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FUJI INTEGRATING WATT-HOUR METER (I)

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I. PREFACE

The history of the manufacture and sales of Fuji Integrating Watt-hour Meter may be divided into three periods:

1. Period of importation and sales of Germany's Siemens products: 1923–1938
2. Period of manufacture and sales of watt-hour meters of Fuji's own design: 1939–1945
3. Period from the end of World War II to the present: 1945 to present

After World War II, because of the change-over of all factories to peace-time industries and extreme shortage of the integrating watt-hour meter in Japan, a rapid development was required for the production of this meter. Fortunately, Fuji Electric was backed by its techniques and facilities retained at their highest level throughout the war, so was able to place its integrating watt-hour meter on the market before any other manufacturer.

Since then, Fuji Electric has been producing successfully all types of integrating watt-hour meters, such as single and three phase watt-hour meters, precision class watt-hour meters, and demand meters. These products are well received for their accuracy and constractions not only in Japan, but also in many parts of the world.

Today, Fuji Electric operates factories in South Korea and India under a technical agreement in which Fuji engineers act as the instructors in the manufacture and testing of the integrating watt-hour meter.

In this issue and those following, the writer will attempt to describe the integrating watt-hour meter for the reader's information.

II. SPECIFICATIONS

An integrating watt-hour meter which measures electric energy is used as a tariff meter. Therefore, its construction and electrical characteristics, etc., are prescribed by standards and only those which pass the rigid tests given by supervising governmental agencies are permitted to be used. The following are the standards known world-wide:

U. S. A.:	American Standard Code for Electric Meters, ASA, C 12
U. S. A.:	AEIG-EEI-NEMA Standard
U. K.:	British Standard Specifications
W. Germany:	Verbandes Deutscher Elektrotechniker
Australia:	Standards Association of Australia
Japan:	Japanese Industrial Standard

Countries other than those listed above also maintain strict standards of integrating watt-hour meters according to their needs.

Fuji Electric manufactures and exports integrating watt-hour meters that conform to the above standards.

III. PRINCIPLE OF INTEGRATING WATT-HOUR METER

An integrating watt-hour meter is generally, composed of an operating apparatus, register, and case. The operating apparatus consists of driving device, braking device and various adjusting devices.

As is well known, the operating principle of an induction type integrating watt-hour meter is as follows: a shifting field is created by a pair of pressure and current coils; the electromagnetic force created by an eddy current induced in the rotating disc forms a driving torque; braking magnets mounted on each side of the rotating disc create braking torque.

When the drive and braking torques are balanced, the disc will rotate with constant speed. These rotations are transferred to the register through a series of gears to register electrical energy.

1. Shifting Field of Induction Type Integrating Watt-hour Meter

The driving section of the integrating watt-hour meter is composed of the rotating dics and electromagnets to partially work on the disc (refer to *Fig. 1*).

These electromagnets are excited by the voltage impressed on the pressure coil and the current that flows in the current coil; the flux created by these passes through the disc. In the induction type integrating watt-hour meter, if the phase angle be-

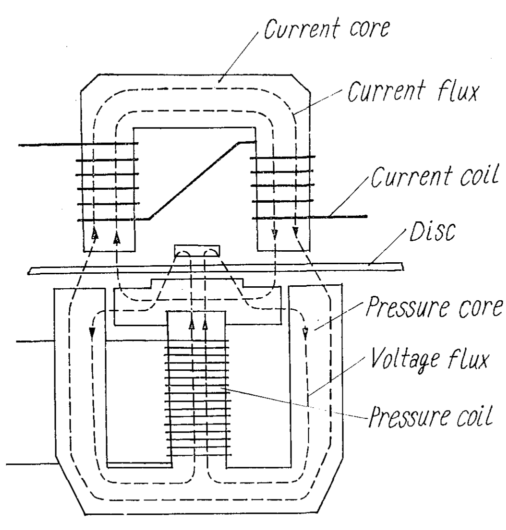


Fig. 1 Arrangement of element and passage of its flux

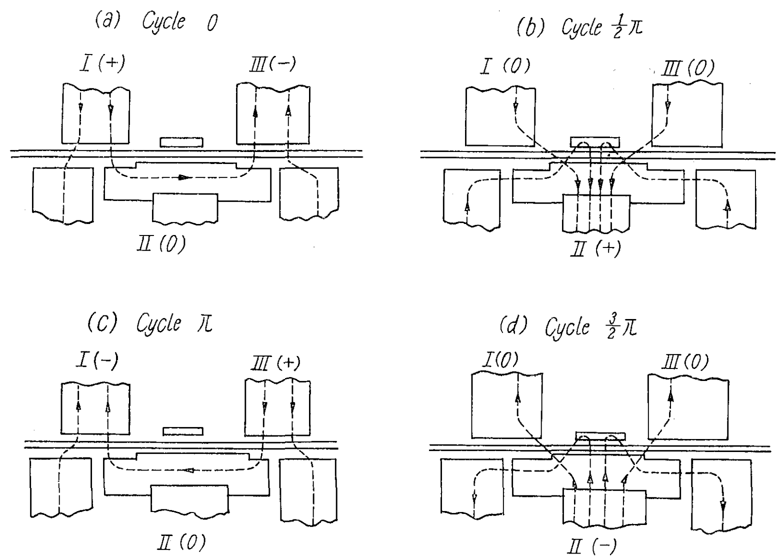


Fig. 3 Direction of current and voltage flux at any period

tween the active flux of the voltage and current is 90° when the power factor is 1, the rotating speed of the disc is proportional to the load.

At this point, the effect of the flux on the disc when the phase difference is 90° will be considered (Refer to *Fig. 2*).

The variation of the voltage and current flux during one cycle is shown in *Fig. 2;* the voltage flux lags behind the current flux by $\frac{\pi}{2}$ (90°). The flux direction at each pole of the voltage and current cores when the voltage and current fluxes have changed one cycle (from 0 to 2π) is shown in *Fig. 3.*

At each point of the poles *I, II* and *III,* if the current or voltage flux penetrating the disc from the upper side is taken as possitive (+) and the flux passing through the disc upward is taken as negative (−), and the direction at each time expressed in a table, data can be recorded as shown in *Table 1.* As can be seen, the positive or negative flux is continuously shifting in the direction of *I→II→III* according to the passage of time. Thus, when an iron core such as shown in *Fig. 1* is used and when the phase angle between the voltage and current fluxes is 90°, two shifting fields are created during one cycle. When this shifting field passes through the rotating disc, an eddy current is created; by the electromagnetic effect of this eddy current and flux, the disc is given a driving torque.

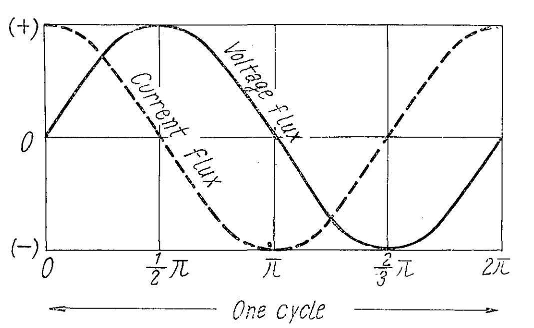


Fig. 2 Variation of current and voltage flux in one cycle

2. Relation between Driving and Braking Torques

If the driving torque given to the rotating disc is denoted by *D,*

$$D = K\,\phi_p\,\phi_c \sin\phi \quad \ldots\ldots\ldots\ldots\ldots\ldots (1)$$

Here K : a constant

ϕ_p : pressure coil flux that passes through the disc

ϕ_c : current coil flux that passes through the disc

ϕ : phase angle between ϕ_p and ϕ_c

On the other hand, if the disc rotates, cutting the flux of the braking magnets, a current flows in the disc; because of this current and the flux of the magnets, a force acting as a braking force of rotation works on the disc. If this force is expressed as T, then

$$T = K_1\, n\phi_m^{\,2} \quad \ldots\ldots\ldots\ldots\ldots\ldots (2)$$

exists.

Here, K_1 : a cnstant

n : disc rotating speed

ϕ_m : magnet flux

When the disc driving torque D and braking torque T become equal, the disc will rotate continuously at a constant speed n.

Table 1. **Polarity of each poles at any period**

Period \ Pole	I	II	III	Remarks
0	+	0	−	Reffer to *Fig. 3-(a)*
$\frac{1}{2}\pi$	0	+	0	Reffer to *Fig. 3-(b)*
π	−	0	+	Reffer to *Fig. 3-(c)*
$\frac{3}{2}\pi$	0	−	0	Reffer to *Fig. 3-(d)*
2π	+	0	−	Reffer to *Fig. 3-(a)*

When $D=T$,

$$K\phi_p\phi_c \sin\phi = K_1 n\phi_m^2$$

$$n=\frac{K\phi_p\phi_c \sin\phi}{K_1\phi_m^2} \quad \ldots\ldots\ldots\ldots(3)$$

This relation is illustrated in *Fig. 4*. When the

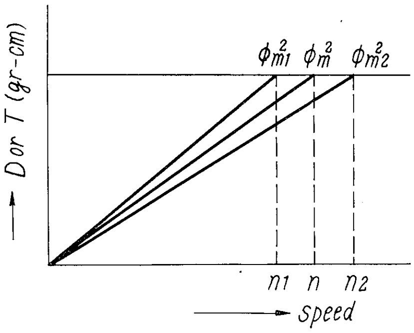


Fig. 4 Relation between rotor speed and flux braking magnet at constant driving torque

magnet flux ϕ_{m1}, is greater than standard flux of ϕ_m, the rotating speed is small; if the magnet flux ϕ_{m2} is less than the standard flux, the rotating speed is faster than standard speed.

The term "Full Load Adjustment" used in adjusting the meter refers to setting the disc rotation at standard speed by changing the magnet flux as referred to above. However, in practice, because of the disc rotation, $\phi_p\phi_c$ flux from the moving elements also causes a braking torque to work on the disc in the same way as the magnets; thus the following formula exists:

$$T=K_1 n\phi_m^2+K_2 n(\phi_p^2+\phi_c^2) \quad \ldots\ldots\ldots(4)$$

When $D=T$,

$$K\phi_p\phi_c \sin\varphi = K_1 n\phi_m^2+K_2 n(\phi_p^2+\phi_c^2)$$

$$n=\frac{K\phi_p\phi_c \sin\phi}{K_1 n\,\phi_m^2+K_2(\phi_p^2+\phi_c^2)} \quad \ldots\ldots\ldots\ldots(5)$$

This relation is shown in *Fig. 5*.

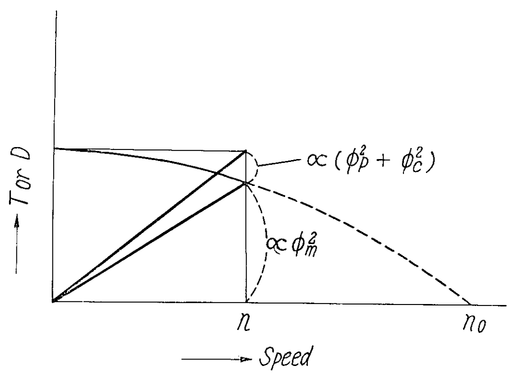


Fig. 5 Relation between rotor speed and braking torque due to ϕ_m ϕ_p ϕ_c

Since the driving torque because of the braking torque due to the moving elements' own flux $\phi_p\phi_c$, the rotation is kept at n_0 when there is no magnet; if the magnet flux is greater than $\phi_p\phi_c$, the formula of (5) approaches the formula of (3).

3. Internal Phase Angle

Power P is

$$P=EI\cos\theta$$

Since the driving torque of an integrating watthour meter must be proportional to this power;

$$D=K_1\phi_p\phi_c \sin\phi$$

to make the above formula proportional to the power; and since

$$D=K_1\,\phi_p\phi_c \sin\phi \propto EI\cos\theta$$

$$\phi_p \propto E,\ \phi_c \propto I,$$

the conditions of

$$\varphi=\frac{\pi}{2}\pm\theta$$

must be satisfied.

Thus, when the phase angle $\theta=0$, the internal phase angle ϕ must be $\frac{\pi}{2}=90°$.

If this relation is shown by vectors, it becomes as shown in *Fig. 6*.

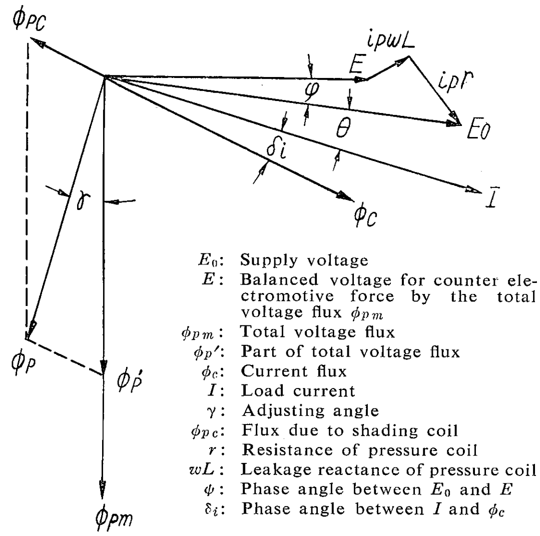


Fig. 6 Vector diagram of internal phase angle

When the standard vector is assumed to be E which subtract a voltage drop from the supply voltage E_0, the relation between E and ϕ_{pm} is always at 90°.

Further, a variation of E in regard to a constant supply voltage E_0 becomes an error; it also becomes an error of the active flux ϕ_p.

At this point, if it is assumed that the current flux ϕ_c is lagging behind I by δi. For the purpose of making perfectly $\angle\phi_c\phi_p$ to 90° at unity power factor, ϕ_p is lagged behind ϕ_p' by γ with the effect of ϕ_{pc} induced by shading coil attached to voltage element. As is clear from the diagram,

$$\gamma=\varphi+\delta i$$

when δi is constant, the adjusting angle γ formed by the shading coil must vary with the variation of φ. In other words, the adjusting angle will vary according to the variation of φ value.

For the power factor adjustment (which is the second important adjustment for an integrating watt-hour meter) there are two methods: one method in which γ is held constant and δi is varied and another method in which δi is kept constant and γ is varied.

Fuji Electric utilizes the former method for its single and three phase watt-hour meters; the latter method for three phase precision class watt-hour meters.

As shown in *Fig. 7,* if a conducting coil is placed at any point where an alternating flux ϕ_m passes, an electromotive force is created and current i flows causing a flux ϕ_{pc}. A composite flux ϕ_p forms and its phase angle lags behind ϕ_m by γ. This is the so-called shading effect; its vector is shown in *Fig. 8.*

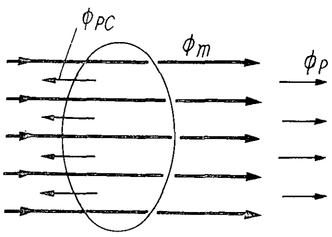


Fig. 7 Principle of phase shifting by shading coil

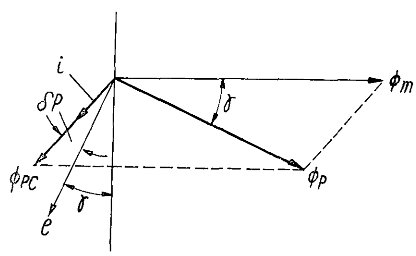


Fig. 8 Vector diagram showing power factor adjusting effect of shading coil

As can be seen from the above explanation, the phase angle of flux ϕ in relation to power-factor angle θ must satisfy the relation,

$$\phi = \frac{\pi}{2} \pm \theta$$

However, when over-adjusted by α, the equation becomes $\phi = \frac{\pi}{2} + \alpha \pm \theta$

and in the case of an inductive load,

$$D = KEI \sin\left(\frac{\pi}{2} + \alpha - \theta\right) = KEI \cos(\theta - \alpha) > KEI \cos\theta$$

and in the case of a capacitance load,

$$D = KEI \sin\left(\frac{\pi}{2} + \alpha + \theta\right) = KEI \cos(\theta + \alpha) < KEI \cos\theta$$

come to exist.

4. Light Load Adjustment

In an integrating watt-hour meter, it is necessary to compensate the friction torque of the rotor parts and bearings. For this purpose, the voltage flux is normally used. As shown in *Fig. 9,* if a part of the voltage flux ϕ_p is passed through the coil L, the flux ϕ_p'' that penetrates the coil lags behind the other part of ϕ_p'; the voltage flux shifts from ϕ_p' to ϕ_p'' and this shifting field creates a torque that causes the disc to rotate in that direction. Compensation of the friction torque by utilizing this torque is an important factor for an integrating watt-hour meter in a light load adjustment.

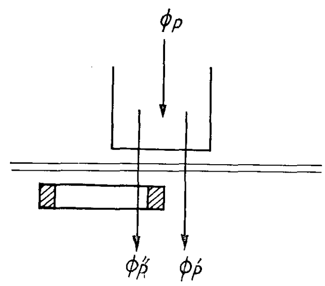


Fig. 9 Principle of shifting field generating by shading coil

IV. CHARACTERISTICS OF INTEGRATING WATT-HOUR METER

1. Current Characteristic

Generally, the driving torque of the integrating watt-hour meter is created by flux that is proportional to the voltage and current. At the same time is created a braking torque that is proportional to the square of the current and voltage flux itself; because of this, as the meter becomes overloaded, the proportion of braking increases and there occurs a negative error.

To decrease this error, three most practical methods used are as follows:

(1) Method that uses a magnetic shunt on the current core.
(2) Method that decreases the meter constants.
(3) Method that decreases the current flux in relation to the voltage flux.

The first method is one which Fuji Electric has been using since it started to manufacture integrating watt-hour meters. It utilizes the magnetic saturation of the magnetic shunt attached to the current core to increase the driving torque of the rotor at overcurrent. The main current flux caused by the load current flowing in the current element divides itself into the active flux that passes through the rotor and the flux that passes the shunt. In this case, the active flux not only furnishes the rotor with a driving torque but also functions to brake the rotor.

For this reason, the rotor speed decreases with overload and meter error becomes a negative error. The magnetic shunt increases the meter torque at overload, shunt core so constructed to become saturated when the flux reaches a certain density. As the load increases, the proportion of the active flux in respect to the shunt flux increases; finally, with the overload, the driving force increases and the overload characteristic is compensated. This is shown in *Fig. 10.* For instance, compared to the case without current shunt core, in a circuit with a shunt, the negative error is compensated as the overloading progresses. Moreover, if the shunt is care-

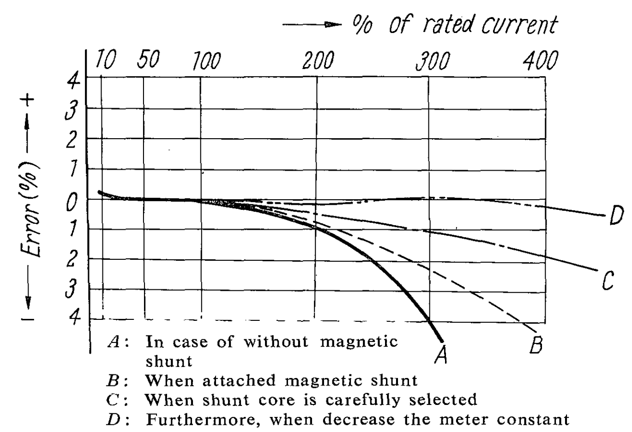


Fig. 10 Current characteristics curves of single phase W. H. M.

fully selected, the characteristic curve can be flattened up to the overload point; in extreme cases, the overload may easily be made into a (+) error. Second method is to strengthen the braking flux of the magnets to decrease the braking proportion of the current flux. In this case, the current and voltage flux is held at the usual value.

A droop characteristic of a watt-hour meter at the time of overload is due to the increase of the braking force caused by the current flux. If the braking magnet flux is large, the proportion of the current flux variation in relation to the total flux decreases, the effect of the current flux variation is lessened and the degree of the meter's droop characteristic become smaller.

In this case, since the density of the current and voltage flux is constant, the increase in the breaking flux inevitably accompanies a lowering of the meter constants. Therefore, when the driving torque is the same and the meter constants are low, it can be assumed that the overload characteristic is generally improved. This relationship between the rotating speed and load characteristic is shown in *Fig. 11*.

The third method is to decrease the proportion of the current flux in relation to the voltage flux. The object of this method is to decrease the proportion of the current flux variation in relation to the overall braking flux.

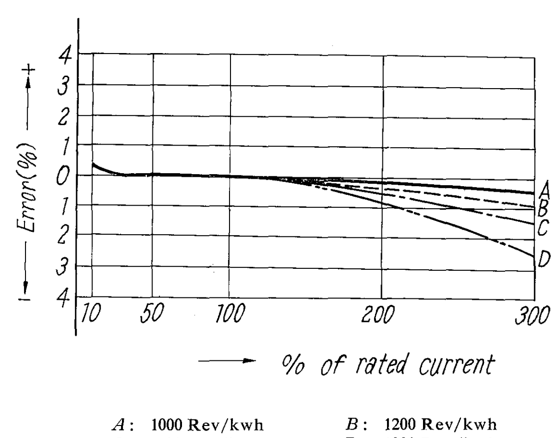


Fig. 11 Change of current characteristics due to rotor speed

The fundamental idea of this method is the same as strengthening the braking magnet flux. In this case, however, a problem lies in the fact that if the current flux is decreased unconditionally, the meter's driving torque becomes lessened. This torque decrease may be prevented to some extent by changing the meter's mechanical conditions, but magnetically, a decrease may be realized by increasing the voltage flux. However, since any increase in the voltage element flux means an increase of watt consumption in the voltage circuit, it is not very favorable. In practice, each of the above three methods is not used singly to compensate the overload characteristic; two or three methods are combined for use.

2. Voltage Characteristic

The range of voltage variation is not as large as that of the load current. For this reason, its effect on the meter errors is not as severe as that of the load characteristic. However, since a smooth characteristic curve is more desirable, a compensation becomes necessary. As in the case of load characteristic, there are the following three methods of compensation:

(1) Method using a voltage magnetic shunt core.
(2) Method in which the magnetism of the brake magnets is increased.
(3) Method in which the proportion of the voltage and current flux is varied.

The action and effect of each of these methods are the same as those in the case of the load characteristics.

3. Frequency Characteristic

Change of error due to the variation of frequency is caused by the variation of permeability μ of the pressure and current cores and the variation of shading effect of the rotating disc and voltage shading coil. The characteristic changes at $pf=1$ and $pf=0.5$ (lag), are oppossed to each other; these characteristics form curves that have a constant angle θ. *Fig. 12* shows this relation. With the reciprocal θ of $pf=1$ and $pf=0.5$ constant, it is comparatively easy to shift the overall position, but it is very difficult to decrease θ. This θ is determined at the time of meter design and cannot be compensated easily. The methods used are as follows:

(1) Method in which the shading effect of the rotor is decreased.

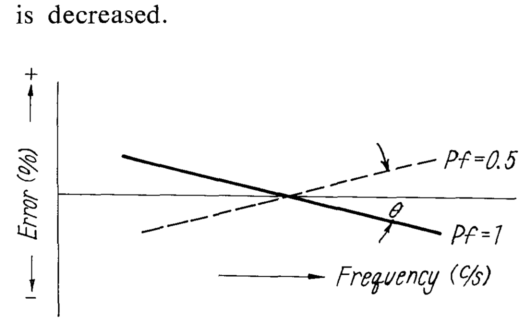


Fig. 12 Frequency characteristics

(2) Method in which the pressure coil resistance is decreased.

(3) Method in which a resistance is inserted parallel to the current circuit.

In the first method, an improvement may be realized by making the rotor plate thin or by changing the material to decrease the permeability; however, the rotor's driving torque is decreased.

In the second method, to decrease the pressure coil resistance, larger wire in fewer turns can be used for the coil; in this case, the voltage element's va, watt loss increases and the voltage characteristic becomes poor. In the third method, in which a resistance is inserted parallel to the current coil, the current flowing in the current element is decreased and the torque decreases to such an extent that the use of the method is inpractical. If any of the above methods is used singly, it inevitably affects others; use of a method or methods is determined only after fully considering the advantages and disadvantages in their entirety.

Generally, if the resistance of the pressure coil is decreased, the $pf=1$ characteristic becomes poor, but $pf=0.5$ characteristic improves. Since the improvement of $pf=0.5$ characteristic is greater in degree than the deteriorating of $pf=1$ characteristic, the frequency characteristic is improved.

4. Temperature Characteristic

In the case of an integrating watt-hour meter, it is a well known fact that unless the internal phase angle between the voltage and current flux is fully 90°, the meter will not function accurately. However, in actual practice, use of simply wound voltage and current coils does not bring the phase angle to 90°. For this reason, the watt-hour meters are equipped with suitable phase compensators. The device usually used is a shading coil mounted on the voltage core.

When a characteristic change due to temperature variation occurs, both $pf=1$ and $pf=0.5$ must be considered.

1) For $pf=1$ (Refer to *Fig. 13*)

In this instance, the phase angle variation due to an increase in the pressure coil resistance, core loss and rotating disc resistance, etc., results in (−) error and the variation due mainly to the braking magnets' magnetism decrease gives (+) error.

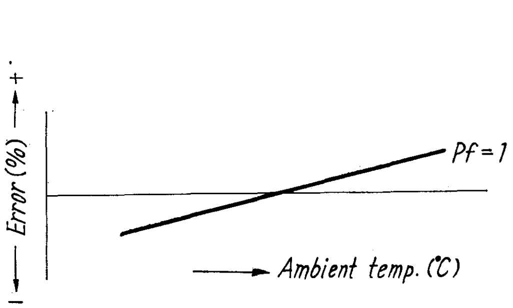


Fig. 13 Temperature characteristics

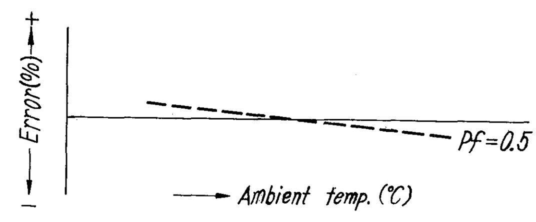


Fig. 14 Temperature characteristics

However, the (−) value due to the phase angle is inconsequential. The (+) component due to the braking magnets affects most prominently and the meter errors come to possess (+) tendency.

2) For $pf=0.5$ (Refer to *Fig. 14*)

In this case, the effect is just opposite to that of $pf=1$. The influence of (−) component due to the phase angle becomes greater and it practically cancels (+) component to make the characteristic curve almost flat.

a. Temperature compensator for unity power factor

Improving of $pf=1$ temperature characteristic is called the primary temperature compensation. As has been stated before, $pf=1$ and $pf=0.5$ temperature characteristics have a difference from the beginning; the angle θ difference of these two does not change with the primary temperature compensation. For instance, improving $pf=1$ temperature characteristic results in shifting of the $pf=0.5$ temperature characteristic from good to poor. This is shown in *Fig. 15*. The following two methods are generally used to compensate the $pf=1$ temperature characteristic.

(1) Method in which either the voltage or current flux is controlled

(2) Method in which the braking magnet flux is controlled

The first method is the one which Fuji Electric employs: it maintains constantly the reciprocal

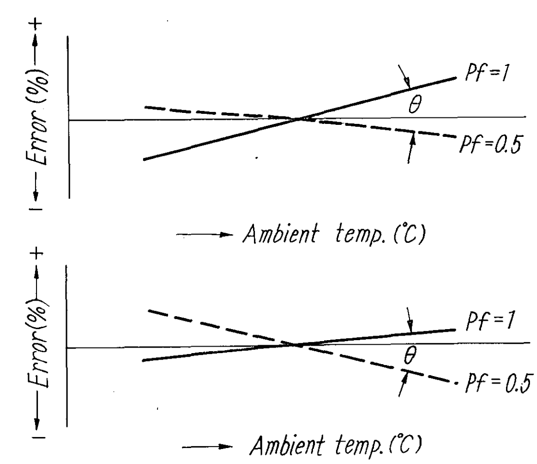


Fig. 15 Temperature characteristics

relation between the braking torque decrease due to temperature rise and driving torque decrease caused by the use of a magnetic compensating alloy steel at an optimum state. In the second method, the magnet's decrease in magnetism due to a temperature rise is accelerated by the use of magnetic compensating alloy steel to balance the driving torque. The above two methods have both advantages and disadvantages, and both are useless for the purpose of improving the relation between $pf=1$ and $pf=0.5$.

b. Temperature compensator for lagging power factor

This is for improving $pf=0.5$ characteristic after $pf=1$ temperature characteristic has been adjusted at its best. This method had been unknown until Fuji Electric used it in its single phase 2-wire type E–71 and other meters. It has proved to be very effective.

As has been stated before, the temperature characteristic of $pf=0.5$, influenced by the pressure coil resistance variation and phase angle variation due to the shading effect of the disc, etc., cancels the (+) variation of the magnets' magnetism decrease and becomes flat. However, its relative position is shifted by the primary temperature compensation; with temperature rise, it indicates (−) tendency. Therefore, for improvement, the following methods may be considered.

(1) Method in which the current flux phase angle is made (−) with temperature rise.

(2) Method in which the voltage flux phase angle is made (+) with temperature rise

To put the first method into practice: a copper collar with a large temperature coefficient is attached to a portion of the current core. As temperature rises and the shading effect of the copper collar is decreased, the lagging angle of the current flux is decreased. Many applications of this method may be found in Fuji Electric products.

The second method is:

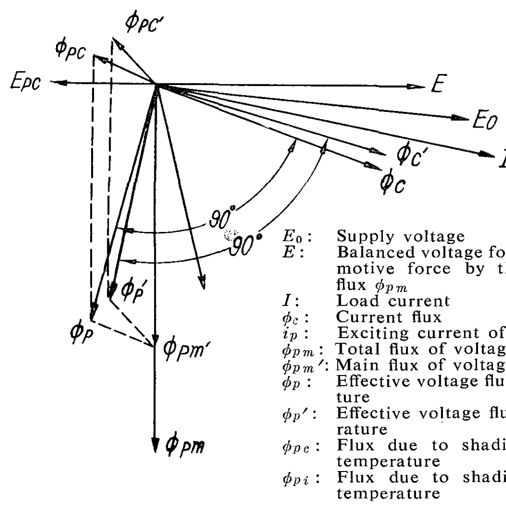
a. a method in which resistance with (−) temperature coefficient is used as the voltage series resistance.

b. a method which employs a device decrease the phase angle of the shading coil in opposite way.

With a material that has (−) resistance temperature coefficient for the pressure coil, the pressure coil resistance decreases with temperature rise; the phase angle becomes (+) and the effect of the secondary temperature compensation is increased. The result is that under a set condition, the torque is decreased. Attaching of a special device on the shading coil is very effective; Fuji integrating watt-hour meter, Model E–71 is a good example.

For these, please refer to the vectors in *Fig. 16* and application example of *Fig. 17*.

In this method, the shading coil is first made inductive. As the temperature rises, this inductivity is decreased to increase the effect of the shading coil. This shifts the phase angle to the (+) side to exhibit the effect of the temperature compensation for the lagging power factor.



E_0: Supply voltage
E: Balanced voltage for counter electromotive force by the total voltage flux ϕ_{pm}
I: Load current
ϕ_c: Current flux
i_p: Exciting current of voltage element
ϕ_{pm}: Total flux of voltage element
ϕ_{pm}': Main flux of voltage element
ϕ_p: Effective voltage flux at low temperature
ϕ_p': Effective voltage flux at high temperature
ϕ_{pc}: Flux due to shading coil at low temperature
ϕ_{pi}: Flux due to shading coil at high temperature

Fig. 16 Vector diagram

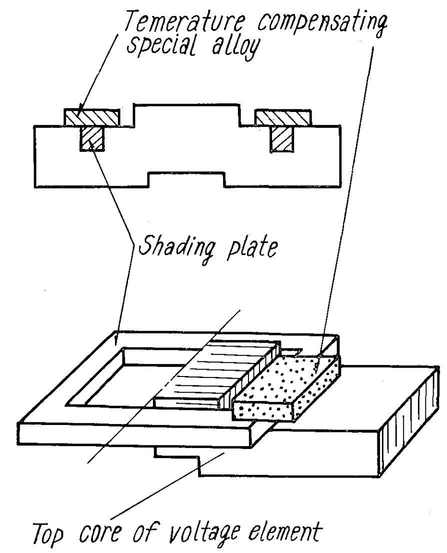


Fig. 17 Temperature characteristics compensator

V. ADJUSTMENT OF INTEGRATING WATT-HOUR METER

There are numerous adjusting methods for the integrating watt-hour meter. Two or three typical methods will be described.

1. Heavy Load Adjusting Device

In heavy load adjusting, the effect of the magnets on the rotating disc is controlled to adjust the error at a certain load: 100% load, for example. This method of adjusting the braking magnets may be divided into the following two methods:

1) Method in which the magnets are shifted

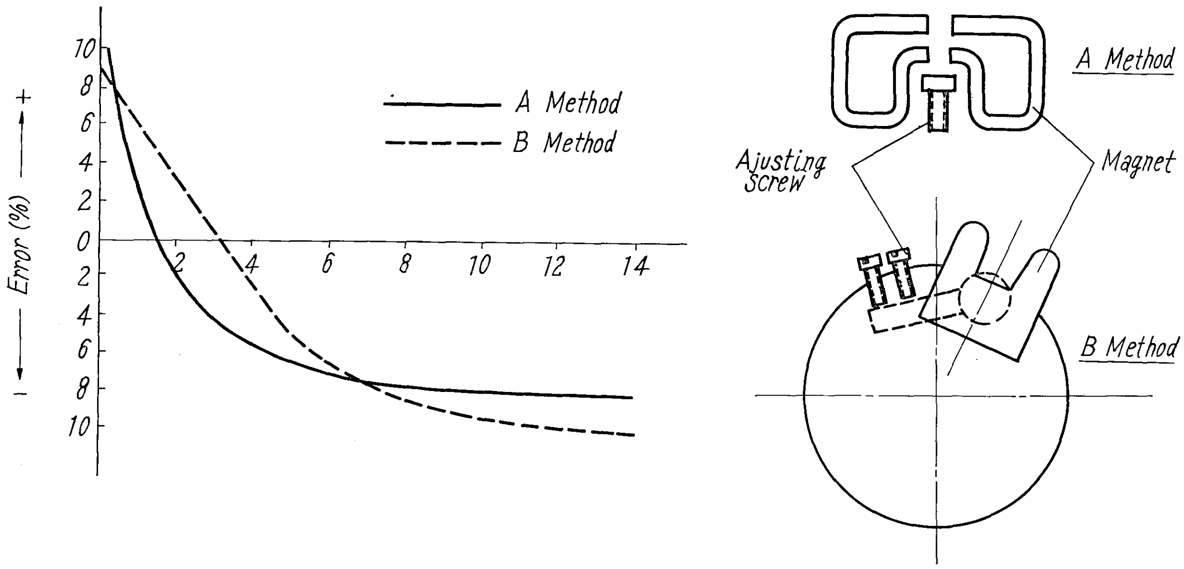


Fig. 18 Range of heavy load adjustment

mechanically (*Fig. 18,* method *B*).

2) Method in which the magnet flux is controlled magnetically (*Fig. 18,* method *A*).

The method of adjusting heavy load by changing the magnet flux position relative to the disc by shifting the magnets has been in use for years. Fuji Electric utilizes this method in its single and three phase watt-hour meters. *Fig. 19* shows the relation between the braking torque strength and the magnet position in relation to the rotating disc. The braking torque, as it moves from the disc center toward the periphery, increases up to a certain point and decreases rapidly once it passes this point. This characteristic is utilized to shift the magnets and to adjust the load point. The effect of the magnet shifting is a parallel shifting of the load characteristic.

In the second method, the magnets are fixed and its flux is magnetically shunted to vary the magnet strength and adjust 100% load point. In this case, the adjusting curve for the former method changes

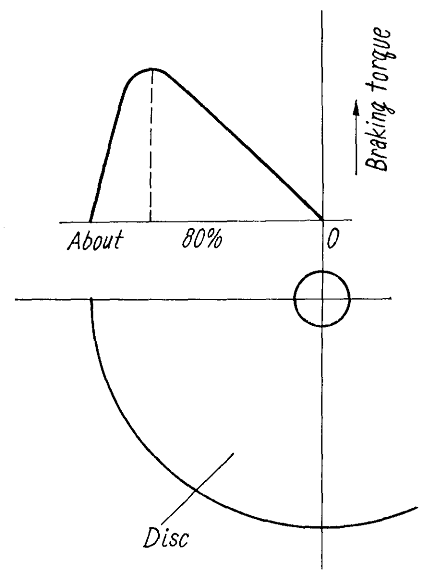
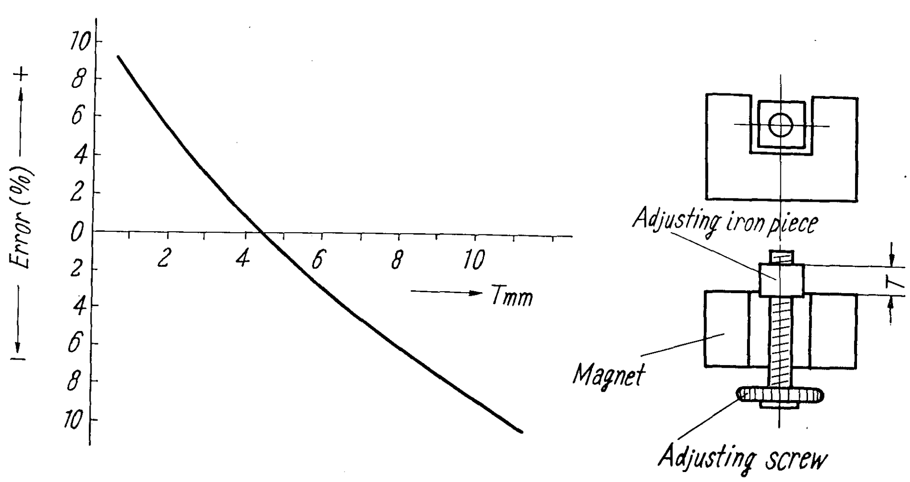


Fig. 19 Relation between braking torque and position of magnet on disc.



No. of revolution of Adjusting screw	Error (%)
0	+7.0
4	+2.6
8	−1.5
12	−4.2
16	−6.3
20	−7.8

Fig. 20 Range of heavy load adjustment

in a straight line while that of the latter method curves, making adjustment difficult. However, if the method which Fuji Electric uses in its precision class watt-hour meters is used, it is possible to obtain a straight adjusting curve. An example of this curve is shown in *Fig. 20*.

2. Phase Adjusting

At the present, the following two methods are used for adjusting the phase :

(1) Method to control the current flux phase angle.

(2) Method to control the voltage flux phase angle.

In the first method, a phase adjusting coil is wound on the current core, a resistance wire is connected to the coil and the current flux phase is changed by varying this resistance ; thus the phase angle in relation to the voltage flux is adjusted. Fuji single and three phase watt-hour meter chiefly use this method.

In the second method, opposite to the first, a required phase angle is obtained by winding a coil on the top of the pressure core to shift the voltage flux phase. In this case, the phase of current flux is not changed.

3. Light Load Adjusting

Theoretically, there is only one light load adjusting ; constructionally, the following two methods may be considered :

(1) Method in which a creeping torque is created at a light load by shifting a path for a part of the voltage active flux.

(2) The second method uses a shading ring on part of the voltage active flux to give phase difference to a part of the total active flux to cause creeping torque.

The first method is one which Fuji Electric has been using since it started to manufacture integrating watt-hour meters. And the adjustment of this method is done by turning to right or left the light load adjusting piece which is attached upon the voltage element through the disc.

The above is a dissertation on the basic problems regarding the characteristics of the integrating watt-hour meter. Starting with the next issue, we would like to describe in detail the actual construction of all types of watt-hour meters.