Analysis of Input Characteristic for a UPS Connected to a Generator

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1. Introduction

In the age of information technology, application of the uninterruptable power supply (hereafter, "UPS") is widespread to meet the requirement of stable supply power for important loads such as computers. In addition, a generator can be used as the input for the UPS when emergency power is required for long periods of commercial power failure. When a generator is connected to a UPS, sometimes , probrem of Sub Synchronous Resonance (hereafter, "SSR") can arise. The generator consists of a rotor, an external driving engine, and a shaft which connect the rotor with the external driving engine. Generally, the inertias of the rotor and that of the external driving engine are different. Therefore, when sudden changes in load occur resulting is a disturbance, SSR is generated due to the rotational speed difference between the generator and the rotor. In some cases, the resulting oscillation is so severe as to break the shaft between generator and rotor. This is one example of SSR. Also, in situations where the disturbance is occurred, output voltage and frequenncy of the generaotor varies . Under this conditions, the UPS is controlled as constant power control and phase control and so on. So, the SSR is affected by the inertias of the rotor and external driving engine in addition to a close relationship with the UPS control [(1)-(2)] . The input characteristic on the UPS side is analyzed in this paper. The following points are described to clarify the relationship with SSR.

1) Control method of UPS (rectifier)
2) UPS input characteristic analysis using Bode diagrams
3) Verification by waveform simulation and experiments

2. Control Method of UPS (Rectifier)

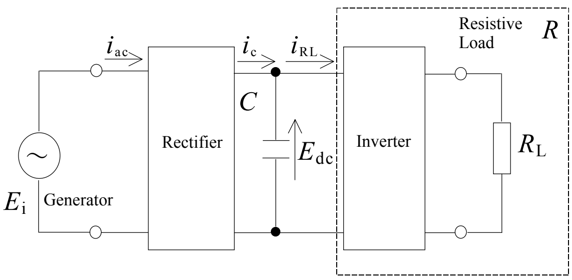

Fig.1 Model of UPS

Fig.1 shows the basic configuration when a generator is connected to the UPS. There are many possible UPS types, but in this example, we would like to take the widely used double conversion type UPS that consists of the voltage type rectifier and inverter. In the double conversion type UPS, a generator, a rectifier, an inverter, and a load are connected sequentially. The control system of the inverter achieves an output with constant frequency and constant voltage that is matched to the commercial power. In other words, if the load is constant, a constant power will be supplied. Moreover, the control system of this inverter allows a very small change in the output voltage even when there is a sudden change in load due to the adoption of an instantaneous voltage control system. Therefore, the inverter outputs power corresponding to the load immediately after the load changes. In addition, because the rectifier control system is controlling the direct current of the rectifier to keep voltage constant and because there is a relatively big electrolytic capacitor, the direct current voltage is approximately constant as well. Therefore, the inverter can be recognized as a constant current source as seen by the rectifier. Therefore, in the model, we assume the inverter part as a resistive load R and input current i_{RL} as a constant.

Now, let's take a look at the control system of the rectifier. In addition to the the above mentioned function that maintains constant DC voltage, the rectifier control system is used to change the input current into a sine wave. As mentioned before, when the load suddenly changes, there is a voltage and frequency fluctuation at the generator output. However, as to the voltage fluctuation, the rectifier input current changes in proportion to the rectifier input voltage (generator output voltage) since the rectifier maintains constant power. If this response is delayed, a pulsation will be generated in the power between the generator and the rectifier. The same principle applys for the frequency fluctuation. When PLL (Phase Locked Loop) is used for the rectifier control system, a phase difference will be generated between the generator output and synchronous signal of the rectifier if the PLL cannot follow the frequency fluctuation. This will result in a power pulsation between the generator and the rectifier. The rectifier with a phase control method will behave in the same way [(3)] .

Considering the above, it is necessary to clarify the rectifier control system when there is a generator output fluctuation (voltage and frequency). In the case of Sanyo's UPS, if there is a frequency fluctuation there will be no power pulsation thanks to the PWM control method for the rectifier that doesn't use PLL technology. The control characteristics during a voltage fluctuation are going to be explained to simplify the analysis. Let's begin with an explanation of the control method for the rectifier. Fig.2 shows the control block diagram for the direct current voltage, E_{dc} (direct current voltage command value is E_{dc}*). DC voltage, E_{dc}, is detected and filtered by a first order filter (the delay element: T_d). The filtered signal is compared to the command value resulting in an error voltage. The error voltage is processed using the PID controller (the proportional element: k_d, integral element: T_1, and differential element: T_2), which creates the input current command value. The input current command value is compared with the input current. The resulting error signal goes through a proportional controller (proportional gain k_i) and PWM control is then used to control the input current and the DC output voltage. By looking carefully at the variable component Δi_c of the current i_c which flows in the capacitor, the relationship between the variable components of the input voltage ΔE_i, of the control signal Δe_c, and of the capacitor current Δi_c can be shown as below.

$$\Delta i_c = \frac{\partial i_c}{\partial E_i}\Delta E_i + \frac{\partial i_c}{\partial e_c}\Delta e_c \qquad \cdots(1)$$

ΔE_i: Variable component of input voltage [V]
Δe_c: Variable component of control signal (input current command value) [A]

Capacitor current i_c results from PWM control in the rectifier and can be put in the expression as shown below.

$$i_c = k E_i f(\theta) \qquad \cdots(2)$$

where $f(\theta)$ is a function of the angle θ as in the PWM control. If capacitor current i_c changes linearly within the range of the control signal fluctuation Δe_c, then we can define the expression as shown below.

$$f(\theta) = A + B e_c \qquad \cdots(3)$$

Therefore, expression (2) can be rewritten as follows.

$$i_c = k E_i (A + B e_c) \qquad \cdots(4)$$

Additionally, if a change of Δi_c is generated in the capacitor current, it can be put in the expression as shown below.

$$\begin{aligned} i_c + \Delta i_c &= k(E_i + \Delta E_i)\{A + B(e_c + \Delta e_c)\} \\ &= kE_i(A + B e_c) + k\Delta E_i(A + B e_c) + k(E_i + \Delta E_i)B e_c \end{aligned} \qquad \cdots(5)$$

The fluctuation component of the capacitor current Δi_c can then be expressed as follows from expressions (4) and (5).

$$\begin{aligned} \Delta i_c &= \frac{i_c}{E_i}\Delta E_i + kBE_i\,\Delta e_c + kB\Delta E_i\,\Delta e_c \\ &\cong \frac{i_c}{E_i}\Delta E_i + kBE_i\,\Delta e_c \end{aligned} \qquad \cdots(6)$$

The third term on the right side in the above expression was disregarded because it is much smaller than term 1 and term 2. As a result, expression (1) can be rewritten as shown by the final result in expression (6).

Because the relation in expression (6) holds true in the PWM control part of Fig.2, the block diagram of the variable component Δi_{ac} of the input current to the variable component ΔE_i of the input voltage is as shown in Fig.3. This figure is derived from Fig.2 while assuming the following conditions.

1) The inverter part is considered as a fixed load since it is regarded as a current source, and the rectifier load current is obtained by adding resistance R to the DC capacitor.
2) Current i_c which flows into the DC capacitor C was set to $\sqrt{3}$ times the input current i_{ac} of each phase because three phase power needs to be taken into consideration (the input current of each phase goes through the three-phase full-wave rectification and flows into the DC capacitor).

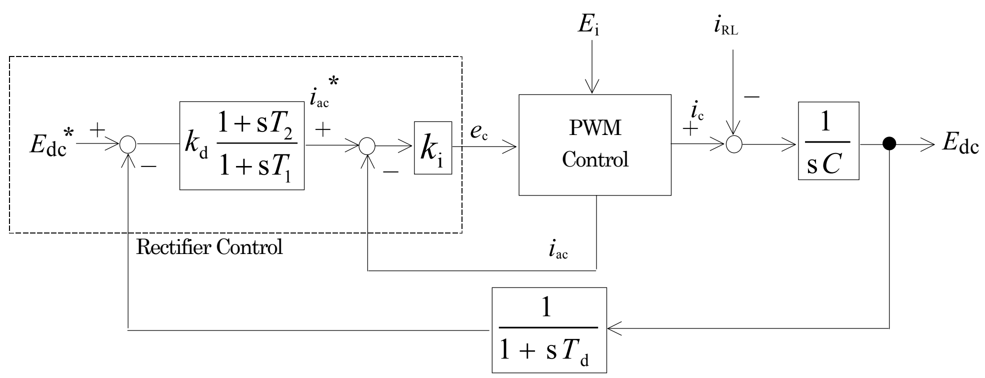

Fig.2 Block Diagram of E_{dc} to E_{dc}*

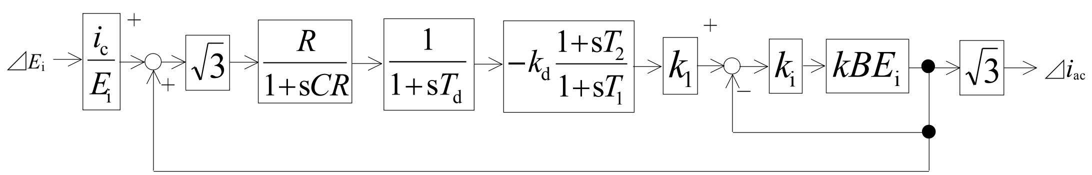

Fig.3 Block Diagram of Δi_{ac} to ΔE_i

3) Considering three phase power again, the conversion factor k_1 of the following expression is used when creating the input current command value per phase from the error signal of DC voltage.

$$k_1 = \frac{P}{\sqrt{3} E_i E_{dc}} \quad \cdots (7)$$

where P is the capacity of UPS [W]

4) The input current is assumed to be following the input current command value as determined by the rectifier control disregarding any actual error due to the dead time, etc. In other words, the input current command value and the input current are assumed to be equal.
5) The input current is indicated by the line current. Since the input current command value created by the controller is the phase sequence current, it is converted to line current using the factor of $\sqrt{3}$.

Therefore, the transfer function for the variable component of the input current to that of the input voltage can be derived from Fig.3 and is shown in the next expression.

$$\frac{\Delta i_{ac}}{\Delta E_i} = \frac{-3\left(i_c / E_i\right)\left(sT_2 R k_d k_1 k_2 + R k_d k_1 k_2\right)}{CRT_d T_1 s^3 + \left(CRT_d + CRT_1 + T_1 T_d\right)s^2 + \left(CR + T_1 + T_d + \sqrt{3} T_2 R k_d k_1 k_2\right)s + \sqrt{3} R k_d k_1 k_2 + 1} \quad \cdots (8)$$

where k_2 is the expression shown below.

$$k_2 = \frac{k k_i B E_i}{1 + k k_i B E_i} \quad \cdots (9)$$

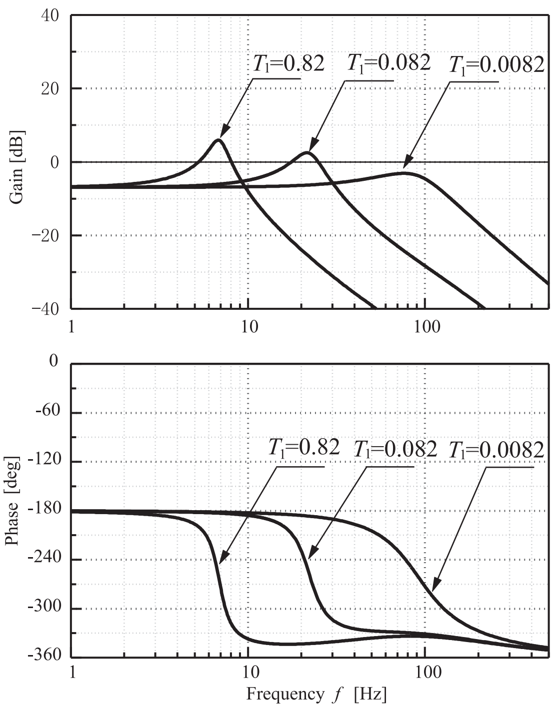

Fig.4 Frequency characteristics when integration element T_1 of PID control is changed

3. UPS Input Characteristic Analysis by Bode Diagrams

The characteristics of our double conversion type UPS (20kVA) are analyzed by the Bode diagram using the expression (8). Fig.4 is the frequency characteristic curves when the integral element T_1 in the PID control is assumed as a parameter. Fig.5 is the frequency characteristic curves when plotting differential element T_2 as a parameter. Fig.6 is the case when assuming the delay element T_d of the DC voltage detection as a parameter. In addition, the main circuit and control values are shown in Table 1. In Fig.4, larger integral element T_1 results in higher peak values and Q tends to become higher. In Fig.5, when differential element T_2 is large, the peak values are reduced with a damping effect. Therefore, Q rises when T_2 becomes a smaller value. Higher Q also results from an increasing delay element T_d in the DC voltage detection as shown in Fig.6. In other words, changes in the integral element T_1 can change the resonance frequency and increasing the differential element T_2 can control the peak of the resonance. Moreover, the delay element T_d is also an important element in the behavior of the system.

Suppose there is no delay element and the control is only P control (T_1=0, T_2=0, T_d=0), then expression (8) becomes a first order delay system and vibration is not generated. In other words, we can say that the PID control and the delay element are the causes of the resonance phenomenon. However, it is not practical to have only P control because it is understood that regular deflection would increase.

Table 1 Each Parameter of Main Circuit and Control Part

Parameter	Symbol	Value	[Unit]
DC capacitor	C	24,600	[μF]
Suspected load	R	7.29	[Ω]
UPS input voltage	E_i	200	[V]
DC voltage	E_{dc}	382	[V]
DC capacitor input current	i_c	52.3	[A]
Current control gain	k_i	8.3	
Voltage control gain (proportional gain)	k_d	160.78	
Voltage control gain (integral element)	T_1	0.082	[s]
Voltage control gain (differential element)	T_2	2.867	[ms]
Detection delay element	T_d	1.15	[ms]
Conversion factor	k_1	0.151	
Control signal initial value	A	0	
Control signal inclination	B	1	
Control variable	k	0.00453	

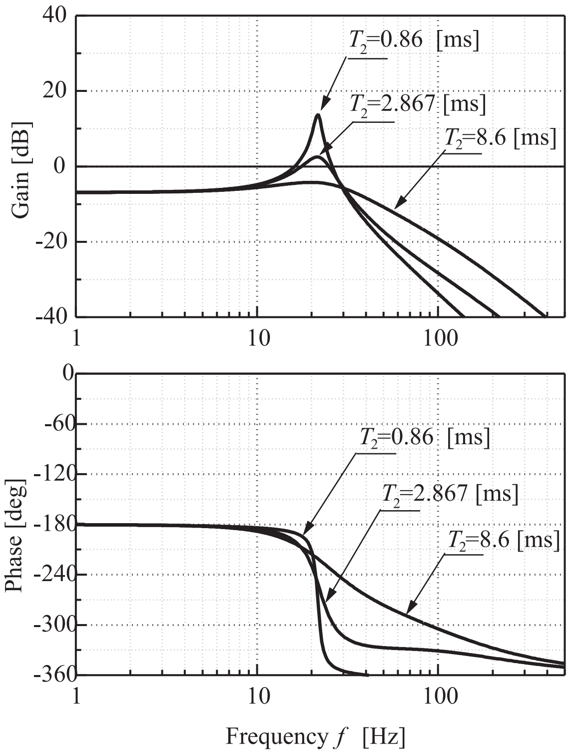

Fig.5 Frequency Characteristic Curves When Changing Differential Element T_2 of PID Control

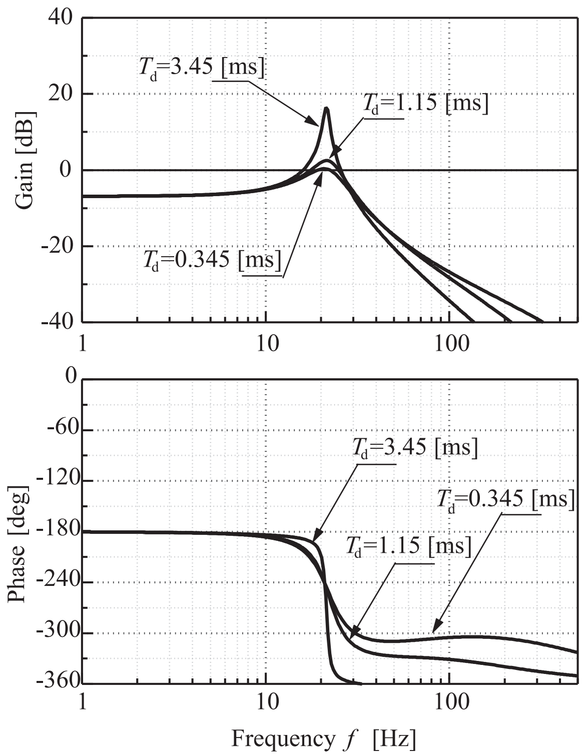

Fig.6 Frequency Characteristics When Integral Element T_1 of PID Control Is Changed

Moreover, the DC voltage control demands high accuracy because the storage battery is charged by the DC voltage control of the rectifier. This is another reason that the PID control for regular deflection is generally used. In short, the PID control should be used for the DC voltage control system and sufficient attention needs to be paid in setting the PID parameters around the low frequency area.

4. Verification by Waveform Simulation and Experiment

Waveforms were calculated from a simulation (using the Euler method when the modulation frequency was 15Hz and the amplitude ratio of the modulation frequency to a basic wave was 10%) and they are compared with actual measurement values as shown in Fig.7. The modulation element of the input current is 180 [deg] behind that of the input voltage because the rectifier has a constant power characteristic. The simulation waveform has reasonable correlation to the measurement values. The simulated waveform in the frequency domain (using our double conversion type UPS (20 kVA)), the measurement value, and the value obtained from the expression (8) were compared and shown in Fig.8. Amplitude aA of the modulation element can be found by FFT (Fast Fourier Transform) since modulation signal E_x can be shown as in the next expression.

$$\begin{aligned} E_x &= A\{1 + a\sin(\omega_x t - \varphi_x)\}\sin(\omega_0 t - \varphi_0) \\ &= A\sin(\omega_0 t - \varphi_0) + \frac{aA}{2}\sin\left\{(\omega_x - \omega_0)t - (\varphi_x - \varphi_0 - \frac{\pi}{2})\right\} \\ &+ \frac{aA}{2}\sin\left\{(\omega_x + \omega_0)t - (\varphi_x + \varphi_0 + \frac{\pi}{2})\right\} \end{aligned} \quad \cdots(10)$$

In Fig.8, the value obtained from the waveform simulation and the measurement value are a very close match at lower frequencies as compared with the value obtained from expression (8). An actual rectifier has a LC filter connected in the input to remove the high harmonics generated by the PWM control. It seems that the error appeared in the high harmonic area because this LC filter was not considered in the block diagram of Fig.3. Thus, the corresponding results for the input current characteristic to a change of input voltage were obtained between the calculation value, the simulation value, and the measurement value in the low frequency area. This shows that there is a possibility for a frequency to which the input current resonates when the input voltage changes, and SSR is generated when this resonance frequency corresponds to the axis resonance frequency of the generator. By the way, an example of the diagram of the rotation speed to the torque of the generator is shown in Fig.9. As described above, the axis resonance frequency on the generator side exists around the resonance point of the UPS input characteristic.

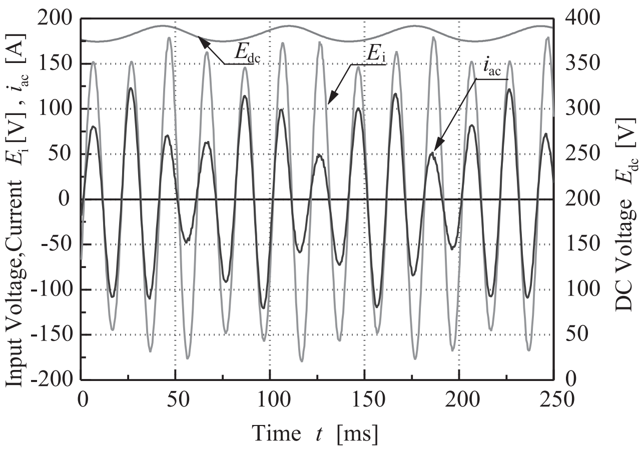

Fig.7(a) Simulation Waveform When There Is Modulation Voltage of 15[Hz]

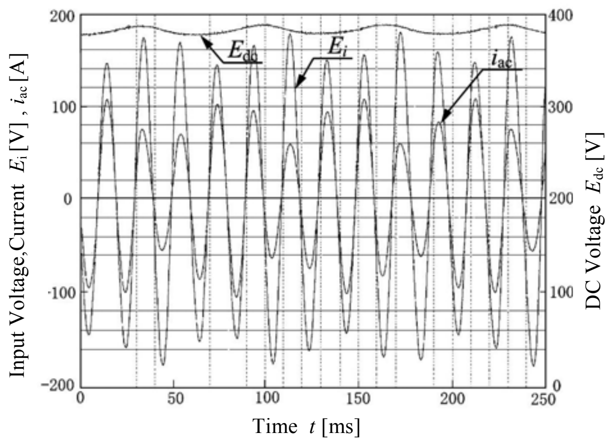

Fig.7(b) Measurement Waveform When There Is Modulation Voltage of 15[Hz]

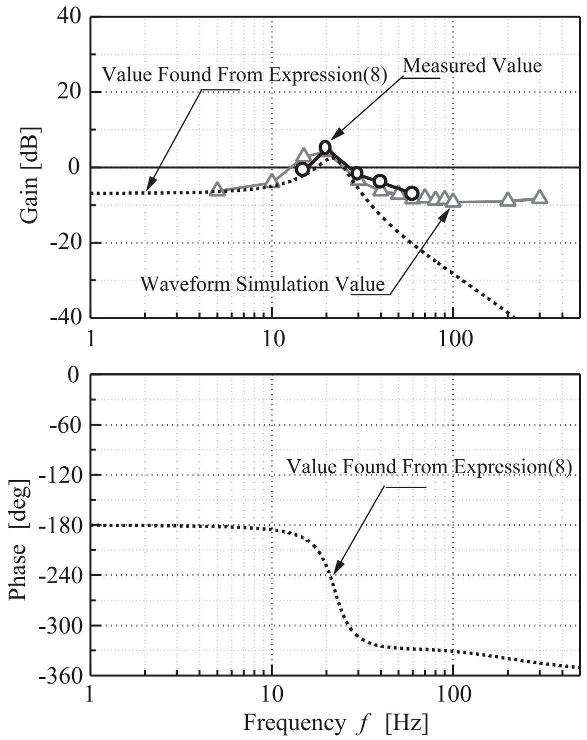

Fig.8 Frequency Characteristics of Input Current to Input Voltage

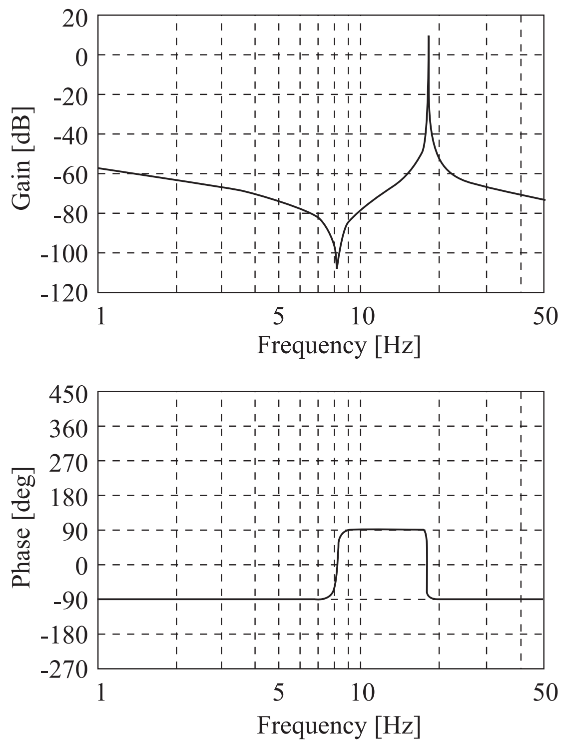

Fig.9 A example of Generator Bode Diagram (torque - rotation speed characteristics)

The transfer function for the system of the entire generator is too complex to practically model, but to simplify, suppose the rotation speed is proportional to the generator output voltage and the torque is proportional to the generator output current, it is then possible to say that Fig.9 on top of Fig.8 is a transfer function of the system. Therefore, the stability of the system can be determined from both figures, and there is a possibility that SSR is generated when both resonance points are corresponding.

5. Conclusion

In this paper, the UPS input characteristic considering a change in the input voltage was analyzed. The following points were described.

1) The transfer function for the variable component of the input current to that of the input voltage was shown, and the frequency characteristics were compared with simulation and measurement values.
2) It was shown that the compared values almost correspond and that a resonance frequency exists in the above-mentioned frequency characteristics. Therefore, there is a possibility that SSR will be generated when the resonance frequency is similiar to the axis resonance frequency of the generator.
3) It was suggested to pay particular attention to the frequency characteristic in the low frequency area when designing the control system for a rectifier.

We will examine detailed stability of the total system including the generator in the future.

Reference

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