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REDUCING VOLTAGE FLICKER OF STEEL MELTING ARC FURNACE BY SYNCHRONOUS CONDENSER

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I. FOREWARD

Rapid developments have been made in steel melting arc furnaces and a 400 t arc furnace has been put into operation in America. The abrupt, irregular fluctuations in the arc current of the steel melting arc furnace produce voltage flicker in the power line voltage. The arc furnace requires a large power network, and if a sufficient network capacity is unavailable, a flicker suppression equipment is required. The synchronous condenser flicker suppression equipment, one method of suppressing voltage flicker, is described in this article. The 8,000 kVA synchronous condenser delivered to the Nambu Steel Manufacturing Co., Ltd. and now operating satisfactorily is described.

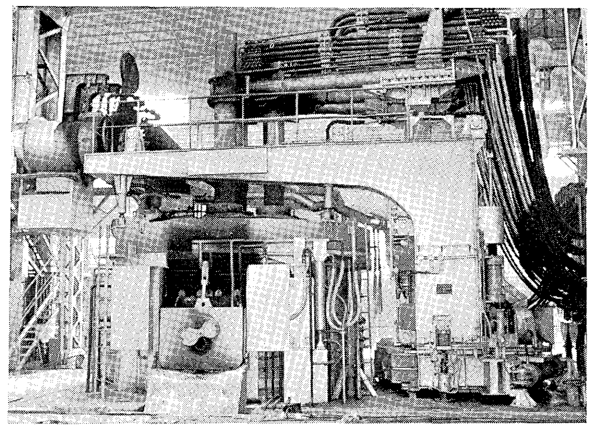


Fig. 1 View of arc furnace

II. STEEL MELTING ARC FURNACE EQUIPMENT AND CAUSES OF VOLTAGE FLICKER

The majority of furnaces have a capacity of up to 30 t now, but the present trend is toward large furnaces having a capacity of over 30 t. The furnace transformer normally connected to the 20～30 kV network gradually being used by direct stepdown from 50～60 kV and 150 kV with the increased size of furnaces. The large current arc between the electrodes and the scrap is repeatedly, abruptly and irregularly varied by sudden shorting of the arc due to the melting down of the scrap and the fluctuations in the length of the arc caused by the shifting of the arc point which accompanies the melting of the scrap. When the scrap is melting the pond of the molten metal is produced. The 3-phase AC arc and arc point is shifted by the mutual electromagnetic force to the furnace wall direction, and when the length of the arc exceeds a certain point, the arc point is again produced under the electrode. When the arc furnace is connected to a relatively weak power network, the impedance voltage drop produced by the arc furnace current periodically fluctuates and is accompanied by fluctuations in the network voltage because the power source side impedance Zs is large.

III. VOLTAGE FLICKER LIMITS AND REDUCING VOLTAGE FLICKER

1. Voltge Flicker Limits

There are various scales used to express the degree of flicker, but the most general method is one in which flicker is expressed as the amplitude $\Delta V_{10}(\%)$ of 10 Hz since wave voltage regulation which is most sensitivity to the human eye.

ΔV_{10} is calculated from the following equation.

$$\Delta V_{10} = \sqrt{\sum(\alpha_{fn} \cdot \Delta V_{fn})^2} \quad \cdots\cdots (1)$$

where : ΔV_{fn} = voltage flicker at frequency fn

α_{fn} = coefficient of visibility (*Fig. 2*)

The permissible values announced in 1964 by the "Lighting Flicker Standards Special Investigative Committee" of the Society of Electric Cooperative Research (Japan) are listed in *Table 1.*

2. Flicker Suppression Countermeasures

1) Reducing the reactance component of the powei line

By adding a parallel generator, or modifying the power network.

2) Compensating for the reactance component of the power line

(1) Series condenser

Table 1 Limit of voltage flicker

	ΔV_{10} (%)	
	Group A	Group B
Maximum value	0.45	0.83
Mean value	0.32	0.45～0.63

NOTE: Group A: 6 power companies
Group B: 3 power companies

(2) Tertiary winding compensating transfermer
3) Compensating for the voltage drop
(1) Stepping up the supply voltage
(2) Booster
(3) Mutual compensating transformer
4) Absorbing the variations in the reactive power of the load
(1) Synchronous condenser and buffer reactor
(2) Parallel connected type saturable reactor
(3) Switching condensers in accordance with the load variations
5) Reducing arc current fluctuations
(1) Series reactor for furnace
(2) Series connected type saturable reactor
6) Network separation
(1) Special power line
(2) Special transformer
7) Others
(1) Improvements of arc furnace
(2) Improvements of power source (DC, harmonic superimposition, etc.)
(3) Improvements of operating method

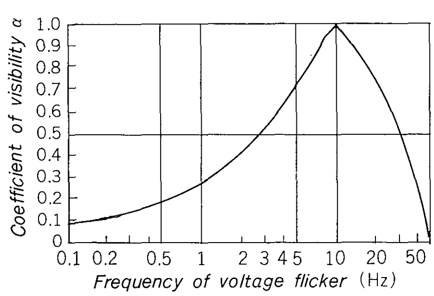


Fig. 2 Coefficient of visibility

IV. FLICKER REDUCTION BY SYNCHRONOUS CONDENSER

1. Absorptive Characteristic of Reactive Power by Synchronous Condenser at Transient

The synchronous condenser (hereinafter referred to as *RC*) can absorb and discharge reactive power in response to sudden changes in the furnace, due to the inherent characteristics of rotating machine, that is " flux constant linkage characteristics ". We consider the case that the *RC* is short circuited at the terminals when operating at rated voltage with no load. The state at which voltage e is impressed on the electrical equivalent circuit consisting of the equivalant resistance *R*, self inductance *L*, and mutual inductance *M*, (*Fig. 3*):

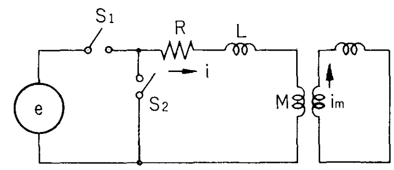


Fig. 3 Equivalent circuit

$$e=Ri+L\frac{di}{dt}+M\frac{di_m}{dt} \quad \cdots\cdots(2)$$

Since R is normally so small that it can be disregarded, the equation for the S_2 on, S_1 off state, becomes,

$$L\frac{di}{dt}+M\frac{di_m}{dt}=0 \quad \cdots\cdots(3)$$

i.e., $Li+Mi_m=\text{constant}$.

This shows that the magnetic flux of the circuit is constant at sudden short circuits. This relation is termed the " flux linkage constant linkage characteristics " and is realized not only at short circuits but also at all sudden load changes. In *Fig. 4* (*a*) the flux links as shown by the arrows by excitation of field winding (rotor) and a no-load voltage is induced in the stator winding. When a sudden short circuit occurs, a transient current flows in the stator winding and the distribution of the flux becomes as illustrated in *Fig. 4* (*b*). Since the current flowing in the stator winding intends to cancel the main flux, the current flowing in the stator winding increases to maintain the flux constant. That is, since reactive power can be quickly supplied with respect to sudden changes in the load, such as occurs in the arc furnace, and also active power can be quickly supplied by the rotating energy as described later, the synchronous condenser is con-

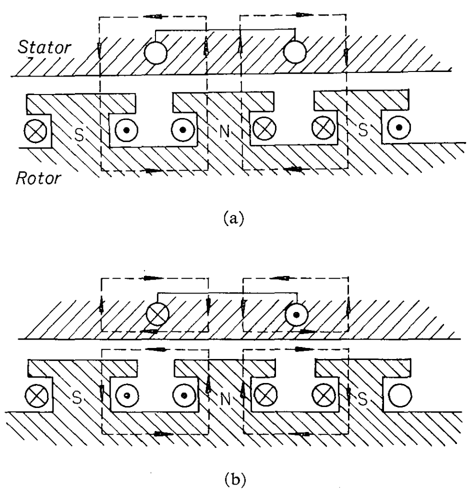


Fig. 4 Distribution diagram of flux

sidered to be most effective to a flicker reduction.

2. The Duty of *RC*

1) The internal impedance X_{RC} of *RC*

The *RC* for improving flicker is normally connected to the furnace bus (flicker bus) and a buffer reactor is installed in series with the network. An equivalent circuit is shown in *Fig. 5*.

The large reactive power fluctuations caused by operation of the furnace are supplied from the network and *RC*. The proportion of each is inversely proportional to the impedance of each. That is, each reactive power can be expressed by the following equation.

Reactive power supplied from power line

$$\Delta Q_S = \frac{X_{RC}}{X_S + X_B + X_{RC}} \cdot \Delta Q \quad \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots (4)$$

Reactive Power supplied from *RC*

$$\Delta Q_{RC} = \frac{X_S + X_B}{X_S + X_B + X_{RC}} \cdot \Delta Q \quad \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots (5)$$

where ΔQ = Reactive power fluctuation

Therefore, voltage fluctuation ΔV becomes,

$$\Delta V = \Delta Q \cdot X_S = \frac{X_{RC} \cdot X_S}{X_S + X_B + X_{RC}} \cdot \Delta Q \cdots\cdots\cdots\cdots\cdots (6)$$

Since the fluctuation prior to improvement is $X_S \cdot \Delta Q$, the improvement factor due to the *RC* can be expressed by the following equation.

Flicker improvement factor due to *RC*

$$= \frac{\left(\text{Voltage fluctuation before improvement}\right) - \left(\text{Voltage fluctuation after improvement}\right)}{\text{Voltage fluctuation before improvement}}$$

$$= \left(1 - \frac{X_{RC}}{X_S + X_B + X_{RC}}\right) \times 100 \ (\%) \quad \cdots\cdots\cdots\cdots\cdots (7)$$

As can be seen from the above equation, the effect of the *RC* is extremely great when X_B is large and X_{RC} is small. The internal impedances of the *RC* consist of synchronous impedance X_d, direct-axis transient impedance X_d', and direct-axis sub-transient impedance X_d''. The transient impedance must be used as the impedance X_{RC} which corresponds to sudden furnace load changes. In accordance with the frequency of the load changes are generally considered to be effective to use. The frequency of the load changes:

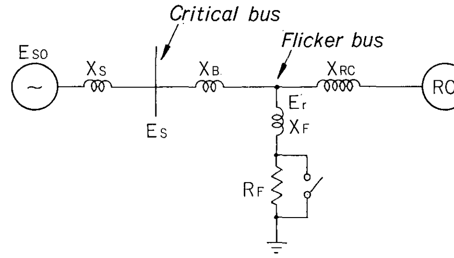
1∼3 Hz: X_d'

3∼20 Hz: $\dfrac{X_d' + X_d''}{2}$

Over 20 Hz: X_d''

Since $X_d' > X_d''$, it is safe to use X_d' for calculation in the planning stage. In normal design, the value of X_d' becomes about 25% and when small value is desired, an economical value is up to about 10%.

2) The reactance X_B of buffer reactor and internal phase angle fluctuation of *RC* and buffer reactance X_B



E_{SO} : Infinite bus voltage
E_S : Critical bus voltage
X_S : Reactance of transmission line
X_B : Reactance of buffer reactor
X_{RC} : Equivalent reactance of synchronous condenser
X_F : Reactance of arc furnace (including furnace transformer)
R_F : Resistance of arc furnace

Fig. 5 Equivalent circuit of synchronous condenser

As shown in equation (4) the flicker improvement factor becomes better as its value becomes larger. However, when X_B becomes large, the internal angle δ of *RC* increases and the power fluctuations also becomes large. In other words, due to the load fluctuation by the furnace, *RC* absorbs and dischanges power, and its internal angle swings. When X_B becomes larger, that is, the connection between *RC* and network is weak, stability is lost. Moreover, power fluctuations also cause the voltage fluctuation to become large and the installation of the *RC* looses all meaning. Referring to *Fig. 5*, when R_F is short circuited, the relation between the internal phase angle δ of *RC* and its output *P* is shown by Eq. (8) from power system equation of the two machines.

$$P_R = \frac{E_{S_0} \cdot E_C}{X_S + X_B + X_{RC} + \dfrac{X_{RC}(X_S + X_B)}{X_F}} \cdot \sin\delta \ \cdots\cdots (8)$$

Next, when R_F is closed,

$$P_0 = \frac{E_{S_0}E_C\left\{\sin(\delta + \beta) + \sin(\delta_0 - \beta)\right\}}{\sqrt{\left\{X_S + X_B + X_{RC} + X_{RC}(X_S + X_B)\dfrac{X_F}{R_F^2 + X_F^2}\right\}^2 + \left\{X_{RC}(X_S + X_B) \cdot \dfrac{R_F}{R_F^2 + X_F^2}\right\}^2}} \quad \cdots\cdots\cdots\cdots (9)$$

Where,

$$\sin\delta_0 = \frac{R_F}{R_F^2 + X_F^2}(X_S + X_B)$$

$$\tan\beta = \frac{X_{RC}(X_S + X_B)\dfrac{R_F}{R_F^2 + R_F^2}}{X_S + X_B + X_{RC} + X_{RC}(X_S + X_B)\dfrac{X_F}{R_F^2 + X_F^2}}$$

This relation is shown in graph form in *Fig. 6*.

RC is operated at a phase angle of $-\delta_0$ and when R_F is abruptly short circuited, disregarding the damping of the machine, phase angle δ of the synchronous condenser advances to δ_0, and if R_f is again not short circuited here, the phase angle δ

swings to the point d, which makes area (ade) the same as area (abc).

If R_F of the furnace is repeatedly short circuited and connected when the maximum angle is reached in this manner, power fluctuations become most severe and unstable and consequently *RC* becomes out of step.

At this time, the most important factor is $K=(X_S+X_B)/X_F$. The smaller K becomes better the stability, but K must be a certain magnitude in order to prevent flicker. Since the voltage fluctuations become large when K is chosen too large, a value of K is normally selected as $K \leqq (0.4 \sim 0.5)$. In other words,

$$K=\frac{(X_S+X_B)}{X_F} \leqq (0.4 \sim 0.5) \quad \cdots\cdots (10)$$

From this, the value of the buffer reactor X_B becomes

$$X_B \leqq (0.4 \sim 0.5) X_F - X_S \quad \cdots\cdots (11)$$

4) Considerations relative to negative sequence component and harmonic component

Since unbalanced short circuiting is repeated frequently in the electric furnace a large negative sequence component is included in the load current. Moreover, a large number of harmonic components are also included due to the unstable changes in the arc current and the irregular of short circuiting. When these currents flow in the primary side of *RC*, they are absorbed by the damper winding.

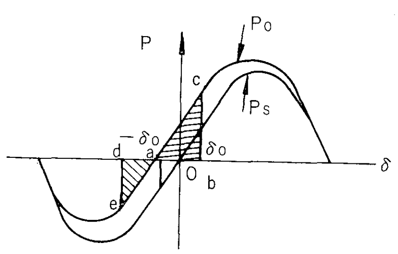


Fig. 6 Power angle curve

These harmonic components of the current absorbed by the damper are considered an equivalent negative sequence current. The harmonic current can be converted to a negative phase by considering the loss due to the harmonic current and the loss due to the negative sequence current equal. In other words, since the equivalent resistance at f_ν is

$$R_\nu \fallingdotseq \sqrt{f_\nu} \cdot R_0,$$

loss due to higher harmonic current $=k\sqrt{f_\nu}\, I_\nu^2$

loss due to negative sequence current $=k\sqrt{f_2}\, I_2^2$

where f_ν: harmonic order, I_ν: harmonic current, I_2: negative sequence current (normally double the commercial power frequency) R_0: DC resistance

Then,

$$\left.\begin{array}{l} \Sigma k\sqrt{f_\nu}\, I_\nu^2 = k\sqrt{f_2}\, I_2^2 \\ f_\nu=\nu f_1,\ f_2=2f_1 \end{array}\right\} \quad \cdots\cdots (12)$$

$$I_2=\sqrt{\sum_\nu \left(\sqrt[4]{\frac{\nu}{2}}\, I_\nu\right)^2} \quad \cdots\cdots (13)$$

Generally, the negative sequence current withstand capacity of the damper winding is given in VDE0530 as:

(1) Rated output under 100 MVA:
 (Cylindrical rotor) 10%
 (Salient pole rotor) 12%

(2) Rated output over 100 MVA:

Decided through consultation with the customer

Moreover, the following is given by IEC.

(a) Under 100 MVA
 (Cylindrical rotor) 8%
 (Salient pole rotor) 12%

(b) Rated output over 100 MVA
 Decided through consultation with the customer and damper windings are normally designed corresponding to the above values.

As previously described, the *RC* used to prevent electric arc furnace flicker has to absorb the equivalent negative sequence component 60% exceeding the above values. This value is abnormally large compared to the permissible value of the normal synchronous condenser and extreme care must be taken in the design and manufacture of the damper winding so that these current may be absorbed.

V. FLICKER ESTIMATE ANALYSIS BY COMPUTER

1. Analysis of Present Flicker and Furnace Characteristics

An outline is shown in *Fig. 7*. The current and voltage of the currently operating furnace are directly analog-to-digital converted, the resultant data is recorded on magnetic tape by a data acquisition system (DATAC), and the higher harmonic component which includeds the characteristics ΔV_f, ΔV_{10}, and current of the furnace is calculated by computer from the known network and plant impedance map. The result

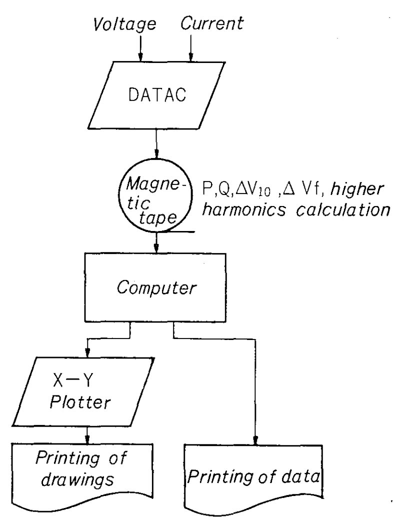


Fig. 7 Flow chart diagram of load analysis

is used for batch processing of drawings and printing using an X–Y plotter.

This system makes finding the characteristics of the furnace easy. Moreover, estimating the flicker of one furnace of one plant during operation and the flicker of one plant by means of the voltage and current contained in the impedance map is possible even when a large number of plants are connected the same system.

2. Calculating the Flicker Improvement Effect when Installing the Synchronous Condenser (*Fig. 8*)

The design data of the synchronous condenser determined by rough calculation, the data from the impedance map, etc. after improvement, and the furnace characteristics are input to the computer which then calculates the transient tidal current during furnace operation.

The synchronous condenser is expressed by the two reaction theory using the Park equation and the phase angle buffer and field control system are expressed by the following equations.

$$\left.\begin{aligned}
&\frac{W}{2\pi f_S}\frac{d\omega}{dt}=-P-\frac{D}{2\pi f_S}\cdot\omega_k\\
&\frac{d\delta}{dt}=\omega\\
&\frac{d\varphi_d}{dt}=\frac{1}{T'_{d_0}}(E_f-E_I)\\
&\frac{dE_f}{dt}=\frac{-1}{T_f}\{\mu_f(E-E_S)+(E_f-E_{fS})\}\\
&\varphi_d=E_I-(x_d-x'_d)\cdot I_d
\end{aligned}\right\}\quad\cdots\cdots\cdots(14)$$

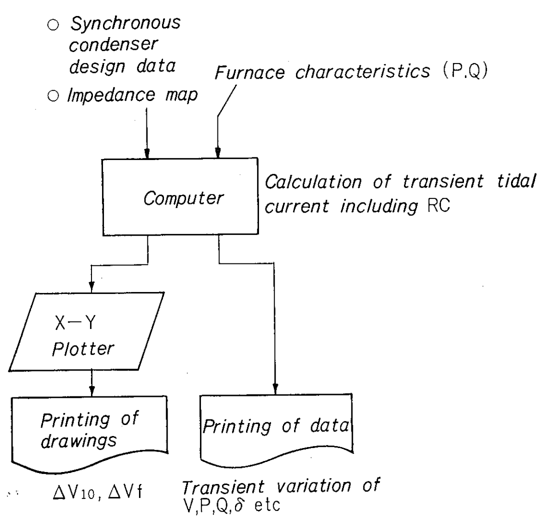


Fig. 8 Flow chart diagram of estimating voltage flicker

The system is represented by the node method. Each node voltage is extracted by the Gaus-Seidel low. The phase angle and flux determined by the rotating system and field system at the synchronous condenser terminals is extracted by the Gaus-Seidel metohd. The transient calculation is performed by the Euler method making based on the normal calculation.

The arc furnace characteristics are added to the branch which respond to the arc furnace as periodic load changes by adding the time changes of P and Q actually measured to the admittance time changes.

$$Y_{ARC}(t)=G_{ACR}(t)+jB_{ARC}(t)\quad\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots(15)$$

In this way, the flicker value after improvement, variation in the internal phase angle of the synchronous condenser, etc. can be easily found. The data recorded by the DATAC is used as the furnace characteristics data. When satisfactory data is unavailable, a simulated model load can also be used, but the use of data based on actual measurement as far as possible is advisable.

We have various furnace measured characteristics and simulation close to an actual system in planning is possible.

3. Actual Examples

An example of the arc furnace characteristics calculated for steel manufacturing is given in *Fig. 9*. Figure (a) shows the calculated effective value fluctuation waveforms of P, Q, V, I and θ based on the actually measured VI of the arc furnace. Figures (b), (c), and (d) show the frequency characteristics of P, Q, and V respectively, Figure (e) is the P and Q fluctuation phase relationship diagram. ΔV_{10} is plotted by simultaneous calculation when finding figure (d).

Fig. 10 shows the effect of installation of the synchronous condenser found by calculating the transient tidal current and is the result of the calculation of the characteristics with respect to the x_d' of various synchronous condensers.

VI. CONTROL OF THE SYNCHRONOUS CONDENSER FOR ARC FURNACE

Since the fluctuation period of the reactive power due to the arc is short in the arc furnace, 100% response of the synchronous condenser is nearly impossible even when the excitation response of the synchronous condenser is high because of the field time constant of the *RC*. Therefore, the excitation response of the synchronous condenser is not needed too high.

However, the voltage regulation must be minimum to synchronizing at the net work voltage. When the arc furnace operates, the bus voltage which connects the *RC* generally fluctuates widely due to the system impedance and the impedance of the buffer reactor. The *RC* acts against this so as to control the voltage fluctuations by generating reactive power even when the field is excited in accordance with the flux linkage constant theory between the field

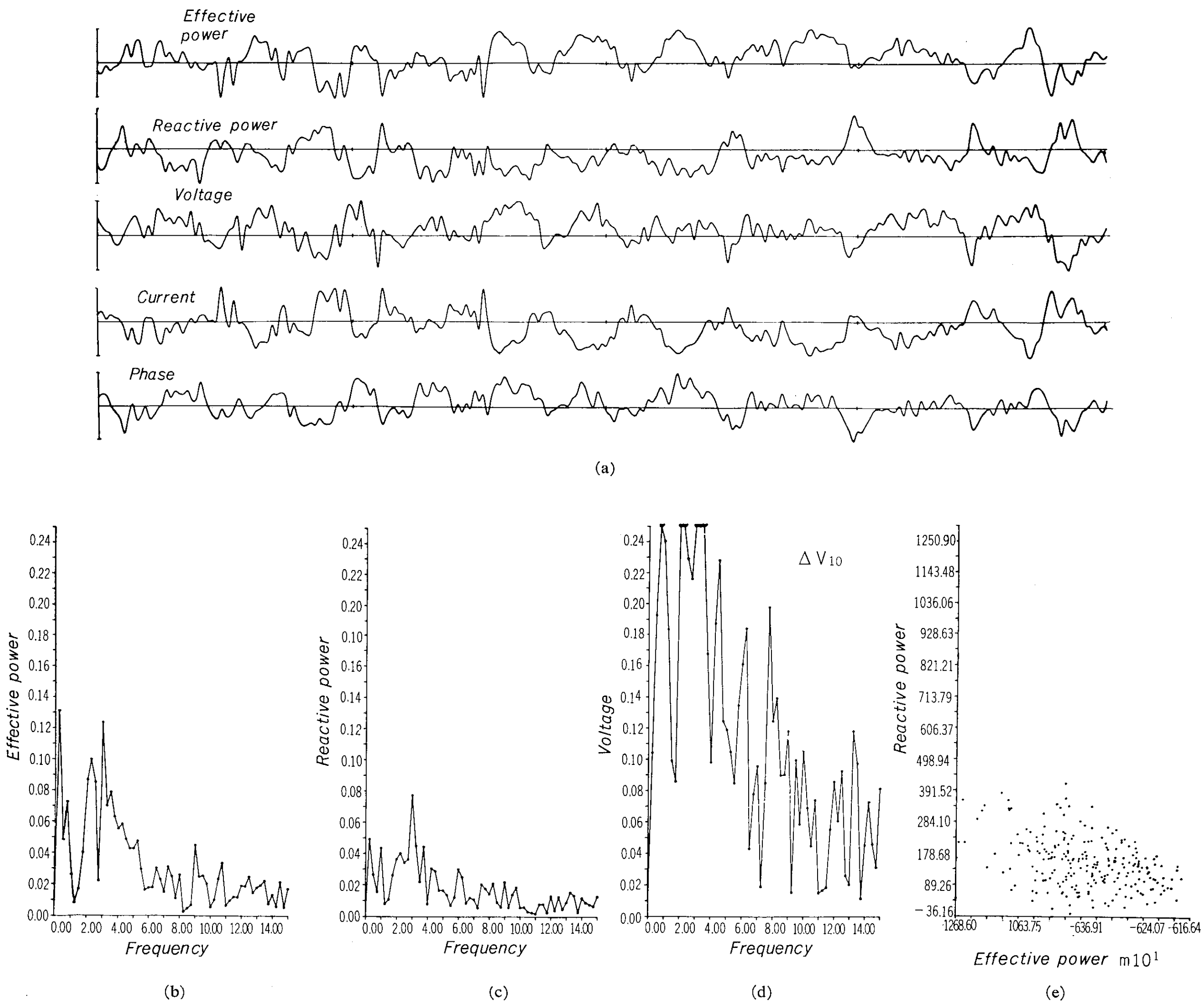


Fig. 9 Characteristic diagrams of arc furnace

and armature.

If the *RC* exciting system is assumed to be controlled by only the characteristics of the automatic voltage regulator (AVR), the *RC* exciting current will fluctuate widely since the fluctuation of the voltage due to the arc furnace load is extremely large. Therefore, voltage setting characteristics are desirable at the voltage detecting section.

The exciting system does not demand high response exciting and since ample maintenance cannot be excepted in poor environments, the brushless exciting system is optimum.

The brushless system is not only advantageous in that maintenance and inspection of brushes is unnecessary, but since the control objective of the exciting system is the field of the AC cxciter, the exciting power source capacity is small and a stable power source exclusively for the exciting system can be obtained by means of a permanent magnet generator, etc.

There are various *RC* starting systems, but since it is connected to a comparatively weak system, the

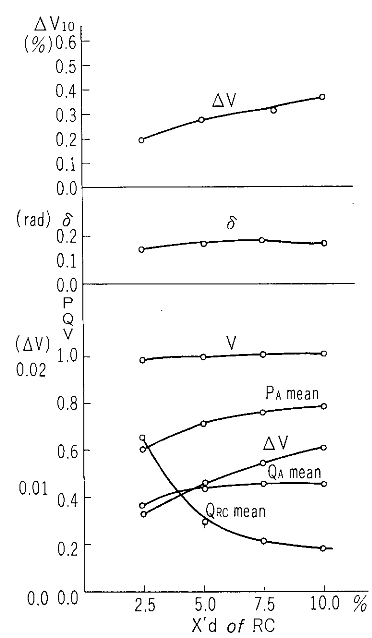


Fig. 10 Effect of synchronous condenser

generation of voltage disturbances to the system by the brush current when starting is undesirable. Therefore, in such facilities a system which synchronizes that *RC* by means of its field adjustment after starting by a short term rating induction synchronous motor is ideal.

VII. COMPARISON OF ACTUAL MEASUREMENTS AT NAMBU STEEL MANUFACTURING CO. AND CALCULATED RESULTS

The need for flicker control at the Nambu Steel Manufacturing Co. accompanied an expansion of the No. 2 furnace. Favorable results were obtained with the flicker suppression use synchronous condenser delivered by Fuji Electric in cooperation with Nisshin Electric Co. in November 1969. An outline of this facility is given below.

1. System Composition and Synchronous Condenser Specifications

A basic outline of the system and the view of synchronous condensor at Nambu Steel is given in *Fig. 11* and *12*. The specifications of the synchronous condenser are given below.

Ratings (Indoor use horizontal type)

Continuous capacity Leading phase 8,000 kVA
Overload capacity Leading phase 16,000 kVA
Rated voltage 3,420 V
Frequency 50 Hz
Number of poles 4
Speed 1,500 rpm
Power factor 0 (leading)
Starting system Induction synchronous motor (400kW)

Characteristic constants (measured values)

X_d 99.5%
X_d' 9.24% (saturated value)
X_d'' 6.0%
X_q'' 4.86%
T_{d_0}' 9.5 secs
T_d'' 0.0044 secs
H 2.25 secs

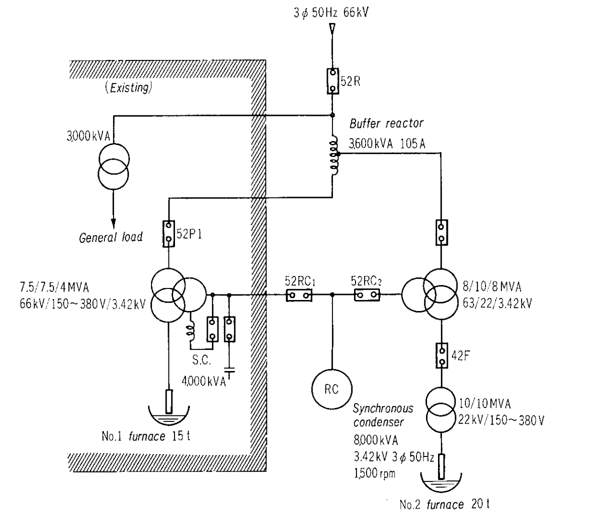


Fig. 11 Skeleton diagram

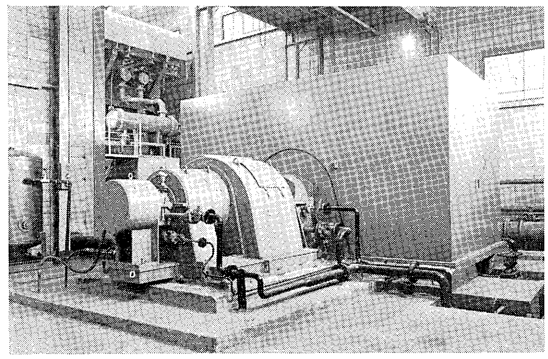


Fig. 12 View of synchronous condenser

A photograph of the completed facility is shown in *Fig. 12*.

2. Comparison of Measured ΔV_{10} and Calculated Value

A comparison of the flicker voltage ΔV_{10} calculated by computer at Fuji Electric and the actual measured values is given in *Table 2*. Chart recordings

Table 2 Comparison list of measured values and caluclating values

Case		Synchronous condenser	Buffer reactor	ΔV_{10}		$RC\Delta\delta_{max}$		RCQ max	RCQ min
Existing furnace	Expanded furnace			Calculated value V	Measured value V	Calculated value	Measured value		
Melting period	Without	Without	Without	0.54	0.45	—	—	—	—
Refining period	Without	Without	Without	0.20	—	—	—	—	—
Without	Melting period	Without	Without	0.72	—	—	—	—	—
Without	Refining period	Without	Without	0.27	—	—	—	—	—
Melting period	Without	With	With	0.27	0.24	4.2°	—	5.4	2.2
Melting period	Refining period	With	With	0.37	0.28	6.2°	—	6.5	2.5
Refining period	Melting period	With	With	0.39	0.28	6.8°	7.0°	6.8	2.7
Refining period	Melting period	Without	With	0.58	0.54	—	—	—	—

NOTE: $RC\Delta\delta$ shows the fluctuation in the intenal phase angle.

of the flicker meter before and after countermeasures were taken are shown in *Figs. 13* and *14.*

The following can be clearly seen from *Table 2* :
1) The magnitude of ΔV_{10} found with the computer closely matches the measured value. In other words, since they are at the safety side, the flicker voltage ΔV_{10} can be estimated with this calculating system.
2) The fluctuation in the internal phase angle of the synchronous condenser also closely matches the measured values.

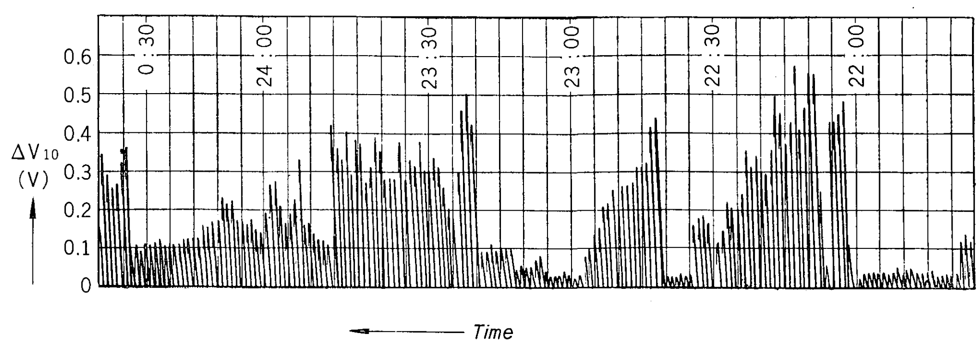


Fig. 13 Voltage flicker ΔV_{10} (without synchronous condenser)

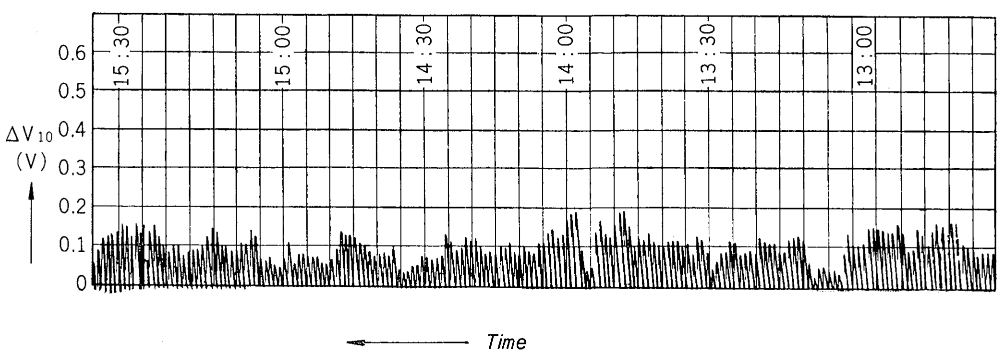


Fig. 14 Voltage flicker ΔV_{10} (with synchronous condenser)