FUJI-SIEMENS TYPE 240 kVA SELF-EXCITED A-C GENERATOR

By

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I. INTRODUCTION

The self-excited compound a–c generator invented by engineer Hartz of the Siemens Company of Germany in 1935 has recently become of much importance due to the increasing use of metal rectifiers. In Japan, it has long been desired to make use of these generators for cargo steamers with heavy load variations.

Thus, to meet this demand, our Company has, from two years back, been carrying on research and experiments on this type of machines and has succeeded in making 240 kVA 450 rpm main generators for marine use, the first of its kind in Japan. This generator, after being put through various tests and proved satisfactory, has been delivered for use to the Namura Ship Building Company Ltd. The following article is a detailed report on the machine.

This machine is not equipped with a rotary exciter and automatic voltage regulator but has a exciting circuit consisting of a reactor, current transformer, potential transformer, condenser and selenium rectifier and the voltage regulation of the generator is of compound character. Tests of this machine showed that even without an automatic voltage regulator the voltage regulation of the generator, when set at 3.5% of the speed regulation of the diesel engine, has a slight variation of only ±1.5% from a no load to full load under a rated power factor.

Also, the transcient character of the generator is good and the dip of the generator voltage is very slight against sudden changes in load variations. For instance with the starting of a cage rotor type induction motor (starting kVA is 1.4 times generator kVA) test results showed that the generator's voltage drop was approximately 14% and voltage recovering time 0.2 seconds. Also it was proven there was no worry about cross-currents occuring at the parallel running of two a–c generators or the distribution of loads. These tests have shown that this machine is most suitable as a a–c generator for marine use. Especially, it is possible to use the a–c pole change type winch motor which receives a power from this type generator. The biggest fault of this motor is the large starting current. Thus with the use of this type of generators it will be possible for ships to use a–c system and to cut ship expenditures.

II. OUTLINE OF 240 kVA SELF EXCITED A-C GENERATOR

1. Generator rating

Rated output	240 kVA
Rated voltage	445 V
Frequency	60 c/s
Speed	450 rpm
Power factor	0.8
Insulation class	A
Exciting system	Self exciting system consisting of reactor, current transformer, potential transformer, selenium rectifier, saturable reactor, transformer for voltage adjusting
Rule	NK rule (Nippon Kaiji Kyokai rule)

2. Construction

As can be seen in Fig. 1 the entire unit is of welded construction and as the rotary exciter is not directly attached, it is smaller and lighter than the

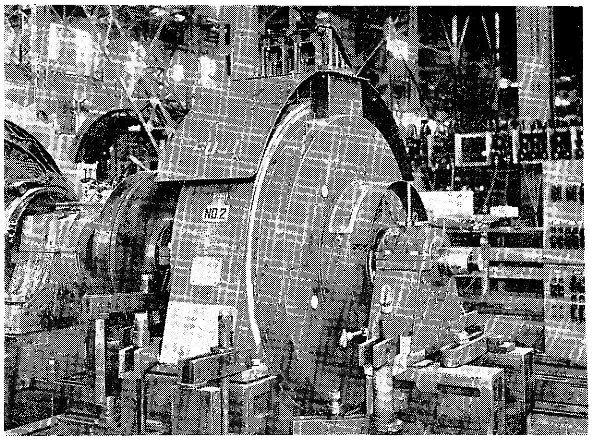


Fig. 1. Outview of 240 kVA 450 rpm self excited a–c generator

ordinary generator. The reactor, current transformer, potential transformer, condenser, selenium rectifier of the exciting circuit are all of static apparatus and, as shown in Fig. 2, are contained in a static exciter cubicle. Because of this, it is not necessary to set the static exciter set close to the generator. It can be set up in any open space in the engine room, thereby utilizing floor space to the fullest. Also it is possible to assemble the exciting circuit in the switch board. In other words it can be set up in whatever case is best.

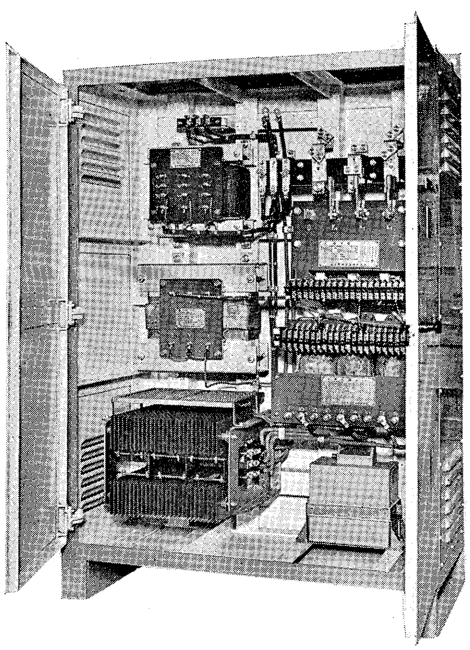


Fig. 2. Exciter cubicle for self excited a–c generator

III. CONNECTION OF EXCITING CIRCUIT

To keep the voltage of the generator constant with the variation of the load, it is necessary to adjust the exciting current according to the load variation. Fig. 3 shows the relation between exciting current ie and load current I_1 of this 240 kVA generator at a set voltage and a set number of revolutions. As shown in the chart the necessary exciting current can be divided, in spite of the load, into a constant component ie_0 and variable component ie_B according to load current I_1. To compose both of these components in vector is shown in the connection diagram of Fig. 4. In this figure G stands for the a–c generator, ① is the metal rectifier and is connected to the transformer ② on the $2ry$ side. On the $1ry$ side of this transformer is connected the reactor ③, current transformer ④, and the saturable reactor ⑦. On the high tension side of reactor ③ is the transformer for voltage adjustment ⑤ and condenser ⑥. This completes the static exciting circuit. As can be seen by this connection diagram, regardless of the load a constant exciting current i_{eo} is sent out from the generator output terminal to ⑤→③, and ⑥→②→①→ the field coil of Ⓖ.

In this case as the reactor ③ and condenser ⑥ are connected parallel if the parallel resonance point is chosen close to the rated frequency the size of the transformer for voltage adjustment can be made small and as the capacity of the exciting current supplied from the generator need not be large the utilization factor of the generator is raised. On the other hand the exciting current ie_B dependent on the load current is supplied from the neutral point of the generator to ④→②→①→ field coil of Ⓖ and the saturable reactor ⑦ is connected to the $2ry$ side of the current transformer ④. This saturable reactor ⑦ serves as a protection against short circuit. When the generator has a dead short circuit, if exciting current ie_B, dependent on the load current, increases according to the increase of the short circuit current, the short circuit current will be extremely large and it makes an abnormal overload on the metal rectifier ①. To protect such a overload the $2ry$ current of the current transformer ④ is limited to some value by saturable reactor.

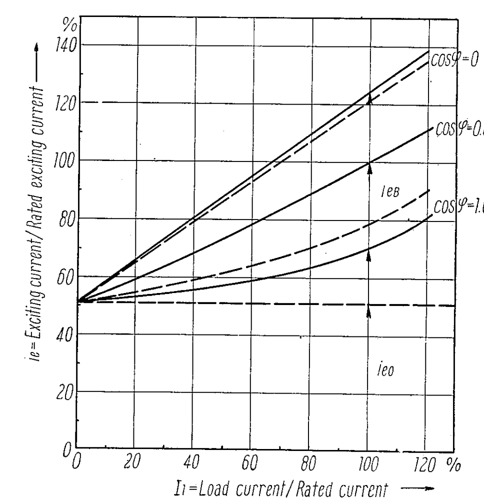


Fig. 3. Relation between exciting current and load current of 240 kVA 445 V 450 rpm a–c generator

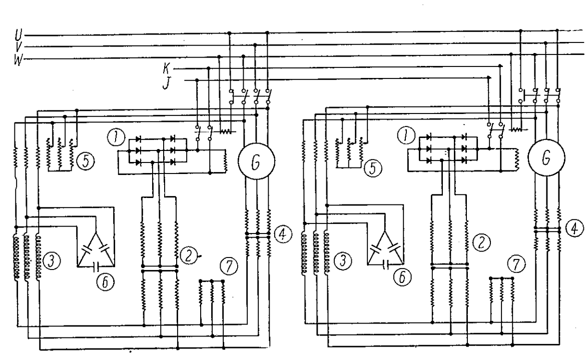


Fig. 4. Connection diagram of self excited a–c generator

Fig. 4 shows the connection between two self excited a–c generators when they are running parallel. In the figure the signs *UVW* are generator output bus bars and *JK* the equalizing connection lines of both exciting circuits. When the generator is feeding to the bus bars *UVW* the exciting circuit is always connected with the equalizing connection lines *JK*. In this way the load is equalized when running parallel.

In the connection system of the exciting circuit mentioned above the current I_D that flows through reactor ③ flows about 90 degrees lagged from the generator current. Also the current I_B that flows through the current transformer ④ flows at the same rate and same phase as the load current. These two current vectors are composed on the 1*ry* side of the transformer ② and this gives rise to the necessary exciting current *Ie*.

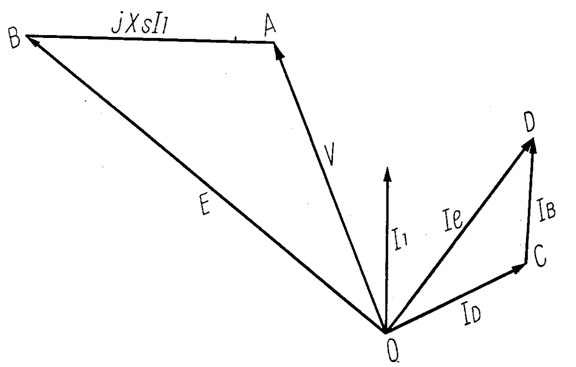


Fig. 5. Vector diagram of self excited a–c generator

Marking the generator terminal voltage as *V*, the internal induced voltage as *E*, the synchronous reactance as X_S, the armature current as I_1 the Vector relations is as of Fig. 5. △ *OAB* and △ *OCD* being of similar shape and with the increase and decrease in the load the compensation of the exciting current is made automatically by the current transformer ④. Thus by setting the suitable current transformer it is possible to keep generator voltage constant for any load current even without the use of an automatic voltage regulator. Also at sudden load variations the rapid responsibility of the static exciter can be maintained.

IV. CHARACTERISTIC CURVE OF SELF EXCITED A-C GENERATOR

The characteristic curve of the self excited a–c generator at a rated revolution of 450 rpm is shown in Fig. 6. In the chart the no-load saturation curve of the generator is marked *a*, the no-load characteristic curve of the exciting circuit is marked *b*, and the meeting point *A* of both characteristic curves is the set operation point of the generator. In the same way both *c* and *d* are the load characteristic curves at power factor 0.8 and set operation point is marked *B*.

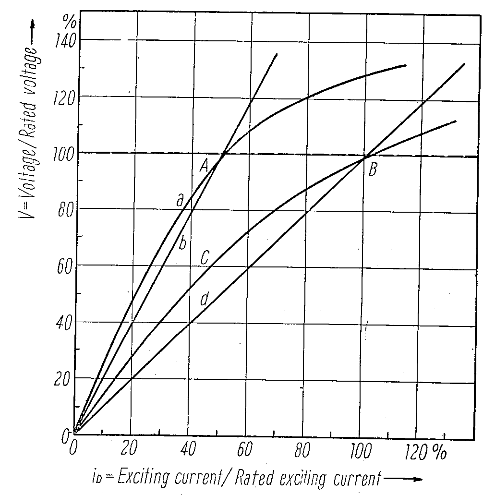


Fig. 6. Characteristic curve of 240 kVA 445 V 450 rpm self excited a–c generator

The Vector diagram as explained in the previous chapter is the ideal condition. The general Vector diagram of the salient pole a–c generator being as shown in the dotted lines of Fig. 7. As can be seen there is a slight error in the exciting current. To keep the generator voltage of a power factor 0.8 at full load to be rated value, the transformer taps of the exciting circuit must be regulated so that the lines $OA = OA'$ as shown in Fig. 7. This means that at a different power factor, the exciting current will not keep the terminal voltage constant and the current locus will flow through $B \rightarrow A \rightarrow C$ at a power factor of 1.0 to 0. Also the necessary exciting current locus will form through $B' \rightarrow A' \rightarrow C'$ and at the power factor of 1.0 will be too large (*OB* larger than *OB'*) and at power factor *O* will be too small (*OC* smaller than *OC'*). Fig. 3 shows these relations, thus the full line marks the necessary exciting current and the dotted lines

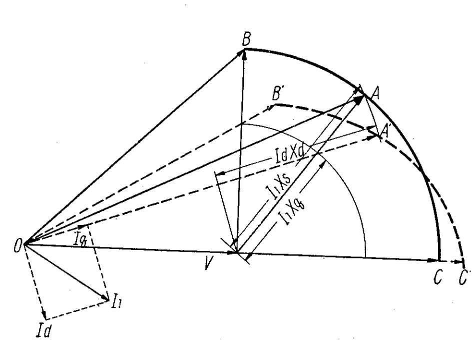


Fig. 7. Vector diagram of the salient pole a–c generator

the actual exciting current. In other words the generator voltage at power factor 1.0 is of rising character and at power factor O is of falling character. Besides this the magnetic saturation and the temperature rise of the field coil effects the generator voltage but as the actual effect is so slight it is of little importance.

Fig. 8 shows the test result of the voltage regulation of a 240 kVA 450 rpm generator operated at a speed regulation of 3.5%. Through this it was found that the under the rated power factor the regulated voltage average curve was within ±1.5% of the rated voltage. This being of guaranteed value.

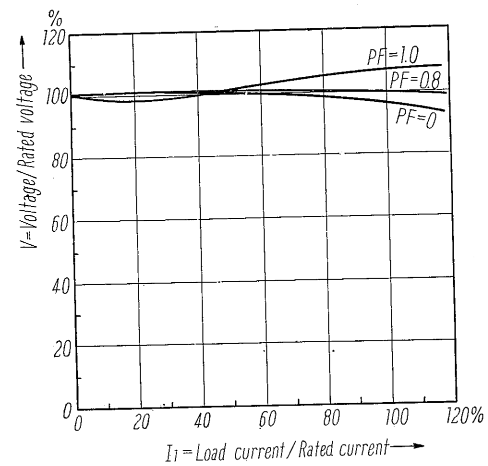


Fig. 8. External characteristic curve of 240 kVA 445 V 450 rpm self excited a-c generator

Actually the power factor of a ship load while on the seas and upon entering or leaving a port is about 0.8 to 0.85 and there is no possibility of it being 1.0 or 0 power factor. Thus this system of not having an automatic voltage regulator for the voltage regulation is quite adequate to the ship's supply system.

Next we will, by explaining the special feature of the over load characteristics, show that the generator that can switch in or off the load of the a-c pole change type winch motor and the cage rotor type induction motor is the most adequate for this type of work.

V. TRANSIENT VOLTAGE REGULATION

When a load is suddenly thrown on a generator that is being supplied a constant exciting current from a exciting source, the terminal voltage drops instantly because of internal reactance drop and decreases gradually to a much lower voltage. This shown in equations is as formula (1).

$$\frac{E}{E_0}=\left[\left(\frac{1}{(x_{d'}+X)(x_q+X)+(r+R)^2}-\frac{1}{(x_d+X)(x_q+X)+(r+R)^2}\right)\varepsilon^{-\frac{t}{T}}+\frac{1}{(x_d+X)(x_q+X)+(r+R)^2}\right]\cdot Z_q\cdot Z\cdots(1)$$

where E ······generator terminal voltage at time t

E_0······generator terminal voltage before load

$Z=R+jX$·················load impedance

$$T=T_{do'}\frac{(r+R)^2+(x_{d'}+X)(x_q+X)}{(r+R)^2+(x_d+X)(x_q+X)}$$

r, $x_{d'}$, x_d, x_q, $T_{do'}$...various impedances of generator and time constant

Z_q··············$\sqrt{(R+r)^2+(x_q+X)^2}$

In an ordinary automatic voltage regulator, because the voltage drop causes to order to increase voltage, there is a time lag before the operation can start. And the voltage recovery begins at a smaller voltage than E at $t=O$. When the automatic voltage regulator begins to operate E which has been regulated by the ceiling voltage and the voltage built up ratio of the exciter recovers gradually but will require a certain length of time and will pass through several vibrations. However as can be seen in Fig. 9 the oscillogram at the induction motor start shows that the voltage recovery by this method is indeed quick. This graph shows that in the next cycle after the load is applied the voltage has already started to recover, the lowest voltage being at the moment of the impact load. And in about 10 cycles without any vibrations the voltage has settled to the regulated voltage, which is an operation that cannot be made in any other automatic voltage regulators. This may be termed as the main reason for this method to be used for voltage regulation in all C.T. operations. The use of this C.T. operation means that as the current flows into the armature the exciting current flows directly into the exciting circuit being independent to the time constant of the field circuit. The exciting current as noted in the oscillogram rises with the applying of the load and regulates in 10 cycles.

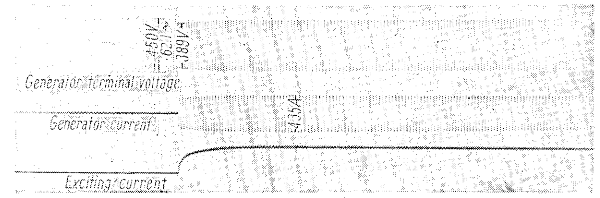


Fig. 9. Oscillogram at induction motor start

This therefore is the main feature of the method, the reason for the small drop of voltage at the moment the load is applied and the quickness of recovery period. In the case of this a-c generator the terminal voltage drop is less than 14% with an induction motor start current of 140% and to regulate in 10 cycles.

By this method the maximum voltage drop is at the moment of the impact load and as can be seen in formula (1) the maximum voltage drop is independent to the time constant of the exciting circuit or exciter response but is settled by the various impedances of the generator. Fig. 10 shows the typical relations between the impact load and the transient voltage drop, and parameter X'_d varies 0.1 to 0.3. Compared with ordinary voltage regulators there is a great difference. With these excellent features as a generator it is possible to use the a-c pole change type winch motor for marine use.

In other word formally on ships with limited electric power source it was not possible to use the cage rotor type induction motor for the winch motor. Thus ward leonard type a-c winch was usually put to use. However it can be easily seen that the better constructed and more economical a-c winch is much better fitted and with the proven tests that even in cases of large starting current the generator voltage can be maintained so that we are certain that these two will be used to greater extend.

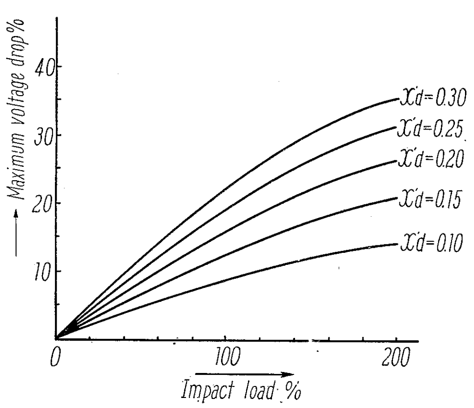


Fig. 10. The maximum voltage drop by the impact load

VI. PARALLEL RUNNING

When several similiar rated generators are put to running parallel they are so built that when the common bus bar *A.C.B.* are closed the field coils of both generators are parallel through equalizing wire. However before touching on the benefits of the equalizing wire let us see what happens on two generators that are not connected with this equalizing wire. For instance when generator number 1 is running on a power factor of 1.0 with load and generator number 2 is fed parallel with no load and there is a difference in the regulated voltage before being fed, a cross current will occur. Marking generator number 1 load current before running parallel I_1, the cross current I_c, the following formula will occur. And unless the output of the generator number 1 is regulated by the speed governor the active current is constant and the reactive current will be I_c.

$$I=\sqrt{I_1^2+I_c^2} \quad \cdots\cdots(2) \qquad I\cdots\text{current of generator 1}$$

$$\cos\varphi=\frac{I_1}{\sqrt{I_1^2+I_c^2}}\cdots(3) \qquad \cos\varphi\cdots\cdots\text{power factor of generator number 1}$$

Thus to find the regulated voltage curve of generator number 1 in relations to I_c it is only necessary to figure out the locus of power factor and current of formula 2 and 3 through the external characteristic curve. This is shown on Fig. 11 by the V_1--I_c curve. Next as the current flowing into generator number 2 is I_c, the characteristic curve on zero power factor becomes regulated voltage curve V_2—I_c. Thus Fig. 11 shows the relations between cross current I_c and the generator voltage of two parallel running machines. And the set running will figure out at the crossing point of the two curves, and if there is a voltage difference of V $(=V_{10}-V_{20})$ before parallel running, crossing point becomes (I_{co}, V_0). When V is constant and the external characteristic proper dV/dI_c will become smaller and the cross current I_{c0} at the crossing point of both curves larger. This means that at the case of the best external characteristics dV/dI_c equal 0 it will not be possible to run parallel at set operations the two generators. If there is any voltage difference before both generators are run parallel, the greater will be the cross current as the external character curve becomes flat and conditions improve.

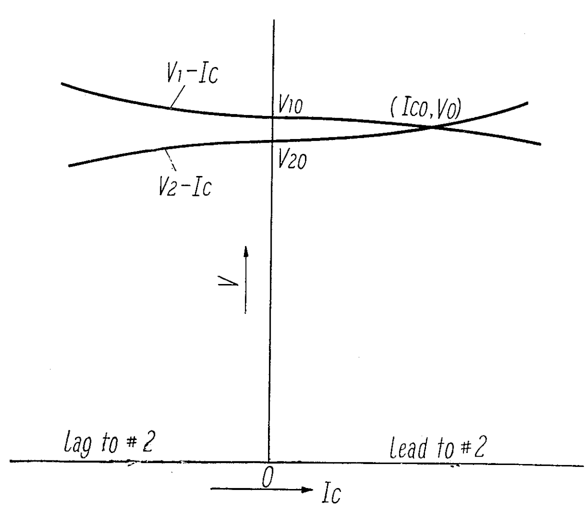


Fig. 11. The relation between generator voltage and cross current

The above rule as explained is adaptable not only when the power factor of generator number 1 is set at 1.0 but whatever the load power factor may be. So in order to lower the cross current and to keep a set running parallel it is necessary for the regulated voltage character to have a drooping characteristic. Or to kill off the constant voltage character which needless to say is very disadvantages. Thus to avoid this feature we have connected the field circuit in parallel simultaneously with the parallel feeding. If the field circuit becomes parallel the field voltage of generators 1 and 2 both become equal. The excitation of the generator with the load becomes under excitation and the power factor leads whereas the no-load generator is of lagging power factor and spreads the reactive power. This also at the end takes on a set load and this set load in figures is shown in the following formula. First generator number 1 in load condition is fed parallel to generator number 2 in no-load condition, the governor is not regulated.

$$\dot{I}_1 = a\dot{I}_0(\cos\varphi - j\sin\varphi) \qquad (4)$$

$$K = \frac{a + 2\gamma\sin\varphi}{a\sin\varphi + 2\gamma} \qquad (5)$$

$$\dot{I}' = \frac{\dot{I}_1}{2}K \qquad (6)$$

$$\dot{I}_1' = \dot{I}_1\left[1 - \sin\varphi\, K + \frac{K^2}{4}\right]^{\frac{1}{2}} \qquad (7)$$

$$\cos\varphi' = \frac{\cos\varphi}{\sqrt{1 - \sin\varphi\, K + \frac{K^2}{4}}} \qquad (8)$$

$\dot{I}_1$ ……load current of generator number 1 before parallel running $/\dot{I}_1/ = a\dot{I}_0$
$\cos\varphi$ ……load power factor of generator number 1 before parallel running
$\dot{I}_0$ ……rated load current
γ ……short circuit ratio
$\dot{I}_1'$ ……load current of generator number 1 after parallel running
$\cos\varphi'$ ……load power factor of generator number 1 after parallel running
$\dot{I}'$ ……reactive current spread by the no-load generator

As can be noted by the above formula when the power factor is zero both generators 1 and 2 share half their load current, and when load power factor differs the reactive current is distributed by both generators. A cross current will occur when there is a difference in the regulated voltage under stable load condition, but in this case the difference is very slight. In other words when the voltage of generator 1 is higher than generator 2 lagging current will circulate through the former. This means that the field current will increase by $\varDelta i_{e1}$ but as the both field circuits is parallel the variation of each field current is $1/2\ \varDelta i_{e1}$. Next as the power factor of generator 2 becomes better if running alone the field current should be $\varDelta i_{e2}$ less but as the current is being equally divided the field current of both generators are $1/2\ \varDelta i_{e2}$ less. Thus variation of the field currents due to cross currents of both generators are $1/2\ (\varDelta i_{e1} - \varDelta i_{e2})$. This is less than the field current $(i_{e1} + \varDelta i_{e1})$ required by generator 1 to maintain its induced voltage E_1, and larger than the field current $(i_{e2} - \varDelta i_{e2})$ required by generator 2 to maintain E_2. Thus the voltage becomes equal to E which lies mid way between E_1 and E_2 of both generator's induced voltage. In this case because of the variation in the flowing cross current due to the load condition it is difficult to get the actual magnitude, but a near figure can easily be figured out. When loading at power factor 1.0 or power factor 0 and there is difference between terminal voltages of both generators, the cross current flowing from the terminal voltage of both generators is set as I_c,

when power factor is 1.0

$$I_c = \frac{\varDelta V}{2 \cdot x_d}\left[1 + (x_d \cdot a)^2\right]_{p.u.} \qquad (9)$$

power factor is 0

$$I_c = \frac{\varDelta V}{2 \cdot x_d}\left[1 + x_d \cdot a\right]_{p.u.} \qquad (10)$$

$\varDelta V$……difference of terminal voltage of both generators $p.u.$
x_d ……synchronous reactance $p.u.$
a ……load current $p.u.$

when this is in case of an ordinary a–c generator

$$\dot{i}_c = \frac{\varDelta V}{2 \cdot x_d} \qquad (11)$$

Compared to the above, the cross current is a little larger because of $C.T.$ action to lessen the voltage variation due to the cross current is very slight but from the overall stand-point not at all important.

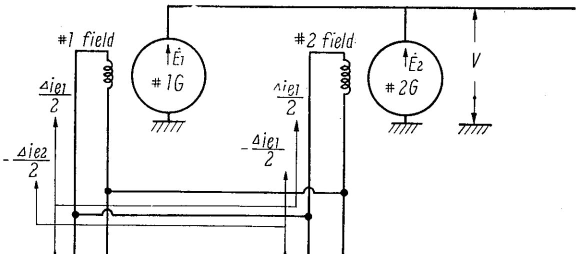


Fig. 12. The variation of the field current by the cross current of generators which are parallel running.

This above formula was again actually proven by tests on a 240 kVA generator. First, when the generator 1, which has a 50% power factor load before parallel running, was fed with no load generator 2, the current variation as calculated in (6) and (7) $I_1'=128$ A, $I'=54.6$ A and as proved in actual tests $I_1'{}_{\text{test}}=131$ A, $I'_{\text{test}}=56$ A·········a very slight difference between them. Also in this difference the differences of the regulated voltage error and the saturation error are included. Thus these tests have proven that slight cross currents caused by external regulated voltage characteristics may not be taken into consideration. Also other load conditions as shown in Fig. 13 shows that actual tests were practically the same as the prescribed formulas.

Next we tested the variation of load current in generator 2 when the governor is opened and kW load is added.

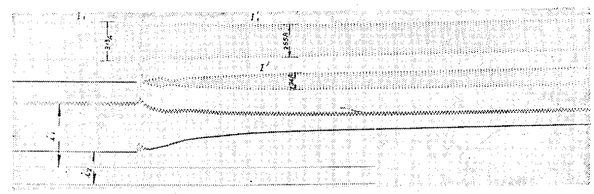
$$I_{j1}=\frac{I_j}{2}-\frac{1}{2\,I_0}\cdot\frac{I_{R1}{}^2-I_{R2}{}^2}{\left(\frac{I_j}{I_0}\right)+2\gamma} \quad\cdots\cdots\cdots\cdots\cdots\cdots(12)$$

$$I_{j2}=\frac{I_j}{2}+\frac{1}{2\,I_0}\cdot\frac{I_{R1}{}^2-I_{R2}{}^2}{\left(\frac{I_j}{I_0}\right)+2\gamma} \quad\cdots\cdots\cdots\cdots\cdots\cdots(13)$$

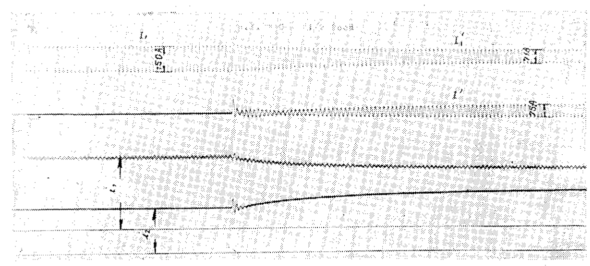
I_{R1}······active current of generator 1
I_{R2}······active current of generator 2
I_j ······reactive load current
I_{j1} ······reactive current of generator 1
I_{j2} ······reactive current of generator 2

If the governor of both generators are regulated and the active load put together the reactive current will be evenly distributed and when there is a difference in the active load due to unregulated governor the reactive current will be less in the generator with more active current. This is shown in the formulas (12) and (13).

Summing up the relations pertaining to parallel running to maintain a constant voltage character and a small cross current it is necessary to connect the field circuit also. The distribution of active current can be done by the governor alone, however if the field circuit is also equalized the reactive current will be evenly distributed. When the active current is not even, the reactive current distribution to the large active current will be less and in the other case the process will be reversed. And the cross current due to the difference in regulated voltage error will be even less. This proves that this type of generators when synchronized can be made to meet any demand.



(I)



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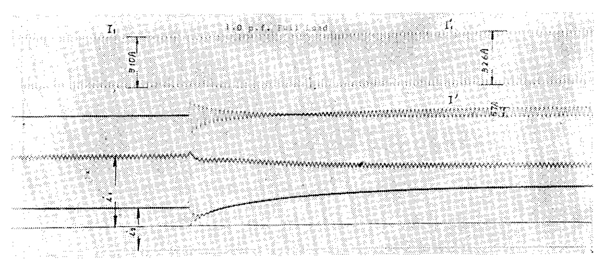

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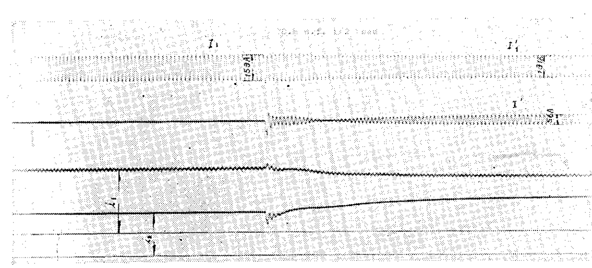

(IV)

Fig. 13. Syncronizing two generators
#1 generator rated load #2 generator no-load.

Table 1. Load distribution when two generators are parallel running

#1 load condition before parallel running		cos φ=0.8 100% load		cos φ=0.8 50% load		cos φ=1.0 100% load		cos φ=0 50% load	
		Actual value (A)	Calculated value (A)	Actual value (A)	Calculated value (A)	Actual value (A)	Calculated value (A)	Actual value (A)	Calculated value (A)
#1 Generator	before parallel	313	313	153	153	310	310	150	150
	after parallel	255	258	131	128	326	322	71	75
#2 Generator	before parallel	0	0	0	0	0	0	0	0
	after parallel	134	127	56	54.6	57	61.5	75	75

VII. CONCLUSION

Thus as mentioned in the preceding article the self excited a–c generator has many advantages···they are

1. A rotary exciter is unnecessary in this generator. Thus space can be saved and without the commutator and brushes maintainance is easy.
2. As the field circuit are all of static apparatus and there are no contact points, accidents are rare.
3. Being of compound character an automatic voltage regulator is not necessary.
4. The over load character is good, and with the rapid variation of load the *C.T.* operation makes for rapid response of the field circuit and vibrations are small.
5. Thus for induction motors it is not necessary to use wound rotor type motor but a cage type induction motor. So this generator can be said to be the most adaptable for the generators to supply power to the pole change type a–c winch motor.