continuous-current rating increases the specific loading of the main current-carrying elements does not decrease as one would expect, thinking in terms of the skin effect at higher current capacities. I am curious regarding this.

Regarding the second item I mentioned, the use of a stored-energy closing mechanism certainly answers the problem of closing a breaker when the control source is taken from the primary circuit. The question then naturally arises: is this advantage worth the increased complexity and loss of accessibility wheich is thereby encountered? In place of two time-proven devices, namely, the solenoid and control relay, we now find a motor and its control scheme, plus a 1,000-to-1 reduction unit, springs, mechanisms, cams, etc., all undoubtedly critical in their adjustments and in their relations to each other.

Very little is said in this paper regarding the overcurrent trip devices, other than that the direct-acting principle has been extended to the full line up to and including the 4,000-ampere frame. By this, I assume that their present standard device has been used. I had hoped to read that they had provided a better means of adjustment for the long-time delay, and at least some adjustment for the short-time delay. My company has found that both these adjustment features are most desirable from the user's standpoint, especially in selective tripping applications. The introduction of a completely new line of circuit breakers should certainly not carry with it certain definite limitations of the superseded line.

I find no reference in this paper to 5,000- and 6,000-ampere frame breakers, and I should like to ask what the General Electric Company intends to do in these sizes. Even though these sizes may not remain standard in the future, there will always be considerable application for them. Therefore, is it the intention of this company to extend their developments higher, or will they continue to offer their present equipment which would now appear rather obsolete by comparison with their new line?

L. H. Romzick (The Detroit Edison Company, Detroit, Mich.): This new line of low-voltage air circuit breakers appears to be an improvement in design of this manufacturer's circuit breakers. However, the stored-energy closing mechanism seems to be more complex than a solenoid mechanism. I believe that a hazard exists to maintenance personnel, inasmuch as the closing mechanism is energized when in the open position. Although provision is made for blocking the loaded springs, I believe that a means of automatically unloading the spring mechanism when the breaker is withdrawn from its cubicle or blocking so that the breaker cannot be withdrawn beyond the test position unless the springs have been released would provide sufficient safety.

The overcurrent trip devices are satisfactory for general applications; however, for essential auxiliary motor feeds in power plants it would be desirable to have high-current instantaneous trip on three poles for fault protection, long inverse time delay on at least two poles for overload protection, and a long-time delay with a making contact for a remote alarm on one pole. This is a common practice for utility companies.

(Author's closure appears on page 1354.)

Field Excitation in Relation to Machine and System Operation

S. B. FARNHAM
MEMBER AIEE

R. W. SWARTHOUT
ASSOCIATE MEMBER AIEE

UNDER normal conditions, an operator can do only two things to a synchronous machine to influence its behavior with respect to the system to which it is connected, that is, he can adjust the throttle valve or change the driven load, thereby changing the shaft torque; and he can turn the rheostat, and hence change the field current.

Even in these operations, he does not have unlimited freedom of choice, for usually the torque can be in one direction only, depending on whether the machine happens to be a generator or a motor. If it is a synchronous condenser, he may not be able to do anything at all about shaft torque, since the shaft may be sealed up inside the housing where it is inaccessible. Happily, however, the operator does have somewhat more freedom of action in what he does to the field current.

It is the purpose of this discussion to indicate, qualitatively and quantitatively, the effects of the operator's manipulation of the field rheostat, both on the individual machine and on the system of which that machine is a part. As referred to here, field rheostat is used in its broadest sense. The discussion will be concerned not only with the conventional resistance box with handwheel or motor mechanism but equally with the automatic voltage regulator, with which most important machines are today equipped, and which can be adjusted by the operator to hold a desired voltage level.

The current interest in field excitation stems from the fact that many systems are now operating at power factors higher than have previously been experienced. This is true for several reasons, among them being the application of capacitors in substantial quantities, the increasing use of underground cable, and the interconnection of system to system, resulting in substantial new mileage of high-voltage lines.

Since all of these things help supply excitation to every machine on the system, the general voltage level tends to rise. As a result, it becomes necessary to reduce the d-c field strengths of synchronous machines so as to hold an acceptable system voltage level. The operator, therefore, logically wonders: what are the effects of operation with weak field, and what are the limits to which this field weakening can reasonably be carried? Also, there have been within the past few years several prominent cases of system shutdowns attributable to complete accidental loss of field excitation, or to lack of means to increase the field strength quickly after a system disturbance.

With this background of interest, a fundamental understanding of machine capabilities will be helpful in answering the questions which arise.

Kilowatts and Kilovars

Just as there is a direct and well-understood relationship between shaft torque and kilowatts, so also is there an equally distinct relationship between field current and that other well-defined commodity, kilovars. Broadly speaking, all synchronous machines are capable of both producing and consuming each of these two separate and distinct kinds of commodity.

By convention, kilowatts are considered positive when they flow from the machine out into the system. Hence, generator kilowatts are plus kilowatts, while motor kilowatts are minus kilowatts. Similarly, when the machine is overexcited, it generates kilovars and delivers them to the system. By analogy to the positive direction of power flow, this is accepted

---

Paper 53-387, recommended by the AIEE System Engineering Committee and approved by the AIEE Committee on Technical Operations for presentation at the AIEE Fall General Meeting, Kansas City, Mo., November 2–6, 1953. Manuscript submitted June 8, 1953; made available for printing August 6, 1953.

S. B. FARNHAM and R. W. SWARTHOUT are with the General Electric Company, Schenectady, N. Y.

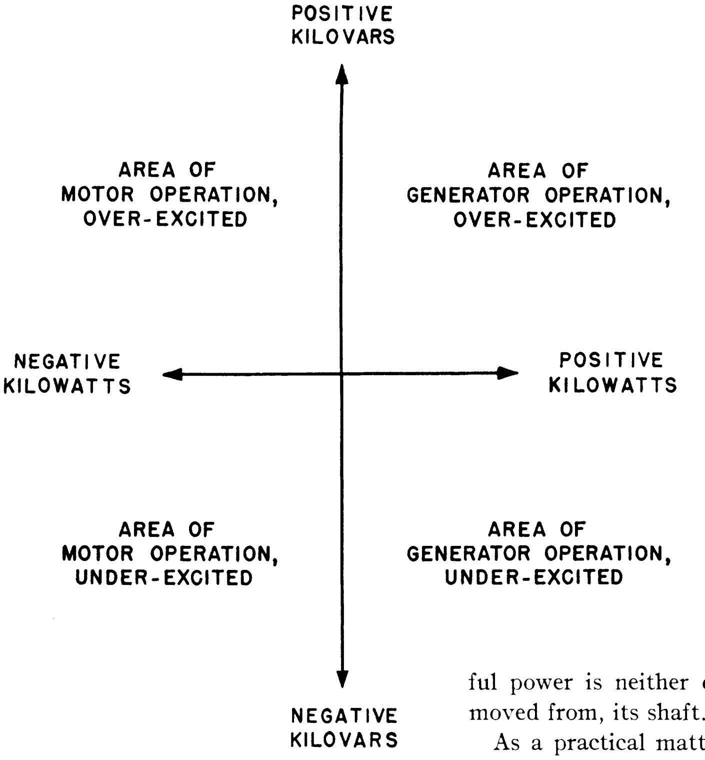

Fig. 1 (left). Definition areas of synchronous machine operation

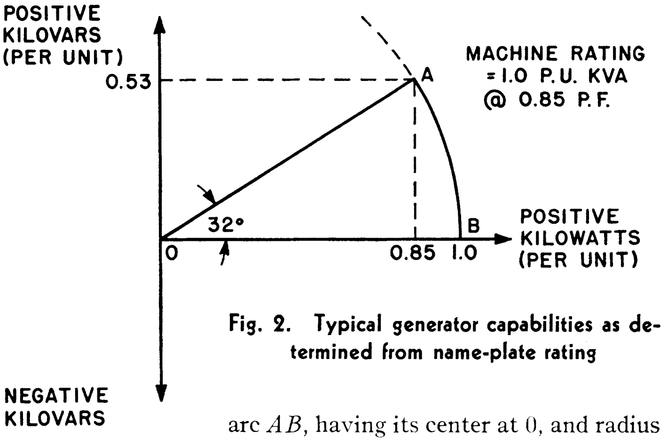

Fig. 2. Typical generator capabilities as determined from name-plate rating

as also being the positive direction of kilovar flow. Negative kilovars, then, are those which flow from the system into the machine to maintain its magnetization when its own field is underexcited.

Fig. 1 shows these concepts translated into diagramatic form, in which kilowatts and kilovars are plotted along co-ordinate axes, with the positive direction upward and toward the right, as is customary.

As previously indicated, a synchronous machine, in the broadest sense, can be operated in any quadrant of Fig. 1. If driven by a prime mover, it operates as a generator somewhere in the positive kilowatt area (right). If the rotation of its shaft is restrained by a driven load, we call it a motor, and it operates in the negative kilowatt area (left). If its field strength is more than enough to supply its own excitation requirements, the excess appears as a component of armature current representing kilovars exported to the system, and the machine operates in the positive kilovar area (above). If its field is underexcited, the deficiency must be made up by armature current, representing kilovars drawn from the system, and the machine operates in the negative kilovar area (below).

A machine operating at unity power factor is just self-sufficient in its excitation. It neither produces nor consumes system kilovars. Hence its operation is depicted along the horizontal axis of Fig. 1. When used as a synchronous condenser, on the other hand, the machine operates very nearly along the vertical axis (except for losses) since useful power is neither deliver to, nor removed from, its shaft.

As a practical matter, most machines are designed for one specific duty only, hence there are definite limitations to the area within which any given machine may be operated successfully. Since this discussion is primarily about generators, and if it is agreed to omit reference to those abnormal circumstances under which they may motor temporarily, we immediately cut the area in half. Fig. 2, then, is merely the right-hand or positive kilowatt side of Fig. 1.

Generator Capabilities

In Fig. 2, there is plotted at point *A* the name-plate rated conditions for an assumed typical 0.85 power factor generator. Rated kilovolt-amperes of the machine are taken as 1.0 per unit on its own rated kva base. Hence, the rated conditions for machine operation, upon which its performance guarantees are based, are 0.85 per unit kilowatts and 0.53 per unit kilovars ($\cos\theta=0.85$), ($\sin\theta=0.53$). Point *A*, however, is just one point in a rather extensive area; and few, if any, machines are operated for any length of time at exactly the conditions stated on the name plate. The question is then: what are the boundaries of the area on the kilowatt-kilovar diagram within which the machine may be operated?

Armature Current Limit

In addition to point *A*, it is usual that generators be suitable for delivering kilowatts equal to rated kilovolt-amperes at unity power factor, corresponding to point *B* in Fig. 2. Thus, by drawing the arc *AB*, having its center at 0, and radius equal to rated armature amperes, we have begun to outline an area of permissible operation. The operator of the assumed typical machine, of course, does not hesitate to operate at reduced load anywhere within the sector *0AB*. He may also on occasion operate at overload in the region to the right of the arc *AB*, but in so doing he encroaches upon the margins which the designer provided to cover the variables that may occur in materials, workmanship, maintenance, or the demands of emergency loading, and over which he has no control. These margins are essential both to the designer's own peace of mind and to the preservation of the good name of the company he represents. It is outside the scope of this discussion to explore overload operation. Rather, it is our intent to define the entire area within which operation within rating is possible, so that full advantage of this flexibility may be taken in securing optimum over-all system operation. Hence the immediate problem is to close off the openings at the top and bottom of the now partially bounded area of Fig. 2. This can be begun from information obtainable from the simple phasor diagram of the assumed typical machine, as shown in Fig. 3.

Field Current Limit

Starting with rated terminal voltage $\boldsymbol{E}_t$ and rated armature current $\boldsymbol{I}_a$, each equal to 1.0 per unit, and at an angle θ with respect to one another ($\cos\theta=0.85$ in the

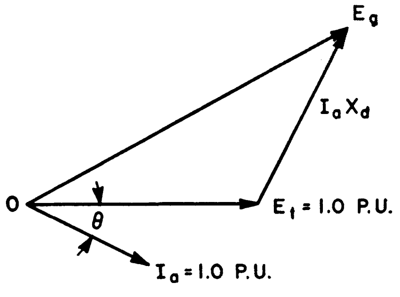

Fig. 3. Typical generator phasor diagram

assumed typical case), we can lay off $\mathbf{I}_a X_d$ at right angles to $\mathbf{I}_a$, where X_d is the synchronous reactance of our machine. $\mathbf{E}_g$ then is internal or generated voltage corresponding to rated terminal conditions. It would also be equal to the terminal voltage if full load were removed without making any change in field current.

Keeping the phasor triangle in mind, refer now to Fig. 4. Here $\mathbf{E}_t$, $\mathbf{I}_a X_d$, and $\mathbf{E}_g$ are each divided by X_d. Also, the triangle is inverted and reoriented so that it falls on the kilowatt-kilovar co-ordinates, with the side representing $\mathbf{I}_a X_d/X_d = \mathbf{I}_a$ so placed as to form the radius $0A$ of the previously determined constant armature current arc AB.

The side of the triangle representing $\mathbf{E}_t/X_d = 1.0/X_d$ falls along the kilovar axis. Note however that, neglecting saturation, the quantity $1.0/X_d$ is equal to the short-circuit ratio of the assumed typical machine. Hence, point C is established on the negative kilovar axis, at a point corresponding to the short-circuit ratio. This value might typically be 0.80, corresponding to $X_d = 1.25$ for the assumed machine $(1/1.25 = 0.80)$.

This leaves only the third side, $\mathbf{E}_g/X_d$, of the phasor diagram triangle to be accounted for. Dimensionally, since it is a ratio of voltage to reactance, it must represent some kind of current; and since we are dealing in per unit quantities, there is no constant of proportionality with which to be concerned. $\bar{\mathbf{E}}_g$ is generated voltage and is proportional to air gap flux, which is in turn proportional to field current, neglecting saturation. Thus $\mathbf{E}_g/X_d$ represents per unit field current. Hence, just as $0A$ represents rated armature current, so CA represents rated full-load field current. Then with C as a center, and CA as a radius, the arc AD may be drawn representing the locus of rated field current, thereby closing off the top of the area within which the machine may be operated.

In any balanced design, point A, the point representing name-plate rating, is also the point at which the designer arranged for the thermal limits of both field and armature to be reached together. Thus the output of the typical machine is limited by field heating from D to A, and by armature heating from A to B.

As an example of the usefulness of Fig. 4, it gives a ready answer to the frequently encountered question: what maximum kilovars can this machine generate at zero kilowatt load? In other words, what is its capability as a synchronous condenser? To answer this, it is only necessary to measure the vertical intercept OD, which represents the maximum permissible per unit kilovars to scale. Or, mathematically

$$OD = CD = CO = CA = CO$$

where, for the constants it is assumed

$$CA = \sqrt{(0.80+0.53)^2+(0.85)^2} = 1.58$$

$$CO = 0.80$$

Hence

$$OD = 1.58 = 0.80 = 0.78$$

This machine, then, can generate maximum kilovars equal to 78 per cent of name-plate rated kilovolt-amperes.

End Region Heating Limit

There remains now only the lower part of the area to be bounded. Since this is a region of low field current, being well below the limiting field current arc DA, it might be said offhand that the limit must therefore be armature current, and so the constant armature current arc AB could be extended all the way around to E. This would, however, be wrong for several reasons. For one, system stability would have been completely overlooked. For another, localized heating in the machine would very likely become a problem, in the case of steam turbine generators.

Now, as the boundary line is extended into the region below the horizontal axis, we come to the one place where generalized reasoning fails, and where specific knowledge of the individual machine is required, namely, in establishing that part of the operating limit resulting from localized heating in the machine iron.

The reason for the problem is that all synchronous machines have an armature reaction end leakage flux at both ends of the stator. This flux is produced by

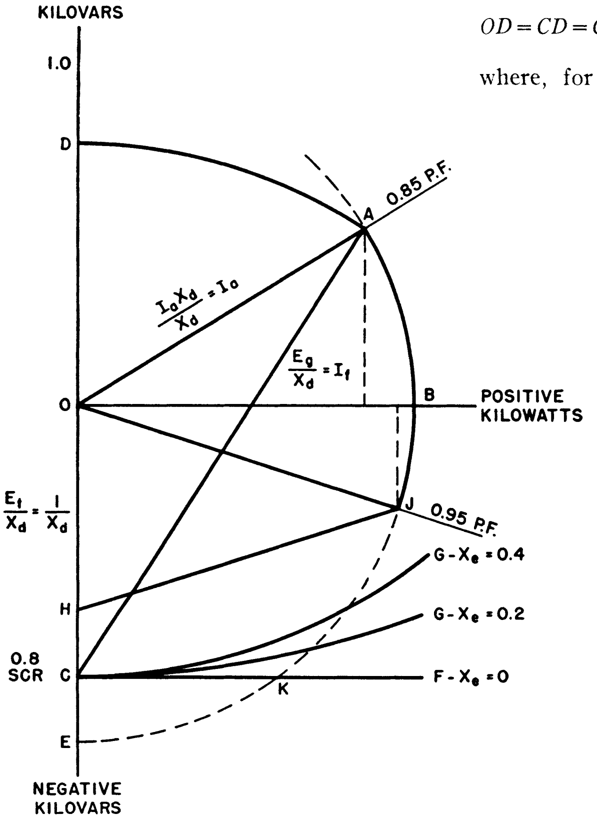

Fig. 4. Composite capability limits of typical generator at rated terminal voltage

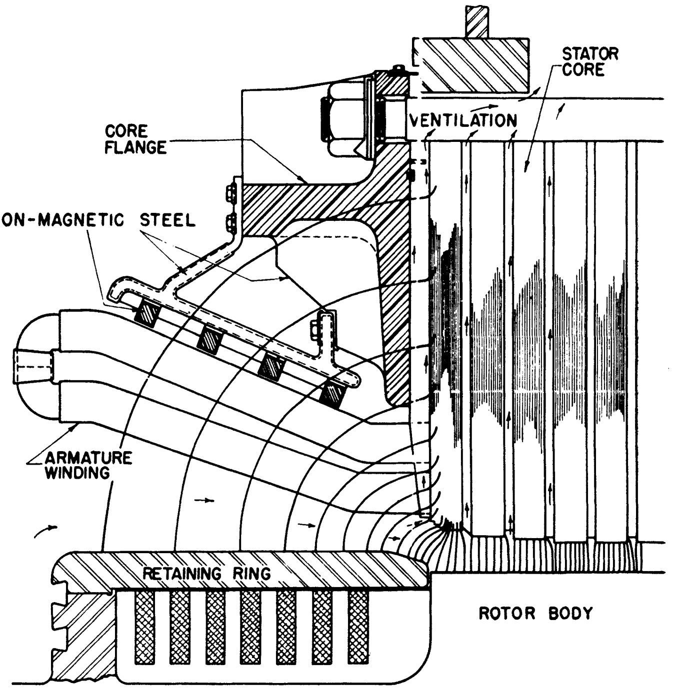

Fig. 5. Sectional view of end-region construction of a modern turbine generator

load current flowing in the stator conductors. It revolves at synchronous speed with respect to the stator, and hence is stationary with respect to the rotor. It crosses from one side of the stator to another point on the stator 180 electrical degrees away. In so doing, it takes the low-reluctance path, which as shown in Fig. 5, representing this portion of a typical steam turbine generator, carries it through the stator core flange and end fingers, across the air gap into the rotor retaining ring, circumferentially around the retaining ring, and so on back across the air gap, fingers, and flange, to the stator core. While the main flux in the body of the stator is parallel to the laminations, it is to be noted that this end leakage flux enters and leaves the ends of the stator in a direction essentially perpendicular to the laminations. Hence the effect of the laminations in reducing eddy currents caused by the end leakage flux is minimized. To understand the significance of this change in flux direction with respect to the laminations, it must be appreciated that the core losses are typicaly something in the neighborhood of 100 times greater for perpendicular flux than for flux parallel to the laminations. Hence, considerable additional heat is generated; and since it is applied to only a relatively small volume of material, dangerously high temperatures may be produced within only a matter of minutes.

Now, how is field current related to this end leakage flux and its resultant heating? Simply in this way: Normal values of field current keep the retaining ring saturated, so that only a relatively small amount of armature end leakage flux traverses the path described. However, when the field excitation is reduced, corresponding to operation of the machine in the region of unity and leading power factor, then the retaining ring is no longer saturated, and permits an increase in armature end leakage flux. As we have seen, this increased leakage flux produces heating in those areas of restricted material cross section, and where the flux direction is at right angles to the plane of the laminations.

This phenomenon has been recognized since the middle 1920's. Several different approaches have been used, either singly or in combination, to reduce the armature end leakage flux and the resultant heating. Among these are the use of nonmagnetic materials for the retaining rings and parts of the stator end structure; changing the end structure surface configuration so that leakage flux is reduced and so that the remaining flux paths are not at right angles to the plane of stator laminations; and also the use of magnetic shields to control the flux paths.

The success of these methods is attested by the fact that modern generators may be operated successfully in the underexcited region down to a line such as *HJ* in Fig. 4, where point *H* is at 60-per-cent rated kva at zero power factor leading, and point *J* is at rated kva, 0.95 power factor leading.

These limits, however, may not apply to older machines; and it becomes necessary to investigate the capabilities of each such machine in question. Sometimes the manufacturer may have test data on that particular machine or on one of very similar design, from which he will be willing to give a reasonably close estimate of the expected capabilities. In other instances the users may have the choice either of accepting some rather conservative estimate based on general knowledge and experience, or of making an actual test on the particular machine itself. If a test is to be undertaken, the manufacturer will generally be willing to suggest the locations at which thermocouples are most likely to reveal the limiting temperatures.

Often, however, the operator already has a fairly clear conception of the capabilities of his older machines, based on his operating temperature records, visual inspections, and maintenance experience over the years. Evidences of having reached the limits of underexcited operation may occasionally be found in the blueing of iron parts of the end structure, or the charring of insulation on the armature bars where they emerge from the core stacking.

Having determined, by whatever means are appropriate to the particular machine, the limits imposed by end heating, these limits may be plotted, Fig. 4, to complete the boundary of the permissible operating area. For illustration, in Fig. 4 this is the line *HJ* which as has been indicated, is typical of a modern machine. For some older machines, this line will be displaced upward toward the horizontal axis, and in a few cases it may be found that point *J* will actually be above the axis, since the end heating limitations of some machines may be such that they can not be operated near full load even at unity power factor. Fortunately, this restriction will apply to only a few of the oldest steam turbine generators still remaining in service. It is not a limitation to the operation of water-wheel generators, because of their generally different construction.

Stability Limitations

It has been hinted that system stability might constitute a limitation. With respect to steady-state stability, it can be shown that if the machine in question is connected through negligibly small impedance into an infinitely large system, then the stability limit may be represented by a horizontal straight line passing through the point on the negative vertical axis representing short-circuit ratio. This line is *CF* in Fig. 4. If the machine is operated at any kilowatt and kilovar loading above this line, it will be stable. On the other hand, operation along the arc *EK*, even if it did not exceed any heating limitation, would be impossible, as the machine would not remain in synchronism with the system. Actually few, if any, machines operate through negligibly small impedance into a system so "stiff" that it approaches the infinite. In most practical cases, the machine operates through impedance representing transformers, lines, and the paralleled value of the impedances of all the other machines on the system. This resultant impedance is typically about 0.20 to 0.40 per unit, based on the individual machine rating, although it is of course determined in any specific case by the system configuration and constants. At any rate, the effect of this external impedance X_e is to bend upward the straight line *CF* to some position such as *CG*. With terminal voltage held constant at 1.0 per unit, it can be shown that *CG* is the arc of a circle whose center lies on the vertical axis at a point $SCR/2+1/2X_e$ above point *C*. Hence, with the aid of numbers already known or readily determinable, the part of the boundary established by steady-state stability can be established. This limit is slightly conservative, in keeping with its determination by the commonly accepted practices of approximating saturation and neglecting saliency.

Transient stability also is of course affected to some degree by the machine excitation as dictated by the kilowatt and kilovar load which it carries, as well as by its operating voltage. However, many other factors outside the scope of this discussion such as type and location of the fault, operating times of relays and clearing times of circuit breakers, system grounding, machine inertias, and automatic reclosing play a so much more dominant part in transient stability considerations that the effect of field excitation in this regard is greatly overshadowed. It would appear to be a very extreme case where system transient stability were critically dependent on field excitation.

It is reasonable to conclude, therefore, that in most practical cases transient stability will not become a barrier to successful underexcited operation if it has not previously been an obstacle while operating in the overexcited region.

To summarize, the limits of generator capability in each of the several potential areas of operation, as illustrated in Fig. 4 are

DA—field heating

AJ—armature heating

JH—armature end region heating

In addition, there may also be a steady-state stability limit *CG* but as has been seen, this would not constitute an operating limit unless the machine under consideration were connected to the system through a tie so weak that the curve *CG* bent upward to intersect *HJ*.

Automatic Voltage Regulators

As a basis for appreciating the role of the automatic voltage regulator in permitting the widest possible flexibility of machine operation within the boundaries established, it may be in order first to consider the case of a machine operating without a voltage regulator. Assume that this machine is carrying a kilowatt and kilovar load as represented by point *P* in Fig. 6. On this figure will immediately be recognized the composite boundary of permissible machine operation *DAJH* as previously determined, for rated terminal voltage. Also shown is the steady-state stability limit *CG*, for this machine and connected system.

It will be apparent from our earlier derivation that the field current of this machine is represented by *CP*. (Remember that *CA* is proportional to rated field current. Hence *CP*/*CA* is simply the proportion of name-plate rated field current; and this is just the amount necessary to permit the machine to handle the kilowatts and kilovars represented by point *P*.)

Now, suppose this machine is called upon to pick up load. This might well be in consequence of the system normal daily load pattern, or perhaps because some other machine on the system has had to drop load. At any rate, let us assume that the load increase on the machine occurs before the operator notices the resulting drop in terminal voltage, and hence that he makes no change in the field rheostat setting. On the co-ordinate diagram of Fig. 6, this situation, namely increasing kilowatts with constant field excitation, is depicted as a movement of the operating point from *P* along the circular arc *PK*. This path runs almost directly into the end region heating limit *HJ* and the system steady-state stability limit *CG*. Whether or not one or both of these limits will be exceeded depends of course on the amount of the kilowatt load increase. The final operating point lies at the intersection of the circular arc with a vertical line, such as *XY*, representing the new kilowatt load, and of course the terminal voltage is substantially below normal.

Several conditions immediately become apparent from inspection of Fig. 6:

1. Load increase without corresponding adjustment of field current pushes the machine operating power factor toward the leading (underexcited) region.
2. The more lagging (overexcited) the initial load power factor, the greater the total load the machine can carry before running into one of the limits.
3. If adequate field strength could always be assured, steady-state stability would, for all practical purposes, never be a problem, because the limit is greater than the capability of the typical prime mover.

A somewhat broader picture of this variation of steady-state stability limit with initial operating power factor is shown in Fig. 7, based on typical constants. It will be apparent from this figure why some operators (who perhaps experienced a shutdown resulting from instability while operating in the leading or near unity power factor region) have a phobia against approaching the unity power factor line. Actually, however, as Fig. 7 shows, there is no precipitous breaking point at unity power factor. The criterion, therefore, should not be what the power factor is, but rather what the maximum available synchronizing power is, relative to the maximum load

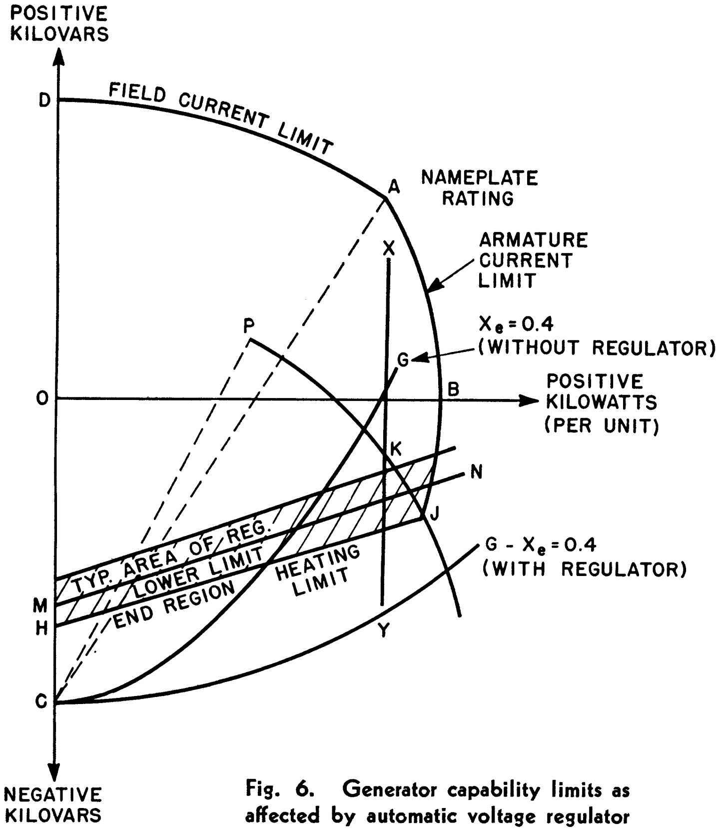

Fig. 6. Generator capability limits as affected by automatic voltage regulator

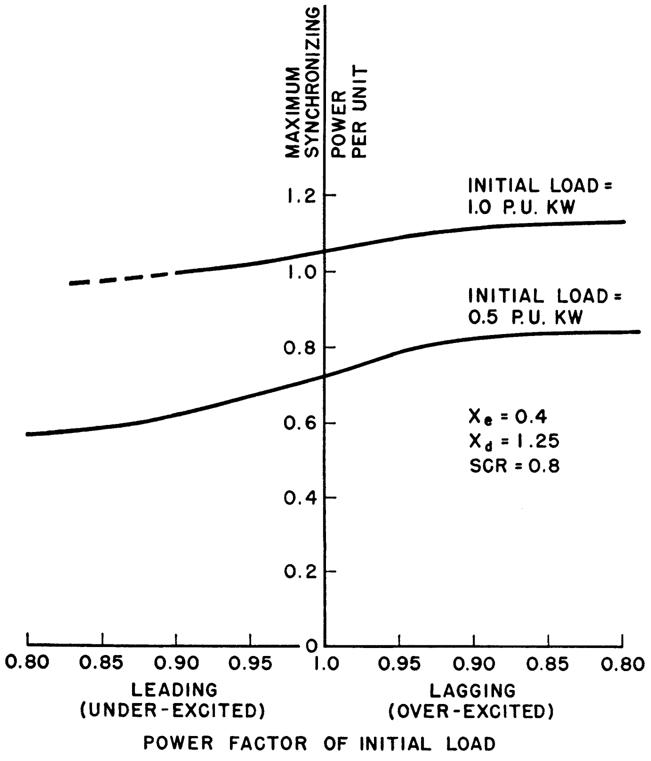

Fig. 7. Ultimate maximum synchronizing power versus power factor of initial load

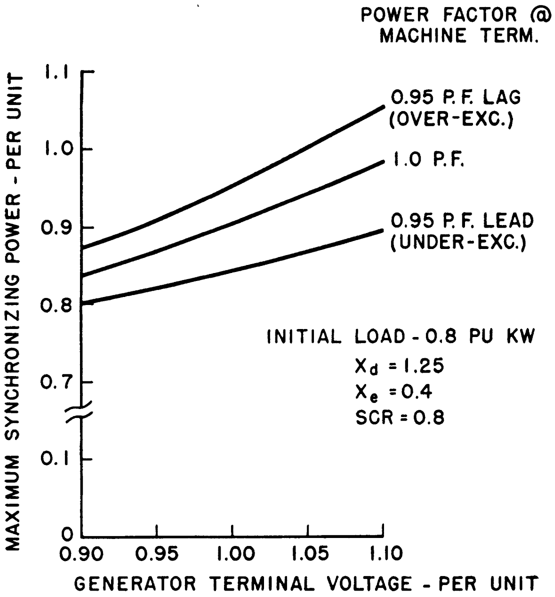

Fig. 8. Ultimate maximum synchronizing power versus generator terminal voltage for assumed initial load of 0.8 per unit

demand that may be made on the particular machine in question. On this basis, any machine under hand control can have its loading so scheduled as to insure stable operation under whatever emergency load condition may be imposed upon it.

With an automatic voltage regulator, however, any practical concern over steady-state stability can be dismissed, for the regulator will hold the machine excitation at a level corresponding to synchronizing power in excess of the maximum capability of the prime mover.

Lower Excitation Limit

Notwithstanding the practical assurance against loss of steady-state stability provided by the automatic voltage regulator holding normal terminal voltage, there may be instances where an operator, in his efforts to reduce system voltage during light load, may lower the setting of the regulator voltage adjusting rheostat so that the machine excitation and terminal voltage are reduced substantially below normal. This action on the part of the operator may reintroduce a steady-state stability problem for, as shown in Fig. 8, the limits, which may be ample at rated terminal voltage, become materially reduced at lower values of terminal voltage.

Recognizing this possibility, some modern voltage regulators include a lower excitation limit which automatically comes into play below a predetermined level of excitation to prevent loss of synchronism. It may also be used advantageously to prevent operation where end region heating might become a problem. The region within which this lower limit is typically set to come into operation is shown by the shaded area of Fig. 6. Actually the characteristic of this device is a straight line, such as *MN*, and may be located anywhere within the area by independent adjustments of its slope and point of intersection with the vertical axis. Hence this characteristic can be set so that the lower excitation limit will come into operation just short of either the end-heating limit or the steady-state stability limit, as determined for the particular machine and associated system.

This obviously is not a fixed minimum field current limit, but rather it varies the minimum allowable excitation automatically with the load on the machine, as measured through instrument transformers connected to the machine terminals. Thereby it permits the maximum of operating flexibility, right up to the limits imposed by the machine and system. This lower excitation limit is a standard feature of all amplidyne-type automatic voltage regulators, but is not adaptable to rheostatic-type regulators.

Loss of Excitation Relay

The extreme case of underexcitation is of course, complete loss of excitation, as may happen, for example, when a field lead is broken or when someone inadvertently trips the field breaker. Loss of synchronism with the system is, under this condition, a foregone conclusion, although the machine may continue to produce kilowatts as an induction generator. The amount of kilowatts thus generated will depend both on the initial setting and droop characteristics of the speed governor, and on whether the excitation failure left the field circuit completely open, or closed (perhaps through a field discharge resistor). In any event, however, it becomes desirable to remove the machine immediately from the system, for two reasons: 1. The machine may be damaged through heating caused by large eddy currents flowing in the surface of the rotor. 2. The system may not be able to withstand successfully the large kilovar load suddently imposed on it. System voltage will drop, and other machines may lose synchronism.

With respect to the first possibility, namely, rotor damage, it is true that machines have been operated for extended periods without apparent damage; and some power companies feel that an operator can correctly diagnose the symptoms in time either to restore the excitation (perhaps by switching over to a spare exciter) or to trip the machine off the system manually. On the other hand, generators have had to be repaired because of damage resulting from this sort of procedure. Regardless, however, of whether the machine suffers obvious damage or not, there is the very real possibility of reduction of field-winding insulation life or other incipient damage which may be impossible to evaluate even through careful examination, and the machine will certainly be out of service while the examination is being made. In contrast, if an automatic protective relay is employed to trip the main breaker before the machine begins to slip poles, there need be no delay in returning the machine to service immediately after the cause of lost excitation is corrected, and without the necessity for examining and testing the rotor insulation.

The amount of the increased kilovar load imposed on the system as a consequence of generator excitation failure will vary, depending on the machine constants and the rate at which it is slipping poles, from something about equal to its name-plate kilovolt-ampere rating to as much as four times this rating. Especially if, previous to the disturbance, the machine was overexcited, that is, delivering kilovars to the system, the net change so far as the system is concerned may be very serious indeed. The newest and largest generator on a well-planned system usually represents the largest block of power that can be lost to the system without causing undue hardship. Often overlooked, however, is the fact that the larger kilovar load resulting from loss of excitation on such a machine may be more of a shock to the system than the loss of its kilowatt output. If other machines on the system are equipped with automatic voltage regulators, and if the resulting demand on them is not excessive, they may be able to supply the necessary additional kilovars and so help maintain system voltage. If, however, these other machines are inadequate to the demand, or if their excitation controls do not provide immediate response to the need, system voltage levels will fall, synchronizing power among them will be reduced, and instability may occur. If this happens, a major system shutdown is probable.

While automatic voltage regulators should always be regarded as the first line of defense, backup protection against this difficulty can be provided by a suitable loss-of-excitation relay on each large or otherwise important machine on the system. Like the lower excitation limit on the regulator, this relay responds to current and voltage at the a-c terminals of the machine, rather than to some arbitrary minimum value of field current or voltage alone. Hence it is immune to false operation when the field strength is purposely reduced, as during times of light load. Its application is clean-cut, and it is fail-safe in the event of open circuit in its supply leads.

Conclusions

Modern system operation is increasingly in the region of unity and leading power factor. Generators may safely be operated in this region, up to limits which usually are readily determinable. Such operation generally is not a determining factor in system transient stability, although steady-state stability may become a problem if machine kilowatt loadings are increased from light-load operation without corresponding increases in excitation. Automatic voltage regulators are very desirable, since they effectively eliminate this problem; and if of a type incorporating a lower excitation limit, they provide a means for automatically avoiding the regions where end heating and stability become limitations. A protective relay, arranged to isolate the machine from the system in the event of failure of its excitation, is desirable, both as primary protection against damage to the machine itself and as backup protection against serious disturbance to the interconnected system.

References

1. Underexcited Operation of Turbogenerators, **C. G. Adams, J. B. McClure.** *AIEE Transactions*, vol. 67, pt. I, 1948, pp. 521–28.

2. Underexcited Operation of Large Turbine Generators on Pacific Gas and Electric Company's System, **V. F. Estcourt, C. H. Holley, W. R. Johnson, P. H. Light.** *AIEE Transactions*, vol. 72, pt. III, Feb. 1953, pp. 16–22.

3. Power System Stability, Volumes I and II (book), **S. B. Crary.** John Wiley and Sons, Inc., New York, N. Y., 1947.

4. Effect of a Modern Amplidyne Voltage Regulator on Underexcited Operation of Large Turbine Generators, **W. G. Heffron, R. A. Phillips.** *AIEE Transactions*, vol. 71, pt. III, Aug. 1952, pp. 692–97; discussion pp. 1134–35.

5. System Stability Limitations and Generator Loading, **H. C. Anderson, H. O. Simmons, Jr., C. A. Woodrow.** *AIEE Transactions*, vol. 72, pt. III, June 1953, pp. 406–23.

◆

Discussion

W. R. Brownlee (Southern Services, Inc., Birmingham, Ala.): This comprehensive summary of various factors influencing the operating limitations on the excitation of generators is most timely because of two important trends. One is the continuing upsurge of unswitched capacitor installations, and the other is the use of larger conductors on and the more economical loading of transmission lines. These factors require greater control of kilovar supplies and generator voltages.

One caution is in order in the use of the curves and equations with respect to the effective external reactance. For example, consider a generating plant with three 60-megawatt units, connected to each other and to the transmission system through a high-voltage bus. If the short-circuit contribution of the transmission system, together with that of generators no. 2 and 3, is taken in determining the excitation limit of generator no. 1, then the only criterion derived might be the ability of this generator to remain at parallel with the other two. For stability with the power system, the external reactance is a function of the short-circuit contribution from the transmission lines only, and is applied on a base of all three generators rather than just one.

While the general tone of the paper is clear and simple, a serious defection appears in the section entitled "Kilowatts and Kilovars," namely the expression "negative kilovars." Usage of this type encourages such dangerous equivocations as "leading reactive," "leading or lagging current," and "impressed voltage reference or induced voltage reference." In view of the action of the AIEE Standards Committee in 1946,[1] it is urged that such expressions be avoided. Actually, there should be no more temptation to say "negative kilovars" than to say "negative kilowatts." The latter would lead to a description of a steam-electric generating station as a "disposal" for negative kilowatts and a means for supplying negative coal to the mines.

Reference

1. The Sign of Reactive Power, **AIEE Committee Report.** *Electrical Engineering*, vol. 65, Nov. 1946, pp. 512-16.

John F. Watson (Union Electric Company of Missouri, St. Louis, Mo.): The authors have done a commendable job, first in their presentation of a method of determining the capabilities of a synchronous generator for a complete range of power factors, and second, in viewing these limits from a standpoint of stability in order to reach some important conclusions regarding machine and system operation.

In the development of the capability curves, the assumption is made that armature and field thermal limitations are reached at the point of name-plate rating. Despite the fact that this assumption is quite commonly made, there may be some question as to whether this actually occurs. Perhaps some elaboration on this point would be helpful.

In regard to the method of rating a generator in the underexcited region of operation, the authors suggest specific limitations for modern machines but go on to say that test data, operating experience, etc., furnish the only definite means of rating a certain machine. While this is true, it does impose a limitation on the usefulness of the rating method because very often it is the absence of specific data and experience that make some method of rating imperative. It may be that no better way of establishing limits is possible, but if a method existed whereby limits could be determined from the more readily available machine data and curves, the usefulness of the whole scheme would be greatly enhanced.

In the initial months of plant operation, operators at the Meramec Plant of the Union Electric System noticed certain oscillatory phenomena which instigated a thorough study of machine stability at high and underexcited power factors. The results of calculations and a network analyzer study agree very well with conclusions presented by the authors regarding transient stability, steady-state stability, and the advantages of an automatic voltage regulator for maintaining stability under conditions of rapid load change. However, the results of this study show an important disadvantage of the automatic voltage regulator which is not mentioned by the authors.

Machine steady-state stability depends on external impedance as well as loading and load changes. If the impedance between the generator and the "infinite" system is increased suddenly as a result, for example, of losing a transmission line, the machine would be forced to deliver the same amount of power to the constant voltage system through an increased external impedance. Under certain conditions this can result in a reduction of excitation and a consequent reduction in stability margin.

This is not as remote a possibility as might first be assumed, for it is rather common for a generator or a plant to be connected into a large system by two or three lines with machine and external impedances, as in the Meramec case, to the typical values used by the authors in their work. It is not suggested that this particular detrimental effect of the regulator is of sufficient importance to be comparable to the many advantages of automatic voltage regulation, but it is believed to be of general interest and possibly worthy of mention and perhaps further investigation.

H. C. Anderson (General Electric Company, Schenectady, N. Y.): The authors are to be congratulated on a paper that explains, in

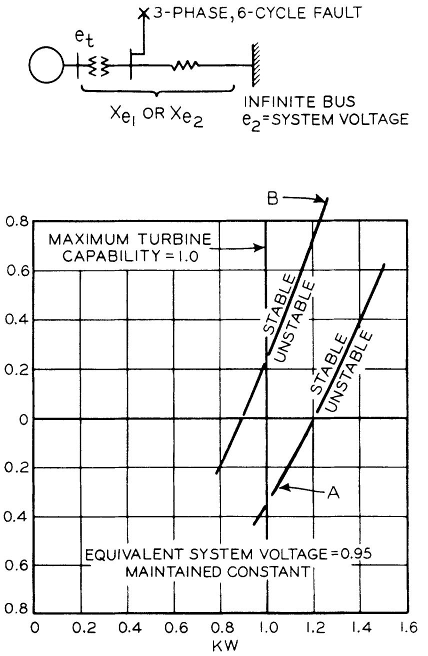

Fig. 9. Transient stability limits for (A) 0.20/0.40 system and (B) 0.40/0.60 system

simple terms, the factors which affect the lower limit on field current.

In their paper a statement concerning the transient stability limit is made. "It is reasonable to conclude, therefore, that in most practical cases transient stability will not become a barrier to successful underexcited operation, if it has not previously been an obstacle while operating in the overexcited region." This statement is correct if the day-to-day generator voltage is not allowed to vary appreciably. In other words, if the reactive output of a given plant is decreased by raising system voltage, as opposed to lowering generator terminal voltage, the transient stability margin is not reduced.

However, in the day-to-day operation of a given plant, generator reactive output is usually varied considerably to meet system requirements. If system voltage is held nearly constant, and generator voltage is lowered to produce a reduction in reactive output, there will be an appreciable decrease in transient stability limit. It is the purpose of this discussion to show how reactive output, and hence field excitation (with system voltage constant), affects the transient stability limit.

In a so-called "low-reactance" system, such as the examples Mr. Farnham and Mr. Swarthout have used, where reactance external to the generator does not exceed 40 per cent (with maximum turbine capability as a kilovolt-ampere base), the generator may be operated over its entire capability range without fear of its becoming unstable. There are other factors, as pointed out in the paper, which will limit its range of operation. However, if the same generator is operated on a higher reactance system, say 50 per cent to 60 per cent, it is safe to assume that transient stability will be a factor determining part of its operating range.

Fig. 9 shows operating limits of a generator when it is connected to either of two different systems. The equivalent system voltage in both cases is that corresponding to initial operation of the generator at maximum turbine capability with unit terminal voltage at 0.95 power factor overexcited. In both systems (0.20 initial reactance and 0.40 initial reactance) the equivalent system voltage is 0.95.

Curve *A* in Fig. 9 is the limit of operation, based on transient stability considerations, of a generator when it is connected to a system whose reactance is 20 per cent initially and 40 per cent after a line or other facility is switched out on the occurrence of a 3-phase fault, 6 cycles in duration. Note that the limit of stable operation for this case is well outside the limits outlined in the paper.

Curve *B* is the limit of stable operation for the same generator operating on a system whose initial reactance is 40 per cent and whose reactance after switching out a line or other facility is 60 per cent. Note that in both cases the transient power limit decreases quite rapidly as the kilovar output is decreased by lowering the field excitation, when system voltage is held constant. However, in the low-reactance system, the decrease in power limit is of no consequence since maximum turbine capability limits the amount of power which can be transmitted.

In the higher reactance system, curve *B*, operation of the generator is somewhat restricted, as long as system voltage is not allowed to increase. The generator may be operated at maximum turbine capability in the overexcited region at power factors up to about 98 per cent (corresponding to about 20 per cent kilovar output) without fear of transient instability. If it becomes necessary to operate at still lower values of kilovar output, the power must be reduced as the kilovars are reduced until at unity power factor the machine may be operated at only about 90 per cent of its maximum turbine capability. If underexcited operation is necessary, the power must be reduced still further. The foregoing explanation applies when the equivalent system voltage is held constant.

If the system is called on to supply more of its own kilovar requirements, either by changing transformer taps or by actually raising system voltage, and generator voltage is maintained nearly constant, the stability margins are increased. As a matter of fact, if equivalent system reactance is truly high, on the order of 70 per cent to 80 per cent, the generator can supply very little kilovar to the system, if stable operation is to be maintained at maximum turbine capability.

S. B. Farnham and **R. W. Swarthout:** The authors are appreciative of the interest shown by all those who presented discussions, both written and oral.

Mr. Anderson has pointed out the reduction in system transient stability that results, at lower than normal voltage, when the external system reactance is abruptly increased. He has thus extended the scope of the paper, which is predicated on the condition of rated machine terminal voltage, except for Fig. 8 wherein is shown the typical variation in steady-state stability limit with changes in terminal voltage. To an operator faced with the practical necessity for maintaining lower than normal voltage levels, transient stability may indeed become a limiting factor, particularly if the reactance between the machine and the system can be substantially increased, as, for example, by the faulting and subsequent isolation of the shorter of two lines which normally connect the machine to the system.

Mr. Watson describes another manifestation of this 2-tie-line problem as it pertains to steady-state stability. Fig. 10 illustrates his statement: "An automatic voltage regulator would, by attempting to maintain a constant generator terminal voltage, decrease the stability limit of the machine." Here, generator terminal voltage is plotted as a function of the increase in system reactance when one of two parallel lines is opened. It is to be noted that, depending on the degree to which the machine is initially operating overexcited (generating kilovars), there is actually a rise in the voltage seen by a regulator at the machine terminals. Hence, the regulator necessarily acts in the direction to reduce the stability limit. However, each curve of Fig. 10 is terminated at the value of react-

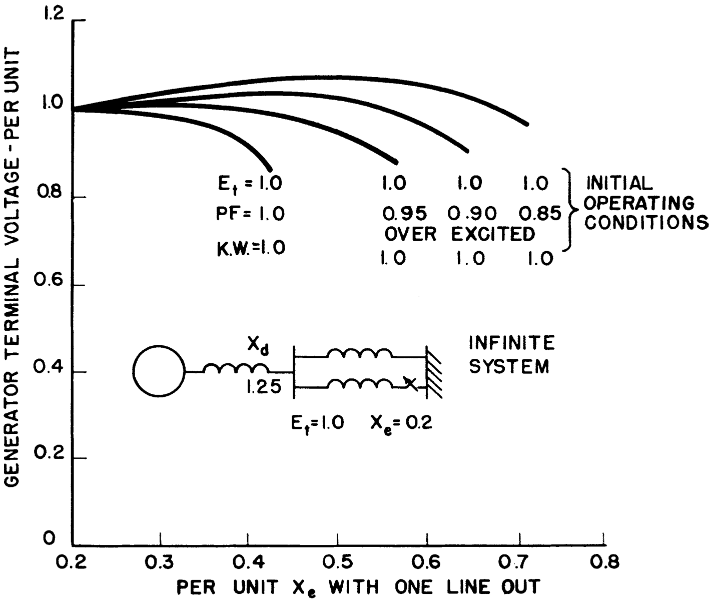

Fig. 10. Generator terminal voltage as system reactance is increased to steady-state stability limit, maintaining constant field excitation

ance representing the stability limit for its assumed initial operating conditions; and it is to be noted that in all cases the terminal voltage has fallen below normal before this point is reached. Hence, it can be concluded that, while the regulator may act in the direction to impair stability in those regions where stability is not a problem, nevertheless it does come into play in the desirable direction before a critical stability situation is reached.

In response to the questions raised by Mr. Watson, it is the usual objective of a balanced machine design to have all parts of that machine meet their thermal requirements at name-plate rating. In this way, the most economical design is achieved. In the case of modern machines, it is a reasonable assumption that the designer has sufficient knowledge to accomplish this objective. With an extremely old machine, however, particularly if it has been rebuilt and rerated, it is possible that the field and armature windings may not both attain the same temperature rise at name-plate rating, and specific knowledge of the particular machine may therefore be desirable if precise operating limits are to be drawn. The published percentage increases in ratings of modern hydrogen-cooled machines permit the same relative increases in loading of both field and armature, again on the premise that the designer has the knowledge to make equally effective application of the cooling medium to both the field and armature windings.

The statement in the paper to the effect that test data, operating experience, etc., provide the only means for determining the operating capabilities in the underexcited region applies only to machines built prior to the mid-1920's. For more modern machines, the limits are definitely set forth in the paper. Hence, it appears that the alleged limitation to the usefulness of the generalized capability data as outlined in the paper would pertain to only a relatively few of the less important machines remaining in service today.

Mr. Brownlee's dissent with the expression "negative kilovars" is well worthy of note. There is only one kind of kilovar. While, for purpose of recording data or indicating direction on co-ordinate diagrams (as in Figs. 1, 2, 4, and 6) the terms "positive" and "negative" or their counterpart plus and minus signs are very convenient, and are widely used, such use must be understood to pertain to direction of flow only. It must not be permitted to lead to a concept that there are two kinds of kilovars, any more than there are two kinds of kilowatts.

Experience and Reliability of Carrier-Relaying Channels

AIEE COMMITTEE REPORT

THE USE of power-line carrier as a pilot channel for high-speed relaying is an accepted practice for transmission-line protection. However, there has been a lack of concrete information on the performance and reliability of carrier-relaying channels. In addition, there is considerable variation among power companies as to the testing and maintenance of the various components of a carrier installation. Recognizing these conditions, the AIEE Carrier Committee several years ago established a project subcommittee to obtain data on the experience and reliability of carrier-relaying channels.

A detailed questionnaire was drawn up to obtain information which would serve two purposes: first, to help users of carrier-relaying equipment in determining reasonable maintenance intervals and procedure; and second, to guide manufacturers in producing more trouble-free equipment. The tabulated results of the questionnaires will also be of benefit to the user of carrier relaying in indicating what degree of reliability he can expect from his equipment.

With these objectives in mind, the following questionnaire on carrier relaying was sent out. It is made up of two parts. Part I covers circuit information and performance data, and each question requires one answer per line section protected by carrier relaying. Part II covers maintenance on the carrier components, and the questions in this part require only one answer from each power company.

Summary of Questionnaire

PART I—CIRCUIT INFORMATION AND PERFORMANCE DATA

1. Length of circuit in miles?
2. Nominal line voltage rating in kilovolts?
3. Number of carrier-relaying terminals on this line?
4. Carrier frequency or frequencies?
5. A. Transmitter output watts for relaying?
   B. Transmitter output watts for voice or telemetering?
6. A. Nominal operating range of relaying transmitter-receiver in decibels?
   B. Nominal operating range of voice transmitter-receiver in decibels?
7. Type of relaying system (directional or phase comparison, transfer trip)?
8. Is this relay carrier channel used for other services?
9. What other carrier channels are on this circuit?
10. Years of service of the carrier-relaying channel?
11. Total outage time of carrier relay channel for routine maintenance?
12. Total outage time of carrier relay channel from terminal equipment defects?
13. Number of outages of carrier relay channel caused by carrier equipment defects?
14. Number of outages of carrier relay channel caused by relaying equipment defects?
15. Number of correct operations?
16. Number of incorrect operations?

PART II—MAINTENANCE

17. How often is the carrier transmission tested? A. Manual. B. Automatic.
18. Is a reserve signed test (or sleet test) made, and if so, at what intervals?
19. What is the inspection schedule on relays? Describe routine very briefly. A. Inspection. B. Calibration and operation check.
20. What is the inspection schedule on the carrier equipment? Describe briefly. A. Transmitter-receiver. B. Coupling capacitor and potential device. C. Line trap.
21. How often are the vacuum tubes checked?
22. What tests are made to determine that a tube has reached the end of its useful life?
23. What are the reasons for removing tubes from service? State results in percentage.
24. What is the average tube life? List by types.

Paper 53-377, recommended by the AIEE Carrier Current Committee and approved by the AIEE Committee on Technical Operations for presentation at the AIEE Fall General Meeting, Kansas City, Mo., November 2–6, 1953. Manuscript submitted March 13, 1953; made available for printing July 29, 1953.

The personnel of the Project Subcommittee are: H. W. Lensner, *Chairman;* T. A. Cramer, G. M. Babcock, J. R. Curtin, W. J. Googe, V. J. Hayes, L. E. Ludekens, M. Warren, J. Youngblood, O. A. Starcke, and B. W. Storer.

The committee wishes to express their appreciation of the co-operation given by the contributing power companies for the data in this report.