with the current reference Ic*.

(5) PWM Control

The PWM circuit determines a gate signal to generate an AC voltage that will produce a desired output current. By the current control circuit, the GTO inverter operates equivalently as a current source.

Calculation of Reactive Component i_Q* of Load Current

A 3-phase load current i_L is expressed as follows if we let a zero-phase component be i_0, a positive-phase-sequence component be i_1, and a negative-phase-sequence component be i_2.

$$\begin{bmatrix} i_{LR} \\ i_{LS} \\ i_{LT} \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix} \begin{bmatrix} i_0 \\ i_1 \\ i_2 \end{bmatrix} \tag{1}$$

where:

$$a = -\frac{1}{2} + j\frac{\sqrt{3}}{2} \tag{2}$$

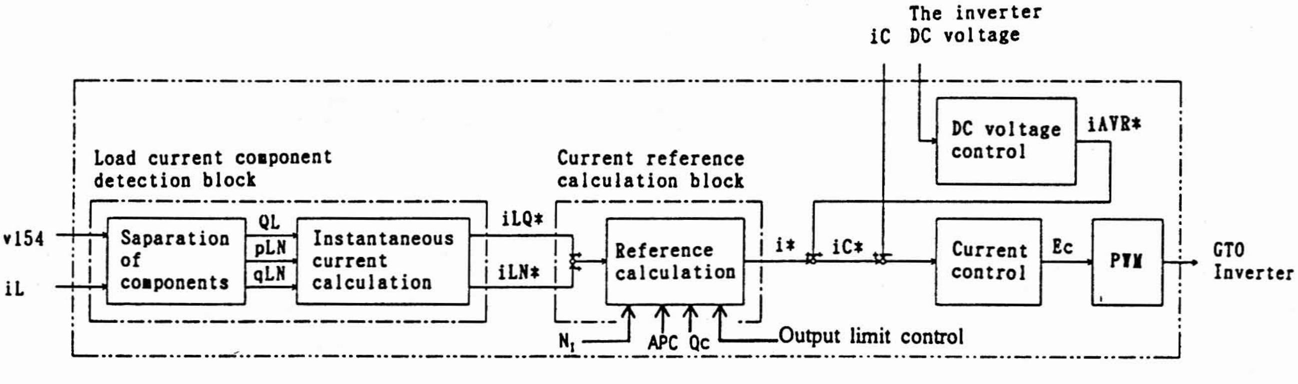


Figure 2 Control block diagram

$$a^2 = -\frac{1}{2}-j\frac{\sqrt{3}}{2} \tag{3}$$

Because the feeding system is an ungrounded system, $i_0=0$ and equation (1) can be developed as follows:

$$\begin{bmatrix} i_{LR} \\ i_{LS} \\ i_{LT} \end{bmatrix} = \begin{bmatrix} i_1+i_2 \\ a^2 i_1 + a i_2 \\ a i_1 + a^2 i_2 \end{bmatrix} \tag{4}$$

Subjecting equation (4) to the 3-phase to 2-phase conversion results in the following equation where $i_L\alpha$ and $i_L\beta$ denote the 2-phase AC currents.

$$\begin{bmatrix} i_L\alpha \\ i_L\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_{LR} \\ i_{LS} \\ i_{LT} \end{bmatrix} \tag{5}$$

$$= \sqrt{\frac{3}{2}} \begin{bmatrix} i_1+i_2 \\ -j(i_1-i_2) \end{bmatrix} \tag{6}$$

Here the effective values of i_1 and i_2 are represented by I_1 and I_2, respectively, and can be expressed as follows:

$$i_1 = \sqrt{2}I_1\sin(\omega t-\phi_1) \tag{7}$$

$$i_2 = \sqrt{2}I_2\sin(\omega t-\phi_2) \tag{8}$$

$$\omega = 2\pi f \tag{9}$$

where ϕ_1 is a phase difference between the positive-phase-sequence current and the line voltage and ϕ_2 is a phase difference between the negative-phase-sequence current and the line voltage, and f (=60 Hz) is a frequency. Based on these, the positive p, q calculation circuit determines a positive instantaneous real power p_P and a positive instantaneous imaginary power q_P. Using the theory of the instantaneous reactive power in three-phase circuits[1], the positive instantaneous real power q_P and the positive instantaneous imaginary power q_P are defined by equation (10). Equation (10) is called a positive instantaneous real and imaginary power calculation.

$$\begin{bmatrix} p_P \\ q_P \end{bmatrix} = \begin{bmatrix} i_L\alpha & i_L\beta \\ i_L\beta & -i_L\alpha \end{bmatrix} \begin{bmatrix} v\alpha* \\ v\beta* \end{bmatrix} \tag{10}$$

where $v\alpha*$ and $v\beta*$ denote 2-phase AC quantities in phase with voltage and have an amplitude of 1 pu. They are expressed as follows:

$$v\alpha* = \sqrt{3}\sin\omega t \tag{11}$$

$$v\beta* = -\sqrt{3}\cos\omega t \tag{12}$$

Substituting equation (11) and (12) into equation (10) results in :

$$p = 3I_1\cos\phi_1 - 3I_2\cos(2\omega t-\phi_2) \tag{13}$$

$$q = -3I_1\sin\phi_1 + 3I_2\sin(2\omega t-\phi_2) \tag{14}$$

Equation (13) and (14) signify that the real power and reactive power for the positive-phase-sequence current appear as DC quantities and those for the negative-phase-sequence current appear as AC quantities that change at a frequency two times that of the fundamental wave. Therefore, by detecting a DC component using a low-pass filter, the real power P and reactive power Q can be determined. The detected reactive power Q is converted into 2-phase AC currents $i_Q\alpha$, $i_Q\beta$ by the positive-phase-sequence instantaneous current calculation and then into 3-phase AC currents $i_{QR}*$, $i_{QS}*$, $i_{QT}*$ by the 2-phase-to-3-phase conversion. These calculations are identical with reverse conversion of equation (10) and (5).

$$\begin{bmatrix} i_Q\alpha \\ i_Q\beta \end{bmatrix} = \begin{bmatrix} v\alpha* & -v\beta* \\ v\beta* & v\alpha* \end{bmatrix} \begin{bmatrix} 0 \\ Q \end{bmatrix} \tag{15}$$

$$\begin{bmatrix} i_{QR}* \\ i_{QS}* \\ i_{QT}* \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ \frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_Q\alpha \\ i_Q\beta \end{bmatrix} \tag{16}$$

Calculation of Negative-Phase-Sequence Component of Load Current $i_{LN}*$

The negative-phase-sequence instantaneous real and imaginary power calculation is the positive-phase-sequence instantaneous real and imaginary power calculation with the voltage signal $v\beta*$ inverted and is defined by equation (17).

$$\begin{bmatrix} pn \\ qn \end{bmatrix} = \begin{bmatrix} i_L\alpha & i_L\beta \\ i_L\beta & -i_L\alpha \end{bmatrix} \begin{bmatrix} vn\alpha* \\ vn\beta* \end{bmatrix} \tag{17}$$

$$vn\alpha* = \sqrt{3}\sin\omega t \tag{18}$$

$$vn\beta* = \sqrt{3}\cos\omega t \tag{19}$$

Substituting equation (17) and (18) into equation (19) results in:

$$pn = -3I_1\cos(2\omega t-\phi_1) + 3I_2\cos\phi_2 \tag{20}$$

$$qn = -3I_1\sin(2\omega t-\phi_1) + 3I_2\sin\phi_2 \tag{21}$$

Equation (20) and (21) signify that the real and reactive components for the negative-phase-sequence current appear as DC quantities and those for the positive-phase-sequence current appear as AC quantities that change at a frequency two times that of the fundamental wave. Therefore, it is possible to detect the real and reactive components of the negative-phase-sequence current by detecting only a DC component with a low-pass filter. Then, as in the calculation of the reactive component of load current $i_{LQ}*$, the negative-phase-sequence component of load current $i_{LN}*$ is determined by a negative-phase-sequence instantaneous current calculation defined by equation (22) and by the 2-phase-to-3-phase conversion expressed by equation (23).

If we let the real and reactive components of the negative-phase-sequence current be p_n* and q_n*, respectively, the following equations hold:

$$\begin{bmatrix} in\alpha \\ in\beta \end{bmatrix} = \begin{bmatrix} v\alpha* & -v\beta* \\ -v\beta* & v\alpha* \end{bmatrix} \begin{bmatrix} p_n* \\ q_n* \end{bmatrix} \tag{22}$$

$$\begin{bmatrix} in_R* \\ in_S* \\ in_T* \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ \frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} in\alpha \\ in\beta \end{bmatrix} \tag{23}$$

Calculation of Current Reference

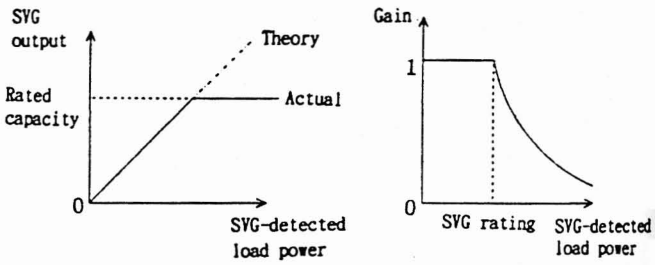
The current reference determined by equation (16) and (23) are combined and then subjected to the positive-phase-sequence instantaneous real and imaginary power calculations. The calculated values are used to determine the gain produced by APC and output limit control (both described later) and then to calculate the power references p*, q*. From the power references p*, q* thus obtained, it is possible to derive the current references i_R*, i_S*, i_T* through the positive instantaneous current calculation and the 2-phase-to-3-phase conversion by using the following equations:

$$\begin{bmatrix} i\alpha* \\ i\beta* \end{bmatrix} = \begin{bmatrix} v\alpha* & -v\beta* \\ v\beta* & v\alpha* \end{bmatrix} \begin{bmatrix} q* \\ p* \end{bmatrix} \tag{24}$$

$$\begin{bmatrix} i_R* \\ i_S* \\ i_T* \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ \frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i\alpha* \\ i\beta* \end{bmatrix} \tag{25}$$

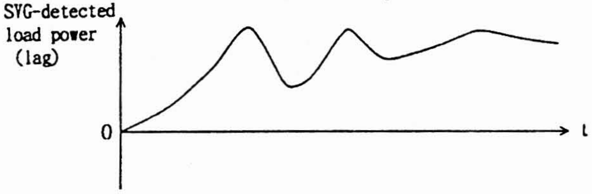
APC

An advanced power control (APC) is a control method for effectively suppressing voltage variation with a limited equipment capability. The SVG compensates for the load reactive power and the negative-phase-sequence current. In reality, however, because there is a limit to the equipment capability, the SVG cannot respond to load variations greater than its rating (Fig. 3(a)). When the load reactive power and the negative-phase-sequence current exceed the rated capacity of the SVG, it is possible to effectively suppress voltage variation by outputting a reactive power and a negative-phase-sequence current both multiplied by the gain shown in Figure 3(b). For a load fluctuation shown in Figure 3(c), for example, constant reactive power and negative-phase-sequence current are output at all times even when the variation exceeds the rating if the APC is not provided (dashed line in Figure 3(d)). When, on the other hand, the APC is provided, the reactive power and negative-phase-sequence current are output in such a manner as to effectively follow the variations of the load reactive power and negative-phase-sequence current even if the load reactive power exceeds the rating (solid line in Figure 3(d)).

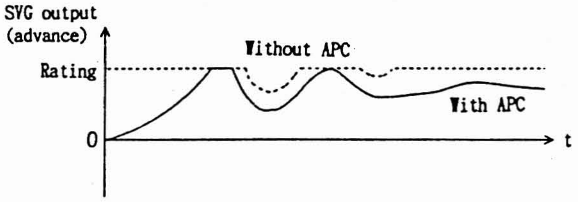


(a) SVG-detected load power and SVG output

(b) APC operation



(c) SVG-detected load power



(d) SVG output

Figure 3 APC

The APC is particularly effective in compensating for a negative-phase-sequence current for the following reasons. As can be seen from equation (13) and (14), the load negative-phase-sequence power detected by the instantaneous real and imaginary power calculation is a waveform having a frequency two times that of the line voltage. If the APC is not provided, in the range where the load negative-phase-sequence power exceeds the rating, the compensating negative-phase-sequence power of the SVG is limited at a constant crest value and the SVG outputs the corresponding current reference, with the result that unwanted harmonics flow into the power system. With the APC, however, the compensating negative-phase-sequence power is controlled to effectively follow, within the rated capacity, the variation of the negative-phase-sequence power, preventing inflow of unwanted harmonics into the power system and thereby effectively suppressing voltage variations.

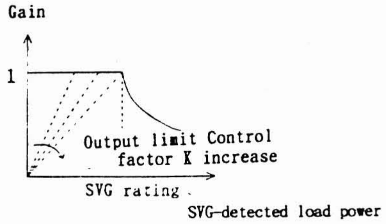


Figure 4. Output limit control

Output Limit Control

Normally, the SVG compensates for 100% of the reactive power and negative-phase-sequence current of magnitudes within the rated capacity. Where the load reactive power and negative-phase-sequence current are small, however, it is possible to suppress the voltage variation within the required range without setting the compensation gain η_T of SVG to 1. The compensation gain η_T is defined by:

$$\eta_T = \frac{\textit{actual amount of compensation by SVG}}{\textit{required amount of compensation}} \qquad (26)$$

In such a case, by lowering the compensation gain η_T of SVG, the loss of the SVG system can be reduced.

Figure 4 shows the method of SVG operation. The abscissa represents a required amount of compensation and the ordinate represents a compensation gain η_T of SVG. Figure 3(b) shows the normal SVG operating condition. When the compensation amount is within the SVG rating, the compensation gain is set to 1.

In the output limit control, on the other hand, when the compensation amount is below a specified threshold level, the compensation gain is changed linearly. For example, when the output limit control factor is set at K=0.6, the required amount of compensation is multiplied by a gain which changes in a range from 0 MVA to 28.8 MVA with a certain linear inclination.

Performance Verification Test Results

A performance verification test using actual train loads was performed for four days from July 25 to July 28, 1994.

2-Minute Window Voltage Variation

The 2-minute window voltage variation factor is defined as a percentage of the difference between maximum and minimum values of the power system voltage in a duration of two minutes. That is, if we let a maximum value of the power system voltage in a two-

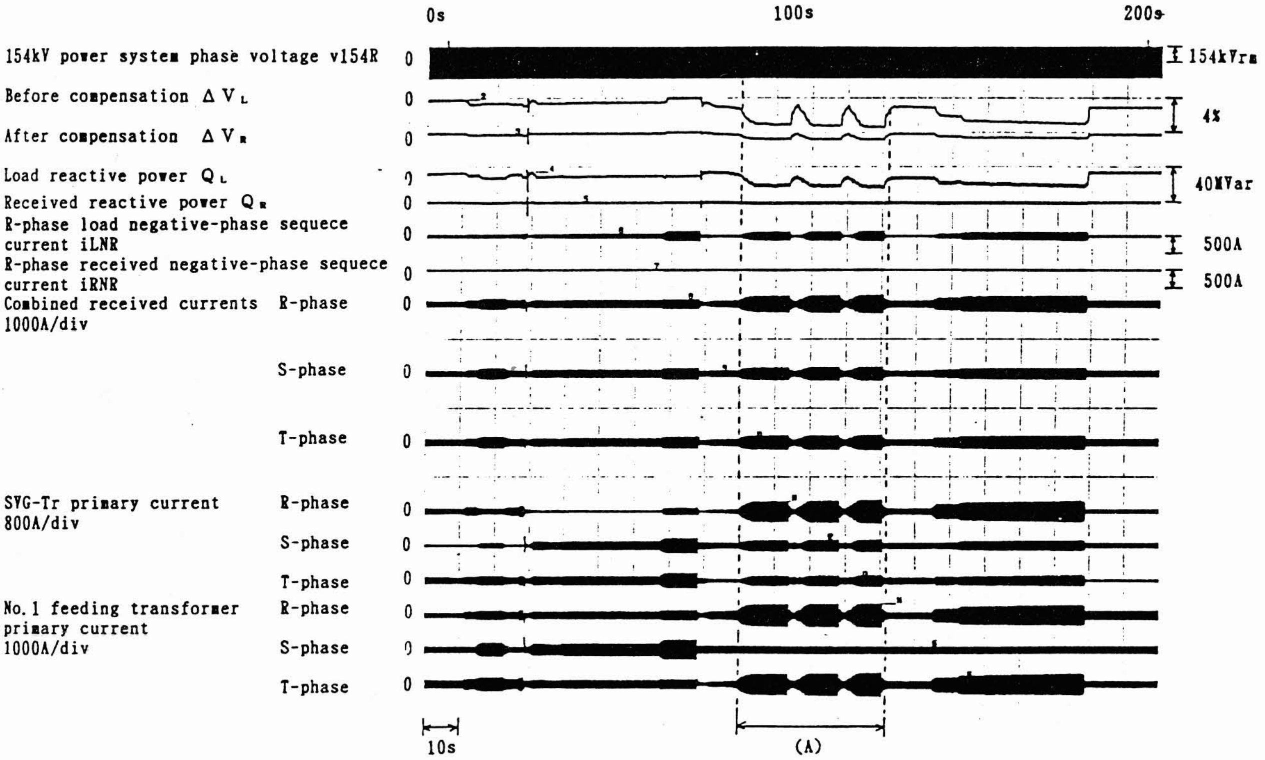


Figure 5 Operation chart

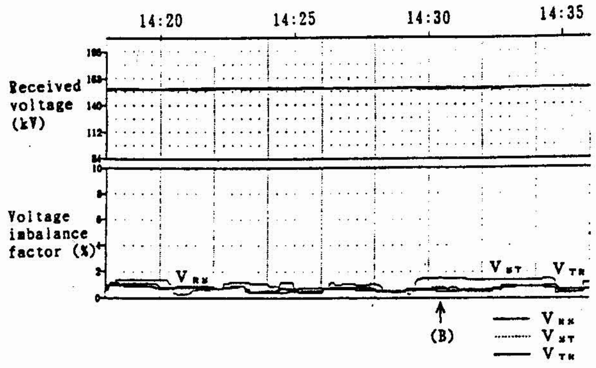


Figure 6 2-minute window received voltage fluctuation factor (July 27 '94, 14:20-14:30)

minute time interval be vmax and a minimum value be vmin, then the 2-minute window voltage variation factor W can be expressed by:

$$W = \frac{vmax-vmin}{vmax} \times 100[\%] \qquad (27)$$

An apparatus developed by Railway Technical Research Institute that can directly measure the 2-minute window voltage variation factor was used.

Results of Measurements

(A case where the load current for train is compensated for:)

(a) Operation on July 26 at 10:14-10:17

Figure 5 shows a chart for the 10:14-10:17 operation on July 26. The reactive power and the negative-phase-sequence current (power) drawn by the train load have the maximum values of about 32 MVar lagging and about 150 Arms (about 28 MVA), respectively, in section (A) which exceed the rated capacity of the SVG system. In this condition, a voltage fluctuation that could not be compensated for by the SVG results, but is only 0.6% at maximum, well below the regulated level, demonstrating an effective suppression capability.

(2-minute window received voltage fluctuation factor and imbalance factor)

Figure 6 and 7 show two-minute window received voltage fluctuation factors for the 14:20-14:30 operation on July 27, voltage fluctuations before and after the compensation and voltage imbalance factors. We found the following:

- The maximum voltage fluctuation is 1.74% at point (B) in Figure 6 verifying a satisfactory compensation capability of the SVG.
- A maximum voltage imbalance factor of 3.6% in section (C) in Figure 7 is limited to below 1% by the SVG.

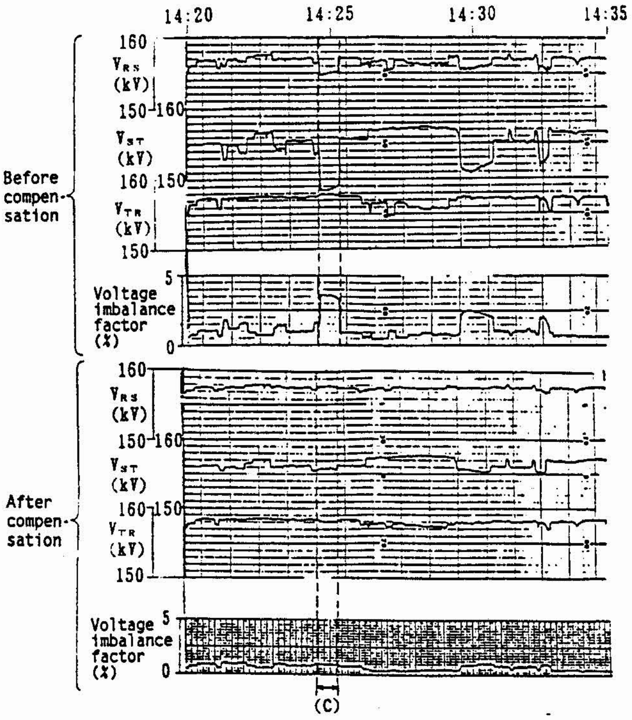


Figure 7 Received voltage before and after compensation (July 27 '94, 14:20-14:30)

- It is confirmed that even when the output limit control with K=0.6 is performed, the SVG can still provide a satisfactory voltage fluctuation suppression for the train load.

Conclusion

The performance verification tests of the SVG installed in the Shinkansen feeding circuit have found that the SVG can reliably compensate for reactive power and negative-phase-sequence current, producing satisfactory voltage variation suppression effects. When the reactive power and negative-phase-sequence current of a load are small, if the output of the SVG is lowered by the output limit control, the SVG is still able to suppress voltage fluctuations effectively.

Reference

[1] H. Akagi, et. al. "Generalized Theory of the Instantaneous Reactive Power in Three-Phase Circuits." IPEC-Tokyo, March 27-31. 1983