OH TYPE SELF-EXCITED WATER TURBINE GENERATOR

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I. INTRODUCTION

Self-excited AC generators have been mainly developed as the power sources of AC pole change type winches, and almost all latest generators in marine use are of self-excited type, but their voltages are 450 V and their capacities are limited to comparatively the small capacity less than 1,000 kVA. Our company has already accomplished about 100 units of self-excited AC generators in marine use in total, about 27,000 kVA, up to now. These generators are very excellent, inexciting response than any other controlling system and it is only a matter of time that these generators are adopted for ordinary land use. For the attempt to increase transmitted electric power and to raise its quality, it is desired all over the world to raise exciting response at present. And it is thought that this aim is to increase the dynamic and static stability, suppression of the voltage change at sudden change of load, and to increase of the limit of power transmission. The weak point of the former exciting system was that the field time constant of a main generator was very large, and although response from the voltage detector to the exciter was very quick, its effect slowly appeared the generator in actual circuits, in which the exciter terminals were connected to the main field windings, and then voltage variation could not be kept off while the voltage variation checked by the detector was conveyed to the exciting circuit. As this counter-measure, the problem that naturally come out is a self-excited AC generator which controls the exciting current dependent on the change of load through CT action. Generators for marine use are small at capacity and not connected to the transmission system. But generators, used as the large power source, differ in that point and this kind of self-excited AC generators need have all controlling and protecting capabilities which the former generators had. For these reasons, our company adopted for large generators OH type exciting system, and quick demagnetizing device, which we developed for ourselves. This time our company manufactured two water turbine generators of this type, one was 8,500 kVA 6,600 V 50 c/s 333 rpm for Tōhoku Electric Power Co., Ltd., and the other was 14,000 kVA 6,600 V 60 c/s 514 rpm for Yakushima Electric Industry Co., Ltd. At the shop test and the field test, we succeeded in operating them in parallel with each other or with the transmission system and we could obtain good result as expected.

II. EXCITING SYSTEM OF SELF-EXCITED AC GENERATOR

The exciting system of a self-excited AC generator is provided with a reactor, a current transformer and a rectifier at least, and as Fig. 1 shows, current I_{D0} which flows in reactor and current I_B which comes from current transformer are superposed vectorically and total current flows into the rectifier circuit. So the exciting current I_e is quickly changed by the sudden change of load current and can compensate the armature reaction. There is no time lag between the voltage detectation and the built-up of exciting current as the former AVR system, and the build up ratio is limited only by the magnetic saturation of the current transformer. Fig. 1 is an ideal vector diagram of the generator, neglecting pole salience and saturation of magnetic paths. Necessary field current can be gained by using the law of similarity between $\triangle OAB$ and $\triangle OCD$, but, exactly saying, this needs some correction. In order to compensate for this small difference, we

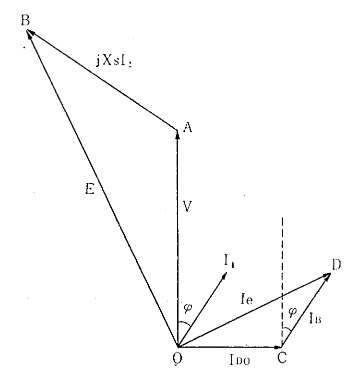


Fig. 1. Vector diagram

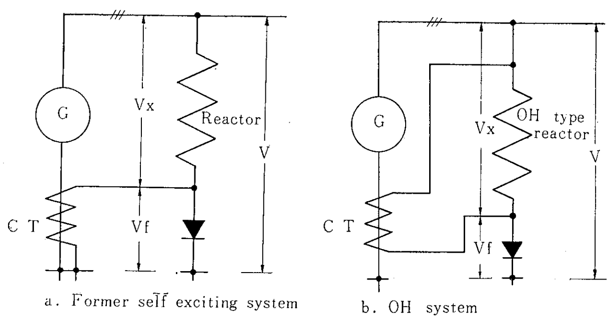


Fig. 2. Skeleton diagram of self-excited AC generator

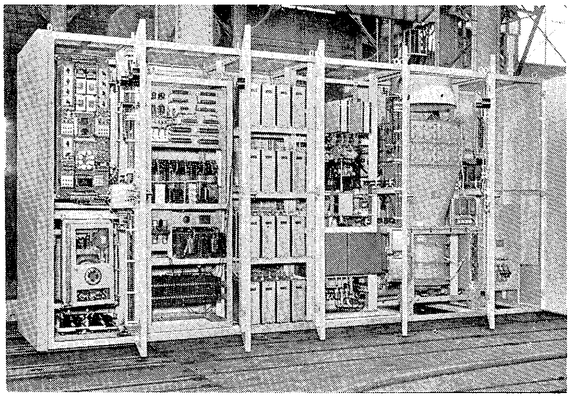


Fig. 4. Exciter and AVR cubicle

make the reactance of the reactor changeable and compensate the difference through changing I_{D0} a little. This method enables voltage and power-factor to be controlled easily. Our company has adopted OH type reactor which plays an important role in this exciting circuit. This reactor is the saturable reactor, which has AC windings and DC controlling windings, then in the AC windings two kinds of Amper-turns are superposed. Self-excited AC generators are classified in two types, essentially differed in use of a current transformer as Fig. 2. In the former type, when secondary current of CT increased, V_f increases, secondary voltage of CT increases and CT becomes easily to be saturated. Moreover at the same time, it is feared that the secondary current of CT of exciting current might escape into the reactor. While, in OH type, when V_f increased, V_X, which is equal to secondary voltage of CT, falls conversely. Then CT does not saturate and the secondary current never escape into the other circuit, so this response is extremely excellent. That is the special merit of OH type. Fig. 3 is a photograph of a self-excited AC generator, 14,000 kVA 6,600 V 60 c/s 514 rpm. Fig. 4 is a exciter and AVR cubicle. A loss of self-excited circuit is almost the same as that of a rotating excitor by comparison.

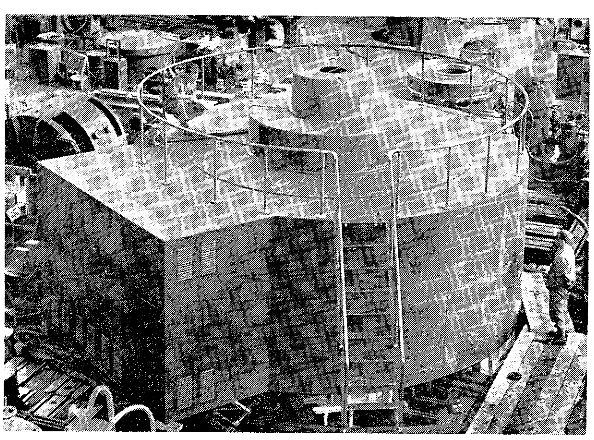


Fig. 3. Self-excited water turbine generator
14,000 kVA 6,600 V 514 rpm

III. BUILT-UP METHOD OF THE VOLTAGE

As the residual magnetism is generally used to build up the voltage of a self-excited generator, it is desirable that the remaining voltage is higher. However, since water turbine generator decreases consciously the remaining voltage to zero by adopting the quick demagnetizing method we take a course that we kick the field windings by small current from a storage battery, when water turbine generator is started. When E_C in Fig. 5, that is a source to control the OH type reactor, is over the certain value, the generator voltage builds up to the rated voltage. But, when E_C is zero, even if we kick by small current from a storage battery, the voltage halts near very low voltage. So we short-circuit the OH type reactor, then the voltage begins to build up and, if E_C reaches to E_{C0}, we open the short-circuited reactor. R in this figure is the resistance to limit the short-circuit current. Fig. 6 is a oscillogram which shows the process to build up the voltage by adopting this method. It was confirmed that we were able to build up the voltage if there were enough battery source which is about 10 percent (15A) of the no load exciting current. We can know the process of the decrease of current from storage battery and of the increase of controlling current of OH type reactor by this oscillogram.

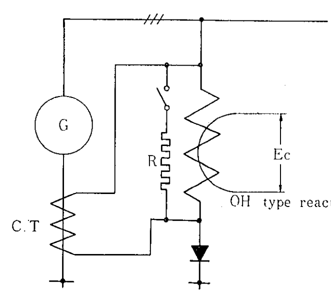


Fig. 5. Method of voltage built up

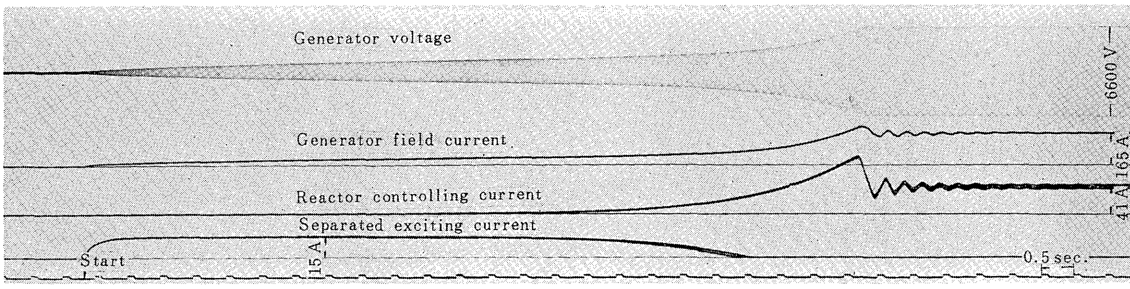


Fig. 6. Oscillogram of voltage build up

IV. METHOD OF VOLTAGE AND POWER FACTOR CONTROL

Fig. 7 shows the connection diagram of the OH type static exciter. We will explain the contents of this diagram. The voltage which is stepped down by 3 ϕ transformer with the static shield (the primary windings of this transformer connected with the terminals of the generator) is impressed to OH type reactor. The control leg of the reactor is controlled by the DC output current I_{DC} of the magamp type main amplifier. Moreover main amplifier is controlled by the pre-amplifier which contains such elements as to detect the positive-phase component of the terminal voltage, or to limit the power-factor and kVA. OH type reactor is provided with the terminals to connect to the secondary windings of the main CT.

We provide the quick demagnetizing device, which we will explain afterwards, inparallel with the field circuit.

SELA and SELAB in this diagram works as the protecting device for the reverse voltage of the main rectifier.

Now, between AC current I_e of this reactor and DC control current I_{DC}, "Equal Ampere Turn's law" exists. So we can control I_e at our discretion within the limits of the usual operation.

Accordingly, the exciting current of the generator I_f can be also controlled by I_{DC}. (There is a limit of the controlling band which is decided by the source voltage, load resistance and magnetic characteristics of the core). For example, if we separate the AC source of this reactor from the generator, it becomes perfect separated exciting system, and it is capable that we control field current from zero,

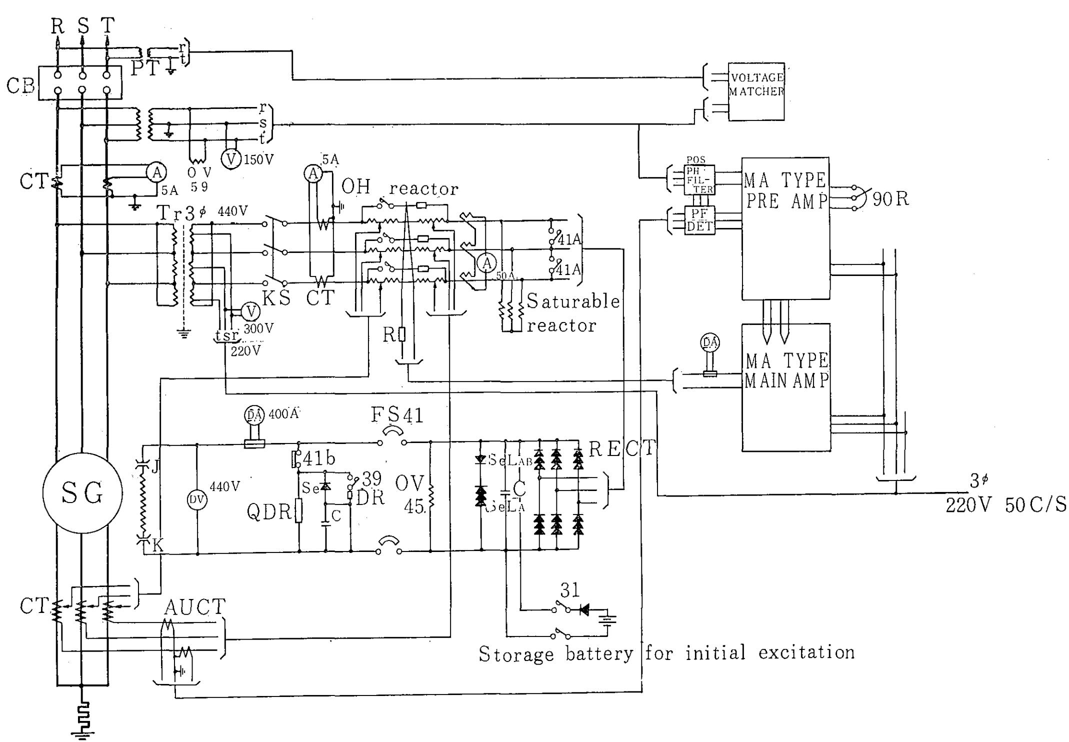


Fig. 7. Connection diagram of static exciter

and line charging can be done freely. When the generator is the source of this reactor, the voltage may be usually decreased to about 1/10 of the rated one by adjusting only DC control current, and in this condition, line charging is also capable. When the pre-amplifiers is included, the range of the voltage adjustment by the resistor 90 R is chosen about ±20%. But we can spread it more if needed.

In ordinary design, the maximum voltage may be raised only by 30∼40% of the rated voltage at continuous operation.

Of course, this limit is decided by the temparature rise of the reactor. More allowance is given to main amplifier.

The pre-amplifier is the same as our standard type. Before we express the voltage regulation of this system, we explain about a general function of AVR a little.

The voltage regulator of a synchronous machine at one individual operation regulates the terminal voltage as we wish. But, when we operate the generator in parallel with the other power system or other machine, we can not freely decide the terminal voltage as at individual operation. For example, in an extreme case, AVR of the synchronous machine which is in parallel with a large power system has the significance as the voltage regulator no longer and plays a part of the reactive power regulator of this power system. Namely in this case, it is mainly used as the power-factor regulator or the current regulator. In fact, such a extreme example is rare and, in common case, according to the ratio of line capacity and self capacity, it plays double roles of AVR and AQR.

There is a voltage droop as the value showing this degree. At individual operation, the voltage droop is zero, and in the case that a generator is in parallel with an infinite bus, it is infinite. The drooping characteristic is indispensable to an AVR of a synchronous generator and the voltage must be regulated freely.

We can say the same about the compound exciter. Namely, when it supplies a power to load at individual operation and has a flat voltage-current characteristics, it takes the role of the ideal AVR at both transient and static conditions. But in case of being connected with an infinite bus, it operates at an unstable condition due to this characteristic. In reality, there is no bus regarded as infinite bus. The other way, there is a case in which the ascending charactaristic is suitable to an AVR to compensate the line impedance drop. So we can not say that such a charactoristic is bad. The AVR with such a characteristic is rather the most ideal for the synchronous generator and this is the best way of the exciting system for raising the transient stability limit of a synchronous machine. The exciting current component which can get from CT dependent on the load current, is vectorically superposed through medium of the flux to the component independent on load in OH type reactor.

We can freely choose the ratio of the both components by choosing the tap of this reactor. Now suppose we choose the best tap. At this time it is ideal that the voltage characteristic is quite flat for any load current and any power-factor. But at the Ōbari generator we choose the CT tap as the generator is not imposed with overload under a transient condition, and we show these results in Fig. 8 and Fig. 9.

As this curve means the characteristic under both transient and steady states (when we ignore the

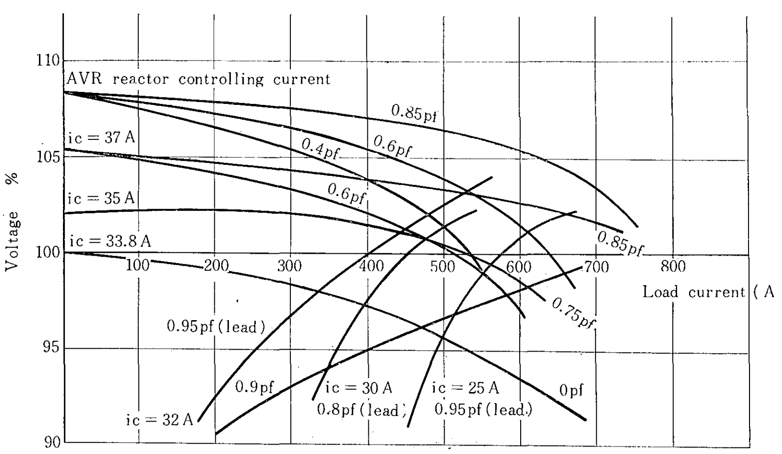


Fig. 8. Voltage-current characteristics at constant power-factor and controlling current

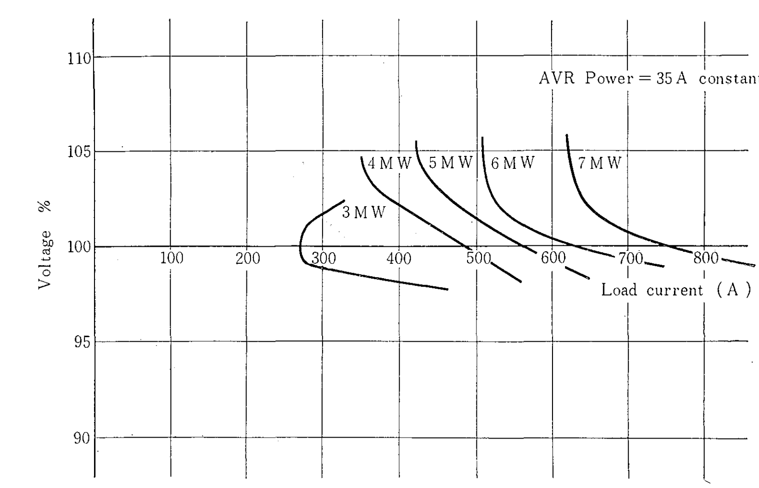


Fig. 9. Voltage-current characteristics at constant output and controlling current

leakage impedance of the generator) the voltage follows these characteristic curves due to the line voltage change.

And so, if we connect directly the generator with the ideal flat charactoristic to infinite bus, and the generator voltage is not same as the bus voltage, it is evident that the reactive power of the generator will go to infinity. So, we must control I_{DC} for limiting the reactive power. We control I_{DC} by magamp type pre-amplifier with drooping characteristics, and this exciting system is wholly stabilized.

In case of using this as the power-factor regulator, it behaves quite same as before. This was originally composed as the voltage regulator. So, according to the change of operating condition, reactive component changes first by this characteristic, and the pre-amplifier acts to return the power factor to the decided value.

V. QUICK DEMAGNETIZING METHOD

When an accident occurs in the line, the generator and so on, it is necessary that we make the induced voltage of the generator become extinct quickly and prevent the expansion of the accident. Using the rotary exciter, we have obtained good result from ago by adopting the vibrating quick demagnetizing method. In this static type, we have also adopted a new quick demagnetizing method which takes the place of this method.

Now, at a short-circuit accident which occurs at the outside of a circuit breaker, the field current which is increased by the armature reaction returns to the former value again by opening the breaker. Since the CT current become extinct in this condition, there is not any obstruction. It makes a matter when there is a internal accident.

In such a case, we can't make the fault current become extinct by only opening a breaker. This fault current is rectified and become the field current and the short circuit current goes to increase fanwise. Even if we control I_{DC} of OH type reactor and make it zero, we can't decrease the short circuit current.

In this system, a part of the field current is obsorbed by the obsorbing saturable reactor which is shown Fig. 7, and prevents the field current from increasing more and more. We can freely choose the maximum field voltage by tap and this is chosen so as not to miss the effect of the quick response in the generator operation. So we have 41A short-circuited and cut off AC circuit from field circuit at the input side of the rectifier and we prevent the increase of fault current. After this, we open the field switch.

Only to open the field switch 41 and to insert the discharging resister, we need, theoreticully, time of infinite till the field current I_f become zero. Even if I_f become zero, it is incapable to extinct the fault current as residual flux remains.

Now, if we open 41 in the circuit of Fig. 7, I_f flows through the circuit of L, R_f, R, C and selenium rectifier, and the voltage which is $I_f R = E_f$ is induced in a field circuit. And I_f begins to decrease at the time constant which is $\dfrac{L}{R+R_f} = T$. The condenser C is quickly charged up by the voltage E and, in spite of decrease of E_f, it remains at the maximum value in charged condition by the effect of the rectifier.

First, electro magnetic energy of the field is 1/2 LI^2 J. but almost of this energy is consumed by resistance R and decreases quickly. When we choose $R \doteqdot \alpha R_f$, energy K_C which remains into C is $K_C \doteqdot \dfrac{1}{2} C(\alpha I_{f0} R_f)^2$ J. and if the reverse current, which is obtained when we impress reversely K_C to the field, is about 1/10 of I_{f0}, we can cut off the residual flux.

Fig. 10 shows the oscillogram of the field current and the terminal voltage of the generator in the demagnetizing process.

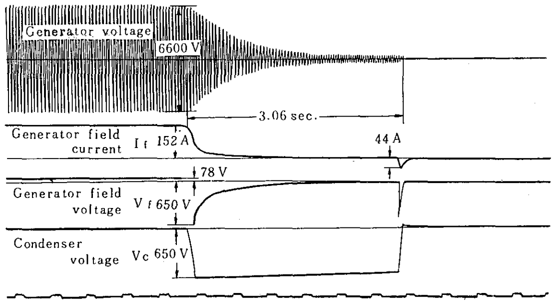


Fig. 10. Oscillogram of quick demagnetizing device

VI. EXCITING RESPONSE

The reasons why we require the quick response of the exciting system differ in each machine, but the object is that we hold down at minimum the change of the voltage or the load angle and the stable operation is performed. At the generator being in parallel with the line, as the change of the nominal induced voltage is found rather remarkably by the movement of the load angle than by the voltage change, it is the best way that we show the comparison of the exciting response by the change of the load angle. Accordingly, a method that expresses response must be one which express the changing value of the nominal induced voltage (which is equal to exciting current) as the function of the load change. And to put it in the concrete words, it must be the method on which we can easily decide a condition of the test and the testing method is simple and by which we can presume the voltage change and load angle change at any load condition. On the former exciting method, we regulate the nominal induced voltage by controlling the exciting voltage. So we can comparatively define the response of exciting system easily by finding the exciter voltage change when we give a certain voltage to the voltage detector as the open loop, which is cut off between a exciter and the generator at the one point of the closed loop (the generator→voltage detector→AVR→the exciter→the generator). Although, at first sight, this definition seems easy, it is so difficult to establish the condition of a test that we have expressed only the response of the exciter itself, which is the centre of the closed loop, and this response is mentioned by making use of the ceiling voltage, voltage build up ratio and nominal exciter response and so on. Today, we are not satisfied with this. And there is a tendency that we define and express the response of a exciting system as abovementioned (deciding every amplification factor at the best condition). In even comparatively a simple rotary exciter, it is difficult to give a difinition of exciting response, so in the self-excited generator, there are many problems which should be solved about the test, and a unified definition does not exist yet.

As the self-excited generator controls the nominal induced voltage through CT, it is meaningless that we cut off the field circuit of the generator. So we must test in the closed loop by any means. It is almost incapable because there is no proper load that we test the exciting response of the large generator at the shop test. So if we wish to know the exciting response, there is no method except the test by which we make a special transient phenomena and measure the change of voltage or load angle. Of course, it is not a satisfactory test because it is almost incapable to presume any other transient phenomena from the test of a special transient phenomena, but it serves as a good reference. We can choose the full load on or off test as a special transient phenomena, then we express the exciting response by the voltage drop or rise. We can also choose the step out test, then we express it by the limit power. We have tried these tests at the site. So we shall study simply the result of the load off test.

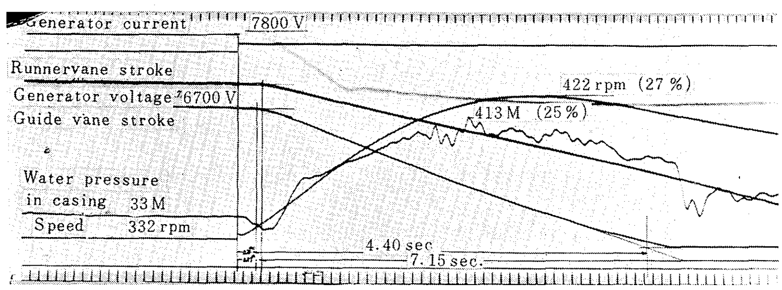


Fig. 11. Oscillogram of rated load off test

EMF which have compensated the armature reaction becomes the excess EMF, if we cut off the load. In order to compensate this, field current decrease extremely in a moment. If the direction of the field current reverses due to this compensating action, over reverse voltage is impressed to the rectifier. But we need not be anxious about it, because the direction of the field current does not reverse by the load off. Referens to Fig. 11, the changing process of the field voltage at the load off, AVR acts to suppress the voltage rise at the load off, and the equivalent inductance of OH type reactor becomes infinite, the field current supplied from OH type reactor disappears, then AC terminals of the rectifier is opened. In this period, magnetic energy of the field discharges through the selenium rectifier and the direction of this current is positive sense of selenium rectifier, the field voltage becomes almost zero.

When the generator voltage recovers to about a set point, AVR works and reopens the supply of the exciting current from OH type reactor, then the generator voltage becomes to the set point. But when the generator have the damper winding, the damper winding suppresses automatically the flux change and we need more time to regulate the voltage than at one without damper winding.

The voltage change at the load off is generally formularized as follows.

$$\Delta e_d = p\psi_d - \Delta\psi_q - \psi_{q0} p\Delta\theta - r\Delta i_d \quad \cdots\cdots (1)$$

$$\Delta e_q = p\psi_q + \Delta\psi_d + \psi_{d0} p\Delta\theta - r\Delta i_g \quad \cdots\cdots (2)$$

$$\Delta\psi_d = \frac{p(x_{1d}x_{afd} - x_{f1d}x_{a1d}) + x_{afd}R_{1d}}{p^2(x_{1d}x_{fd} - x_{f1d}^2) + p(x_{1d}R_{fd} + x_{fd}R_{1d}) + R_{1d}R_{fd}}\Delta e_f - \left(x_d - \frac{p^2(x_{1d}x_{afd}^2 - 2x_{f1d}x_{afd} + x_{fd}x_{a1d}^2) + p(x_{afd}^2 R_{1d} + x_{a1d}^2 R_{fd})}{p^2(x_{1d}x_{fd} - x_{f1d}^2) + p(x_{1d}R_{fd} + x_{fd}R_{1d}) + R_{1d}R_{fd}}\right)\Delta i_d \quad \cdots\cdots (3)$$

$$\Delta\psi_q = -\left(x_q - \frac{p x_{a1q}^2}{p x_{1q} + R_{1q}}\right)\Delta i_q \quad \cdots\cdots (4)$$

ψ : flux linkage
i : current of the generator
e : voltage of the generator
θ : angular position of rotor with respect to stator

$$p=\frac{d}{dt}$$

suffix d : direct axis
q : quadrature axis
f : field circuit
1 : damper circuit
0 : initial value
$af, a1, f1$: mutual interlinkage between armature and field or armature and damper or field and damper.

When we consider about the abovementioned, e_f becomes zero at the instant the load is cut off. And so applying $\Delta e_f=-e_{f0}1$, $\Delta i_a=-i_{d0}1$, $\Delta i_q=-i_{q0}1$ to the above equations (1)～(4), we can get Δe_d and Δe_q. $p\Delta\theta$ is the speed change of the generator, and it increases in proportion to time. Then $p\Delta\theta$ is shown by kt (k = constant). Δe is the sum of four terms, the three terms decrease with each different time constants, and the other term increases in proportion to time. This calculation result coincided to the test result.

The voltage rise at the instant the load is cut off was about 25% in the former exciting system and we needed about 4 seconds until the voltage reached the set point. But the test results of the self-excited AC generator shows that the maximum voltage rise is about 16% and the voltage reaches the set point in 1 second. It is a remarkable progress.

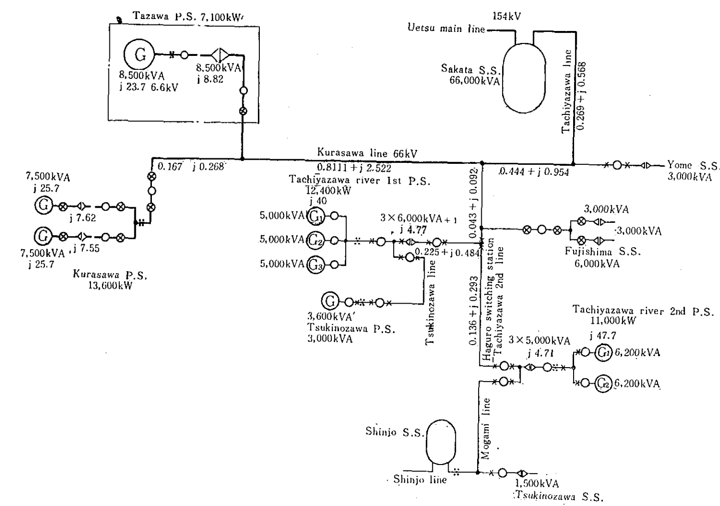
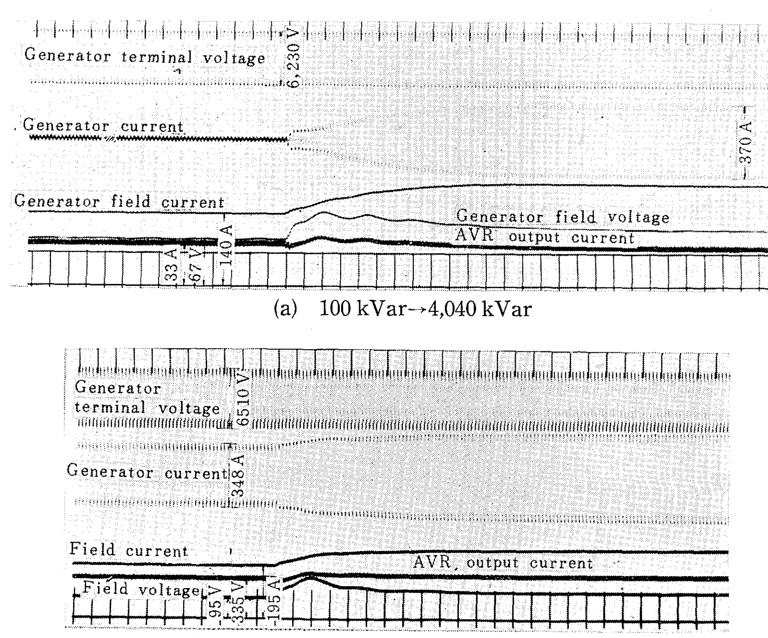


Fig. 12. Power system diagram



(a) 100 kVar→4,040 kVar

(b) 3,920 kVA, 0.866 pf→5,800 kVA, 0.586 pf

Fig. 13. Oscillogram of transient response at reactive power swing of power line system

In order to study the response of the self-excited AC generator when the distribution of the reactive power in the transmission system suddenly changes, we cut off the load of the Kurasawa generator which was supplying 10 MVar (lagg) in parallel with the system shown in Fig. 12, and we examined the response of the Ōbari generator. Fig. 13 is the oscillogram of this test.

i) The current distribution of the system at the instant interrupting 10 MVar equals the current when we transmit—10 MVar1 from the Kurasawa power station and the current of the Ōbari generator is decided by subtransient impedance.

ii) After this, the increase of lagging current supplied from the Ōbari generator is decided by the CT ratio of compounding.

iii) The self-excited AC generator generates very large reactive power in comparison with the generator adopting the former exciting system. Especially, the difference between them is remarkable after 0.2～0.5 seconds and becomes about scores of percent.

At the generators connected with some system, which need not so quick exciting response, we can design the generator most economically by making the short-circuit ratio small due to the limit power increasing by this exciting system. Thinking the composition of the exciting apparatus in this method, there is not a limit of output of the generator for which this method can be adopted. And so, it can be thought that all generators will make rapid strides to be a self-excited type in the near future. However, there is a case that each exciting response of every generators running in parallel are not equal. In such case, we have a danger that, if the line voltage hunts, only the generator, which has quick exciting response, takes more apparent power and over-loaded. And so, in order to prevent such operation, we have the absorbing saturable reactor connect in parallel with the field circuit and limit the apparent power.

VII. OVER VOLTAGE OF THE CIRCUIT

Certainly, the remarkable progress of the latest self-excited AC generator is mainly due to great stride of metal rectifiers. But this does not mean that all the faults of metal rectifiers were taking away. Even today, permisible reverse over voltage of metal rectifiers is comparatively small and we need satisfactory investigation beforehand for the over voltage which might occur in the operating period. If we examine completly the over voltage and can provide the proper method of protection according to the demands, we can say that the latest rectifiers have progressed as we can operate them without any anxiety. Next, we will briefly examine the over voltage. As especially we test carefully about a lightning surge, we express mainly that result.

1. Over voltage by a lightning surge

A part of the impulse voltage which is transmitted from the transmission line enters to the field circuit through the power source transformer for the exciting apparatus. Another part of it enters into the stater and is transmitted to the field circuit across the airgap. The sum of these transmission voltage appears as impulse voltage with the complex wave form on the field circuit. We can think the equivalent circuit for this impulse voltage of the field circuit as Fig. 14.

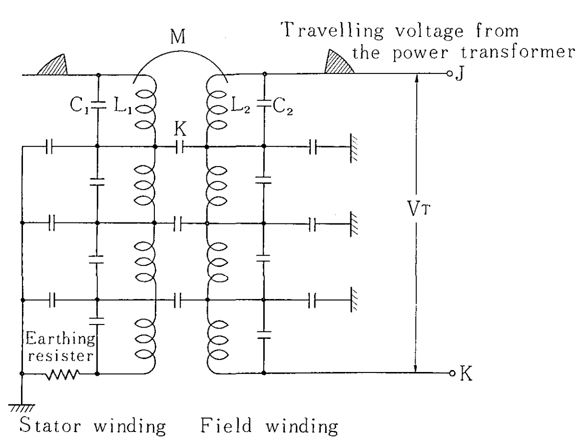


Fig. 14. Equivalent circuit of impulse voltage

So we must investigate these phenomena classifing in two different cases about the voltage (V_E) between the field coil and the earth and about voltage (V_T) induced between J and K. We can think V_T as the voltage which is impressed the metalic rectifier and V_E as the voltage which is induced in the field circuit.

We will study the wave form of V_E. At first the impulse voltage enters into the stator. At the same time, the static voltage, which is decided by the capacity K of the airgap and the capacity C between the field windings and the earth, appears in the field circuit, and the static voltage, which is devided by the capacity between the primary and the secondary of the power source transformer and C; appears too. As the result of this, the potential of the field circuit becomes higher than the earth potential in a moment. But this only make the potential of the whole field circuit higher and the potential difference does not appears among every points of the field circuit.

In other words, we could not find this kind of voltage between the terminals of the field winding or OH type reacter. However, this voltage, devided by capacity, occurs only in case of the steep front wave with the less than 1μs duration of wave and decreases in about 0.5μs. As the impulse voltage, which enters into the operating generator, is transmitted through the transformer, the arrester and so on, the impulse wave becomes the long front wave (about 10μs), we need not think this voltage. Simultaneously with this voltage, there are conparatively high frequency voltage, which is induced by the voltage oscillation in the stator windings or in primary windings of the transformer, and the other voltage by the voltage oscillation of the field circuit itself and so on. These appear supperposing each other. As the voltage, which is transmitted through the power source transformer, is generally higher than voltage which is transmitted from the stator in this machine, we prevent the electric coupling between the primary and the secondary of this transformer by inserting the earthing plate among these windings for the static shield. When we study V_T, which has most connection with the permisible reverse voltage of the metalic rectifier, we can find only oscillating voltage but the peak value is very small, we need not take care of this.

To measure quantitatively these relation, we impress the impulse voltage to the output terminals of the generator from the impulse analyser set at the standstil condition, and we measure the potential of every point to earth and potential difference of every part. We show testing circuits in Fig. 15 and test records in Table 1. Studying this record, the voltage to earth, which is first appeared in early stage by transmitted steep front wave, is about 20% in the

Table 1. Test record of surge analyse

Testing condition \ Measured point	1			2			3			4			5	6		7	8	
	R–S	S–T	T–R	R	S	T	R	S	T	R	S	T	J–K	J	K	l–m	l	m
Single phase impress: R phase impress	12.9	3.7	13.4	7.6 (10.3)	6.0 (10.3)	6.0 (10.3)	9.2	4.4	4.4	1.7 (11)	1.7 (11)	1.7 (11)	0.1	1.7 (12.0)	1.7 (12.0)	6.0	1.6 (10)	1.6 (10)
Single phase impress: S phase impress	11.8	11.8	3.4	5.8 (13.4)	6.5 (13.4)	5.8 (13.4)	4.4	7.2	4.4	1.8 (13)	1.8 (13)	1.8 (13)	0.1	1.7 (13.5)	1.7 (13.5)	6.0	2.3 (13.4)	2.3 (13.4)
Single phase impress: T phase impress	2.5	13.3	13.3	5.8 (13.3)	5.8 (13.3)	7.5 (13.3)	4.4	4.4	9.2	1.8 (13.3)	1.8 (13.3)	1.8 (13.3)	0.1	1.7 (12.8)	1.7 (12.8)	6.0	1.6 (13)	1.6 (13)
Three phase impress	5.3	5.3	5.3	3.0 (19)	3.0 (19)	3.0 (19)	3.2	3.2	3.2	3.2 (19)	3.2 (19)	3.2 (19)	0.1	3.4 (20)	3.4 (20)	0.5	2.4 (19)	2.4 (19)

( ): Show the initial travelling voltage with the steep wave form.

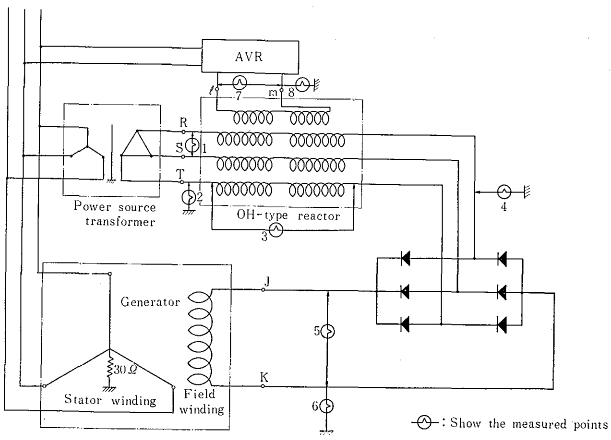


Fig. 15. Test circuit of surge analyser

transformer secondary windings and the field circuit at the three phases impress and about 13% at the one phase impress, but in case of long front wave, oscillating voltage is 3.5% at the three phases impress, and at the one phase impress the transformer secondary voltage is 5.5∼7.5% and the field circuit voltage is 1.7%. The transmitted maximum voltage which is decided by the limiting voltage of the arrester is 35 kV in 6,600 V generator as this machine, and so the maximum voltage between the field circuit and earth does not over 1,230 V, and this is out of the question. The terminal voltage of the rectifier is only about 0.1%, 35 V. This is because that a selenium plate has considerably high capacity and we can regard the rectifier is shorted by the condenser against high frequency voltage. This has not relation with the polarity of the rectifier. If we reserve the polarity of impulse voltage which is impressed to the selenium rectifier in order to confirm the effect of the polarity, we can't find the difference at all. So this proves that the above facts is true even if the impulse voltage is impressed to forward or reverse direction. When we use a silicon rectifier, we can expect the same effect by inserting condenser in parallel with the silicon rectifier. According to the abovementioned result there is no anxiety to lightning surge at all.

In such a particular case as there is a danger that the impulse voltage with steep front wave may enter in the high voltage machine, only the potential to earth may rise, so we can easy protect by earthing it through the condenser which has proper capacity, but we need not do so, in normal case.

2. Over voltage at short-circuit accident

We have examined about the over voltage at the short-circuit accident in many ways and it is apparent that there is no harmful phenomena for the rectifier. But we state briefly.

Simultaneously with the short circuit, the short-circuit current causes the armature reaction, so, to compensate this reaction and to maintain the flux linkage, the field current increases to the direction by which this current make the flux increase, namely to positive sense of the rectifier. And there is not a danger that the reverse high voltage occurs. Even if the field current contains twice harmonic wave components in the single short-circuit, the field current does not reverse its direction and the rectifier is safe. In the usual phenomenon at the short-circuit, over current is rather matter.

The calculation of the field current at this short-circuit depends intricately upon the turn ratio and saturation factor of the current transformer and so on. At some time, this short-circuit current can increase as time goes by.

Namely, sometimes the relation between the increase of the short-circuit current and the increase of the field current through CT diverges, if we ignore the saturation of CT. In order to protect this relation, the saturable reactor inserted in parallel with the field circuit absorbs the excess field current which exceeds the fixed limit.

For this additional circuit, we can guarantee the maximum rectifier current, and we can keep the maximum short-circuit current less than the fixed value. Generally it is common to set the saturation point of the absorbing saturable reactor so that the steady state short-circuit current will be less than the sub-transient, current, and so, the maximum short-circuit current is the sub-transient current.

The short-circuit current of a self-excited machine and a separately excited machine will be computed together on the same equation regarding the sub-transient current. Therefore, if the former selection level of the interrupting capacity of the breaker was decided by this sub-transient current, we need not change this former selection level in case of a self-excited AC generator too. In order to confirm about these above mentioned, we had taken the single phase suddenly short-circuit test at Ōbari P.S. We short-circuited between phases R and T at generator terminals. In Fig. 16 we show the short-circuit current, the field current and the field voltage.

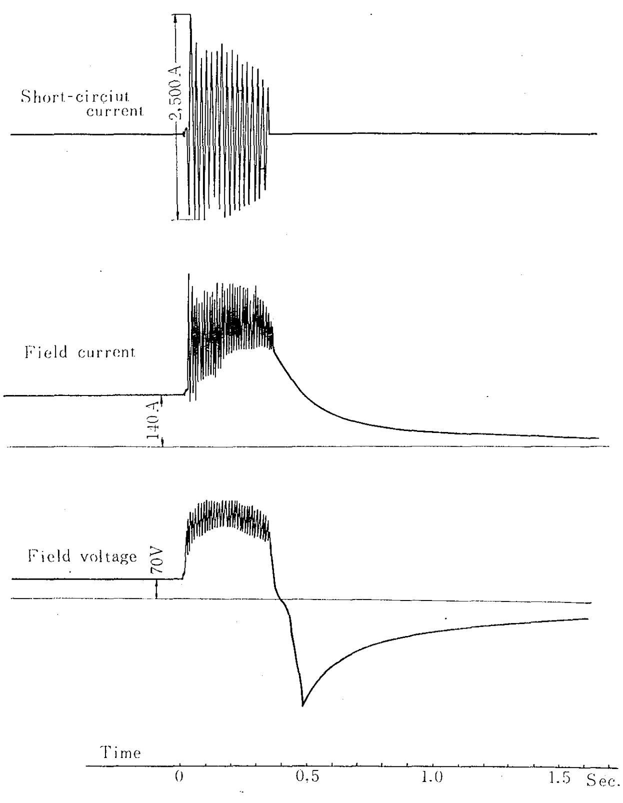


Fig. 16. Oscillogram of 2ϕ short-circuit test

The short-circuited terminals and the field circuit terminals were opened after about 0.35 seconds, and the resistor was inserted between the field circuit terminals J.K.

The peak value of the field voltage and the field current is also suppressed by the absorbing saturable reactor as we have expected.

3. Other article

As a self-excited AC generator has a high transient power limit, the possibility that the generator will fall out of step is rare, but if it will fall out of step, alternating voltage with slip frequency is induced in the field circuit. The protection against this is the step-out detector. It detect early step-out and we make assurance doubly secure by separate it off the power system, before the frequency becomes high and the induced alternating current gives the rectifier a great harm.

VIII. CONCLUSION

Now, we explained about our OH type self-exciting system, adopted by the water turbine generator of 14,000 kVA and 8,500 kVA. It was confirmed in these tests that this method had essentially many excellent merits for a large self-excited AC generator. Especially our system adopted the quick demagnetizing method got rid of the weak points of a self-excited AC generator. At present, our company is manufactuaring 6,700 kVA, 8,400 kVA, 14,000 kVA, 15,000 kVA, 28,000 kVA generators and so on as self-excited AC generators. This is a tendency that this kind of generator will be adopted as the generators of large power plants.

At this time, we hope and are glad that this report will serve as any good reference.

In the end, we express our gratitude to the Tôhoku Electric power Co., Ltd. and Yakushima Electric industry Co., Ltd.