THE PRINCIPLE OF PHASE ADVANCER

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Introduction.

The interest for the improvement of the power factor in the line is gradually increasing over the whole world. Many methods are known, and these methods are divided into two groups, viz:

either – one substitutes those motors, which consume wattless capacity and thus cause the low power factor by those, which do not have this disadvantage – or else – one provides some substations with machines, which are capable of delivering wattless capacity.

The first method, which consists of the use of synchronous motors, compensated motors or motors with phase advancer etc, gets at the bottom of the trouble. But this method cannot absolutely be carried through for one can hardly attain that the small asynchronous motors with cage rotors, which are of the most reliable working conditions should be replaced by other motors, which are not so efficient or not so safe in running.

The second method ignores the evil and lessens the consequences in such a way that it provides for a considerable group of motors a synchronous or asynchronous condenser.

Both methods were already referred to in this periodical.*

The following shall be a supplement to the essays about the phase-advancer, trying to discuss its characteristic qualities.

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* 富士電機時報大正十五年一月 馬場氏 進相電流發生裝置としての同期化非同期電動機
〃 〃 四月 石川氏 非同期進相機用並高力率誘導電動機用三相交流勵磁機
〃 大正十四年二月 近田氏 力率の改善
〃 〃 九月 青柳氏 近田氏 高力率電動機に就て

1. General explanation.

For improving the powerfactor of an asynchronous motor, an E. M. F. which enables flowing of magnetizing current in the rotor, must be induced in the rotor circuit. For neglecting the rotor leakage, the rotor current finds only ohmic resistance in rotor circuit and therefore the current vector i_2 and the resultant voltage vector have the same direction. The rotor voltage induced from the stator shall be e_2 for the rotor, not rotating and $s.e_2$ for the rotor, running with the slip s. If any voltage will be inserted by special means in the rotor circuit, the rotor current vector will be turned therefore, *f.i.* from i_2 to i_2' [see Fig. 1]

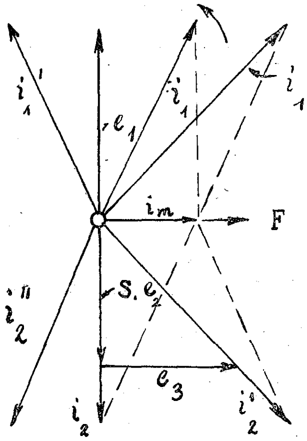

Fig 1

This turning of the rotor current by attaching a proper voltage into the rotor circuit is the method of improving the power factor by the phase-advancer. For, if the rotor current vector is turned, the stator current will be turned into the same direction, because the stator ampere turns and the rotor ampere turns compensate each other besides the ampere turns caused by the exciting current i_m and generating the magnetic flux F. The figure 1 shows this: if the current i_2 can be turned to i'_2, the stator current changes the direction from i_1 to i'_1. "Clockwise" turning of i_2 results also "clockwise" turning of i_1 and reverse. So the current i'_1 is leading, the current i''_1 is lugging. Therefore if the phase advancer makes possible to turn the vector i_2 in the "counter clockwise" direction it results the turning of primary current i_1,*i.e* the improving of the powerfactor.

For each electric machine using the principle of voltage generating by induction a magnetic flux must be produced. As it is well known, the field is generated by the exciting ampere turns. The exciting current is always lugging with nearly 90° behind the voltage and causes the lugging powerfactor. As by turning the rotor current vector, the current gets one component in direction of the exciting current, we can say, the phase advancer generates the exciting current for the motor or the phase advancer is to be called "three phase exciter machine".

As we have learned now, which simple method enables the self exciting of an induction motor, we will start with the description of the method, how this turning of the rotor current may be obtained. First it should be considered that the method of inserting the leading voltage e_3 (see Fig. 1.) in the rotor circuit is essentially the same as to insert lugging voltage. And as the phase advancer is not so well known as for instance the transformers and the reactance coil, we will explain the principle of the phase advancer, comparing it with the principle of the transformer or the reactance coil.

II. Self excited phase advancer.

The self excited phase advancer is in theory very similar to the reactance coil, only with the difference that the reactance coil produces lugging voltage and the phase advancer leading one, as it will be explained in the following.

Each reactance coil is self excited, *i.e.* the current flowing through the coil, generates the field, the vector of which is in the same direction as the current itself. This flux generates the reactance voltage being 90° lugging behind the flux, because each voltage is lugging 90° behind the generating flux, as it is well known (see Fig. 2) ; of course the rotor current i'_2 must be always 90° leading before the voltage e_3. Now the principle of the phase advancer can be easily understood. (Fig. 3) The rotor current of the main motor passes the brushes with the frequence of few cycles (slip-frequence) and either if the rotor is running or not, the rotor current produces the field, similar to that of the

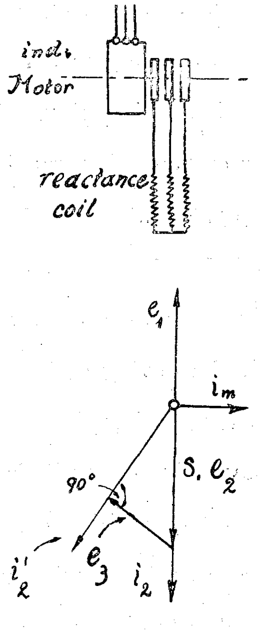

Fig 2

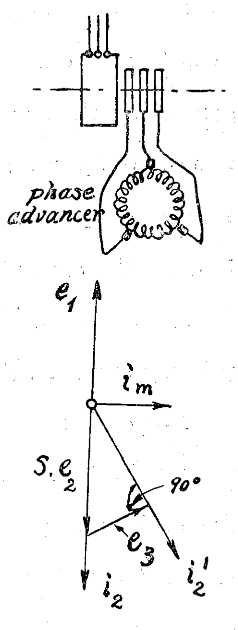

Fig 3

reactance coil, which is proportional to the current from zero till one limit given by the saturation of the core iron. Of course this field is fluctuating with the same number of cycles as the rotor current i'_2 and is rotating only with the small slip-frequence relatively to the stator core and to the fixed brushes. If the armature of the phase advancer is not rotating the described flux generates a lugging voltage component just as in the case of the reactance coil, as we have learned. But as the number of cycles is very small, also the lugging voltage component is very small.

Now by means of a driving motor we will turn the armature and of course we must distinguish the direction of rotation. Supposing that the flux is turning in clockwise direction with the slip-frequence $s.\ c_1$ in which case c_1 shall be the frequence of the stator current of the main motor, the rotation may also be clockwise, *i. e.* in the same direction as the field or counter clockwise, *i. e.* against the field rotation. Now we shall consider which E.M.F. will be generated in the winding of armature for this two different directions. By the rotation against the field the following E.M.F. will be generated:

$$e_3 = -f.\left[s.c_1 + \frac{n_p.p_p}{60}\right].F_p$$

n_p number of revol./min of phase advancer.
p_p 〃 〃 pol pair 〃 〃 〃
F_p magnetic flux of 〃 〃
f factor, depending from the winding and the field form only.

As the frequence in the armature turns is added to the frequence of the rotating flux $s.\ c_1$ the E.M.F, is lugging as in the case of reactance coil (Fig. 2). It might be said that the sign "minus" designates the E.M.F. lugging behind the current.

The opposite direction of rotation, *i.e.* the rotation with the field generates the following E.M.F:

$$e_3 = -f\left[s.c_1 - \frac{n_p.p_p}{60}\right].F_p = +f\left[\frac{n_p.p_p}{60} - s\,c_1\right].F_p$$

The changed direction of the rotation is marked by the sign "minus". Now the following three cases are to be distinguished:

1) $0 < \frac{n_p.p_p}{60} < s.c_1$

The value of e_3 remains negativ, *i.e.* the voltage is lugging, but smaller than for not rotating motor.

2) $\frac{n_p \cdot p_p}{60} = s.c_1$

The value of e_3 is zero.

3) $\frac{n_p \cdot p_p}{60} > s.c_1$

The value of e_3 is positiv, *i. e.* the voltage is leading.

Fig. 4. shows the dependence of the voltage from the number of revolutions for constant rotor current of the main motor, *i.e.* for constant field of the phase advancer.

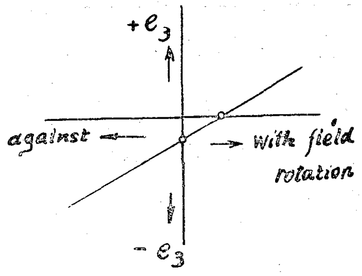

Fig 4

The comparison with the reactance coil allows now to develop the quality of this kind of phase advancer:

a) As we can learn from the formula, the E.M. F. is proportional to the frequence, just as for the reactance coil. The frequence is:

$$\frac{n_p \cdot p_p}{60} - s.c_1$$

and therefore the voltage increases with the number of revolution. But practically by the commutation a limit of too high speed is stated.

b) The E.M.F. is proportional to the flux F_p which is zero, when the rotor current is zero, as above stated and increasing with the rotor current of the main motor. As for no load running, the current is nearly zero, it is not possible to generate some E.M.F. in the phase advancer therefore it is not possible to compensate the lugging power factor in case of noload. This is the principle difference between the selfexited phase advancer and the separately exited phase advancer.

c) The wanted E.M.F. e_3 is exactly adjustable by the airgap *d*, just as in the case of the reactance coil with iron core parts. This dependency is shown in Fig. 5. In this

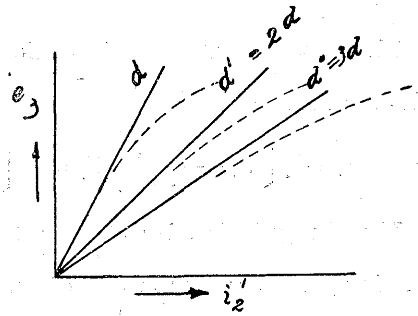

Fig 5

figure the lines are drawn out, if the iron saturation is neglected, while they are dotted, if the iron saturation is taken in account. Therefore the voltage e_3 is adjustable by the airgap for a certain rotor current i'_2, this current i'_2 being determined, of course, as the rotor current of the asynchronous motor. The changing of the airgap, therefore, would also allow the changing of e_3, *i.e.* the compensating also for partial loads in some limits, but as this method would be too complicated the airgap will be adjusted for full load, *i.e.* the stator current of asynchronous motor is leading for overload capacity and lugging for partial load. If the right saturation curve is chosen, the *p.f.* = 1,0 will be kept about from 70% to 125% load.

III. Separately excited phase advancer or frequence changer.

The name frequence changer shall only be used for the purpose of explaining that the machine, to be described, is nothing else but a rotating machine for changing the frequency. It is well known that the frequency may be changed by the using of a commutator, *f.e.* in the case of D.C. machines the armature current of the frequency $c=\frac{n.p}{60}$ is converted in D.C., *i.e.* the frequency zero. The same effect can be gained in the machine of each rotary converter and therefore the frequence changer is indeed nothing else but an armature of a rotary converter, rotating in a stator without any winding.

In the general explanation, already, we have pointed out that a proper voltage inserted in the rotorcircuit of an asychronous machine may turn the vector of the secondary as well as of the primary current. In the case of the self-exited phase advancer this "proper" voltage was induced by the rotation of the armature of the phase advancer in its own field: the "proper voltage" is generated in a similar way as the voltage of the reactance-coil. In the case of the separately excited phase advancer the voltage is not "generated" at all, but taken from the line. So we learn that the principle of the two different kinds of phase advancer is quite different, although the machines itselves seem to be quite similar.

Now let us see how this proper voltage is taken from the line. The first condition for inserting the proper voltage is the equality of the cycles. The frequency in the rotor circuit of the asynchronous machine shall be $s.c_1$ cycles, when s is the slip of the asynchronous machine, the line frequency c_1, therefore, must be converted in the frequency $s.\,c_1$. The principle connection is given in Fig. 6. The line is connected with the stator of the asynchronous machine and with the slipring of the frequency changer. The two machines have the same number of poles and are coupled directly, therefore the rotation of both machines is $n=(1-s)c_1\dfrac{60}{p}$ revol,/min. in the sense of the field rotation. The voltage on the sliprings of the frequency changer fluctuates with the frequency c_1 and if the armature stands still, the frequency of the voltage in the coil of the armature is c_1, the field is rotating, seen from the stator with the velocity corresponding to c_1. But, if we turn now the armature with some revolution/min. against the field rotation, the velocity decreases seen from the stator. Let us think for demonstration's sake of the "carussel", which we all have still in our mind from our childhood days. When a child is running around the carussel (merry-go-round) while staying still, the observer from outside sees the child appearing and disappearing with a certain "frequency". If the rotation of the merry-go-round is against the running direction of the child, the "frequency" decreases for the outside observer. If the merry-go-round is rotating just as quickly as the child is running, the observer sees the child always on the same spot of the room, the frequency is zero. —As both the machines are coupled together, they are running in the same direction, therefore we must change the sense of the slipring voltage of the frequence changer (by changing of the two leadwires). The frequency of the voltage from the sliprings is $-c_1$, the revolution of the armature corresponds to $+(1-s).c_1$, so the frequency of the field, seen from stator ("outside observer",) amounts to

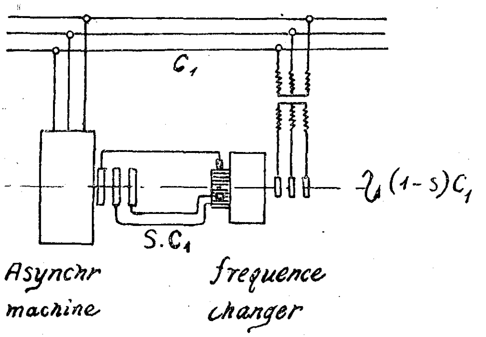

Fig 6

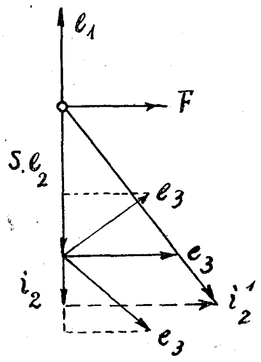

Fig 7

$$-c_1+(1-s)c_1=-s.c_1$$

i.e. against running direction.

As the brushes of the commutator are standing still in the room the frequency on the brushes will be: $-s.c_1$.

From this we can learn, that the first condition for the equality of frequency is fulfilled exactly, if

a) the frequency changer is mechanically connected with the asynchronous motor, either coupled directly (if the number of poles is the same) or joined by tooth-wheel, if the relation of the number of teeth is the same as the relation of the corresponding number of poles.

b) the rotation of the armature of the frequence changer is against the rotation of the field (in the case of tooth wheel the running direction of both the machines is contrary, so the field direction of the two machines must be the same.).

The second condition is to choose the "proper voltage". As we have learned from Figure 1. the "proper voltage" would be e_3, the vector of which is in the same direction as the flux. It can very easily be found out from the figure 7 that the voltage e_3 produces very effectively a current component in the direction of the field F, if the voltage is also in the direction of the mean field of the asynchronous motor, as for any other directed voltages the component parallel to F would be the only useful one. It might be noted here that the component in or against the direction of $s.e_2$ can be used for regulating the speed of the asynchronous motor, but as we are now investigating the phase compensating of the asynchronous motor only, we will limit our investigations to the component parallel to the flux F only. A very simple method enables us to catch this component:

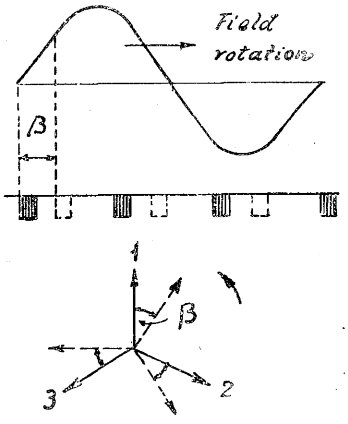

Fig 8

The brushes-ring can be moved on the commutator and by moving it with 360° *el.* degree, the voltage e_3 is also turned with 360° *el.* degree. This fact might be easily understood, if we remember that the voltage of the frequence changer is rotating with the slip cycles on the brushes, just as the field, so by turning the brushes with the angle ß in the stnse o the field rotation, the brushes will come later into the point of field zero; at a certain time, corresponding to the angle ß, *i.e.* by moving the brushes in the sense of the field rotation, (*i. e.* against the running direction), the phase of the voltage on the brushes is turned back into the same angle ß *el*· degree (see figure 8.)

Now we can find out, already, the principle qualities of the separately excited phaseadvancer, which we can compair with the qualities of the selfexcited phaseadvancer mentioned under item a) b) and c).

a) The E. M. F. inserted in the rotor circuit is depending upon the voltage attached to the sliprings of the phaseadvancer. For three-phase brushes-connection the voltage on the brushes is just the same as the voltage on the sliprings (neglecting a rather small drop in voltage). For other phase combinations we always finda constant relation between the voltage of the brushes and the voltage of the slipring. The number of revolutions does not have any influence for the voltage on the brushes, but only warrants the proper frequency.

b) The E.M.F. on the brushes is independent from the load, as under all conditions the voltage depends on the voltage of the sliprings only. Thereforc the current component which enables the leading stator current is in all loading conditions the same.: The powerfactor will be compensated also in case of partial load and no load.

c) As the voltage on the brushes is not depending on the airgap a determination of the voltage by changing the airgap is not possible.

IV. How to determinate the capacity.

In the following part we will state some formulas which are rather important for the design of both, the self excited and the separately excited phase advancer. In figure 9 and 10 the rotor voltage diagram is given for the same motor, one time with self excited phase advancer and the other time with separately excited phase

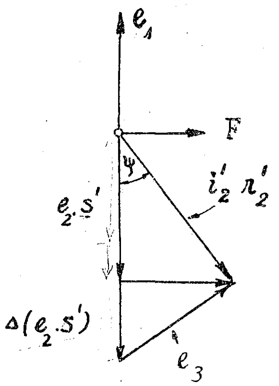

Fig 9

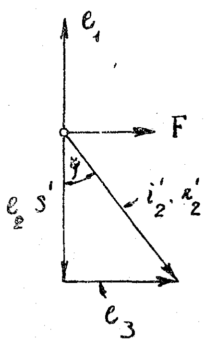

Fig 10

advancer. Neglecting the rotor leakage (which is very small, as the number of cycles in the rotor circuit is very small too) we find the two E.M.F.s $e_2 . s$ and e_3 in the rotor circuit. The geometrical sum of these two voltages compensates the ohmic voltage drop $i_2' . r_2'$, if r_2' includes all resistances in the circuit, *i.e.* the rotor resistance of the asynchronous motor and the armature resistance of the phase advancer, furthermore the ohmic voltage drop in the slipring brushes of the asynchronousmotor and the one of the commutator brushes of the phase advancer.

In the following s' shall be the slip calculated with the resistance r'_2. We can very easily, now, get the following formulas from the diagram, if we distinguish between i_2, the rotor current of the motor without the phaseadvancer and i_2', the rotor current of the motor with phase advancer. (i_2 is in the same direction as $e_2\, s$).

Voltage, current and resistance are to be understood as per phase.

a) self excited phaseadvancer	b) separately excited phaseadvancer
1.) $\dot{i}_2' = \dfrac{\dot{i}_2}{\cos\psi}$	1.) $\dot{i}_2' = \dfrac{\dot{i}_2}{\cos\psi}$
2.) $e_3 = e_2 . s' . \dfrac{\mathrm{tg}\psi}{\cos\psi}$	2.) $e_3 = e_2 . s' . \mathrm{tg}\psi$
$e_3 . \dot{i}_2' = e_2 . \dot{i}_2 . s' \dfrac{\sin\psi}{\cos^3\psi}$	$e_3 . \dot{i}_2' = e_2 . \dot{i}_2 . s' \dfrac{\sin\psi}{\cos^2\psi}$

and as the output of the motor 3·*a*) $W = (1 - s') . e_2 . i_2 . 3$

further the capacity of the phaseadvancer 3.*b*) $W_p = e_3 . i_2^1 . 3$

(supposing three-phase arrangement)

therefore follows:

3.) $\dfrac{W_p}{W} = \dfrac{s'}{1 - s'} \dfrac{\sin\psi}{\cos^3\psi}$	3.) $\dfrac{W_p}{W} = \dfrac{s'}{1 - s'} \dfrac{\sin\psi}{\cos^2\psi}$
4.) $s'' \doteq \dfrac{e_2 . s' + \triangle(e_2 . s')}{e_2} = \dfrac{s'}{\cos^2\psi}$	4,) $s'' = \dfrac{e_2 . s'}{e_2} = s'$

wherein s'' means the slip if the motor is running with the phaseadvancer.

The two formulas (3) are replaced by the curves Fig. 11 and 12. It is remarkable that the capacity and the voltage are $\dfrac{1}{\cos\psi}$ times greater in the case of self-excited phase advancer than in the case of separately excited phaseadvancer, while the current is the same in both cases. Further from formula (4) follows that the slip is different for both the cases.

Some remarks may follow with regard to the angle ψ and the slip s' :

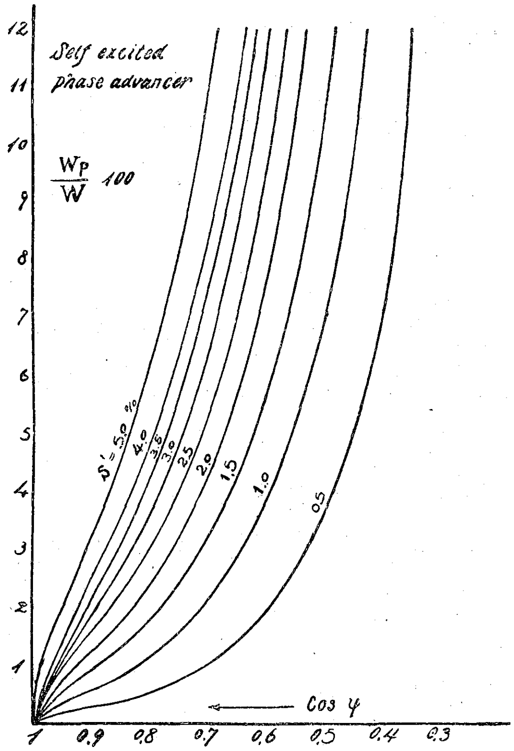

Fig 11

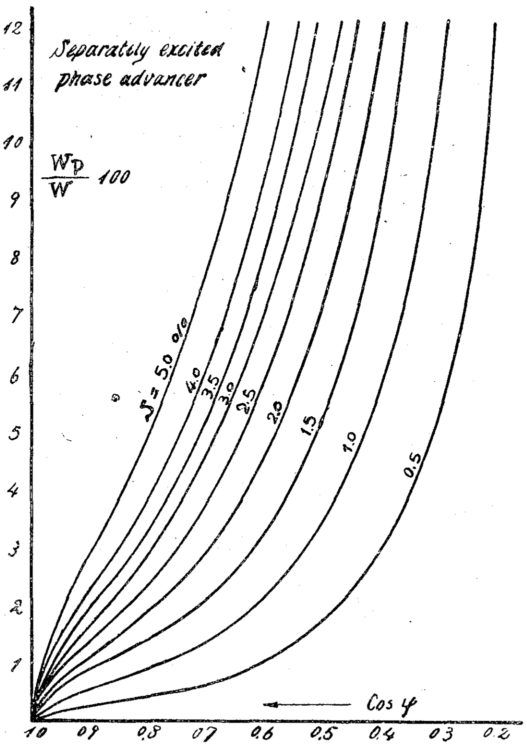

Fig 12

ψ is the angle between the two vectors i_2 and i_2' *i.e.* the angle, which results from the E.M.F. e_3 of the phaseadvancer. This angle is in a simple relation to the primary powerfactor, as we learn from the wellknown circle diagr. for the induction motor (*f.i.* specified in the Denki Kyokai rules of 1924). If we draw the diagram, we can easily find the angle ψ directly by measuring, if we move the point P in a horizontal line to P_1 or P_2 or P_3 see Fig. 13.

Fig. 13. P_1: *p.f.* compensated from $\cos\varphi$ to $\cos\varphi_1 = 1{,}0$

P_2; 〃 over— 〃 〃 〃 leading (overexc).

P_3: 〃 under— 〃 〃 〃 lugging (underexc.)

If it is too inconvenient, to draw a diagram as the data for its construction are not all known, a simple and quite accurate, but not exact formula is the following;

6.) $\mathrm{tg}\psi = \mathrm{tg}\varphi_1 + \mathrm{tg}\varphi$

For compensating to p.f. = 1,0 we can state: $\varphi \sim \psi$ and the error is very small, as this is to be learned from the circle diagram.

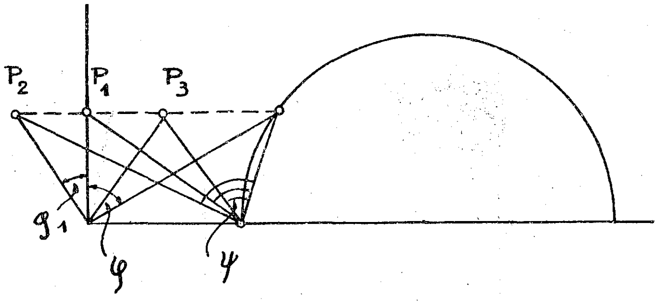

Fig 13

s' is the slip in which the resistance of the total rotor circuit is included, as already above stated. But the difference between s and s' is produced at most part by the voltage drop in the brushes of the phase advancer, the amount of this may be between 1 and 1,5 Volt for each brush, medium value abt. 1, 25 Volt. Therefore the losses of brushes and armature for threephase arrangement are about:

$$L_B = 3 \cdot 1{,}5 \cdot i_2$$

But as the slip is given by the rotor copper losses

$$L_R = s \cdot e_2 \cdot i_2 \cdot 3$$

we find

6.) $s' = \frac{L_R + L_B}{e_2 \cdot i_2 \cdot 3} = s + \frac{2{,}6}{E_2}$ if E_2 means the maximal slipring voltage independing from the connection of the rotor (delta or star).

Practically the slip s' will be about 1,1 till 1,25 times the slip s.

So it is now easy, to find the capacity of the phase-advancer either selfexcited or separately excited. A sample may illustrate it:

A motor with the following qualities shall be compensated to power factor = 0,9 overexcited:

1000 HP, 3000 Volt, $\cos\varphi = 0{,}87$, 16 poles, 369 r/m.

max. rotorvoltage 950 Volt, synchron. speed 375 r/m

We calculate:

$\cos\varphi = 0{,}87$, $\operatorname{tg}\varphi = 0{,}565$ $\cos\varphi_1 = 0{,}90$, $\operatorname{tg}\varphi_1 = 0{,}484$

5.) $\operatorname{tg}\psi = \operatorname{tg}\varphi_1 + \operatorname{tg}\varphi = 1{,}049$ $\cos\psi = 0{,}69$.

$$s=\frac{375-369}{375}=0{,}016 \qquad 6,)\ s'=0{,}016+\frac{2{,}6}{950}=0{,}0187$$

$$3a)\ i_2=\frac{1000\cdot 0{,}746\cdot 1000}{950\cdot\sqrt{3}\cdot[1-0{,}0187]}=462\ \text{Amp.} \qquad 1.)\ i_2'=\frac{462}{0{,}69}=670\ \text{Amp.}$$

	Selfexcited phase adv.	Separately excited phase adv.
Fig. 11 & 12 : $\frac{W_p}{W}100$	4,3	2,9
W_p k.V.A.	$1000.0{,}746.\frac{4{,}3}{100}=32{,}0$	21,6
4.) s''	$\frac{0{,}0187}{0{,}69^2}=0{,}0393$	0,0187
Speed	$375-0{,}0393.375=360$	368

Now we learn from these figures that the separately compensated phase advancer will be more favourable than the selfexcited phaseadvancer, but no in all conditions. Generally may be said that the selfexcitedphase advancer is available for motors, which are running mostly with half till fulload. The separately excited phase advancer may be available if the motor is often used for loads smaller than ½ load, or if the motor is often running in no-load condition. As in these conditions the motor is overexcited, leading current flows into the motor and this is suitable for the purpose of improving the line power factor. But there are to be considered many questions, whether a phase advancer is available or not, and which kind of phase advancer may be chosen, and these points of view shall be investigated in a following essay.

The performance of the phase-advancer was already mentioned in this magazine.* There also the phase advancer with compensating winding in the stator core is mentioned. The advantages of this patented compensating winding are two essentially: the first is improving the commutation of the phase-advancer, which—it can be stated—becomes faultless, the second is the reducing of the current flowing from the line to the sliprings of the phase advancer. In the consequence of both advantages the losses of the phase advancer with compensating winding are smaller than the losses without compensating winding.

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* 富士電機時報大正十五年四月 石川氏 非同期進相機用並高力率誘導電動機用三相交流勵磁機

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