DIMENSIONING OF A VOLTAGE CONTROLLED COMPOUNDING SYSTEM FOR SYNCHRONOUS ALTERNATORS

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1. Voltage control

The basic structure of the compounding circuits of synchronous alternators reflects the well-known fact, that the exciting current necessary for maintaining a constant terminal voltage is essentially composed of a constant part being independent of load, i.e. of the no-load exciting current and of a load component the magnitude of which is proportional to the magnitude of the load current. This latter has to be added vectorially to the no-load exciting current. The active component has to be added perpendicularly and the reactive component without angular deflection.

Since the requirements raised on the accuracy of voltage stabilization which is of considerable severity in many cases cannot always be met by simple compounding, additional voltage control is often used influencing the operation of the compounding system to increase the accuracy of voltage stability. Such an additional voltage control has also further advantages which will be dealt with in detail in the following.

The compounding and voltage control system discussed in this paper produces the exciting current necessary for keeping the voltage at a constant value by use of the circuits illustrated in Fig. 1. The three-phase bridge-connected semiconductor rectifier SR feeding the field coil FC of the alternator rectifies the sum of two alternating currents. One of these currents is the phase current of three phase reactor XE which is delayed by approximately 90 electric degrees in comparison to the phase voltage of the alternator, while the other alternating current is the secondary current of the current transformers CT1, CT2, CT3. The former current supplies the no-load excitation of the alternator and the latter one the load component.

The components of the circuit already listed in the preceding are, if properly dimensioned, sufficient to keep the voltage of the alternator at a constant value with an accuracy of a few per cents independently of the load, provided that the speed of the alternator is kept within a specified narrow range, but to achieve this at least the air gap of reactor XE has to be adjusted with each alternator individually. Thus, the exciting units or alternators of the same type can be interchanged but after an undesirable readjustment procedure has been carried out. To avoid this drawback and to increase the accuracy of voltage stability and the operating speed of the system so that they meet any possible requirement, also a corrector unit is provided for in the circuit. This senses the terminal voltage, compares it to the reference value and influences the operation of the system by premagnetizing current transformers

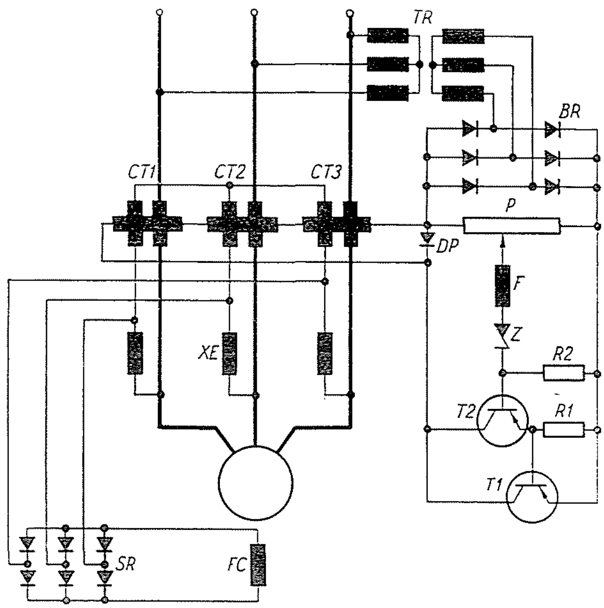

Fig. 1

CT1—CT3 in such a manner as to keep the terminal voltage at the prescribed value. The reactance of the current transformers is dependent on the intensity of their premagnetization. The alteration of this reactance influences the magnitude of the alternating current flowing into rectifier SR both in the no-load state and in the loaded state of the alternator in the manner to be discussed later so that any decrease of the reactance of the current transformers caused by the increase of premagnetization makes the exciting current of the alternator decrease and vice versa.

By the application of the corrector circuit the exciting system becomes a voltage controlled compounding. This method of realizing voltage controlled compounding was first described by STORM [1] in 1951. The transistor circuit used as voltage corrector differs from the corrector system described by STORM using a saturating choke and is in several aspects more perfect.

In the transistorized voltage control circuit the sensing organ is composed of transformer TR and bridge-connected rectifier BR. The rectified voltage feeds the collector circuit of the transistors and also appears across the terminals of voltage divider P.

The direct voltage divided by potentiometer P being proportional to the terminal voltage of the alternator is compared to the stabilized reference signal produced by Zener diode Z. The difference of the two voltages, as an error signal, controls the amplifier consisting of transistors T1 and T2 the output current of which saturates current transformers CT1—CT3 and thereby helps to keep the alternator voltage within narrow limits.

The required voltage can be adjusted by changing the position of the tapping of voltage divider P. The function of diode DP is to protect from excess voltages transistors T1 and T2 feeding the highly inductive premagnetizing circuit of the current transformers. Choke F is a filter element in the voltage sensing circuit.

The structure of the transistorized voltage control circuit reveals two important properties. One of them is the fact that the sensed voltage is dependent on all three line voltages of the alternator. The other property is that the voltage control is independent of the frequency, since the comparison to the reference signal takes place in a d.c. circuit. The former property is of advantage in cases of asymmetrical load, while the latter is advantageous, when at least a part of the consumers calls for a voltage stability independent of the frequency (e.g. incandescent lamps).

From the viewpoint of the mode of operation of the transistorized control circuit the fact, that the transistors practically operate as switches and consequently the dissipation and heating of the output transistor are moderate, is of great importance. The switching operation is ensured by the ripple of the direct voltage also without the application of a separate trigger circuit.

2. Equivalent circuit, working diagram

In the knowledge of the operation of the circuit shown in Fig. 1 one becomes aware of the difficulties which hinder an analysis which is intended to serve as a basis for the dimensioning of the elements of the circuit. The difficulties of the analysis lie in the non-linear behaviour of the system. Sources of non-linearities are rectifier SR of the exciting circuit and saturating current transformers CT1—CT3. As a consequence of the non-linear behaviour of the above-mentioned elements the majority of the alternating voltages acting in the system and of the currents flowing in the a.c. circuits is not sinusoidal, so that in calculating their magnitude one is confronted with extraordinary difficulties. The analysis can be based on two different principles, namely, regard-less of the difficulties, on the consideration of the non-linearities or on a possible linearization. The following deals with the description of this latter method.

The method is based on the principle of the equivalent circuits widely used with linear or linearizable systems in the heavy current techniques and on the vector diagrams to be plotted on the equivalent circuits and draws its conclusions from the same. FRANČIĆ [4] was successful in applying a similar method to a compounding system of different structures without voltage control.

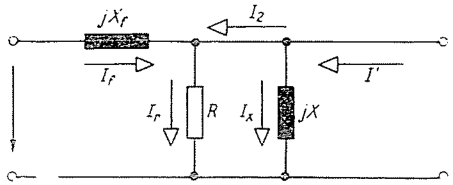

Fig. 2

The equivalent circuit to be plotted on one phase of the exciting system [1, 2, 3] is shown in Fig. 2. The input quantities of the equivalent circuit are the two really sinusoidal quantities of the compounding system, namely phase voltage U of the alternator and I' which is the main current referred to the

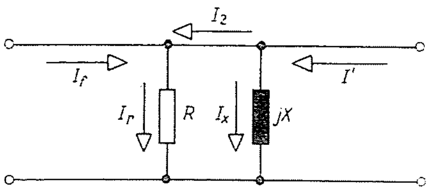

Fig. 3

secondary side of the current transformer. In the equivalent circuit X_f denotes the reactance of the air-gap reactor and X the main magnet circuit reactance of the secondary winding of the current transformer, while resistance R results from the distribution of the load represented by the field coil of the alternator into three phases, including also the losses of the rectifying elements. The illustrated equivalent circuit linearizes the compounding system by assuming that it is permissible to replace the rectifier-fed field coil with a pure ohmic resistance and the saturable current transformer with the variable but linear reactance X. The ohmic resistance and the leakage reactance of the secondary winding of the current transformer and the ohmic resistance of the choke coil are neglected.

The equivalent circuit can be further simplified if according to reality it is assumed that R and X are of the same order of magnitude and that $X_f \gg R$. In this case both input quantities of the equivalent circuit may be currents which are not interdependent. The new, extraordinarily simple equivalent circuit diagram is shown in Fig. 3.

If the alternator operates unloaded $I' = 0$ and the equivalent circuit diagram has but a single input current, I_f. This current is divided proportionally to the conductivities of the ohmic and inductive branches into two current components which are perpendicular to each other. Consequently, the variation of X causes final point F of current vector $\bar{I}_{fr}$ to move on a circle the diameter of which is current vector $\bar{I}_f$ (Fig. 4). $\bar{I}_{fr}$ represents the no-load

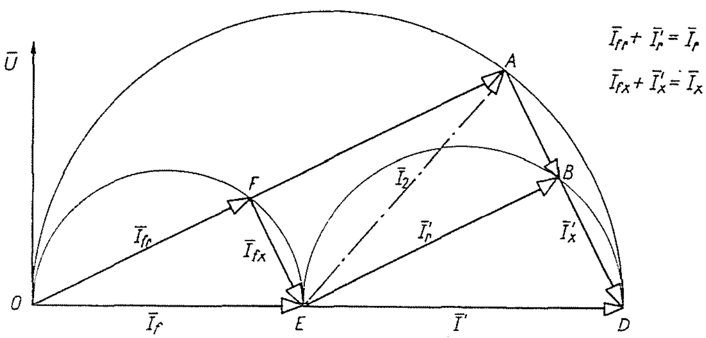

Fig. 4

exciting current of the alternator and $\bar{I}_{fx}$ the current which has to be taken up by the secondary winding of the current transformer in no-load operation at a given reactor current $\bar{I}_f$. It is assumed that the transistorized regulator is capable of adjusting the secondary reactance of the current transformer by its premagnetization so that current I_{fx} may be taken up by the secondary winding.

The range which can be covered by final point F of current vector $\bar{I}_{fr}$ on the circumference of the circle and thereby the limits of the no-load exciting current of the alternator excited by the compounding circuit is determined by the possible limits of variation of X. These partly depend on the secondary winding data and magnetic circuit of the transductor-like current transformer and partly on the thermal loadability of its premagnetizing coil and finally on the maximum output current of the transistorized voltage control circuit. In cases realized in practice point F may, at low premagnetization, closely approach point E, while at high but thermally still permissible premagnetization it may attain the highest point of the semicircle. This means that the no-load exciting current requirement of an alternator to be operated with a given compounding system may show a maximum dispersion of approximately $\pm$ 17 per cent to avoid the necessity of changing the reactance of the choke by altering its air gap. In practice, the permissible tolerance is restricted to a dispersion of $\pm$ 10 per cent in the no-load exciting current requirement, since safety considerations do not recommend to fully utilise the above-mentioned range.

It should be pointed out that here and in the following the definition no-load exciting current means the exciting current required for maintaining the rated voltage of an alternator loaded merely by its compounding and voltage control system. Under these conditions the load influencing the required exciting current is formed essentially by the reactive load represented by the three-phase choke, since in no-load operation the active exciting power is of negligible amount and the energy consumption of the corrector is insignificant.

The effect of the load current can be readily taken into consideration on the basis of Fig. 3, because the equivalent circuit behaves symmetrically as far as currents I_f and I' are concerned. If pure reactive load is assumed, the direction of vector $\bar{I}'$ corresponds to the direction of $\bar{I}_f$. If, at the same time, it is assumed that the magnitude of X will not be altered by the transistorized voltage control circuit as a consequence of the load, because the adjustment of the amount of compounding is perfect, then current $\bar{I}'$ will fall into its components $\bar{I}'_x$ and $\bar{I}'_r$ according to a rectangular triangle geometrically similar to the triangle characterizing the no-load condition.

By adding the components with respective indices we obtain the resultant currents flowing in branches R and X, among which $\bar{I}_r = \bar{I}_{fr} + \bar{I}'_r$ represents the exciting current of the alternator valid for the given load condition. It has to be emphasized that I_x is a fictive current, in the secondary winding of the current transformer flows current I_2 and the cross section of the conductors of the winding has to be chosen according to this.

Current $\bar{I}_2$ can be easily found in the vector diagram either on the basis of relationship

$$\bar{I}_2 = \bar{I}_r - \bar{I}_f \tag{1}$$

or on the basis of relationship

$$\bar{I}_2 = \bar{I}' - \bar{I}_x \tag{2}$$

in the form of length EA.

Naturally, the common final point A of vectors $\bar{I}_r$, $\bar{I}_x$ lies on the semicircle drawn over diameter OD and the length of vector $\bar{I}_r$ representing the exciting current of the loaded alternator changes as a function of X according to the same relationship, as has been found in connection with no-load component $\bar{I}_{fr}$. This allows to take into consideration the fact that with the alternator loaded the premagnetizing current and consequently reactance X may change so that the direction of excitation vector $\bar{I}_r$ differs from that of vector $\bar{I}_{fr}$ valid for the no-load condition. This case will be described later in detail. For the present it is assumed that the premagnetizing current and also the reactance X remain constant even under load.

The simplified equivalent circuit shown in Fig. 3 has illustrated a property of the system hardly obvious from Fig. 1, namely, that the premagnetization of the current transformers is both in no-load state and under load an equally effective method of influencing the exciting current, in spite of the fact that the current transformer is a passive reactor in the former state while in the latter state it acts as a power source.

The vector diagram plotted on the basis of the equivalent circuit reveals another property of the circuit that is not evident. With the primary current unchanged in magnitude but varied in phase angle the current flowing in the

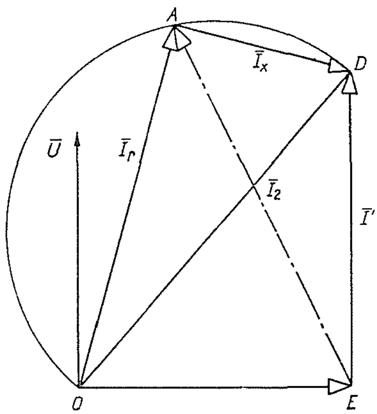

Fig. 5

secondary winding of the current transformer will not attain its maximum value when the alternator calls for a maximum exciting current i.e. when feeding a pure reactive load. To illustrate this statement Fig. 5 brings the vector diagram for the same intensity of load current as in Fig. 4, but for unity power factor.

As it may be seen the secondary current of the current transformer has increased, while the exciting current pertaining to the active load current has considerably decreased. At the same time this is the maximum secondary current belonging to various load currents of unchanged magnitude and changing phase angle, since on the basis of the relationship

$$\bar{I}_2 = \bar{I}'_r - \bar{I}_{fx} \tag{3}$$

derived from Fig. 4 it is evident that $\bar{I}_2$ will be maximum when $\bar{I}'_r$ and $\bar{I}_{fx}$ have the same direction, a case presenting itself at a load of unity power factor. Consequently, from a thermal point of view, the most unfavourable operating condition of the current transformers presents itself when the alternator supplies its rated current at cos $\varphi = 1$, i.e. when the thermal state of the alternator itself is the most favourable.

3. Dimensioning on the basis of the working diagram

The relationships derived from the current vector diagram are not only useful in the apprehension and the qualitative evaluation of the properties of the compounding and voltage control system, but lend themselves advantageously for dimensioning purposes. Naturally, it is necessary to establish a theoretical or experimental relationship between the quantities encountered in the equivalent circuit and those measurable in the real system.

One of these relationships is the ratio of current I_r to the real exciting current. If the current I_r of the equivalent circuit is assumed to be identical with the real current I_a flowing into the a.c. terminals of exciting rectifier SR then the experimental relationship

$$I_r = 0.75\ I_e \tag{4}$$

between r.m.s. value I_r and exciting current I_e may be accepted for valid.

The operating conditions of the rectifier circuit fed simultaneously by two current sources are rather complicated and it does not seem worth while attempting to deduct a theoretical relationship between currents I_a and I_e if it is considered that the empirical relationship (4) is valid with good approximation between no-load operation and full-load condition for all power factors.

By using this empirical relationship and neglecting the losses of the rectifier elements the following power equation may be written:

$$I_e^2 R_e = 3\,(0.75)^2\, I_e^2 R \tag{5}$$

and hence

$$R = 0.59 R_e \cong 0.6 R_e \tag{6}$$

It is justified to neglect the losses of the rectifier elements, if these latter are semi-conductor diodes and the rated exciting voltage of the alternator is at least 50 volts. The resistance changes caused by the heating of the field coil entail a much greater uncertainty of the calculation than this neglection.

In the knowledge of the above statements it is possible to dimension the principal parts of the compounding and voltage controlling system.

Since the reactor is provided to supply the no-load exciting current, its dimensioning has to be based on the no-load operation and the permissible dispersion of the no-load exciting currents of the individual alternators has to be taken into consideration.

In Fig. 6 lengths OF, OF″ and OF′ represent the no-load exciting currents of alternators with medium, maximum and minimum no-load exciting current, respectively, and according to the scale established by relationship (4). The vectors pertaining to the thickened portion F′F″ of the semicircle with a diameter OE are current vectors $\bar{I}_{fr}$ corresponding to the no-load exciting currents of all alternators while arc portion F″E has to be considered a safety reserve. The reasonable magnitude of this latter is influenced by the manufacturing accuracy of the compounding equipment, by the method of quality control and by the security of the initial build up of the excitation of the generator. The length of diameter OE and consequently the magnitude of reactor current I_f is decided by the relative length of reserve arc F″E. The required reactance of the choke can be calculated with good approximation from the condition that the whole alternator voltage falls on the choke. To increase the accuracy

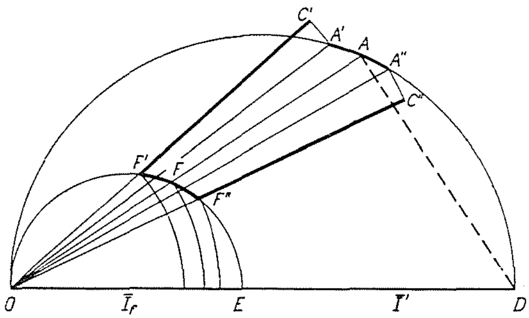

Fig. 6

of the calculation the modifying effect of R and X may be taken into consideration. R is known from relationship (6) and the ratio X/R to be realized can be taken from the vector diagram.

As it has been outlined in the preceding, no-load exciting current means the exciting current requirement of the alternator loaded with the three-phase reactor alone.

Since the proper reactor current is established in the course of the dimensioning procedure from the exciting current requirement of the alternator loaded with the reactor itself, the magnitude of the reactor current has to be previously established by estimation and subsequently corrected. In estimating the magnitude of the reactor current it may be assumed that it is numerically equal to the true no-load exciting current of the alternator.

As it is evident from the above the compounding and voltage control equipment adapts itself to the various no-load exciting current requirements of different alternators by the premagnetization of the current transformers. Premagnetization is maximum at point F′ and minimum at point F″ in Fig. 6.

In dimensioning the current transformers it is recommended to start out from a pure reactive load. The plus excitation pertaining to the maximum permissible reactive current of the alternator has to be established from calculated or measured data of the alternator. By measuring this plus excitation according to the scale of relationship (4) on the extension of straight line OF of the alternator having a medium no-load exciting current, point A will be obtained which represents the full excitation current. This procedure is justified by the assumption that the amount of compounding is accurately adjusted to the alternator of medium no-load exciting current so that the voltage corrector does not change the ratio X/R as a result of load.

In the next step a perpendicular line is drawn from point A to straight line OA which intersects the extension of straight line OE at point D. The length of the portion ED gives, when measured in current scale I', the primary current of the current transformer reduced to the secondary side. Primary current I being a known value the required turn ratio can be calculated by dividing I by I'. The semicircle drawn over portion OD as diameter represents the working diagram of the system.

On the basis of the working diagram one can follow the modifications occurring when the compounding and voltage control system properly adjusted to an alternator of medium no-load exciting current will be connected to an alternator of minimum or maximum no-load exciting current. In this case the whole exciting current requirement is represented by straight portions OC′ and OC″, respectively. It is assumed that the plus load excitation is identical for all the alternators and hence $\overline{F'C'} = \overline{FA} = \overline{F''C''}$. The obtained points C′ and C″ are off the working diagram so that current vectors with the length of OC′ and OC″ are not possible in the indicated directions. Vectors OA′ and OA″ having the same length may come into existence by the decrease or increase of the premagnetizing currents pertaining to no-load points F′ and F″. The premagnetization is changed by the corrector being a true voltage regulating circuit and tending to keep the voltage at a constant value. Since, however, the corrector is a proportionally operating voltage regulator having a residual error the exciting currents necessary for keeping the voltage constant cannot be realized perfectly, and a slight voltage deviation occurs in a negative sense with an alternator of minimum no-load exciting current and in positive sense with an alternator of maximum no-load exciting current. These deviations of the voltage can easily be corrected by proper adjustment of voltage divider P.

If extraordinarily severe requirements are raised on the accuracy of voltage stability, these can be appropriately met by an individual matching to a given generator. This can be done by properly adjusting partly the air gap of the reactor, partly the secondary tapping of the current transformers. This method needs not be used in the usual fields of application, which is one of the principal advantages of voltage controlled compounding, since both the compounding equipments and the alternators can be interchanged without the necessity of individual adjustment.

The secondary current of the current transformers can be established from the vector diagram in the manner described in section 2. When dimensioning it is necessary also to establish the unsaturated reactance of the current transformers and the reactance with rated premagnetization, their maximum induction in nominal operating condition and the data of the premagnetizing windings. The reactance pertaining to rated premagnetization can be established from the vector diagram, since in no-load condition distance OF is proportional to $1/R$ and distance FE to $1/X$ while under load distance OA is proportional to $1/R$ and distance AD to $1/X$. R is known from relationship (6) so that X can be calculated.

The description of the method of dimensioning the current transformers goes beyond the limits of this paper dealing mainly with the working diagram. Therefore, it should be merely noted that the current transformers are dimensioned essentially in the same way as magnetic amplifiers of the current control type.

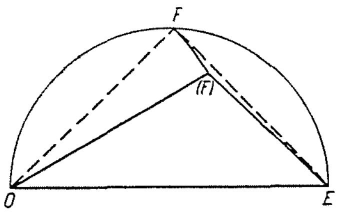

Fig. 7

4. Deviations from the calculated values

To be able to utilize successfully the current vector diagram for dimensioning purposes one has to know the deviations existing between the currents taken from the diagram and measured in the real system.

Current I_r has been assumed to be identical with current I_a flowing into the a.c. terminals of the three-phase bridge-connected rectifier. Between this current and the exciting current exists the empirical relationship described by equation (4). As already mentioned, experience shows that relationship (4) is valid both in no-load condition and with loads of various magnitude and phase angle. Consequently the value of I_r is as accurate in the current vector diagram as accurately the exciting current necessary in the examined operating condition could be established.

The required turn ratio of the current transformer can be established very precisely from the current vector diagram by using the described method. This can be explained by the fact that the construction used for establishing the required turn ratio is based on current $I_r = I_a$, which is, according to the preceding, highly dependable.

For the current I_2 flowing in the secondary winding of the current transformer the current vector diagram supplies a considerably less accurate value. This is represented in no-load condition by length EF and on load by length EA. As it has been previously stated current I_2 attains its maximum value at rated active load of the alternator so that the accuracy of its establishment is extraordinarily important just for this state of operation. Experience shows that if for the no-load condition lengths proportional to the r.m.s. values of currents I_f, $I_r = I_a$ and $I_x = I_2$ are used for constructing a triangle, this will not be a rectangular one and the angle enclosed by I_r and I_x will be obtuse (Fig. 7). This means that the r.m.s. value of $I_x = I_2$ is less than that obtained on the basis of rectangular construction.

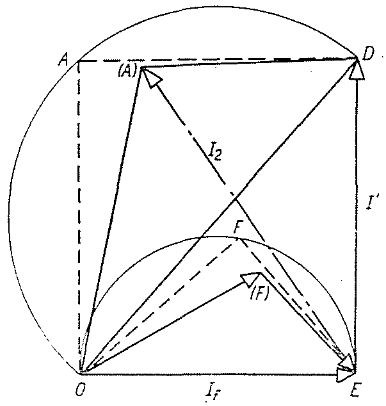

Fig. 8

If the triangle constructed with currents measured in no-load condition is considered an expression of the ratio of currents I_r and I_x valid for all conditions of operation, values of I_2 being closer to reality will be obtained. The length of current I_2 thus constructed for the case of purely active load is shown in Fig. 8. It is more appropriate to speak of current lengths instead of current vectors, since in this case the non-sinusoidal quantities are not reduced to sinusoidal ones but the r.m.s. values of the non-sinusoidal quantities are directly represented by lengths.

It has to be pointed out that by using the simplified equivalent circuit shown in Fig. 3 the fact that current I' has in addition to R and X a third parallel circuit X_f (Fig. 2), has been neglected. If this is taken into consideration in the current vector diagram the calculated and measured values of I_2 will be closer to each other. The same does not apply to no-load state when $I' = 0$, therefore this neglection cannot be considered the only reason of the deviations experienced. It is not necessary to look for other reasons, since the fact that a non-linear system has been analysed by linear methods represents a fundamental source of minor or major deviations.

With regard to the fact that compounding and voltage control units are generally not individual but serial products, any acceptable dimensioning method is required to help in the production of a nearly perfect prototype, which can still be refined in some of its details. A second unit, however, has to be perfect. This requirement is fully met by the dimensioning method based on the application of the simplified current vector diagram.

Summary

Because of their excellent dynamic properties self-excited line-current compounded synchronous alternators are widely used in various local, portable and standby current sources. If the requirements raised on the accuracy of voltage control are severe, the compounding system may be completed with a supplementary voltage regulating corrector unit. In the paper the dimensioning principles of such a voltage controlled compounding system are outlined on the basis of a simplified equivalent circuit and working diagram. Deviations resulting from an arbitrary linearization of the essentially non-linear problem are traced. By using the suggested dimensioning method, correctly operating prototype equipments may be produced.

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