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RESTRAINING METHOD OF VOLTAGE FLUCTUATION BY SYNCHRONOUS CONDENSER

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I. INTRODUCTION

In mill drive equipment, set capacities reach 20~30,000 kW and the loads change is extremely large. For example, a blooming mill requires large step fluctuation and the load of a rougher of hot strip mill increases or decreases from 0 MW to about 50~100 MW at step intervals of 1~2 seconds. The MVAR change is almost the same level as these severe MW changes. The derivative of the load change is about 0.2 sec. In blooming mills, this is very small compared with the power network capacity and the influence on the network frequency is almost no problem, but in the hot strip mills, there is a strong influence on the bus voltage, which has local characteristics.

The features of the severe load changes in steel works which cover large areas are generally as follows:

(1) The load change pattern is not constant for various types of mill and materials

(2) The various mill loads perform no special combininig operation in individual processes.

Such random reactive power fluctuations not only cause large changes in the bus voltage in the steel works but also influence changes in the network voltage in accordance with the receiving network conditions.

The on-off control method by several condenser banks is generally considered as the method of suppressing such fluctuations. However, in this system, the continuous control characteristics and quick response are poor, furthermore the life of the circuit breaker present a problem. On the other hand, in the control system using a thyristhr type switch, there are several difficulties such as the phase characteristics of the voltage and current and the voltage rating in respect to the large capacity condenser banks.

Fuji Electric uses a synchronous condenser to suppress voltage fluctuations of this type. In the investigation stage, a total system program was developed including the load characteristics, the operating characteristics of generator and motor, and the network conditions. Detailed investigations of various load conditions were made using a computer and the equipment capacities and control system were determined. In particular, the determination of the equipment capacities is based on the statistical method using a computer.

In order that the equipment can sufficiently exhibit its capabilities, it is the most important that reactive power is supplied rapidly in both the forward and reverse directions in respect to load changes in addision to the utilization of transient characteristics due to the rotational energy of a synchronous condenser. For this reason the excitation system employs a thyristor complete bridge type so that the exciation ceiling voltage is obtained up to 10 times for no load excitation. The reactive power peaks of each load pattern are high and all the condensers must bear the total of all the peaks. This is the only reason for the large capacity of the equipment. Since it is uneconomical, only the reactive power fluctuation are detected in hot strip mills or cold rolling mills where the peaks are large. This is used as control input and it is necessary to distribute the large base reactive power among other generators and motors. Therefore, in addition to general AVR control system, the load VAR detection system, automatic field current control system and incomplete derivative circuit system, full use is made of the equipment capabilities to the maximum limit (patent applied for). From the results of site operation tests, it has been confirmed that the planned performance is obtained.

II. CHARACTERISTICS OF SYNCHRONOUS CONDENSER

1. Transient Characteristics of Synchoronous Condenser

When a synchronous machine generates a voltage due to excitation, a large transient current flows if there is a sudden short circuit across the terminals. In order to explain this phenomenon, an electric circuit with a resistance R, self inductance L and mutual inductance Mn is employed. When a voltage is applied to the terminals of the circuit, the following equation is established:

Table 1 Supply list of synchronous condenser

Comparison items	Nippon Steel (Kimitsu)	Kobe Steel (Kakogawa)	Certain company
Capacity	84 MVA (Lead 84 MVA Lag 30 MVA Peak 120 MVA 1 min)	50 MVA (Lead 50 MVA Lag 18 MVA Peak 70 MVA 1 min)	26.5 MVA (Lead 26.5 MVA Lag — Peak 35 MVA)
Withstand capacity for negative phase current	17% (negative phase)	17% (negative phase)	20% (negative phase)
Voltage, frequency	9 kV • 50 Hz	11 kV • 60 Hz	9 kV • 60 Hz
No. of poles, speed	6 P • 1,000 rpm	6 P • 1,200 rpm	6 P • 1,200 rpm
Use conditions	Outdoor	Outdoor	Outdoor
Cooling system	Hydrogen cooling	Hydrogen cooling	Totally enclosed internal cooling
Excitation system	Thyristor exciting	Thyristor exciting	Thyristor exciting
Excitation capacity	300 V 790 A	250 V 880 A	650 A
Starting system	Induction synch. motor (3.3 kV 1,800 kW 10 min.)	Induction synchronous motor (3.3 kV 1,300 kW 10 min.)	Half voltage starting
Connection	Star conn. without neutral grd.	Star conn. without neutral grd.	Star conn. without neutral grd.
Lead-in	Top busduct	Top busduct	Cable
X_d, X_q	210% 160%	200% 150%	175%
X_d', X_d''	38% 23%	34% 22%	33% 19%
X_2, X_0	23% 9%	22% 9%	19%
T_{d0}', T_d', T_a	10 sec., 1.8 sec, 0.24 sec	7 sec, 1.3 sec, 0.22 sec	7 sec, 1.5 sec, 0.17 sec
Voltage wave deform factor	Less than 5%	Less than 5%	Less than 5%

$$e=Ri_1+L\frac{di}{dt}+Mn\frac{di_n}{dt} \quad \cdots\cdots (1)$$

When the resistance R is disregarded and there is a short circuit across the terminals, the following arises :

$$L\frac{di_1}{dt}+Mn\frac{di_n}{dt}=0 \quad \cdots\cdots (2)$$

Therefore :

$$Li_1+Mni_n=K \quad \cdots\cdots (3)$$

Equation (3) shows that the circuit flux is constant at the instant of the short circuit. This is the well known "Constant flux interlinkage law" for electric circuits. This holds not only for simple short circuits but also at the instant of all load changes.

In *Fig. 1 (a)*, when there is a sudden short circuit under the condition that the flux is linked as shown by the arrows so that a voltage at no load is induced in the stator coil by excitation of the field coil, a transient current flows in the stator coil to maintain the linkage flux with the coil constant. *Fig. 1 (b)* shows the flux distribution. The DC component which flows to maintain the linkage flux constant with the coil at the time of the short circuit induces the current in the rotor winding.

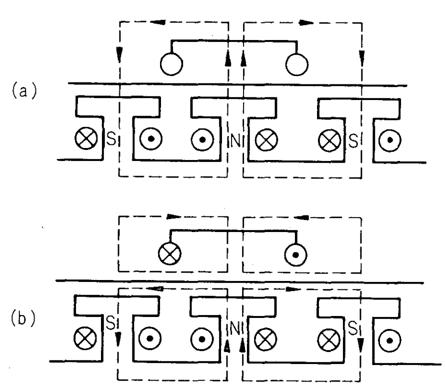

Fig. 1 Flux path

With the synchronous condenser (SC) connected in the network, the armature current I_q (reactive component) and the field current I_f as well as the changes of the internally induced voltage when there is a sudden change of 10% in the network voltage, were investigated by the following equations.

$$2\pi fH\frac{d^2\delta}{d\tau^2}=T_M-T_L \quad \cdots\cdots (4)$$

$$T_M=\frac{1}{X_1}(\psi_{md}\psi_q-\psi_{mq}\psi_d) \quad \cdots\cdots (5)$$

$$\psi_q=-e_L\sin\delta,\ \psi_d=e_L\cos\delta \quad \cdots\cdots (6)$$

$$\frac{d\psi_{fd}}{d\tau}=e_{fd}-\frac{r_{fd}}{X_f}(\psi_{fd}-\psi_{md}) \quad \cdots\cdots (7)$$

Where
H : starting time constant
X_1 : leakage reactance of SC primary
e_L : network voltage
r_{fd} : field resistance
X_f : field leakage reactance

$$\psi_{md}=\frac{\frac{\psi_d}{X_1}+\frac{\psi_{fd}}{X_f}}{\frac{1}{X_1}+\frac{1}{X_{ad}}+\frac{1}{X_f}} \quad \cdots\cdots\cdots\cdots (8)$$

$$\psi_{mq}=\frac{\frac{\psi_q}{X_1}}{\frac{1}{X_1}+\frac{1}{X_{aq}}} \quad \cdots\cdots\cdots\cdots (9)$$

Where X_{ad} : direct axis mutual reactunce
X_{aq} : quadrature mutual reactance
T_L : load torque (only machine loss in this case)
δ : internal phase angle difference
T_M : electric torque of SC

Fig. 2 shows the results obtained using a computer from the above equations with the calculation values inserted for the various constants. From these results, the following statements can be made.

(1) At the instant the network voltage is reduced by 10%, 30% per unit of the stator current I_g flows. The field current I_f instantly rises 30% to compensate for the magnetic flux which decreases when I_g flows. Therefore, it is also evident that the voltage E' behind X_d' does not vary at the instant $t=0$. The above phenomenon is identical to that described in II-1 and shows that the circuit has the capacity to supply reactive current instantly.
(2) The field strength can be raised to the ceiling voltage in the same manner as in actual operation. When assembled as input data, t becomes greater than 0 so that the field strength increases and I_g increases following the increase in I_f. After 0.5 sec., I_g increases to $\simeq 0.85$ (p. u.).
(3) When $t=0.5$ sec., if E is returned to the value when $t<0$, i. e. raised by 10%, a phenomenom which is completely opposite to that of (1) occurs. In other words, since the network voltage has risen only by ΔV, $\Delta I_g=30\%$ instantly flows into SC and I_g is reduced by ΔI_g. In order to maintain the magnetic flux constant by reducing the increasing flux, I_f decreases instantly by $\Delta I_f=30\%$. At this point, the phenomenon described in II-1 appears and it is evident that the circuit has the capacity to instantly reduce the reactive current.
(4) When $t>0.5$ sec., the decreasing abilily of the excitation circuit causes I_g and I_f to decrease along the path shown in *Fig. 2* (*b*).
(5) When the interval for returning the network voltage to the value $t<0$ is $t=1$ sec., the decrease follows the path indicated by the broken line in *Fig. 2* (*b*).
(6) Under the various conditions, the increase characteristics of I_g at $0<t<0.5$ sec. and $0<t<1.0$ sec. correspond to the load increases. Since saturation of the core is disregarded in the calculations, the increase tendency of I_g at above $I_g>1.0$ p. u. is slightly greater than that of an actual machine.
(7) Under the various conditions, the decrease characteristics of I_g at $0.5<t$ and $1<t$ correspond to the load decreases.

From the above, it is evident that a synchronous machine has the capacity to supply or absorb reactive current instantaneously at the instant of load changes.

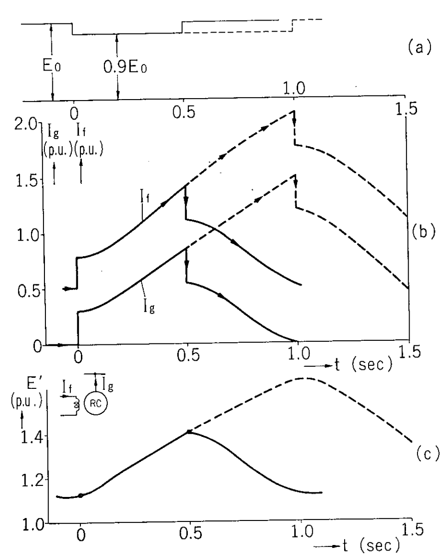

Fig. 2 Response characteristics of synchronous condenser

2. Effectiveness of the Synchronous Condenser Against Voltage Variation When a Load is Applied

The results will now be given of a study on the instant voltage induced by cold and blooming mill load in the case of the Kimitsu network of Nippon Steel.

1) Calculation conditions

The network conditions were as shown in *Fig. 3* and the following assumptions were employed in the calculation :

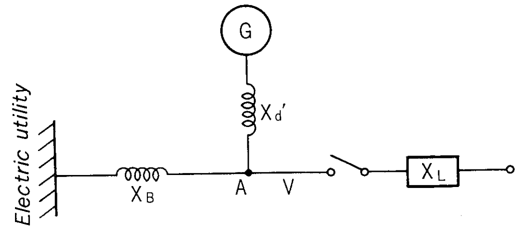

Fig. 3 Equivalent circuit

(1) For the impedance of each synchronous machine, X_d' on the severe side was adopted for instantaneous voltage drops.
(2) t_d' back voltage was constant.
(3) For the load, a case in which one cold rolling mill (0→57 MVA) and a blooming mill (0→50 MVA) are applied simultaneously, was assumed.

2) Calcuation results

Under the conditions given in 1), the instantaneous voltage drop of each section was calculated with a FACOM 230–50. For comparisons in calculation, case involving only the network and case involving the network and synchronous machine groups were studied. Calculations were performed for these cases. From *Table 2,* the following can be stated :

Table 2 **Instant voltage dip**

Terminal locations / Condition	3 (When normal voltage regulation of 2% or less is required)	4 (When normal voltage regulation of 5% or less is required)	17	2
System only	4%	7.6%	3.1%	1.7%
System+SMG	1.4%	1.4%	1.2%	0.6%

In cases involving only the network, voltage drops of 4% occurred at point 3 and voltage drop of 7.6% at point 4. In cases involving the network and synchronous machine groups, the voltage drop were reduced to 1.4% and 3.7% respectively. When the above is considered qualitatively, it can be substituted in the equivalent circuit in *Fig. 3.*

The voltage drop $\varDelta V$ at point A can be expressed by equation (10).

$$\varDelta V=\frac{V}{1+X_L\dfrac{X_d'+X_B}{X_d'\cdot X_B}} \quad \cdots\cdots\cdots\cdots\cdots\cdots\cdots (10)$$

In the case involving on the network, $X_d'\rightarrow\infty$ and equation (10) becomes as follows :

$$\varDelta V=\frac{V}{1+\dfrac{X_L}{X_B}} \quad \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots (11)$$

In equations (10) and (11),

$$X_L\frac{X_d'+X_B}{X_d'\cdot X_B}\gg 1,\ \frac{X_L}{X_B}\gg 1$$

and therefore they become as shown below :

$$\varDelta V\cong V\frac{X_B}{X_L}\cdot\frac{X_d'}{X_d+X_B} \quad \cdots\cdots\cdots\cdots\cdots\cdots\cdots (12)$$

$$\varDelta V\cong V\frac{X_B}{X_L} \quad \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots (13)$$

In other words, if synchronous machine groups are employed, the voltage drop in respect to the voltage drop in the case involving only the network, is approximately $\dfrac{X_d'}{X_d'+X_B}$ time smaller.

As shown in *Table 2,* the voltage drop at point 3 is reduced from 4% to 1.4% and $X_B=3.86\%$, then X_d' becames 7.1% because of

$$\frac{X_d'}{X_d+3.86}=\frac{1.4}{4}=0.35.$$

III. ANALYSIS INCLUDING NETWORSK AND LOAD

In an analysis of the process for plant voltage variations caued by loads in independent operations, it is necessary to have (1) the system impedance map, (2) the various load patterns (power and reactive power), and (3) the various constants and control loop transfer functions for the internal synchronous generator, synchronous condenser, synchronous motor loads, etc. The features of the transient power flow calculation method including rotary systems developed by Fuji Electric aıe as follows :

(1) The *PQ* patterns for each load are easy to use as input.

(2) The transfer functions of the synchronous machines are expressed by the 2-axis method with direct and quadrature axis. The effects of subtransients are included.

(3) Governor characteristics of prime movers and field control systems are also included. Swing phase angles of rotors can also be calculated.

An example of a result obtained by this method is shown in *Fig. 4.*

The capacity of the synchronous condenser was decided as follows. There is a control delay and if conditions are considered in which there are independent operations for each load at which voltage drops arise in accordance with fluctuation component of the reactive power flow of a network from which the transient response component of the synchronous condenser had been removed as was described previously, these voltage drops become very large when

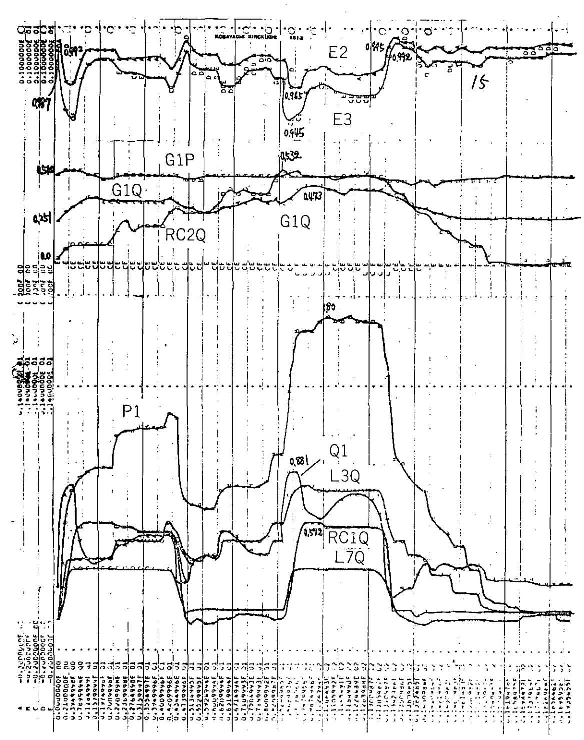

Fig. 4 Voltage and reactive power by computer

the loads overlap. In other words, the problem concerning the voltoge drops is the probability of the loads overlapping. Therefore, we calculated the probability of any load pattern overlapping by assuming the operation percentage of every load and adding the pattern of absorption of the reactive power by field control of the synchronous condenser. We then developed a calculation program in which the voltage drop histogram is made as shown in *Fig. 5*. With this program, the capacity of the synchronous condenser is determined. *Fig. 5 (a), (b)* and *(c)* shows the histogram calculation results concerning voltage drops when the synchronous condenser capacity was altered from 25 to 30 to 35 MVA in the case of an example planned for a certain steel works. The ordinate shows the voltage drop rate and the abscissa shows the aggregate time in which there voltage drops occur in one day.

The capacity of the synchronous condenser is determined by considering the permissible occurance probability over the set voltage drop value (hours of continuous voltage drop/24 hours).

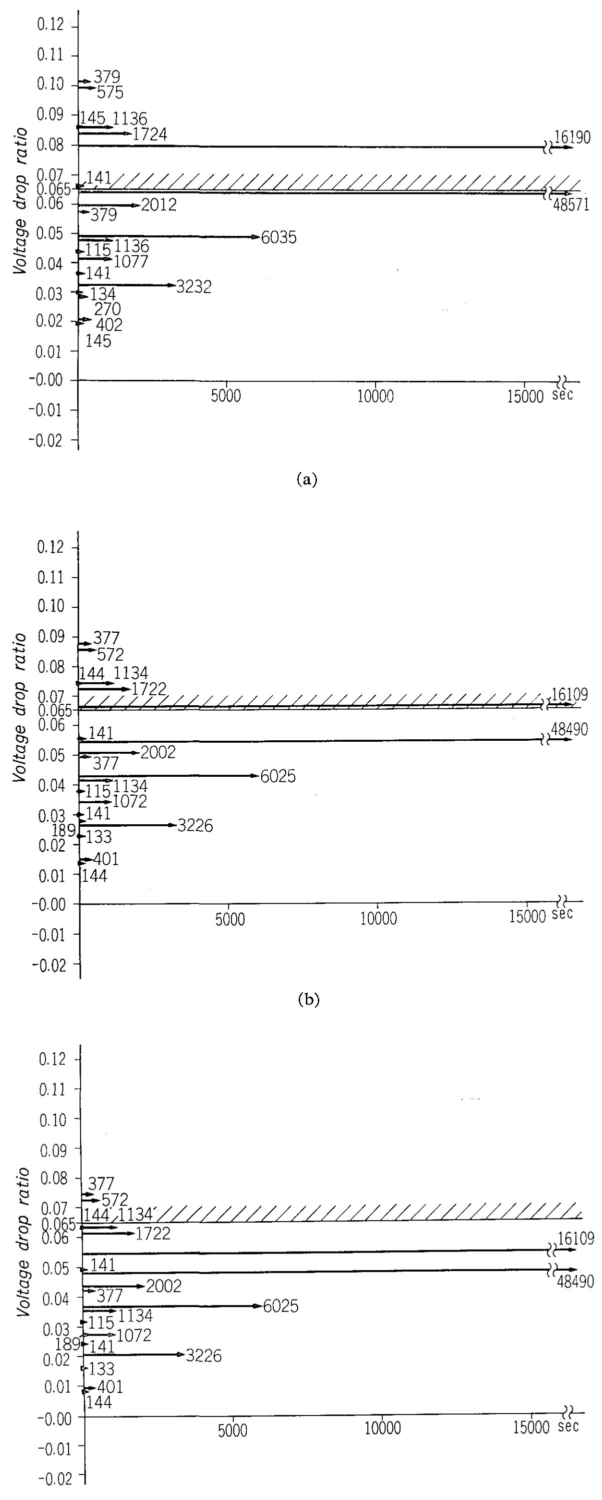

Fig. 5 Probability of voltage drop by computer

IV. MAIN CIRCUIT CONSTRUCTION AND CONTROL SYSTEM

1. Main Circuit Construction

Fig. 6 shows examples of the main circuit construction of the synchronous condenser. The system shown in (a) uses a synchronous induction motor to start the synchronous condenser. After the induction motor is started, the slip of the current induced in the secondary winding is utilized to pull in the synchronous conditions via the thyristor type secondary current control device. The voltage phase

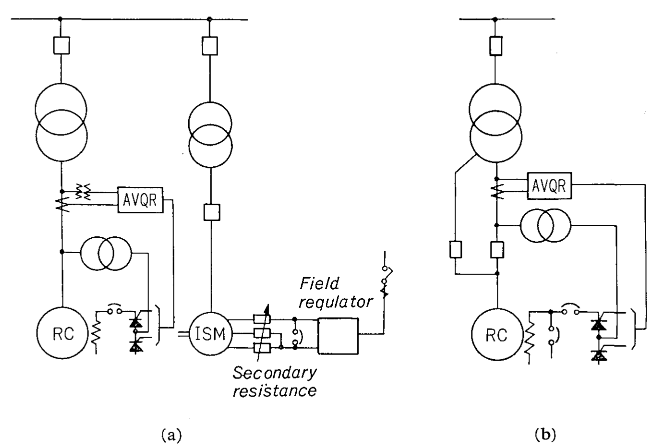

Fig. 6 Starting method

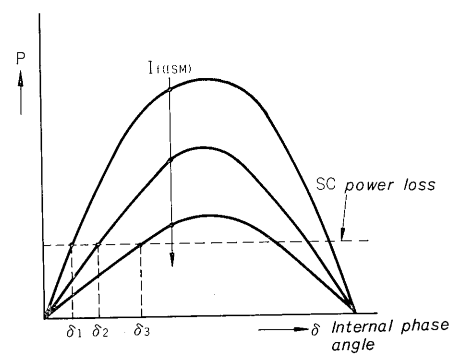

Fig. 7 Internal angle characteristics of ISM

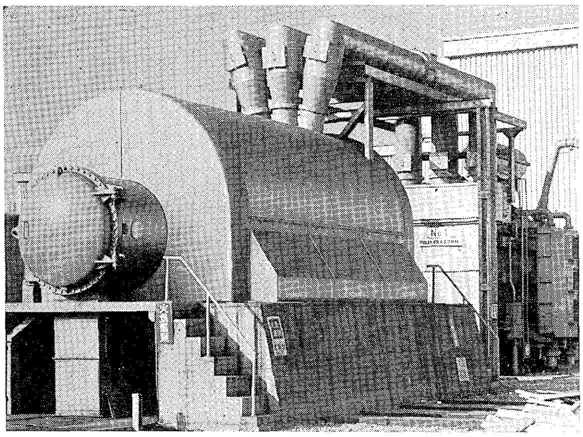

Fig. 8 Outerview of 84 MVA (outdoor type)

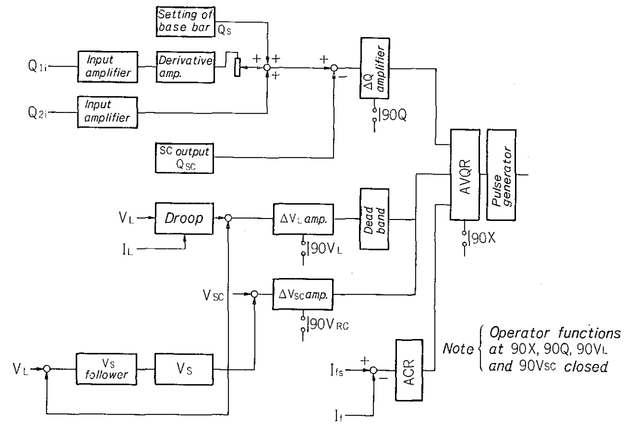

Fig. 9 Block diagram of control loop

control with the network of the synchronous condenser is fine controlled via the ISM field current. In reference to *Fig. 7*, the ISM circuit breaker is released after synchronization. This sequence is controlled by the master SW.

In *Fig. 6 (b)*, the synchronous condenser is started by the center tap on the low voltage side of the main transformer as the induction motor. When the specified slip is reached, there is conversion to the normal voltage, excitation occurs and synchronous conditions are pulled in. This can be applied to 26.5 MVA SC.

When the internal network voltage fluctuations due to the mill load are suppressed by the synchronous condenser, the most important design condition is to make the exciting response high.

The escential condition for increasing the exciting response is to first employ thyristor exciation equipment. The thyristor power gain and the AVQR gain are as high as possible so that the inherent field time constant of the sychronous condenser is decreased considerably. It is recommended that the thyristor type rectification device employ a 3-phase full bridge rather than a mixed bridge.

In order that the AVQR have the ability to amplify various types of mixed computing, it is most appropriate to be used with transistor type amplifiers.

2. Purpose and Characteristics of the Control Loops

A block diagram of the control loop is given in *Fig. 9*. All control loops consist of TRANSIDYN type amplifiers. The power sources for these control devices are permanent magnet generators rather than internal power sources. Therefore, constant power can be supplied with no influence from external disturbances.

(1) ΔV_{SC} control loop

Purpose: Automatic voltage control before paralleling the synchronous condenser. After network paralleling, $_{\Delta}Q_L$ and ΔV_L controlloops are ON.

Characteristics: Synchronous condenser terminal voltage (V_{SC}) is constant.

Setting: Motor driven type V_S setter is used.

(2) ΔV_L control loop

Purpose: Automatic voltage control of the synchronous condenser after network paralleling. The control objective is the bus voltage of *SC* transformer high tension side.

Characteristcs: Normally, the synchronous condenser has a base output according to setting Q_S and setting inputs Q_i and Q_j*1. However, when the network bus voltage exceeds the specified value (dead band) and varies greatly, it functions as an automatic voltage regulator with a voltage drooping characteristic. The voltage drooping is determined by the impedance between the *SC* transformer and the power system bus. In other words, from the relationship between the variation of the load reactive power and the above impedance, the response ΔV_L is determined. If the above voltage regulation continues for an extended period, the V_S setter is follow-up controlled by the system bus voltage, V_S matches the network voltage and since it is driven into the dead zone, *SC* again responds to the setting inputs Q_i and Q_j.

Note) *1 Q_i: proportional response to load variations

Q_j: incomplete differential response to load variation.

(3) V_S follow-up control

Purpose: When the network bus voltage exceeds the specified dead zone width with respect to V_S during V_L control, the circuit temporarily generates a reactive power in accordance with the voltage drooping. If the above condition persists, V_S is matched to V_L and *SC* must constantly exhibit maximum capacity with respect to Q_i and Q_j.

Characteristics: When a dead band of 0～2% is exceeded, the circuit has the following characteristics since V_S is made to follow up V_L through an interrupter.

(4) ΔQ control loop (Patent applied for)

Purpose: Control of the reactive power output of *SC*.

Characteristics: In the loop setting, the base output is Q_S, the proportional input is Q_i and the incomplete differnential input is Q_j.

Setting: Q_S 0～100% lead, adjustable.

Q_i Each rective load power quantity (in blooming, etc.) is used as setting input via a proportional calculator. 0～100%, adjustable type.

Q_j Each reactive power load (in cold rolling and hot rolling mills) is used as a settsng input via an incomplete differential calculator.

(5) Field current control loop (ACR)

Purpose: When the field current of *SC* increases with respect to control signals $\Delta Q=(Q_S+\Sigma Q_i+\Sigma Q_j)\sim Q_{SC}$ of AVQR and its value reaches the maximum permissible value, the control gignal for the thyristor autmoatically switches from the AVR to the ACR and when $\Sigma Q_i+\Sigma Q_j$ or a great voltage variation during V_L control rised above the specified value, the loop keeps the field current constant.

Characteristics: When combined with the main controller, if the field current exceeds the ACR setting value and after a constant time limit (due to the integrating characteristics) the ΔI_f control signal potential is relatively high with respect to the ΔQ control signal potential, a shift is made from AQR to ACR automatically. (Refer to *Fig. 10*).
An operational amplifier having PI characteristics is employed. The main controller of the AVQC is also of the PI type. The constant settings of each is made in the same characteristics as those of the AVQC.

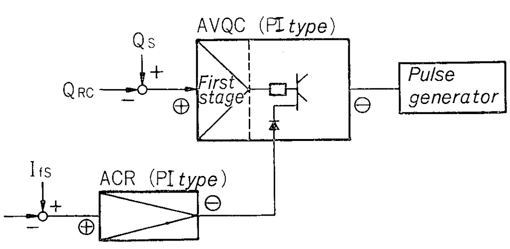

Fig. 10 ACR loop

(6) Overall AVQR characteristics

The overall characteristics of the various AVQR operational loops are shown below.

AVQR input signals

$$=U_{\Delta V}+V_{\Delta Q}\cdots\cdots\cdots\cdots U_{\Delta If}<U_{\Delta V}+U_{\Delta Q}$$

$$=U_{\Delta If}\cdots\cdots\cdots\cdots\cdots\cdots U_{\Delta If}>U_{\Delta V}+U_{\Delta Q}$$

Where,

$$U_{\Delta V}=K_0\Delta V_{RC} \text{ or } K_0\Delta V_L$$

$$U_{\Delta Q}=K_1\Delta Q=K_1[(Q_S+\Sigma Q_i+\Sigma Q_j)-Q_{RC}]$$

$$U_{\Delta If}=K_2\Delta I_f=K_2(I_{fS}-I_j)$$

(7) Reactive power detector

For quick excitation of synchronous condenser it is undesirable that the reactive power detector have any delay in its detecting operations.

To solve this, many reputable FV converter are improved to make the 100% response time less than 20 m sec.

V. TEST RESULTS

Test results for the 84 MVA synchronous condenser delivered to the Kimitsu steel works of the Nippon Steel Corporation are shown in *Fig. 11.*

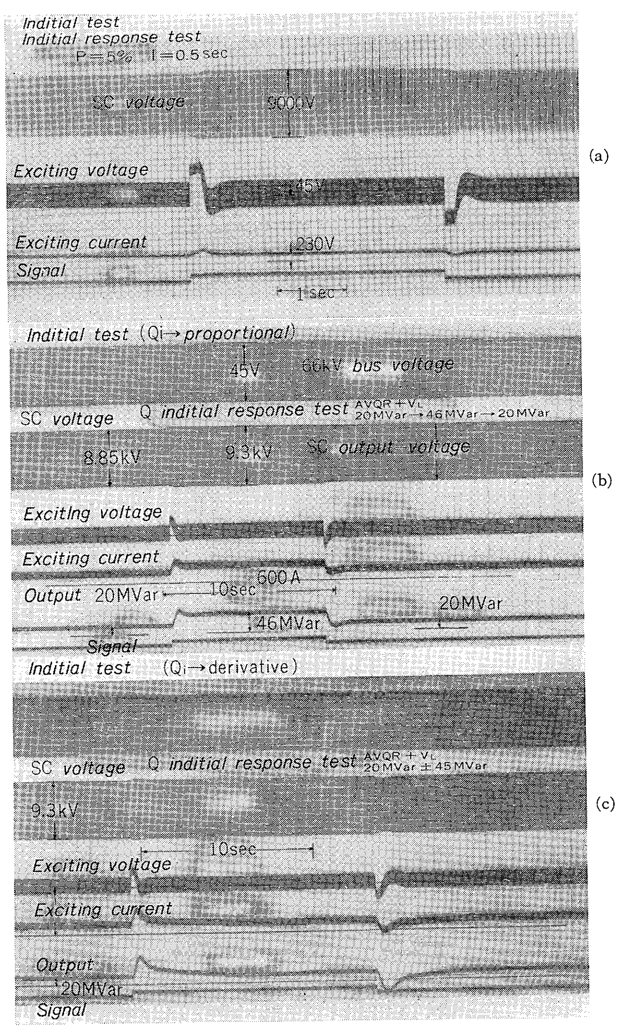

Fig. 11 Inditial response test

Fig. 11 (a) shows the inditial response tests results for the ΔV_{SC} loop where $\Delta V_S = 90 \rightarrow 100 \rightarrow 90\%$ *Fig. 11 (b)* shows the inditial response tests results of the ΔQ loop (proportional setting input) where $\Delta Q_i = 20 \rightarrow 46 \rightarrow 20$ MVAR. *Fig. 11 (c)* shows the inditial response test results for the ΔQ loop (incomplete differental setting input), where $\Delta Q_i = 20 \pm 45$MVAR. According to this oscillogram, there is an effective response only to the rapid fluctuation parts for the reactive power loads such as hot strip mill rougher loads, and it is attained in several hundred thousand kVAR. The reactive power is shared among the power network and the synchronous machines in the work's plant and it is proven that the synchronous condenser is effective in respect to sudden reactive power disturbances under normal conditions.

Performance tests were also conducted on the synchronous condenser in the same steel works. The performance of the synchronous condenser was found to be satisfactory (refer to *Table 3*).

***Table 3* Measured values of voltage fluctuation**

No.	Condition of SC	σQ_{HOT}	σQ_{SLAB}	σ TOTAL	σVL
1	HOT derivative SLAB proportional	24.833	2.747	20.308	1.121
2	HOT proportional SLAB proportional	15.348	2.959	8.045	0.444
3	HOT proportional SLAB Zero gain	19.099	2.598	9.412	0.520
4	STOP	10.170	2.443	19.393	1.071
5	STOP	17.254	1.801	17.084	0.943

Collecting data of the sychronous condenser output, reactive power input, house power voltage by a data collector (DATAC), the wave form analysis was performed by means of a computer.

The results of actual tests performed on the 50 MVA unit in the Kakogawa Works of Kobe Stell confirmed that the unit operation is highly effective. Prior to intstalling the synchronous condenser, there were voltage fluctuations of 2,000 on the 77 kV bus but after installation of the condenser, these were reduced by several hundred volts.

VI. CONCLUSION

For the part one or two decades, there have been no demands for synchronous condensers, because of the increasing the static condenser and the cable occupation factor in networks, etc. Howevr, motors in the recent large scale rolling mills have become of the types with direct thyristor control in place of the former MG system and fluctuations in reactive power have increased. As a result, voltage fluctuations are induced and this not only has a bad infleuce on the machinery in the plant, especially the plants which thyristors are used, but also causes voltage disturbances in the power network bus line.

Fuji Electric has concentrated on transient reactive power output which acts magnetically in synchronous condensers and by means of the network transient calculation method developed by Fuji (simultaneous calculation of up to 20 synchronous condensers and 50 network branches is possible), it has been concluded that sufficient suppression of voltage fluctuation can be obtained by increasing the response of the excitation system of synchronous condenser. Already, one 84 MVA unit has been delivered to the Kimitsu Works of the Nippon Steel Corporation, one 50 MVA unit to the Kakogawa Works of the Kobe Steel, 26.5 MVA unit to certain company and three both are operating satisfactorily.