POLE CHANGE TYPE SALIENT-POLE A-C GENERATOR

By

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I. GENERAL

In pumping up power station, it is considered most desirable that a synchronous machine which is directly coupled to reversible turbine will operate at one speed when generating and a different speed when pumping. The two speed type of synchronous machine has the advantage of better efficiency since maximum efficiency of the unit for turbine operation occurs at a lower speed than for pumping. In this case, the number of poles of the synchronous machine must be changed inversely proportional to both number of revolutions in order to obtain two speed operation.

From this point of view, Siemens-Schuckertwerke A.G. in Germany had deliverd to Hohenwarte pumped-storage station in 1940 a pole change type a-c generator, 20,000 kVA 50 c/s 44/36 poles 136/167 rpm, which adopted distributed winding rotor. As it was impossible from mechanical strength to adopt distributed winding rotor for larger size generator than the above generator, S.S.W. devised a pole change method with salient pole and manufactured a testing machine rated 450/400 kVA, 50 c/s, 22/18 poles, and 273/333 rpm. This machine adopted a well-known method that only 4 poles out of 22 poles are not excited when operating at 18 poles. So the component of harmonic wave is available which is corresponding to 18 poles in the irregular magnetic field in air gap.

At the same time, stator windings are switched so that they may have the distribution for 18 poles. As utilization factor of the machine is not necessarily good in this method, it is defective that the machine size becomes larger. For instance in the testing machine of S.S.W.

$$B_{22} : B_{18} \cong 1 : 0.67$$

where B_{22} is the crest value of maximum fundamental magnetic flux density when operating at 22 poles and B_{18} is that at 18 poles.

It becomes therefore necessary that the machine should be constructed in larger size for the drop of utilization factor of magnetic flux when operating 18 poles.

In the United States, pole change type salient pole a-c generator rated 8,500 kW/13,000 HP., 60c/s, 28/24 poles, and 257/300 rpm, which was formerly furnished by Allis-Chalmers Company for the Flatiron power plant, had provided with two electrically independent and complete stator windings, one of which was used for 300 rpm and the other 257 rpm operation. The method to switch connections of rotor coils adopted the same method as S.S.W.

If the S.S.W. method of pole change was adopted in a two speed unit, it would be inevitable to need larger size of generator than that of the conventional one. This method is therefore not somewhat economical considering increase of about 30% additional weight, although it variates with pole change ratio. We have now completed a new pole change type salient pole testing machine by Fuji-Denki method, which increases utilization factor of magnetic flux by switching connections of rotor poles skilfully which consist of two kinds of poles, large and small poles, so that the defect of S.S.W. method may be improved. This paper is the illustration of its outline and we are very glad that it will be available for readers.

The testing machine is rated at 200 kVA, 440 V, 60 c/s, 14/12 poles and 514/600 rpm, and the ratio of crest value of the magnetic flux density at both number of poles is as follows.

$$B_{14} : B_{12} \cong 1 : 0.823$$

That is to say, utilization factor is remarkably increased more than that in S.S.W. method. We have had therefore an expectation that this type of generator will be able to be manufactured with only about 10% additional weight.

II. PRINCIPLE OF FUJI POLE CHANGE METHOD FOR SALIENT POLE SYNCHRONOUS MACHINE

Up to the present a synchronous machine with pole change of the salient pole type has been applied to pole change ratio of 1 : 2, 1 : 3 and rarely 2 : 3, by placing two or three poles of the rotor magnetically in parallel.

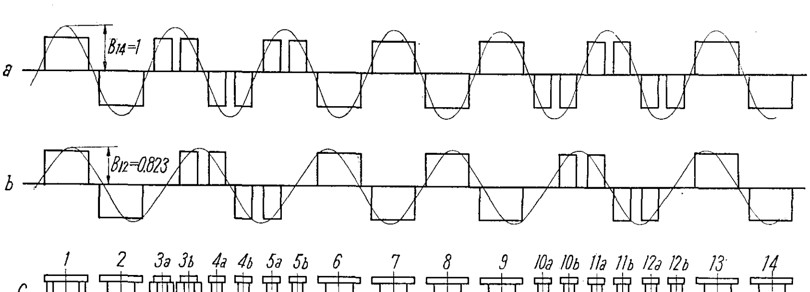


Fig. 1. Pole change with a ratio of 6:7 for a a Salient pole machine

This method agreeds with a fundamental principle that magnetic field of alternater must be formed in distribution of sinusoidal wave as much as possible. But in such a method optional pole change cannot be obtained economically. Especially in pumping up power station, it is desirable to adopt pole change ratio of 5 : 6, 6 : 7, 7 : 8, 7 : 9 and 9 : 11 etc., in order to increase the efficiency of pump turbine remarkably. Then the method of S.S.W was devised in which the harmonic wave components were utilized by designing stator winding skilfully although the magnetic field formed by rotor pole was irregular. But utilization factor of the machine is not so good in S.S.W. method itself as mentioned in foregoing chapter.

Then in the testing machine of our 200 kVA generator its pole change ratio was selected 6 : 7 and two kinds of rotor magnetic poles, large and small, were arranged as shown in Fig. 1 so as to increase utilization factor of the machine (This method is applying for a Fuji Denki Patent). When they are excited as well as usual generator as shown in Fig. 1 (a), magnetic field of 14 poles are produced. If there are stator windings for 14 poles, voltage of 60 c/s will be induced at 514 rpm and the power output will be supplied to a common bus ; namely the operation at 14 poles is the same as that of the conventional generator. Next, when operating at 12 poles, four small magnetic poles shown as 3a, 5b, 10a, 12b in Fig. 1 (c) are not excited and moreover their field windings are short-circuited. Taking magnetic balance into account, they are adequately distributed on circumference of rotor respectively, and it is necessary to consider their arrangement so that utilization factor of magnetic field of 12 poles may be raised to its maximum. At the same time, through field windings of 4a, 5a, 6, 7, 8, 9, 10b, 11b, the exciting current flows in the reverse direction contrary to that in operating at 14 poles. Then 12 poles of unequal intervals are obtained as shown in Fig. 1 (b). In the Fig., B_{12} is the fundamental wave of 12 poles of this magnetic field computed by Fourier series. If the maximum flux density B_{14} of the fundamental wave at 14 poles is assumed a unity, there is in the ratio

$$B_{14} : B_{12} = 1 : 0.823$$

Assuming the flux distribution of S.S.W. method with this pole change ratio, there becomes in the ratio.

$$B_{14} : B_{12} = 1 : 0.676$$

To adopt pole change with Fuji method causes a machine to increase utilization factor of it about 22%. It is therefore the aim of this method that a machine size need not be made in larger size as the S.S.W. method in order to obtain two speed generator. So we believe firmly that this method is very useful to reduce the cost of two speed generator.

In the explanation mentioned above, only crest value of the fundamental wave is treated concerning both 14 poles and 12 poles. Since even in the magnetic field of 14 poles magnetic poles of 3,

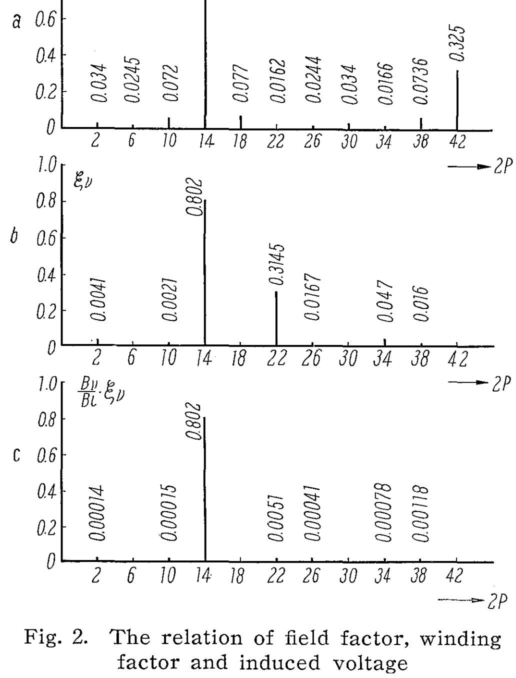


Fig. 2. The relation of field factor, winding factor and induced voltage

4, 5, 10, 11 and 12 are able to form a magnetic field corresponding to ordinary one pole with two poles of small magnetic pole, the magnetic flux includes not only the fundamental wave of 14 poles, but also other harmonic waves in its distribution.

The ratio of components of these harmonic wave to the fundamental wave of 14 poles are shown in Fig. 2 (a). As obvious in this Fig., the fundamental wave and its 3rd harmonic wave of 14 poles (42 pole wave) are remarkably large in amplitude and others small. A similar consideration is applied to the case of 12 poles, in which 12 poles of unequal intervals are formed by losing the function of adequate small magnetic poles. Consequently the magnetic flux includes components of harmonic waves of comparatively large amplitude as well as the fundamental wave of 12 poles. The ratios of these components of the harmonic waves to the fundamental wave of 14 poles are shown in Fig. 3 (a). Fig. 3 (a) shows that the magnetic flux includes many harmonic waves.

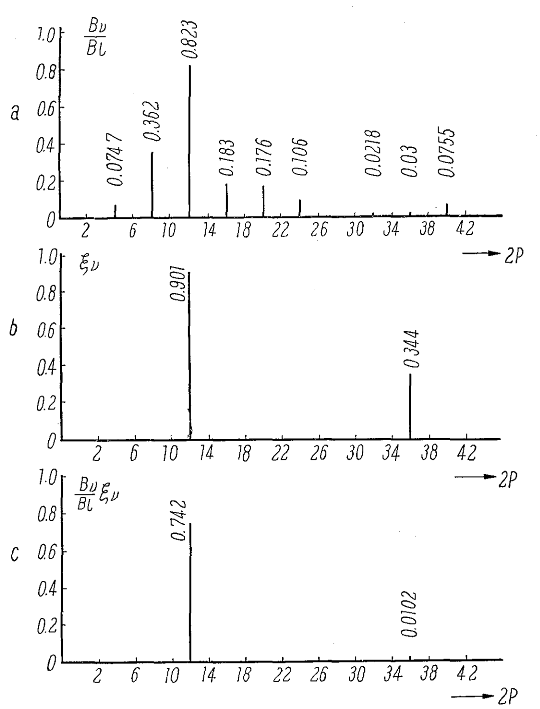


Fig. 3. The relation field factor, winding factor and induced voltage

Provided that out of these harmonic waves in Fig. 2 (a) or Fig. 3 (a) only the fundamental wave of either 14 poles or 12 poles is produced in the stator windings, the generator will be able to operate at both number of poles. If there were two independent stator windings of 14 poles and 12 poles, the object would be simply accomplished by using them adequately. But this method is not so economical on material that a single stator winding had better be used by switching its connection. It coincides with our desirable aim that the winding factors of the stator winding are designed as low value for 14 poles of high utilization factor of magnetic field and high value for 12 poles of low utilization factor of magnetic field and moreover as extinguishing many other unnecessary harmonic waves. Fig. 2 (b) and Fig. 3 (b) show the winding factor ξ_ν respectively in both number of poles. The products of these ξ_ν and B_ν/B_l already mentioned are proportional to the voltage induced in the stator winding at the same revolution, the values of which are shown in Fig. 2 (c) Fig. 3 (c) to each harmonic wave. As evident in that Fig., the components of harmonic waves of $\xi_\nu \dfrac{B_\nu}{B_l}$ are neglegibly small compared with crest value of the fundamental wave in either 14 poles or even in 12 poles.

When we compare the fundamental induced voltage of 14 poles with that of 12 poles, the ratio of E_{12}/E_{14} is as follows at identical exciting current,

$$\frac{E_{12}}{E_{14}}=\frac{B_{12}}{B_{14}}\cdot\frac{\xi_{12}}{\xi_{14}}\cdot\frac{14}{12}=\frac{0.823}{1}\cdot\frac{0.901}{0.802}\cdot\frac{14}{12}\cong 1.08$$

that is, the induced voltage when operating in 12 poles is about 8% above that in 14 poles.

When we examine it in S.S.W. method, the ratio as follows is obtained.

$$\frac{E_{12}'}{E_{14}'}=\frac{B_{12}'}{B_{14}'}\cdot\frac{\xi_{12}}{\xi_{14}}\cdot\frac{14}{12}=\frac{0.67}{1}\cdot\frac{0.901}{0.802}\cdot\frac{14}{12}\cong 0.88$$

It is easily understood how the utilization factor of magnetic flux is raised by Fuji Denki method.

The matter described above is of pole change with a ratio of 6 : 7, while other pole change ratios can be considered similarly in which the utilization factors of magnetic flux are almost invariable compared with that of above pole change ratio of 6 : 7 in range of most adequate revolutions used in ordinary pumping up power stations. This pole change method can be applied not only to the ordinary pumping up power stations in which a two speed machine is in generator operation at low speed and in motor operation at high speed, but also to the pumping up stations having considerable variations in head where the machine is skilfully able to operate as generator at two speed and as motor at two speed and moreover to two cycle hydraulic power plant where it operates as two cycle generator at constant speed.

III. POLE CHANGING SYSTEM

The principle of pole change is already described in the above chapter, but a simple pole changing system is required from a practical point of view. Therefore rotor winding must be changed simply and exactly without stopping the machine. For that purpose field winding is divided into three groups as shown in Fig. 4. In the 1st group polality is kept

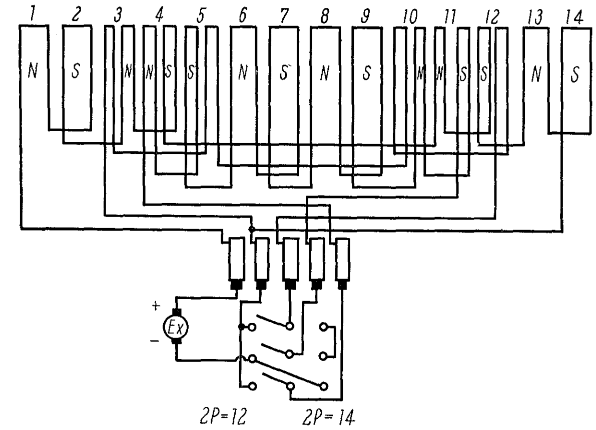


Fig. 4. Connection diagram of field winding

constant, in the 2nd group it is inverted and in the 3rd group field winding is short-circuited without excitation, when the number of pole is changed. Then, if each terminal of them is connected to five slip rings, an exact and immediate pole changing is possible by providing a pole changing switch outside the rotor. In that case the rotor is not necessarily required to keep stopping, but also the switch can be very simple by currentless switching. The case of pole change ratio 6 : 7 is illustrated in this connection diagram and this method is able to be applied to all other cases. Fig. 5 shows the rotor of 200 kVA pole change type testing generator. The connection of field winding is simpler than what is imagined from Fig. 4.

Though pole changing of stator winding becomes quite simple if a machine has two electrically independent windings, this method is not so economical on material that a single stator winding had better be used by switching its connection. The pole changing system of single stator winding is the same kind with those which have been used for the induction motor. But such cases of pole change ratio as 5 : 6, 6 : 7, 7 : 9, 9 : 11 etc., are seldom used for induction motors. Therefore a pole changing system, practically designed to decrease the number of terminals, is adapted. Fig. 6 indicates the pole changing system for 14 poles and 12 poles. In this diagram

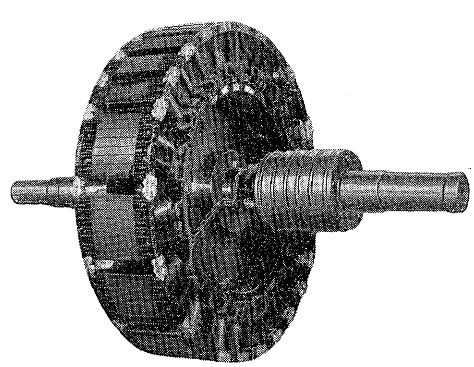


Fig. 5. Rotor

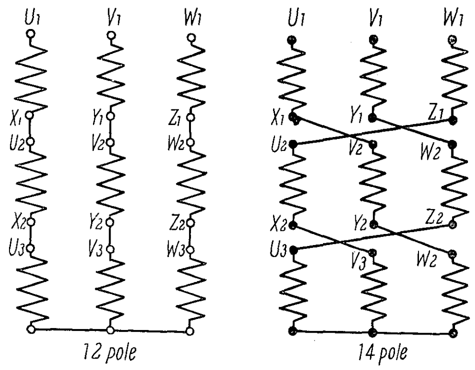


Fig. 6. Connection diagram of stator winding

the group of coils which belongs to *u* phase in 12 poles connection is divided into three groups in 14 poles winding ; one of them is connected to *u* phase, another to *v* and the other to *w*. Using this method of Fig. 6, that is, to divide the coils of each phase into three groups considering the direction of E.M.F., pole changing of single winding comes to be possible with 12 terminals. The pole changing switch can be small and simple, as the case of rotor pole changing, when it is operated at no load condition.

IV. GAIN AND LOSS IN PUMPING UP POWER STATION, WHEN THE GENERATOR ADOPTED TO THE POLE CHANGE TYPE

In hydro-electric power stations with pumped storage, where the head is sufficiently great, reversible turbines are often used, so that the same machine can be used as a pump or as a turbine. In this case, we only need one hydraulic machine. Moreover, the auxiliary machine of the pumpturbine, penstock, draft tube and other equipments in the power station not only become economical, but also their arrangement can be all the same as those ot the conventional francis turbine.

However the pumpturbine has also the weak points, that the efficiency is not so good and the rated speed is slow compared with the usual turbine. In this system, we need longer switching time from the pump operation to the turbine operation or conversely than in the separate operation system, which has each exclusive use runner for the both operations.

Especially the speed at which pump has the maximum efficiency and the speed at which turbine has it are not the same, so when operate the hydraulic machine at the same speed by pump operations or by turbine operations the efficiency becomes lower than the maximum efficiency. Recently the progress of the study of the pumpturbine is remarkable and the difference of the both speeds at which pump or turbine is operated most efficiently becomes very

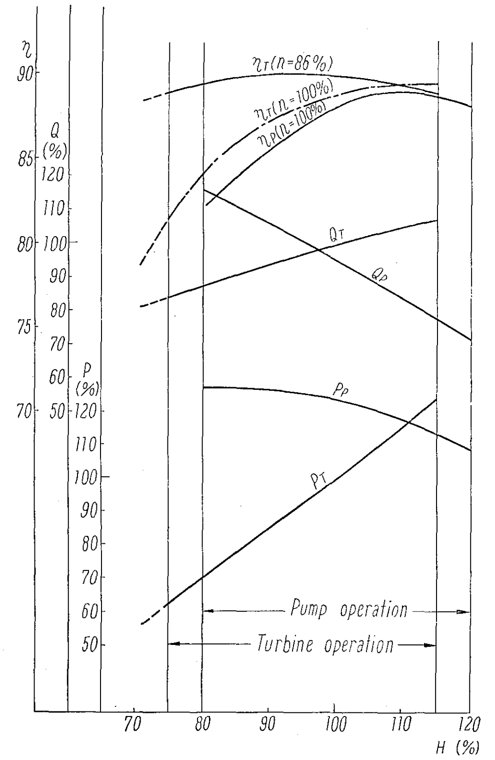


Fig. 7. Characteristic curve of water turbine

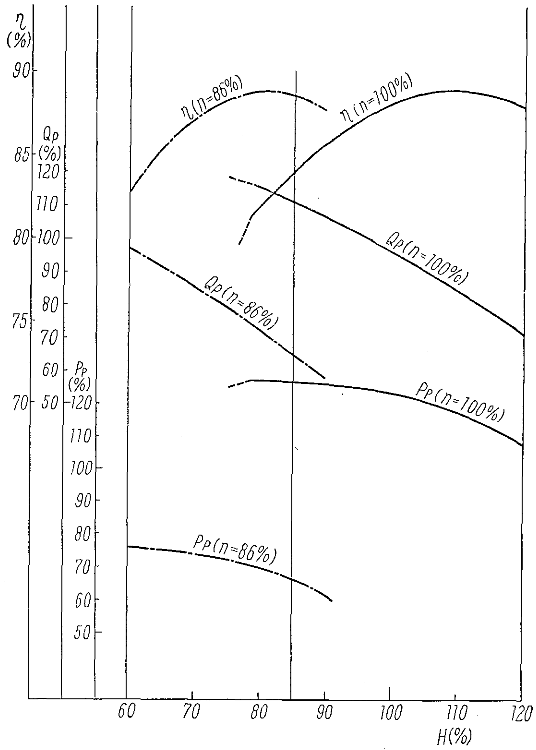


Fig. 8 Characteristic curve of pump

small, lowering of the efficiency becomes also small. But the pumpturbine can not have the maximum efficiency yet.

This is because of the use of same runner for the pump and turbine operation. To improve it, we must operate changing the pump speed and turbine speed so that we get more efficiency at the both operations. Therefore if we couple the pole changing type a-c generator with the pumpturbine, we can improve efficiency of the pumpturbine. We point the good charactor of the pumpturbine on Fig. 7. In this Fig., the horizontal axis means the head H and the vertical axis means efficiency η, water quantity Q or power output P. The suffix p means pump operation, t turbine operation, and n's are revolving speed. When we compare the efficiency at 100% speed with that at 86% speed, we can see the improvement of efficiency which is about 3% or 7% in the highest degree though it is not always owing to H. On the other hand, the mechanical loss increases owing to the increase of the machine size, the stray load loss increases owing to the irregularity of magnetic flux distribution in the pole change type generator compared with the ordinary generators. On this type the efficiency are almost 0.2% lower than the conventional generator on the both operations. Accordingly, this is almost out of consideration for the improvememt of the pumpturbine efficiency, and the overall efficiency was improved largely. Therefore, considering the construction cost of power plant, it will be the most modern thought to use in the pumping up station the pumpturbine which is directly coupled to pole change type synchronous machine.

For pumped storage power station where considerable variation ranges of head of water may occur, this system presents more advantage. That is to say, as shown in Fig. 8, we divide the variation range into two parts, pumps are used which can operate either at a higher speed for a greater head, or at reduced speed for reduced head; this makes it possible to obtain higher efficiency of the pumps over a greater range of powers. Moreover, this operation is profitable in cavitation. We can say the same in the case of the turbine operation.

Next, switching time of the pumpturbine from pump operations to turbine operations is almost out of the question today. Because, using electric brake and other methods, we can almost reduce the time of that.

V. TEST RESULTS OF 200 kVA TESTING MACHINE

In order to get an accurate data, we made a testing machine with an output of 200 kVA, which was comparatively a large capacity for testing.

When we tested it, we coupled a fly wheel of a large capacity, so that the inertia coefficient of the machine increased to about 7 kW sec./kVA, which was similar to the value of actual pumping up station. Therefore we could confirm the performance of the testing machine as a motor, i.e., that of starting and synchronous pull-in characteristics.

Test results are as follows.

1. Wave form of no-load voltage

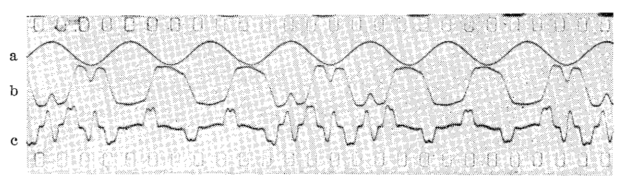
At 12 poles or 14 poles running, we took each oscillogram of no-load wave form at normal speed and voltage.

Fig. 9 shows them, where *a* is the wave form at terminal voltage, *b* is the magnetic wave form, and *c* is induced voltage of search coil which is inserted to detect the internal magnetic field. In spite of the irregularity of the magnetic field wave, the wave form of the no-load voltage at 12 poles or 14 poles running was sinusoidal, so that we measured the distortion factor of the no-load voltage by distortion factor meter. The results were as follows.

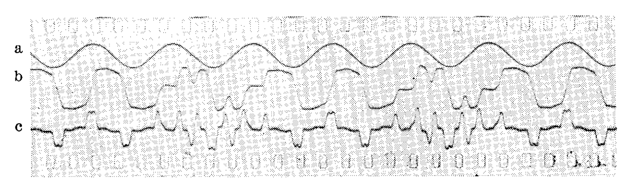
distortion factor (at 14 poles running) = 1.0%

distortion factor (at 12 poles running) = 0.4%

These values are nearly equal or rather small than that of the ordinary a-c generators, so that we can expect the good wave form of the pole change type generators.



14 Pole



12 Pole

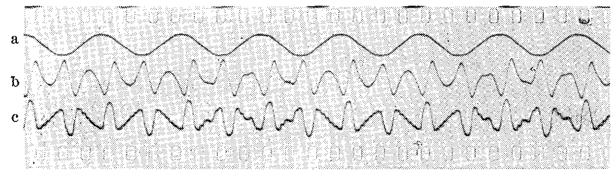
a. No-load wave form
b. Magnetic field wave
c. Induced voltage of search coil

Fig. 9. Wave form of no-load voltage

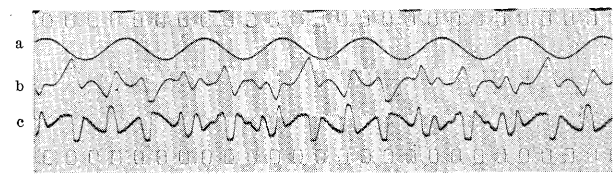
2. Wave form of short-circuit current

In Fig. 10 *a* is the oscillogram of the three phase short-circuit current, *b* is the magnetic wave form, where the testing machine runs at each normal speed, 14 poles and 12 poles, and the current is the rating.

Though the magnetic field wave in the oscillograms *a* is distorted remarkably by the armature back ampere-turns, the three phase short-circuit currents are nearly sinusoidal. In the same manner, Fig. 11 shows the wave form of two phase short-circuit current.



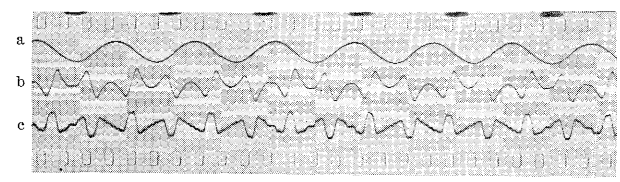
14 Pole



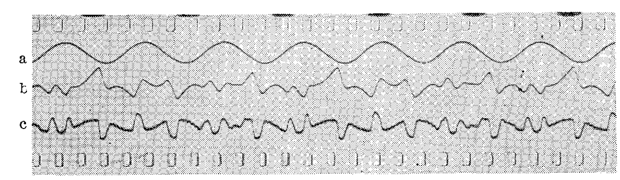
12 Pole

a. 3-phase short-circuit current wave form
b. Magnetic field wave
c. Induced voltage of search coil

Fig. 10. Wave form of 3-phase short-circut current



14 Pole



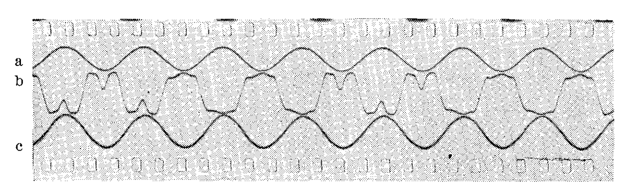
12 Pole

a. 2-phase short-circuit current wave form
b. Magnetic field wave
c. Induced voltage of search coil

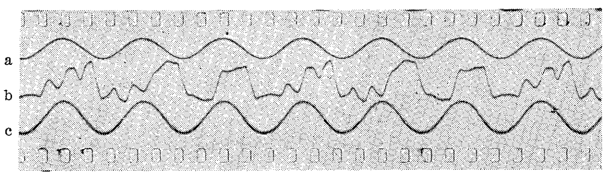
Fig. 11. Wave of 2-phase short-circuit current

3. Wave forms of the generator voltage and current on-load

Wave form of the terminal voltage and the generator currents are seen in the oscillogram of Fig. 12, where the testing generator runs at full load of 200 kVA $\cos\varphi = 0.8$ lagging. In them, we can see really fine wave form as that of an usual generator. *a* is the terminal voltage 440V, *b* is the magnetic field wave and *c* is the load current of 262 A.



14 Pole



Pole 12

a. Wave form of generator voltage
b. Magnetic field wave
c. Wave form of load current

Fig. 12. Generator voltage, current, field wave form at full load

4. Wave forms of voltage and current at single phase loading

Wave forms of the voltage, current and exciting current were taken in oscillogram as Fig. 13 and Fig. 14, and when we took them, the testing generator was connected to single phase resistance load and was fully loaded at 12 poles or 14 poles running. In these oscillograms, though the wave forms of the generator voltages are distorted to some degree by the armature back ampere-turns, we can find that the generator runs normally at 12 poles notwithstanding its irregular magnetic fields as well as at 14 poles. Further negative sequence current of $2f$ frequency is superposed on the exciting current waves.

During these testing, though we had investigated the magnetic noise, vibration and so on, the generator had no qualitive difference to any other machines, but showed rather good performance.

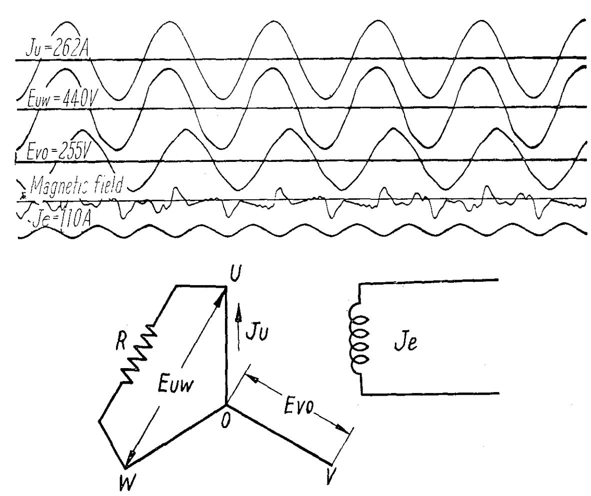


Fig. 13. Wave form of load current J_U, Voltage E_{UW}, E_{V0}, magnetic field and field exciting current for 2-phase resistance load. (14 pole running)

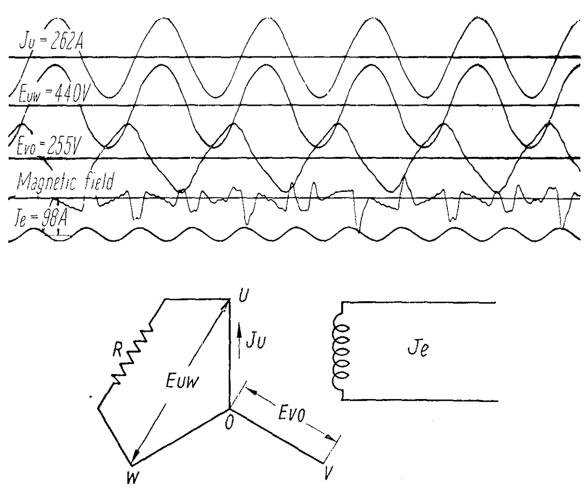


Fig. 14. Wave form of load current J_U, Voltage E_{UW}, E_{V0}, magnetic field and field exciting current for 2-phase resistance load. (12 pole running)

5. No-load saturation characteristic curve and three phase short-circuit characteristic curve

No-load saturation curve and three phase short-circuit curve of the testing machine coincided with the design. Induced voltage at 12 poles running is about 8% larger than at 14 poles running under the same exciting currents as Fig. 15. In them short-circuit ratio at 14 poles running is about 1.27 and at 12 poles running is about 0.74.

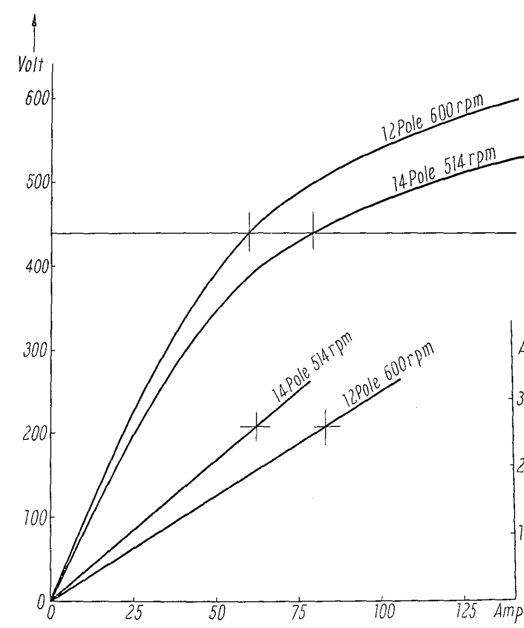


Fig. 15. No-load characteristic curve and 3-phase short-circuit curve of pole change generator

6. Increase of losses

In the results of loss measurements we found neither abnormal increase of core loss nor of stray load loss.

The fact that the core loss increase was not found, is based on the Fuji pole changing system radically, in which the utilization factor is better and the induced voltage is higher at same exciting current than the S.S.W. method.

On the other hand, in the results of stray load loss measurement, loss at 12 pole running is more than that of the ordinary by about 0.1% of the rated kVA. The increased loss, however, scarcely gives an influence to temperature rise of stator windings, but is absorbed almost in damper winding. This owes to the suitably designed damper winding. The increased losses of generator are almost negligible to overall losses. Therefore, it is a great success, we believe, that we have got posibility to manufacture the pole change type generators of large capacity through the testing machine, the efficiency of them are supposed lower only about 0.2% than the ordinary, including the increases of mechanical and windage losses.

7. Starting test as a synchronous motor

When this pole change system is adopted as a generator of pumping up station, it must be able to start as a synchronous motor at higher speed running, that is to say, the fewer pole numbers of the machine, which has the irregular magnetic field. Of course, it is capable of starting enough, similar as an ordinary synchronous motor by using the magnetic field of the higher harmonics. In order to confirm this phenomenon, we took an oscillogram of the starting at full voltage 440V. From the oscillogram, acceleration torque and starting current are investigated, starting characteristics are given as shown in Fig. 16. There is not an abnormal torque due to any other higher harmonics outside the fundamental wave of 12 poles as an ordinary motor. Though the inertia coefficient of the machine is chosen about 7 kW sec./kVA in the test, in order to investigate a phenomenon of synchronizing, the machine is as well synchronized as we supposed, and does not show any difference from an ordinary.

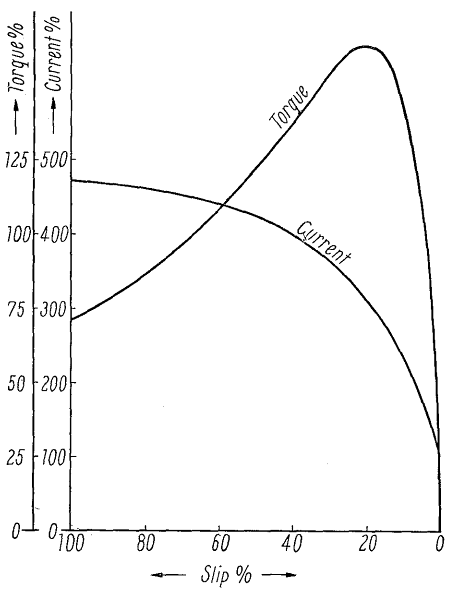


Fig. 16. Starting performance of synchronous motor

VI. SUMMARY AND CONCLUSION

The investigation and the many tests carried out have served to establish a very favourable method of pole changing for a synchronous machine with salient poles. For ratio of the number of poles ranging from $p_2/p_1=0.9$ up to 0.75, to adopt pole change with Fuji method causes a machine to increase utilization factor of it about 22%. It is therefore the aim of this method that a machine size need not be made in larger size as the S.S.W. method in order to obtain two speed synchronous machine. We have had therefore an expectation that this type of generator will be able to manufacture with only about 10% additional weight. So we firmly believe that this method is very useful to reduce the cost of two speed machine.

This pole change method can be applied not only to the ordinary pumping up power stations in which a two speed machine is in generator operation at low speed and in motor operation at high speed, but also to the pumping up stations having considerable variations in head where the machine is skilfully able to operate as generator at two speed and motor at two speed and moreover to two cycle hydraulic power station where it operates as two cycle generator at constant speed.

The matter described above was the illustration of its outline and it is hoped that it will be available for readers.

Referens:

(1) J. Tittel: "Variable-speed synchronous machines for Hydro-Electric or pumped storage power station" 1954 CIGRE

(2) H. Roth: "Dual stator windings permit two synchronous speeds" 1952 Power