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DESIGN DATA SHEET
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NAVAL SHIP ENGINEERING CENTER

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DDS311-2
VOLTAGE REGULATION OF A. C. SHIP SERVICE ELECTRIC POWER SYSTEMS

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1. Scope

The operation and performance of all electric apparatus are affected to some degree by variations of the applied voltage regardless of whether these variations are of a steady-state or transient nature. Increased use of electronic equipment, modern missile systems, fire control systems, and power control systems on naval ships has made it necessary to place particular emphasis on the transient voltage conditions which may occur in a.c. power systems. In addition, in 3-phase systems, unbalance of phase voltages due to unbalanced loads may produce excessive heating of connected induction motors.

Variations in the supply voltage may:

(1) Result in no noticeable effect on equipment if variations are reasonable.

(2) Cause equipment performance to be inadequate. This condition may arise because the power source variations were not factored into the equipment or system design or because the performance required could not be obtained with the existing power supply variation.

(3) In extreme cases, cause damage to equipment, if the variations are severe and were not factored into the design.

To control the voltage regulation of a power system effectively it is essential, first, to determine the effect of abnormal applied voltages on the operation of the apparatus; second, to establish the permissible voltage limits; and third, to analyze each of the factors that contribute to voltage changes and their relative importance. The last is particularly important and involves consideration of the cable voltage drops, motor starting currents or other fluctuating loads, and the characteristics of the generating plant and its excitation system. Accordingly, data is presented herein whereby the system voltage limits can be established together with data on the influence and relative importance of each of the factors affecting the system voltage regulation and the methods of calculating the regulation under both transient and steady state conditions.

2. Effect of system voltage regulation on the operation of electric auxiliaries

Lighting

As shown by figure 1, the light output and life of incandescent lamps are greatly affected by the steady-state applied voltage. Under steady-state conditions, it is therefore desirable that the lamp voltage be maintained within definite limits if satisfactory life combined with light output is to be obtained. Because there is little, if any, thermal inertia in the lamps, transient voltage disturbances will produce changes in the light output to the same degree as that obtained for variations in the steady-state voltage. The resulting flicker may prove detrimental to the efficient performance of duties by ship personnel. Perception of flicker is dependent on the magnitude and frequency of the voltage transient as indicated in figure 2. Because of the relatively small magnitudes of the voltage changes which will produce perceptible flicker even at frequencies of one or less per second, it is not possible from an economic standpoint to maintain the system voltage transients within the limits required for eliminating lamp flicker.

Because fluorescent lamps are not connected directly to an electric power line, but are connected to a ballast, there is no specific voltage associated with any fluorescent lamp. A ballast, however, does connect to the electric power line during operation and it therefore carries specific voltage range rating.

Therefore, with fluorescent lamps the voltage at the fixture should be kept well within the normal operating voltage range for the ballast. Low voltage, as well as high voltage, reduces efficiency and shortens life. This is in contrast with filament lamps where low voltage reduces efficiency but prolongs life. Low voltage on fluorescent lamps may also cause instability in the arc and starting difficulty. On voltages above the specified range, the operating current becomes excessive and may not only overheat the ballast but cause premature end-blackening and early lamp failure. Voltages below the specified range may lower the preheat current to a point where the electrodes fail to emit their proper quota of electrons. Such a condition may cause the lamps to flash on and off without starting. If the lamps do start, the emission material may waste away too rapidly, with consequent shortening of lamp life. For best performance, the line voltage should not vary more than plus or minus 10 percent.

Heating devices

The output of heating devices is proportional to the square of applied voltage. Consequently, operation of these devices at very near rated voltage under steady-state conditions is desirable in order to obtain rated output. Transient voltage changes will have negligible effect on such devices.

Electromagnetic devices

An electromagnet of the type commonly used as a voltage relay for providing low voltage protection of motors or for operation of automatic bus transfer equipment is shown schematically in figure 3. It can be shown [1*] that the armature pull of this device is given by the equation

$$F = \frac{B_a{}^2 A_a}{72}$$

where:

F = armature pull in pounds
B_a = flux density in air gap (kilomaxwells per square inch)
A_a = area of air gap in square inches.

When an a.c. voltage is applied to the electromagnet, the following relations exist between the applied voltage and the flux:[5]

$$N\frac{d\varphi}{dt} + Ri = Em \sin (\omega t + \lambda)$$

Neglecting Ri drop and assuming that $\lambda = 0$

$$N \frac{d\varphi}{dt} = E_m \sin \omega t$$

Integrating

$$\varphi = \frac{-E_m}{\omega N} \cos \omega t + C$$

Assuming that $\varphi = 0$ at $t = 0$

$$C = \frac{E_m}{\omega N}$$

Then $\varphi = \frac{E_m}{\omega N} (1 - \cos \omega t)$

or $\varphi = \varphi$ max. $(1 - \cos \omega t)$

where φ max. $= \frac{E_m}{\omega N}$

and

t = time in seconds
λ = the angular displacement between the point where the applied voltage goes through zero and the instant when the electromagnet is energized.
E_m = peak value of voltage = $\sqrt{2}$ Erms
f = frequency of applied voltage in Hz

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*Superscripts indicate number of reference in the list of references at the end of the text.

N = Number of turns in coil
φ = total flux linking coil at time t
φ max. = Maximum value of flux under steady state conditions
$\omega = 2\pi f$
C = Constant of integration, evaluated in terms of the residual magnetism.

These relations show that the total flux (φ) is proportional to the voltage and independent of the air gap. For a fixed air gap, B_a is a fixed fraction of the total flux, and the force is, therefore, proportional to the square of the total flux, hence, to the square of the voltage. However, when the air gap is increased, B_a becomes a smaller fraction of the total flux because of increased leakage flux. Consequently, the force will decrease when the air gap is increased while the voltage and total flux remain constant. The change in the force as a function of the air gap depends on the type of magnet and the length of the stroke. For short-stroke magnets the change in force with the air gap is relatively small whereas for long-stroke magnets greater changes in leakage flux and force take place over the working range. Clapper type magnets commonly used as relays have a short stroke and the armature pull is as shown in figure 4. Solenoid or plunger type electromagnets used directly for operation of large contactors have a relatively long stroke with a characteristic as shown in figure 5.

Referring to figure 5 and superimposing the spring pull characteristic, it is evident that there is a definite relationship between the pickup and drop-out voltage values for electromagnets which is dependent on the armature pull characteristic, the spring constant, and the ratio of the lengths of air gap in the open and closed position. In general, it is found that the drop-out voltage is not more than 85 percent of the pick-up voltage, as illustrated in figure 5.

Under a transient voltage change wherein the voltage momentarily falls below the relay drop-out value, the lack of inertia in the system causes an almost instantaneous increase in the air gap. Subsequent return of the voltage above the drop-out point does not therefore prevent opening of the relay unless the voltage rises to the pick-up value within 3 or 4 Hz (on a 60 Hz base).

From the above discussion it may be concluded that to prevent false operation of electromagnetic devices under transient voltage conditions, the voltage must not be allowed to dip below the drop-out value of the device, or that a suitable time delay dependent on the voltage recovery characteristic of the system should be provided in the drop-out of the device. Moreover, steady-state operation at below normal voltage is likely to cause increased chattering of a.c. magnets resulting in greater noise and maintenance.

Motors

The vast majority of motors on naval ships having an a.c. ship service power system are induction motors and the discussion herein will therefore be restricted to this type. In analyzing the effect of system voltage regulation on the operation of induction motors consideration must be given not only to the transient and steady-state voltage regulation under balanced three-phase conditions, but also to unbalanced applied voltages caused by single phase loads on the power system.

Figure 6 shows the operation of a fully loaded induction motor under balanced applied voltages above and below the normal value. Although every motor characteristic is affected to some degree, the torque and temperature rise changes are the most significant from the standpoint of electric system design. The torque varies directly as the square of the applied voltage, and the temperature rise varies inversely with the voltage to a degree dependent on the ratio of copper to iron losses in the particular motor. In general, the increased temperature rise does not become excessive unless the voltage is considerably below the normal value (10 percent or more).

Typical speed-torque curves of an induction motor at rated and reduced voltages are shown in figure 7. The reduction in motor torque caused by low values of applied voltage is a particularly important consideration under starting conditions and also in cases where the load on the motor fluctuates such as occurs in intermittent duty applications. Thus, the use of reduced voltage starting equipment, excessive voltage drop in the circuit to the motor, or both, may reduce the starting torque below the value necessary to accelerate the load and will, in any case, prolong the starting time. The normal starting times of induction motors, at rated voltage, when driving the fan, pump, and compressor loads of the type usually found on shipboard, are approximately 1 to 2 seconds. With reduced voltage starting this time may be increased to 10 seconds or more.

Because of the relatively low inertias of the average motor and load combinations encountered on shipboard, transient voltage dips may result in a sufficient reduction in torque to cause stalling of the motor. This is particularly true on motors operating on intermittent duty cycles wherein wide fluctuations in load torque usually occur. For this reason, a suitable margin must be provided in the maximum torque of the motor, with respect to the maximum load torque, to permit satisfactory operation at reduced values of voltage under transient as well as steady-state conditions. Conversely, the system voltage regulation must be such as not to require this margin to become excessively large. Normally, the maximum motor torque is at least 200 percent of rated torque and, therefore, the applied voltage should in no case be less than 70 percent of normal.

As explained in a later paragraph of this section, large single-phase loads on the power system will produce an unbalance in the three-phase voltages which may be resolved by the method of symmetrical components[2] into a set of balanced positive sequence and negative sequence voltages. (No zero sequence voltages can exist in a 3-phase, 3-wire ungrounded system.) Positive sequence voltage applied to an induction motor produces torque in the normal direction of rotation just as occurs under the normal balanced applied voltage conditions. Negative sequence voltage, on the other hand, produces torque tending to rotate the motor in the opposite direction. Thus, unbalanced applied voltages produce a reduction in the resultant motor torque. The amount of this reduction depends on the relative magnitudes of the positive and negative sequence voltages, that is, the degree of voltage unbalance, and the slip of the rotor. At standstill the torque reduction is greatest and is directly proportional to the square of the ratio of negative to positive sequence voltage. The voltage unbalance, that is, the difference between the maximum- and minimum-phase voltages, expressed in percent of rated voltage, on ship service power systems seldom, if ever, exceeds 3 percent, which corresponds to a negative sequence voltage not exceeding 2 percent of the positive sequence voltage. This corresponds to a torque reduction of less than 1 percent, which is negligible.

The most serious effect on the performance of an induction motor, produced by an unbalance in the applied voltage, is the large unbalance in the phase currents for a comparatively small unbalance in voltage. As a consequence, large increases in local heating can occur in one phase of a fully loaded induction motor under unbalanced supply voltage. The extent of the additional heating is shown in figure 8 wherein it is evident that even a small voltage unbalance of 5 percent may produce as much as 10 to 15 percent increase in temperature rise in one phase of the stator.

Electronic, weapon, and servicing systems

Radar, sonar, and electronic devices.

Electronic equipments, such as radar and sonar, are inherently sensitive to changes in the power supply voltage. For example, the operation of radar equipment requires observation of an image on a cathode ray tube screen. The position of the image is determined by the instantaneous values of the voltages applied to the elements of the tube and, due to lack of electrical and mechanical inertia, the image follows the voltage even during extremely rapid changes. Because of these effects and the high degree of concentration required for operation of the equipment, voltage transients which have no effect on other equipment may seriously impair operation of radar, sonar, and other electronic and weapons system loads.

Nominal variations in the steady-state applied voltage of 5 percent are permissible on conventional electronic equipment since their effect may either be negligible, because of their steady character, or may be corrected by adjustments in the apparatus.

Malfunctioning of electronics equipment which could be attributed to the power supply performance has been infrequent. This is probably explained by the fact that the power supply performance is specified in Mil. Spec. MIL-E-16400 and the manufacturer of the electronic equipment is aware of what he can expect of the power supply.

Momentary impairment of operation during the transient is permissible but the transient shall not cause failure of any part or prevent resumption of normal operation or require the equipment to recycle when the transient has ceased. Necessary correction in most cases is then included in the design of the equipment.

In a few cases some trouble has been experienced with harmonics. The first of recent difficulties was with a doppler radar which gives erroneous signals from any extraneous noise. A 23rd harmonic existed in the power supply and the radar locked on this frequency regardless of the speed of the aircraft. This was corrected by filtering. As a result of this incident, measurements were made on representative ships. Some of the results are shown in Table I. In still another case the same harmonic caused noise in certain electronic equipment on CVA38. This was also corrected by filtering.

3. Steady state system voltage regulation

The voltage regulation of ship service a.c. power systems is determined by the characteristics of the generating plant and the voltage drop in the feeder circuits. Control of these two factors is therefore both sufficient for, and necessary to, the effective regulation of the system voltage. Under balanced steady-state load conditions, the system voltage regulation is actually governed primarily by the voltage drop in the feeder circuits, since the generators are equipped with automatic voltage regulators, which maintain the switchboard bus voltage substantially constant. However, unbalanced load conditions and the requirements for reactive load division during parallel operation cause deviations in the normal bus voltage. For these reasons it is desirable to review briefly the factors influencing the steady-state voltage regulation of a.c. generator, and the operating characteristics of the different types of automatic voltage regulators.

Steady-state voltage regulation of a.c. generators—balanced load conditions

The conventional simplified vector diagram of an a.c. generator operating under balanced steady load conditions is shown in figure 9. The vectors e_t and i represent the terminal voltage to neutral and the armature current, respectively. Upon adding the armature resistance drop (ir) and armature leakage reactance drop (ix_ℓ) to e_t, the vector e_ℓ is obtained, which represents the voltage developed by the air gap flux (φ) which leads e_ℓ by 90 electrical degrees. This flux represents the net flux in the air gap. To produce this flux, an mmf proportional to I_t is required. The armature current produces an mmf by armature reaction, which is in time phase with it, and in terms of the field current can be expressed by Ai. Hence, to produce the net mmf represented by I_t the field current must be of such magnitude and the field structure must adjust itself to such position as to equal I_f. I_f and Ai added vectorially equal I_t. Neglecting saturation, OB, designated as e_i, is the open circuit voltage corresponding to the field current (I_f). It is the voltage taken from the air gap line of the no load saturation curve given in figure 10 for the abscissa corresponding to I_f. By combining the voltage drop AB, which is equivalent to armature reaction, with the armature leakage reactance drop (ix_ℓ), a single equivalent reactance drop (ix_d), called the synchronous reactance drop is obtained. The synchronous reactance (x_d) is therefore a reactance, which, when multiplied by the armature current and added vectorially to the terminal voltage, gives the internal voltage (e_i). Thus, referring to figure 11, which is the vector diagram of the generator under zero power factor load conditions, it is evident that, neglecting saturation, the terminal voltage of the generator, for any zero power factor load, can be obtained by subtracting the synchronous reactance drop directly from the air gap voltage corresponding to the value of field current.

TABLE I

TYPICAL DATA ON THE HARMONIC CONTENT OF THE VOLTAGE WAVES

	Magnitude in Percent				
Harmonic	DE765	DDR882	DE679	CVL48	CVA14
1	96.2	99.5	99.6	98.3	100
2		3.76			
3	1.48	1.62			
4		2.02			
5	3.72	1.27	2.65	1.5	1.59
7	1.33	1.37	1.97	2.75	1.7
11	1.38	0.96	1.15	0.98	
13	1.24		1.11	1.09	
17	1.69		1.79	0.87	
19	2.84		2.3		
23	24.1 *				0.881
25	8.13*				0.884
29	1.99	*	*		
31		1.94*	3.7*		
35				*	
37			0.97	10.4*	0.872*
41		1.07			
47	1.79				
49	1.83				
59		1.91	2.36		
61		2.04			

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* Slot frequencies of generator.

Notes—a) Where values are not given, they were insignificant.

b) From Fourier analysis the rms or effective value of the voltage wave equals the square root of the sum of the squares of the rms value of the individual harmonics.

It will be noted that all of the above discussion has been based on no saturation. In an actual generator, considerable saturation occurs as illustrated in the no-load saturation curve of figure 10. The effect of saturation is to cause the synchronous reactance to vary with the amount of field current and armature current, decreasing with the former and increasing with the latter. Taking into account the effect of saturation, the steady-state operating characteristics of an a.c. generator can be represented by the saturation curves of figure 10. These illustrate the changes in field current necessary to maintain normal voltage under various steady-state load conditions.

While a corrected value of synchronous reactance, taking into account the actual saturation existing in the generator for the particular operating condition, is necessary in making most calculations, the unsaturated value is a fundamental constant of the generator which is of considerable value in predicting its performance. The unsaturated synchronous reactance (X_d) can be obtained most conveniently from test data giving the no-load saturation curve and the full load zero power factor curve. In figure 10, the field current OA is the amount necessary to circulate full load current under short circuit conditions, the terminal voltage being zero. In this case, all of the internal voltage must be consumed as synchronous reactance drop in the machine. The unsaturated synchronous reactance in ohms can, therefore, be found by dividing the air gap line-to-neutral voltage AB, corresponding to the field current OA, by the rated current of the generator, the current flowing at field current OA. In the per unit system, the unsaturated synchronous reactance equals the voltage AB, divided by the current flowing at field current OA divided by rated current. Since the currents are equal in this case, they cancel and the unsaturated synchronous reactance equals the voltage AB divided by rated voltage.

From the above discussion it is apparent that the no load to full load regulation of a.c. generators is inherently very large (usually about 40 percent), and because of this an automatic voltage regulator is essential for satisfactory operation. There are three basic types of automatic generator voltage regulators available for use on a. c. generators:

(a) Direct-acting rheostatic type. —This type consists of a variable resistor acted on directly by the control element of the regulator. The variable resistor is usually located in the exciter field.

(b) Rotary amplifier type. —This type consists of a specially designed exciter having a number of control fields with a high ratio of amplification excited from a static control element which in turn is energized from the a.c. generator output voltage.

(c) Static type—Because of the different components used to control the exciter current, and the speed of regulation, this type is further subdivided into two types. Both types use only completely static components such as resistors, capacitors, reactors, transistors, magnetic amplifiers, and rectifiers.

The first type, for purposes of this DDS shall be called the Static SCPT type, uses a saturable current potential transformer (SCPT) to provide excitation power. A static voltage regulator senses generator voltage deviations and controls the excitation power by varying the control current, and hence the saturation point, in the SCPT's.

The second type, for purposes of this DDS shall be called the Static SCR type, derives excitation power from a current potential transformer (CPT) and controls this power with shunt silicon controlled rectifiers (SCR's). The static voltage regulator senses generator voltage deviations and modifies the firing signals to the SCR's to maintain rated line voltage.

Insofar as their ability to maintain constant voltage under steady-state or gradually changing load conditions is concerned, each of the above-mentioned types of regulators gives substantially identical performance with the single exception that the rotary amplifier type is somewhat sensitive to frequency errors.

The static SCR type gives performance superior to that of the other type systems in regard to maximum voltage dip and recovery time following a sudden change in operating conditions. Likewise, the rotary amplifier and the static SCPT types give performance superior to that of the direct acting type. Figure 21 shows the comparative performance of the first two types, while Figure 17B shows the comparative performance of the two type static regulators.

Also shown in figure 21 is the performance of the indirect acting type which is no longer used, but may be found on a number of older generator sets.

The static SCR type has very fast response and begins to control the voltage while the generator is still in the subtransient period, while the other types have longer time delay and begin to control the generator field excitation in the transient period.

In addition to the differences in electrical performance of the above-mentioned regulators, there are a number of other differences which also require consideration relative to their suitability for use on shipboard, such as, space, weight, reliability, and maintenance.

In general, both static type regulators afford a number of advantages over the other regulator types. These include reduced maintenance, improved reliability, and improved performance.

In the parallel operation of a. c. generators the division of real power load between the machines is determined solely by the governor settings. On the other hand, the reactive load division is determined by not only the relative excitation voltages and reactances of the machines, but also the division of real power. Thus, for fixed excitation on each machine, the reactive load taken by any one machine will decrease as the real power load on that machine increases. However, changing the excitation of one of several a. c. generators operating in parallel will change only the division of reactive load; it will not change the real power load division.

From the above, it is immediately evident that two quantities must be controlled in order to achieve satisfactory parallel operation of a. c. generators, namely, the governor settings and the excitation.

There are several methods of controlling the excitation of a. c. generators so as to insure the proper division of reactive load when operating in parallel. On ship service a. c. generators, the preferable method is to provide a droop in the voltage of each generator with increase in reactive load. This eliminates the need for any cross connections between the various generators making each one a self-contained unit. The voltage droop is obtained by a reactive load compensator, which inserts a voltage proportional to the reactive load current in series with the line voltage applied to the to the control element of the regulator causing the latter to decrease excitation with increase in reactive load.

There are two major factors which determine the ability of the voltage regulator to maintain proper division of reactive load in the manner described above. These are the amount of droop and the sensitivity of each regulator. The sensitivity of a voltage regulator is defined as the minimum voltage change which will cause the regulator to respond and initiate a change in the excitation of the generator. The action of the various types of regulators is somewhat different, but the general relationship between the width of the sensitivity band and the amount of voltage droop in effecting generator excitation, and consequently the reactive load division is applicable for all types. Figure 12 shows this relationship for the indirect acting type regulator.

It is evident that reactive load compensation by means of voltage droop as described above results in variations of the switchboard bus voltage with changes in reactive load. The usual values of compensation used are such as to produce a 4 percent drop in generator voltage when the load varies from no load to full load at rated power factor. Load changes of this magnitude seldom occur and in any event the switchboard operator usually readjusts the voltage to normal under all steady-state load conditions.

Steady-state voltage regulation of a.c. generators—Unbalanced load condition

Lighting, arc furnace, interior communication, radio, radar, fire control systems, and similar loads may produce an unbalance in the loads on the three phases of a.c. ship service generators. The effects of such load unbalances on the voltage regulation of the generator may be most readily analyzed by the methods of symmetrical components.[2] Thus, it can be shown that unbalanced phase currents in a generator will produce an unbalance in the terminal voltages which can in turn be resolved into a set of balanced positive and negative sequence voltage components. The positive sequence component of the terminal voltage is determined by the excitation and the synchronous reactance of the generator and the load magnitude, in the same manner as the terminal voltage under balanced load conditions. The negative sequence voltage is determined solely by the negative sequence impedance of the generator and the magnitude of the load unbalance. Under balanced load the negative sequence voltage is zero and the positive sequence voltage equals the terminal voltage.

The negative sequence voltage is related to the unbalanced single phase load current and the generator negative sequence impedance by the following expression:

$$E_2 = \frac{I_1}{\sqrt{3}} Z_2 X100$$

where,

E_2 = negative sequence voltage in percent
I_1 = single phase load current in per unit
Z_2 = negative sequence impedance of generator in per unit.

The voltage unbalance depends upon not only the magnitude but also the phase angle of the negative sequence voltage, and the latter is determined by the phase angle of the single-phase load current. However, for a given magnitude of negative sequence voltage the voltage unbalance will not exceed a certain maximum value regardless of the phase angle of the single-phase load current. Figure 13 shows the maximum voltage unbalance, that is, the maximum difference between the phase voltages expressed in percent of normal voltage as a function of the negative sequence voltage in percent. To illustrate the application of the above formula and figure 13, assume that the unbalanced single phase load current is 15 percent of the generator rated current, and the negative sequence impedance is 0.30 per unit, then, the negative sequence voltage will be 2.6 percent, and from figure 13 the maximum voltage unbalance is 4.5 percent. Where close voltage unbalance limits are specified, such as 1 percent for type III ship service power (refer to Mil. Std. MIL-STD-1399, Sect. 103), figure 13A should be used to determine the maximum load (KVA) unbalance.

NOTE: In figure 13A, X_2 is the negative sequence reactance. This value can be used in the above equation for Z_2, thus neglecting R_2.

Induction motors connected to the generator bus from which the unbalanced load is supplied act as phase balancers by providing an additional path for the flow of the negative sequence component of the unbalanced load current. This is equivalent to reducing the value of the negative sequence impedance of the generator and thereby the negative sequence component of the terminal voltage. However, unless the induction motor load is relatively large with respect to the generator, its effect will not be significant in reducing the voltage unbalance.

It is evident from the above discussion that with unbalanced loads the resulting unbalance of the phase voltages of an a.c. generator is due entirely to the negative sequence impedance of the generator and the magnitude of the negative sequence current, and is, therefore, entirely independent of the action of the voltage regulator. The latter controls only the excitation and thereby the value of the positive sequence voltage, which establishes the average voltage level, but not the unbalance. To limit the voltage unbalance, it is necessary to control the negative sequence voltage.

The degree to which the voltage regulator affects the voltage level under unbalanced load conditions depends on what voltage or voltages are applied to the regulator control element and the type and amount of reactive load compensation. If the control element is responsive to the 3-phase voltages, such as is the case for a torque motor or a solenoid energized by a 3-phase rectifier, the regulator will maintain the average value of the three phase voltages at a value differing from normal voltage only by the amount of droop compensation. Moreover, it may be shown that the average value of the 3-phase voltages is approximately equal to the positive sequence voltage, if the magnitude of the unbalance, or negative sequence voltage, is relatively small. Figure 14 shows a typical single-phase regulator connection wherein the control element is energized by the line voltage of one phase and droop compensation from another phase. The regulator does not affect the voltage unbalance, but by changing the value of positive sequence voltage it changes the voltage level maintained at the switchboard bus.

A summary of the effects of different types of voltage regulators on the terminal voltage of an a.c. generator under unbalanced loads is given in figures 15 and 16. It is evident from the figures that for small values of single-phase load current, up to 20 percent of the generator rating, there is a negligible difference between the performance of single-phase and three-phase regulators in maintaining the average value of the terminal voltage. Under sustained short circuit conditions with a fault on the unregulated phase, it will be noted from figure 16 that the single-phase regulator will not produce as high a current as the three-phase regulator, regardless of whether or not droop compensation is present. However, without droop the sustained single-phase fault current and the latter is actually the determining factor in providing fault protection. In any event, by using a saturating current transformer, with the compensator, the influence of the droop can be effectively eliminated under short circuit conditions.

From the foregoing discussion, it is evident that to reduce the system voltage unbalance, due to unbalanced loads, it is necessary to reduce either the magnitude of the unbalanced load or to reduce the negative sequence impedance of the generator. Unfortunately the latter is not independent of other generator constants, the most important of which is the subtransient reactance.[3] The generator subtransient reactance determines the system short circuit currents and in many cases must be kept as high as possible to reduce these currents to a minimum. A high value of subtransient reactance will result in a relatively high value of negative sequence reactance. Consequently, since in actual practice the unbalanced loads on ship service power systems are usually relatively small, it is generally desirable to require a high value of subtransient reactance, even though this also means some increase in the possible voltage unbalance.

Constants for typical naval generator sets were arrived at with due consideration of these factors.

In addition to producing a voltage unbalance, large unbalanced loads may also cause excessive heating of the generator from which supplied. Most of the additional heating will usually occur in the generator rotor, and where the unbalanced load is large, it is essential that the rotor (field structure) have damper windings to reduce the losses and consequent heating to a minimum. The negative sequence resistance is the generator constant which determines its ability to carry unbalanced loads without overheating, and from which the additional losses can be calculated. Measurements made on representative ships indicate that the voltage unbalance is well within values specified in Mil. Std. MIL-STD-1399, Sect. 103, for type I, II, & III ship service power.

Voltage regulation of cables

Because of the relatively short lengths of most of the cable runs on the ship service power system, current carrying capacity is usually the governing factor in the choice of cable sizes, particularly on 450-volt a.c. systems. However, voltage limits are necessary and calculations need to be made to ensure that the system will perform as specified. Also, where type II or III power is to be supplied, cable regulation is an important item and must be taken into consideration by remote sensing, by means of taps in the equipment transformers, if the load on the transformers is constant, or by the use of line voltage regulators.

System voltage regulation overall based on normal operating load conditions

Normally, Section 300 in applicable Ship Specifications, state that all electric power consuming equipment shall be selected to have one of the nominal voltage ratings and tolerances specified in Mil. Std. MIL-STD-1399, Sect. 103. The various tolerances specified therein were based on both the need for tolerance from an equipment viewpoint, and the ability to supply electric power having the tolerances specified.

Voltage drop limits and the voltage regulation as permitted in applicable ship specifications, and the equipment specifications, are based on maximum values for the design of components which comprise the power supply system. For type I power the value of plus or minus 5 percent at the load is arrived at for system operation by adjusting the maximum deviation voltage percentage values to arrive at the practical deviation based on actual operating conditions. For example, the maximum steady state voltage deviation permitted in the generator specifications is approximately 4 percent, due to load change from 0 to 100 percent, with a deviation of plus or minus 1 percent permitted for the voltage regulator under steady load conditions. Under actual operating conditions the load on the generator should not change more than 25 percent without the operator adjusting the voltage. Accordingly, the generator voltage deviation under actual operating conditions will be far below the maximum deviation allowed by the equipment specifications. Actual voltage drops in cable will also be far below the value normally specified in Section 304 of applicable Ship Specifications, normally, since current carrying capacity generally determines the cable size. Also, the actual voltage drop is below the calculated drop, since the calculations are based on maximum current and temperature conditions. Transformer regulation of 2 to 3 percent is based on full load; whereas, under actual operating conditions, the load will not vary over full range, or will be considerably below full load rating. Shipboard measurements have shown the voltages at the load to be within the plus or minus 5 percent steady state regulation specified.

The limitations given in Mil. Std. MIL-STD-1399, Sect. 103, for type I ship service electric power are suitable for almost all power consuming equipment. The characteristics given are those which exist under normal operating conditions. When emergency operating conditions prevail; that is, conditions due to major equipment failures or battle damage, the values indicated are not guaranteed. Adequate protection should be provided for equipment which is subject to damage because of the following during these emergency operating conditions:

a. When the performance of the power source goes outside the specified limitations.

b. When power is momentarily interrupted and restored during power transfer from normal to alternate or emergency supplies.

Types II and III power are established for supplying equipment needing more accurate voltage and frequency regulation, such as critical electronic equipment and missile system components.

The electrical characteristics itemized in Mil. Std. MIL-STD-1399, Sect. 103, will be supplied to a distribution point, that is, the input terminals of the power consuming equipment or system. In general, this point will be dependent on the load supplied and can be located at one of two places:

a. The input terminals of the consuming device. For example, at the illuminator for the AN/SPG-55A radar.

b. The input terminals of a system made up of many components located in several parts of the ship, but not at the input terminals of each component. Therefore, the characteristics listed for types I, II and III power may not be supplied to all loads. This will depend upon the extent of the distribution system controlled by those responsible for the utilization equipment. For example, at the IC switchboard bus which supplies the IC system.

Because of the close tolerances on types II and III power, loads supplied must be limited to those specific items which require such tolerances. All motors larger than 7-1/2 horsepower should be designed to operate on type I, 60 Hz power. In order to control voltage and frequency transient limits, large transient producing equipment, as well as switching of large loads, should be minimized for all three standard power supplies, and in particular for types II and III power. This must be handled on a case basis, but, where possible, type III power should not be specified to furnish large transient producing equipment. Steady state voltage and frequency tolerances can be more easily met if the load is held reasonably constant or at least varied over as narrow a range as possible. Preference, therefore, in the selection of standard power supplies should be given first, to type I, and then to types II and III as required.

The standards given in Mil. Std. MIL-STD-1399, Sect. 103, should be used in the development of new systems and components which require electric power. Use of types II and III power must be minimized if a practical shipboard installation is going to result. Performance requirements for types II and III power can be met only with the cooperation of those responsible for the utilization equipment. Therefore, in specific cases, after it is known that a given system or component will require types II and III power, NAVSHIPS and NAVSEC should be notified in order that adequate planning can be made during the design and construction period of the ship. Requests for types II and III power supplies should be fully justified, since they add to the size, weight, and cost of the ship. Included in the justification should be the estimated cost of acceptable alternatives, if any, which would permit the use of type I power. This information would aid in the support of the need for the special power supplies.

4. System voltage regulation under transient conditions.

Motor starting is the major source of transient voltage disturbances on ship service service a.c. power systems. The allowable voltage dips due to full voltage motor starting are normally specified in Section 302 of applicable Ship Specifications. The starting currents of induction or synchronous motors, when energized from rated voltage, are normally equal to 6-8 times the motor full load current, depending on the motor design, efficiency, and torque requirements. The power factor is approximately 0.35. Thus on shipboard, where many of the motors are relatively large, with respect to the generator rating, motor starting can impose large low power factor loads on the generating plant. The voltage disturbances that are produced thereby are more severe than those due to any other load changes on the system.

When a load is suddenly applied to an a.c. generator, a voltage drop occurs, the magnitude of which is determined by the following factors:

a. The magnitude and power factor of the applied load.

b. The characteristics of the generator.

c. The characteristics of the generator excitation system.

In order, therefore, to effectively control the system voltage regulation under transient loads it is necessary to analyze the influence and establish the relative importance of each of these factors.

Normally, Section 304 of applicable Ship Specifications, permits various voltage dips as a result of motor starting, depending upon the frequency at which the motor is expected to be started and stopped. Figures 17A and 17B represent typical (RMS) voltage transients such as those caused by induction motor starting initiated at the nominal voltage of the system. It should be noted that these are typical shapes for the transient showing the maximum permissible voltage dip, and many variations can occur. The minimum voltage reached in this case is the minimum value which will occur, except under emergency operating conditions. However, the time to reach the minimum value may vary from 0.01 to 0.3 seconds and recovery time may vary from 0.02 to 2.0 seconds, depending on the rating of the generator and type of excitation system employed. The maximum voltage indicated is the value normally occurring. However, in some cases, the maximum voltage can be as great as the negative voltage excursion. The total recovery time indicated is the maximum transient voltage recovery time, and, in most cases, voltage transients will recover in 1.2 seconds or less.

Generator characteristics

Figure 17 was plotted from typical oscillograms and shows the terminal voltage, line current, field current, and field voltage of an a.c. generator when a fixed impedance load is suddenly applied with the generator equipped with an automatic voltage regulator of the direct-acting type, operating in the exciter field. Study of the voltage curve shows that an instantaneous drop in voltage (a-b) occurs when the load is applied, followed by a period of voltage decay to a minimum value (point c) at which time the voltage regulator has changed the generator field current sufficiently to begin returning the voltage to normal. It is immediately evident from this figure that the magnitude of the initial voltage dip is entirely independent of the operation of the voltage regulator, and that the latter only influences the point to which the voltage decays.

Figure 17B shows results of a 2.0 per unit impedance load suddenly applied on a wound rotor generator. Curve A is the response obtained with the generator equipped with the static SCR type. It can be seen that the voltage recovery is extremely fast. Curve B is the response obtained with the static SCR type replaced with the static SCPT type. It is seen that the voltage is not corrected in the subtransient range (dotted line) but extends beyond this point, and is corrected in the transient range.

The transient phenomena associated with the starting of a relatively large motor from a small generator is very similar to that associated with a short circuit of the generator, and consequently may be handled in the same manner. Figure 18 shows a typical short circuit current vs. time curve of an a.c. generator, operating without a voltage regulator for a 3-phase short circuit from no load. As shown in the figure, the total current may be resolved into a steady-state, a transient, and a subtransient component. The factors which determine the magnitudes of each of these currents are the same as those which produce the drop in generator terminal voltage under motor starting conditions.

The steady-state short circuit current is the final sustained value. Due to the large demagnetizing effect of this current, the flux density in the generator is below the point where saturation is present. The steady-state current is therefore equal to the air gap voltage corresponding to the field current required to give rated voltage on the no load saturation curve, divided by the unsaturated synchronous reactance:

$$i_d = \frac{e_{\text{air gap}}}{X_d} \tag{1}$$

If the steady-state component is subtracted from the total current and the remainder plotted on semilog paper, figure 19, the straight line portion of the resultant curve gives the transient component of current. Extending the straight line back to zero time, and adding the steady state component, gives the initial value of the transient current which is defined through a reactance called the transient reactance by the expression,

$$i'_d = \frac{e_{\text{rated}}}{X'_d} \tag{2}$$

The nature of the transient reactance may be explained briefly as follows. Before the short circuit occurred, the flux associated with the field winding can be resolved into two parts as shown in figure 20, consisting of φ, the main flux crossing the air gap, and φ_ℓ, a leakage flux linking only the field winding. The total flux linkages with the field winding are then equal to $(\varphi + \varphi_\ell)$. Under any operating conditions these flux linkages cannot change instantly. Consequently, the demagnetizing effect of any sudden increase in armature current must be overcome by an increase in field current. If the field current increases, then φ_ℓ, which is proportional to it, must also increase and, in order for $(\varphi + \varphi_\ell)$ to remain unchanged, φ must decrease. Consideration of the steady-state operating conditions has shown that the air gap voltage (e_ℓ) is proportional to the air gap flux (φ). Hence, under the sudden short circuit, e_ℓ, which was initially equal to the terminal voltage, is decreased in proportion to the decrease in φ. The initial value of transient short circuit current is equal to e_ℓ divided by x_ℓ, the armature leakage reactance. Since e_ℓ has decreased as described above, the transient current is less than would be obtained by dividing the no-load open-circuit terminal voltage by the armature leakage reactance. However, by combining the decrease in air gap flux and voltage with the armature leakage reactance, a single reactance equal to the transient reactance is obtained, which, when divided into the rated voltage in accordance with equation (2), gives the initial short circuit current. The transient reactance is, therefore, slightly greater than the armature leakage reactance and includes the effect of the increased field leakage flux accompanying the increase in field current under short circuit conditions.

It is evident from the above discussion that the initial high values of armature short circuit current are sustained by the induced current in the field circuit. The latter current decays exponentially with a time constant known as the transient short circuit time constant T'_d, and, consequently, the air gap flux and armature current also decay with the same time constant in accordance with the expression,

$$(i'_d - i_d)e^{-t/T'_d}$$

The nature of the time constant T'_d may be readily seen by considering the case of the generator with the armature open circuited and the application of a direct current voltage to the field. Under this condition, the field current will build up at a rate determined by the ratio of field inductance to field resistance. The time constant associated with this rate of change of field current in this case is designated as the open circuit transient time constant (T'_{do}). Under sudden short circuit of the armature, the increase in field current associated therewith, decreases the effective inductance of the field circuit, since the flux remains constant and the field current increases. Hence, the time constant of the field circuit is decreased under short circuit conditions from the value obtained with the armature open circuited. The change in the time constant is proportional to the change in field current and is given by the expression,

$$T'_d = \frac{X'd}{Xd}\, T'_{do} \qquad (3)$$

In generators equipped with damper windings, or where other paths exist for eddy currents, the air gap flux at the first instant of short circuit is prevented from changing appreciably by the currents induced in the damper windings. For this reason the initial value of the total short circuit current is actually higher than that determined by dividing the terminal voltage by the transient reactance. This higher current is designated as the subtransient short circuit current, and is defined by the subtransient reactance in the expression,

$$i''_d = \frac{e_{rated}}{X''_d} \qquad (4)$$

Because of the relatively large ratio of the resistance to inductance of the damper windings or other paths in which the induced currents supporting the subtransient current flow, the latter component of the total current decays very rapidly (two to three cycles).

Since the operating time of the static SCR type is less than 3 Hz, the phenomena associated with the subtransient currents and reactances on the generator are considered, while with the slower acting type regulators, such as direct-acting rheostatic type, rotary amplifier type, and static SCPT type, the subtransient currents and reactances may be neglected in the voltage regulation problem and consideration need only be given to the transient reactance, synchronous reactance, and the time constants associated therewith. The type regulators that operate in the transient range and the type that operate in the subtransient range are presently in service and are separately discussed herein.

Voltage regulators that operate in the transient range.

By taking into account the fact that the applied load is other than zero impedance, and that the generator terminal voltage has a finite value, the above analysis of generator performance under short circuit conditions can also be applied to the determination of the voltage regulation under motor starting conditions. To do so, it is necessary to convert the motor starting current to an equivalent impedance, combine this with the impedance of the feeder to the motor, and calculate the actual current and resulting voltage drop when this impedance is connected to the generator terminals. For example, assume the generator to be operating initially at no load, without a voltage regulator, and it is desired to find the voltage dip produced when a zero power factor constant impedance load is suddenly applied. Let x_e equal the equivalent impedance of the applied load. Then using equation (2) the initial transient current (the subtransient current may be neglected for the reasons previously discussed) is given by the expression,

$$i'_d = \frac{e_{rated}}{X'_d + X_e} \qquad (5)$$

and the initial generator terminal voltage dip is equal to $i'_d X'_d$, or the generator terminal voltage is,

$$e'_t = i'_d X_e = \frac{e_{rated}}{X_d + X_e} X_e \tag{6}$$

Similarly, the sustained value of generator terminal voltage is, from analogy and using equation (1), given by,

$$e_t = i_d X_e = \frac{e_{rated}}{X_d + X_e} X_e \tag{7}$$

The rate of voltage decay from the initial value, e_t, is governed by the same considerations as the short circuit current, namely, the time constant of the field circuit. However, in this case a corrected value of the time constant is necessary. The corrected time constant is given by the expression,

$$T'_d = \frac{X_{d'} + X_e}{X_d + X_e} T'_{do} \tag{8}$$

and the expression for the generator terminal voltage as a function of time is, therefore,

$$e = (e'_t - e_t) e^{-t/T'_d} + e_t \tag{9}$$

Referring again to figure 17, it is now evident that the initial voltage dip (a-b) is determined by the transient reactance drop in the generator, and that, if there were no voltage regulator, the voltage would decay to the value shown at point "d", determined by the synchronous reactance drop; the rate of voltage decay being dependent on the transient time constant of the generator field circuit.

Generator excitation system

The above analysis has demonstrated the manner in which the generator characteristics influence the magnitude of the system voltage drop occurring under motor starting conditions. The next factor to be considered in this problem, is the effect of the characteristics of the generator excitation system, that is, the voltage regulator and exciter.

If reference is made to the curve in figure 17 for the exciter voltage, it will be seen that in approximately 6 cycles after the load was energized, the exciter voltage has begun to increase very rapidly. This has taken place as the result of the voltage regulator short circuiting all of the resistance in the exciter field circuit. The rate at which the exciter voltage builds up is defined as the exciter response, and is a fundamental constant of the machine. The maximum value of the exciter voltage is termed its ceiling voltage.

The generator field current increases in response to the rise in exciter voltage with a small time lag determined by the time constant of the generator field circuit. In this manner, the decay of flux in the generator produced by the demagnetizing effect of the motor starting current is opposed by the increase in field strength, and thus at point C of the curve, generator line voltage begins to return to normal. The time corresponding to point C and the rate at which the voltage returns to normal is thus dependent on the time required for the voltage regulator to short out the exciter field resistance, the rate at which the exciter voltage builds up, and the time constant of the generator field circuit.

Accordingly, it can be concluded that the generator excitation system influences the voltage drop due to suddenly applied loads by establishing the point on the generator voltage decay curve at which the voltage begins to return to normal, and the time required to reach normal voltage. The shorter the operating time of the voltage regulator, and the higher the speed of response of the exciter, the less will be the time interval existing before corrective action is begun, and, therefore, the less will be the voltage drop and recovery time.

The above analysis and the voltage-time curve of figure 17 have been based on a generator equipped with a voltage regulator of the direct acting type operating in the exciter field. For the indirect-acting and rotary amplifier types the phenomena is essentially the same, except for the recovery period. The comparative performances of these three types of voltage regulators are illustrated in figure 21, which has been prepared from oscillograms of the generator terminal voltage under identical applied loads. It will be noted that one of the major differences between the performance obtained, is that the rate of voltage decay following the transient reactance drop is much greater in the case of the indirect-acting type voltage regulator operating in the generator field circuit. This is due to the reduction in the transient time constant of the generator field circuit caused by the presence of the resistance inserted by the motor operated rheostat. To maintain the voltage drop at the same value in both cases, it is necessary for the high speed contactors of the voltage regulator in the generator field to operate in 3 Hz, instead of the 6 Hz permissible with the direct-acting exciter field type regulator. The recovery time of the former is excessive because of the inherently slow-mechanical speed of the motor operated field rheostat in changing the excitation to correspond to the added load condition. Moreover, increasing the speed of this rheostat is not possible, because it will result in excessive hunting under steady loads. Because of its higher speed of response, the rotary amplifier type has the minimum recovery time.

The static magnetic type excitation system has performance characteristics essentially the same as the rotary amplifier type.

Voltage regulators that operate in the sub-transient range

As described earlier in this DDS, this excitation system has a very fast response. The generator voltage starts to recover immediately after the initial change. The initial voltage dip, or rise, is the maximum transient voltage. Mathematical proof of this is not included in this DDS. However, the test results (Figure 17B) confirm it.

The effect of initial or remaining load on voltage transient under sudden load application, or rejection, is small. The following formulas and the curves of figure 23B are derived under the assumption of no initial or remaining load.

Initial (maximum) voltage dip for machines where X_d'' and X_q'' are approximately equal. (The difference is 10 percent, or less.)

ΔV_o = Initial voltage dip due to suddenly applied load

$$= 1 - \frac{1}{\sqrt{1+\frac{1}{Z_L^2}\left[2r_a R_L + X_L(X_d'' + X_q'') + X_d'' X_q''\right]}} \text{ per unit (p.u.)}$$

where

R_L = resistance of suddenly applied load, p.u.

X_L = reactance of suddenly applied load, p.u.

Z_L = impedance of suddenly applied load, p.u.

r_a = effective generator resistance, p.u.

X_d'' = generator direct axis subtransient reactance, p.u.

X_q'' = generator quadrature axis subtransient reactance, p.u.

r_a can be neglected if the load power factor is less than 90 percent. If the voltage dip is not measured right at the generator terminal, the external reactance and resistance due to cable connectors, bus bars, and the like, should be added to the generator reactances and resistance.

Initial (maximum) voltage rise due to suddenly rejected load, when X_d'' and X_q'' are approximately equal (difference 10 percent, or less)

$$\Delta V_o = \sqrt{1 + \frac{1}{Z_L^2}\left[2r_a R_L + X_L(X_d'' + X_q'') + X_d'' X_q''\right]} - 1.0 \text{ p.u.}$$

r_a can be neglected if power factor of the rejected load is less than 90 percent.

Numerical example:

A 60 percent .7 power factor load is suddenly applied to a generator having a direct axis subtransient reactance (X"d) of .16 p.u., and a quadrature axis subtransient reactance (X"q) of .165 p.u. Calculate the voltage dip.

Note $X_L = Z_L \sqrt{1-PF^2}$, 100/% Load = Z_L p.u.

$2\ r_a R_L$ is neglected since the power factor is less than 90 percent

$$\text{then:}\quad \Delta V_o = 1 - \frac{1}{\sqrt{1 + \frac{1}{(1.67^2)} \cdot \left[1.67\sqrt{1-.7^2} \cdot (.16 + .165) + .16(.165)\right]}}$$

$$= .067 \text{ or } 6.7\%$$

The above formulas, or the curves of figure 23B, should be used for estimating the magnitude of the transient voltage for sudden application of loads when the generator is equipped with a static SCR type regulator.

The actual calculation of the drop in generator terminal voltage under sudden load application is somewhat more complicated than is indicated by the above analysis. This is particularly true when an attempt is made to include the effects of initial generator load; saturation, applied loads of other than zero power factor, and the voltage regulator. Because of their length and relative complexity, the more detailed and accurate methods of calculation are not presented herein. However, these more accurate methods do not in any way greatly change the fundamental nature of the phenomenon as presented, nor the relative importance of the generator characteristics.

Pulsed type loads, such as sonar or radar loads, may cause voltage modulation depending on the magnitude of the pulse and the period between pulses and the time constant of the regulator and exciter. As a guide, pulsed loads exceeding the limits shown in figures 25A, 25B, 25C, and 25D, will cause voltage modulations exceeding the limits specified in MIL-STD-1399, Sect. 103. Figure 25A or 25B should be used for all loads supplied by generators equipped with regulators and exciters that operate in the transient range. When the generator supplying the loads is equipped with a regulator and exciter that operates in the sub-transient range (static SCR type), Figure 25C should be used for type I and II 60 Hz and 400 Hz loads, and Figure 25D used for type III 400 Hz loads.

Magnitude and power factor of applied load

It is immediately evident from a consideration of the factors which influence the regulation of an a. c. generator that for a given generator and regulating system, the voltage drop under sudden load application will be a function of both the magnitude and the power factor of the applied load.

Analysis has shown that for load power factors in the range of 0.4 and below, no substantial change in the voltage dip occurs, whereas for higher power factors, a considerable reduction in the voltage dip, corresponding to a given applied load current, is obtained. The influence of power factor is illustrated in figure 22.

Because of saturation, the initial load on the generator also influences the voltage dip for a given applied load to some extent. The maximum dip occurs with no initial load and decreases with load, the amount of the decrease depending on the amount of saturation and the character of the initial load, that is, whether it is a constant impedance, or one where the current increases with decrease in voltage, such as, an induction motor under load. On ship service power systems the latter type of load predominates and the voltage dip with initial load tends therefore to approach the no load value.

Combining all of the factors discussed in the above analysis, the curves of figure 23, 23A, and 23B have been prepared to enable the maximum voltage dip to be calculated when a given load or motor is started on a given generator. Figures 23 and 23A should be used for generators equipped with voltage regulators that operate in the transient range. Figure 23B should be used for generators equipped with regulators that operate in the subtransient range. It is noted that the curves of figure 23 show the dip to be a function of only three variables, that is, the magnitude of applied load, the generator transient reactance, and the generator transient open circuit time constant. This has been found possible by assuming certain average values for the generator synchronous reactance, exciter response, load power factor, and regulator operating time. This assumption is justified, because these factors are of more or less secondary importance, and particularly because they are closely the same for all sizes of standard Navy 450-volt generators and excitation systems.

In the determination of maximum voltage dips from figure 23, it should be noted that applied load must be expressed in terms of percent of generator rated current at rated voltage. In the calculation of the curves, the added load was treated as a fixed impedance. The impedance of a normal induction motor remains constant at the locked rotor value for speeds up to at least 75 percent of full speed and, in general, the motor will not reach this speed before the regulator has had time to stop the downward trend of the generator voltage, therefore, to determine the voltage drop under motor starting by means of figure 23A, induction motors can be assumed to have a constant impedance.

As an example of the use of the curves of figure 23, assume that a motor having a locked rotor current at rated voltage equal to 1200 amperes is to be started across the line on a 1500 kw., 2400 ampere generator having 20 percent transient reactance and an open circuit transient time constant, T'_{do}, of 4.0 seconds. The motor starting current is, therefore, equivalent to an applied load equal to 1200/2400, or 50 percent of the generator rating. Hence, from the curve for 20 percent reactance, and T'_{do} equal to 4.0 seconds, the maximum voltage dip is 9 percent.

In many cases, the motor to be started is not directly at the generator terminals, and it is therefore desirable in such cases to include the feeder voltage drop in calculating the voltage dip at the generator terminals.

For generators equipped with regulators that operate in the transient range, this can be done as follows:

Let

I_g = Generator rated current
E_g = Generator rated voltage line-to-neutral
Z_m = Motor locked rotor impedance in ohms
Z_f = Feeder impedance in ohms
I_e = Applied load in percent of generator rating

then, $I_e = \frac{E_g}{(Z_m + Z_f)I_g} X100$

Using this value of I_e the generator terminal voltage drop is then found from figure 23. To determine the voltage at the terminals of the motor during starting under this condition, let

E_t = minimum generator terminal voltage during motor starting from figure 23.
E'_m = minimum motor terminal voltage during starting then,

$$E'_m = \frac{E_t Z_n}{Zm + Zf}$$

While motor starting is the primary cause of voltage transients on type I ship service systems, other load switching must also be considered, particularly for 400 Hz type III ship service systems, where the transient voltage limitation is plus or minus 5 percent. Since the power factor of many of the critical electronic and weapon system loads is usually around 70 to 90 percent lagging, the voltage dip for the same KVA will not be as large as for motor starting. The curves of figure 23A should be used for estimating the magnitude of the transient voltage for sudden application of these loads. These curves are based on 400 Hz generator characteristics and constants.

NOTE: Constants used on these curves are:

T_e = time constant of exciter build up.
T'_{do} = Open circuit transient time constant
X_q = quadrature - axis synchronous reactance.
X'_d = direct - axis transient reactance
X_d = direct - axis synchronous reactance

Methods of reducing transient voltage disturbance

It might be inferred from the foregoing discussion that a reduction in the generator reactance would be desirable in order to reduce the magnitude of voltage dips under motor starting conditions. Unfortunately, this can be done only to a limited extent, because of the interdependence of the transient and subtransient reactances; the latter usually being not more than 60 percent of the former. In many cases, particularly on generators above 500 kw, it is desirable to keep the generator short-circuit current low in order not to exceed the circuit breaker interrupting ratings, and it is necessary, therefore, that the subtransient reactance be high. This, in turn, establishes a minimum value of transient reactance. Thus, a compromise is generally necessary between the low reactance values dictated by voltage dip requirements and the high reactance values necessary to reduce the short-circuit currents.

With the generator and generator excitation system constants established, the only practicable method of reducing system voltage disturbances is to reduce the value of motor starting currents. However, the possibility of decreasing the locked rotor currents of induction motors is determined by the motor speed, the degree of enclosure, the torque requirements, and the permissible temperature rise. In general, the higher the motor speed, the higher will be the locked rotor current. Totally enclosed motors will usually have locked rotor currents higher than those of open motors. The average starting current of Navy motors is approximately 700 percent of full load current.

In view of the limited extent to which reductions in the generator reactance and induction motor locked rotor currents can be achieved, reduced voltage motor starting equipment must be utilized where necessary to maintain the system transient voltage dips within the required limits. There are three types of reduced voltage motor starters: line resistor, line reactor, and autotransformer. For the same starting torque the resistor and reactor types are not as effective in reducing the line current, and consequently the voltage dip, as the autotransformer type; the latter reduces the line current in proportion to the square of the voltage applied to the motor. On the other hand, the resistor and reactor are the simplest type starters and ensure somewhat smoother acceleration and reduced starting time because of the decrease in current and consequent increase in applied voltage as the motor comes up to speed. However, the most commonly used type on shipboard is the autotransformer, principally because of its greater effectiveness in reducing the line current for a given torque.

In the application of reduced voltage starters, care should be taken to ensure that the reduction in starting torque is not such as to prevent accelerating the load, and that the transition from reduced voltage to full line voltage does not produce excessive transient currents.

Starting large motors where voltage regulation may be disregarded.

The size of the largest motor which may be started across the line on ship service power systems is in general limited by considerations of the effect on the system voltage regulation. However, in some cases where no other loads are connected during the starting period, it may be found possible to start a relatively large motor without regard to its effect on the system voltage regulation. Moreover, in such cases it may also be necessary to ensure the maximum possible torque output from the motor, that is, maximum power input, in order to accelerate the load. Under such conditions the question as to what is the most effective method of starting the motor may therefore be raised. The answer to this question involves consideration of the power output characteristics of both the generator and its prime mover.

It can be shown[4] that the maximum power transfer from an a.c. generator to an inductive load occurs when the absolute magnitude of the load impedance equals the internal impedance of the generator. Thus, for maximum power input to a motor during starting, the locked rotor impedance of the motor, as seen by the generator, should be equal to the synchronous reactance of the generator (neglecting armature resistance). However, as previously discussed, the synchronous reactance of an a.c. generator is not a constant, but varies with both field current and armature current. For this reason it is difficult to determine the value of load impedance that will match the synchronous reactance without first knowing to an approximate degree, at least, the armature current. Consequently, it is usually more satisfactory to construct a set of curves such as are shown in figure 24 giving the terminal voltage, kw, and the kva, as a function of armature current for a given load power factor and ceiling excitation. These curves can be readily obtained by graphical methods from the no load and full load zero power factor saturation curves. The curves of figure 24 are for a typical ship service generator, and show that at a load power factor of 0.4 lagging, which corresponds to that of the average induction motor while starting, the maximum power output is 0.75 per unit or 75 percent of the rated kilowatts of the generator. In other words, this is the maximum power which the generator can supply at 0.4 lagging power factor, regardless of the capacity of the prime mover. Moreover this value applies only at rated speed. If the speed changes, the power output will vary as the cube of the speed.

From the above, it is evident that for maximum power input to a motor, its locked rotor impedance must be equal to the impedance of the load corresponding to that giving maximum kw, as found in figure 24. Thus, for this generator the locked rotor impedance must be equal to 0.50 per unit for maximum power transfer. In other words, the locked rotor current of the motor at full voltage should be 200 percent of the generator rating. If the impedance is less than this value, that is, the locked rotor current is greater than 200 percent of the generator rating, the impedance should be increased by means of an autotransformer until it equals this value. (An autotransformer will increase the apparent impedance of the motor in proportion to the square of the step-down voltage ratio). Actually, however, as shown in figure 24 the load impedance may vary over a considerable range without greatly affecting the maximum power output. Consequently, unless the impedance is very much lower than the optimum value, the use of an autotransformer is not justified. On the other hand, if the motor locked rotor impedance is above the optimum value, the use of a step-up autotransformer to increase the power input is obviously not necessary, since without the transformer, figure 24 shows that rated voltage will be maintained at the motor terminals, and it will therefore develop rated starting torque.

shows that rated voltage will be maintained at the motor terminals, and it will therefore develop rated starting torque.

It should be noted that figure 24, and the foregoing discussion, have been based on the steady-state conditions existing after the motor has been connected to the line and the voltage regulator has reached the position corresponding to ceiling excitation. Prior to this time a transient voltage dip will have occurred together with a power surge of somewhat smaller magnitude than the maximum value. That the latter is true may be inferred from the fact that the transient reactance being only about 0.20 per unit will not match the optimum load impedance for maximum power transfer.

It is evident from the foregoing analysis, that for loads of low power factor an a.c. generator acts automatically to limit the peak power to a value below the rated kilowatts. Consequently, where the prime mover is a diesel engine, for example, there is no likelihood of stalling the diesel during motor starting regardless of the motor size, if there is no other load on the system. Moreover, where there is other load, the rated kilowatts will not be exceeded unless the resultant load power factor exceeds approximately 50 percent.

4. Ramp loads.

Ramp loading is the application of a load in KW/second increments to its maximum value. When the total ramp loading time exceeds the time required for the generator's regulator-exciter to begin to control the voltage, the maximum voltage deviation will be less for a ramp load than for a one step load of the same magnitude. Only the static SCR type regulator-exciters operate fast enough to show an improved voltage deviation when a ramp load is applied.

Some radars and sonar loads employ the ramp loading technique. Figures 26A, 26B, and 26C, may be used for selection of ramp loading rates that are permissible on generators with characteristics as shown on the figures and have static SCR regulator-exciters. The 2 percent modulation permitted by MIL-STD-1399, Sect. 103, is the limiting factor on which the curves were drawn.

The generator ramp loading graphs are based on ramp loads having a .8 lagging power factor being applied to a .5 per unit (50 percent) initially loaded steam turbine generator.

Example for use of the graphs: For a .5 PU loaded generator having a $T'_{do} = 4.0$ seconds, and a $X'_d = .3$, find the maximum ramp rate permissible to ramp on a load equal to .5 PU of the generator rating. Using figure 26A, the maximum ramp rate is 2 PU/second. (See dotted lines on figure 26A).

Graphs for generators with magamp or rotary type regulator-exciters are not drawn, since at even the slow ramp rate of .2 PU second the voltage modulation limit of 2 percent is exceeded.

5. Summary

The foregoing analysis has shown that there are a great many factors which may influence the voltage regulation of a.c. ship service power systems. However, in the majority of installations many of the factors which have been discussed at considerable length herein, actually become of minor importance. For this reason, it is desirable to summarize briefly the voltage regulation problem on ship-board with particular reference to the relative importance of factors, such as, unbalanced voltages, generator reactances and excitation systems, feeder voltage drops, and reactive load compensation.

In a typical a.c. power system on a naval ship the most important, and most frequently encountered voltage regulation problem which occurs, is that involving the transient voltage fluctuations produced by the starting of induction motors, which are relatively large with respect to the generating plant. In such cases, it is necessary that the maximum voltage dip be determined and that it be maintained within the prescribed limits by means of either reduced voltage starting, design of the generator constants (primarily the transient and sub-transient reactance), or a combination of both. The curves of figures 23, 23A, and 23B are the principal tools required in the solution of this problem.

The steady-state voltage regulation problem and the effect of unbalanced loads are generally of relatively minor importance in a type I ship service a.c. power system. The magnitude of load unbalance usually encountered is seldom very large, normally being well below 10 percent of the capacity of the connected generators. Thus, it is necessary to become involved in considerations of unbalanced voltages, negative sequence reactances, overheating of generators and motors, and similar problems associated with unbalanced loads, only in unusual installations where it is definitely known that large single-phase loads will occur. Similarly, steady-state voltage regulation is seldom a problem in actual installations, since it is adequately taken care of by providing a generator voltage regulator. However, for types II and III power voltage, unbalance and steady state voltage regulation must be considered. Only very rarely does the rated load voltage drop on power feeders exceed 5 percent and it is normally necessary that it be checked only under motor starting conditions. Perhaps the most important single factor associated with the steady-state voltage regulation problem is the provision of suitable reactive load compensators in the generator voltage regulators, to ensure satisfactory parallel operation.

In view of the above the voltage regulation problems actually encountered on a.c. ship service power systems are reasonably simple ones. Moreover, they have been further simplified by the establishment of certain standards for the characteristics of generators and their excitation systems, which represent a reasonable compromise of the various factors entering the problems. Deviation from these standards should be necessary only in exceptional cases.

LIST OF REFERENCE BOOKS

1. Electromagnetic Devices, by H. C. R. Roters; John Wiley & Sons.
2. Symmetrical Components, by C. F. Wagner and R. D. Evans; McGraw Hill Co.
3. Electrical Transmission and Distribution Reference Book, Westinghouse Electric & Manufacturing Co., East Pittsburgh, Pa.
4. Communication Engineering, by W. L. Everitt; McGraw Hill Co.
5. Alternating - Current Circuits, by R. M. Kerchner and G. F. Corcoran.

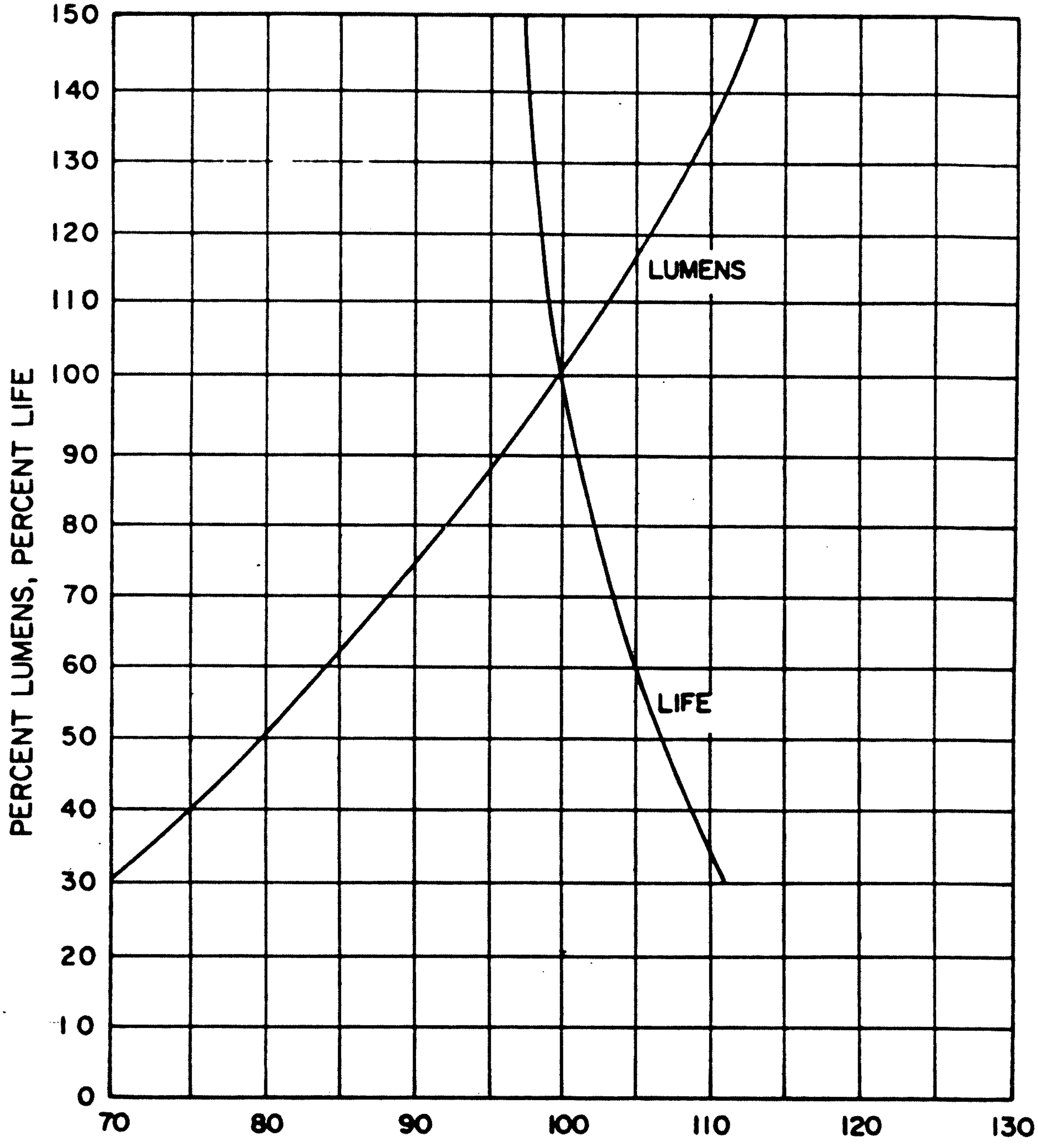


FIGURE 1-EFFECT OF APPLIED VOLTAGE ON THE LIFE AND LIGHT OUTPUT OF INCANDESCENT LAMPS.

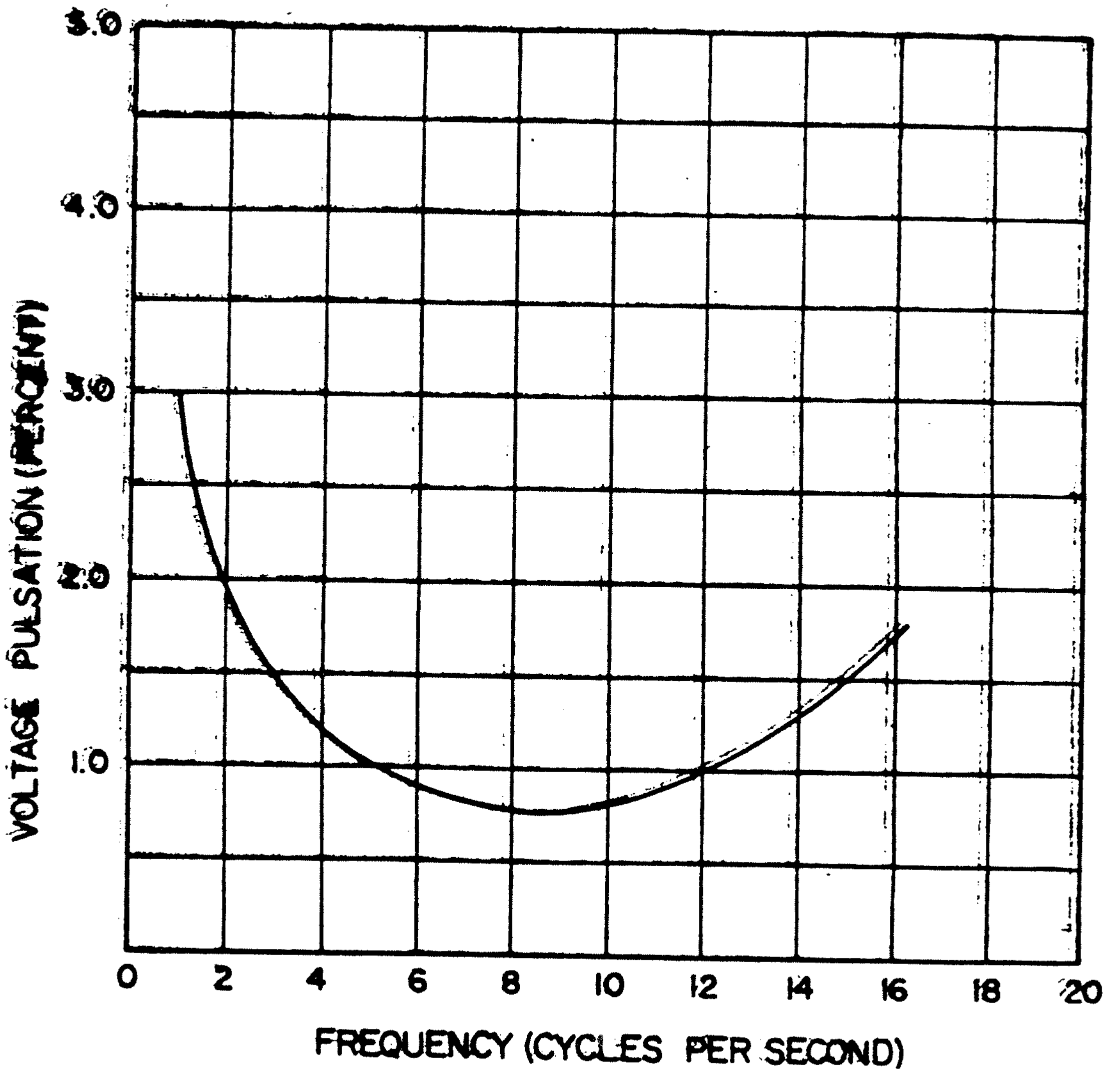


FIGURE 2 - MAGNITUDE OF VOLTAGE PULSATION AS A FUNCTION OF FREQUENCY AT WHICH PULSATION BECOMES PERCEPTIBLE TO VISION.

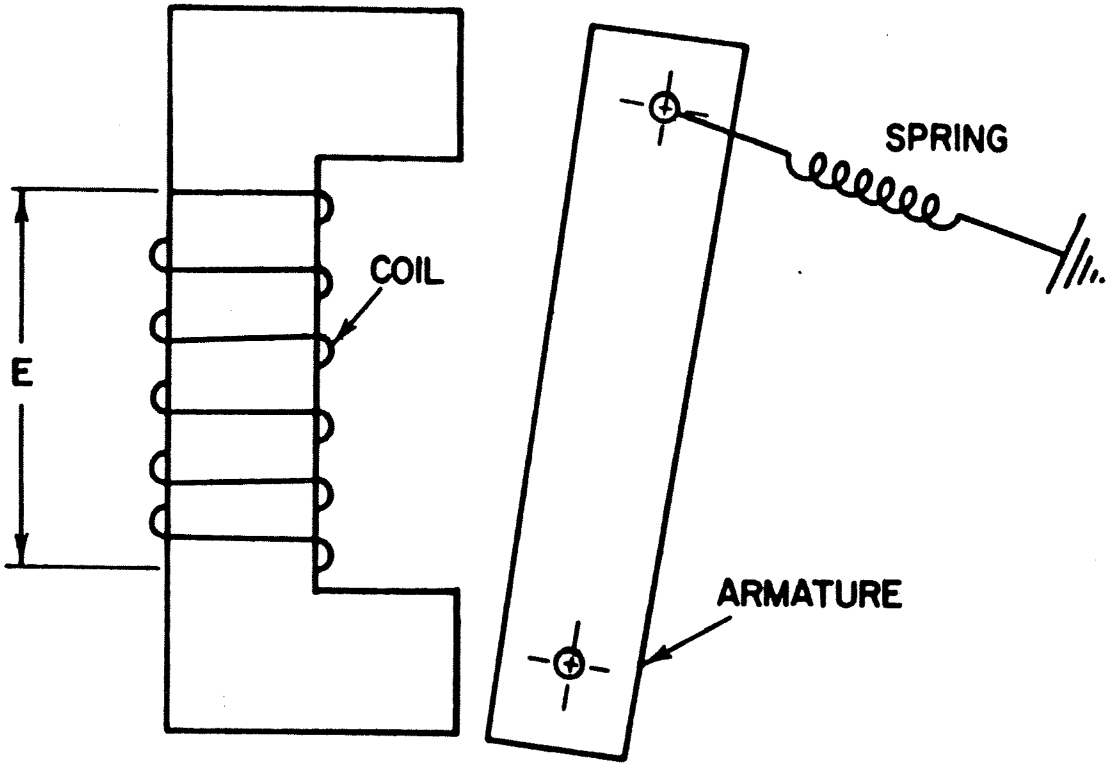


FIGURE 3 - SCHEMATIC DIAGRAM OF TYPICAL ELETROMAGNET USED ON VOLTAGE RELAY.

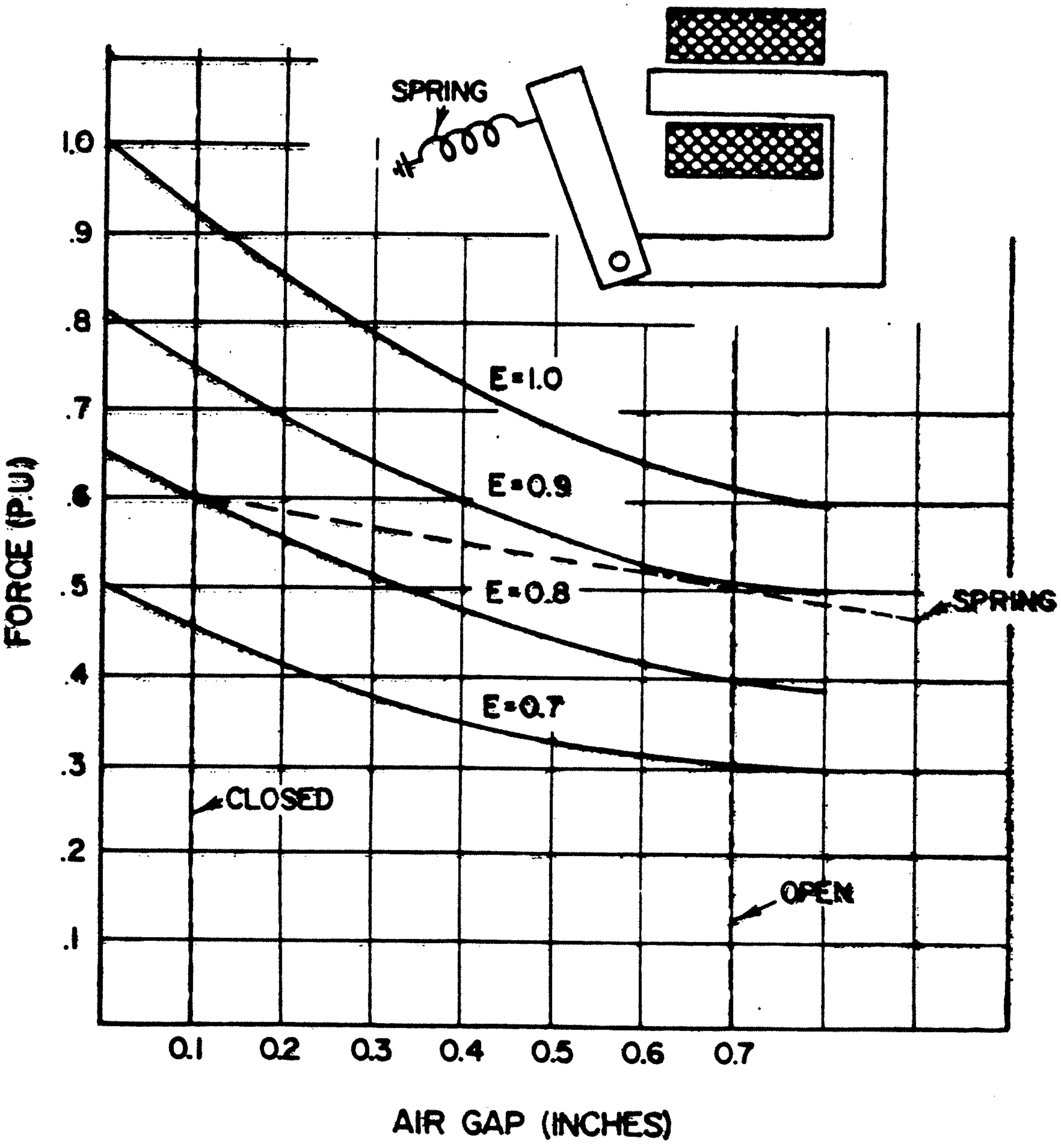


FIGURE 4 - TYPICAL FORCE VS. AIR GAP DIAGRAM FOR SHORT STROKE ELECTROMAGNET SHOWING EFFECT OF CHANGES IN APPLIED VOLTAGE.

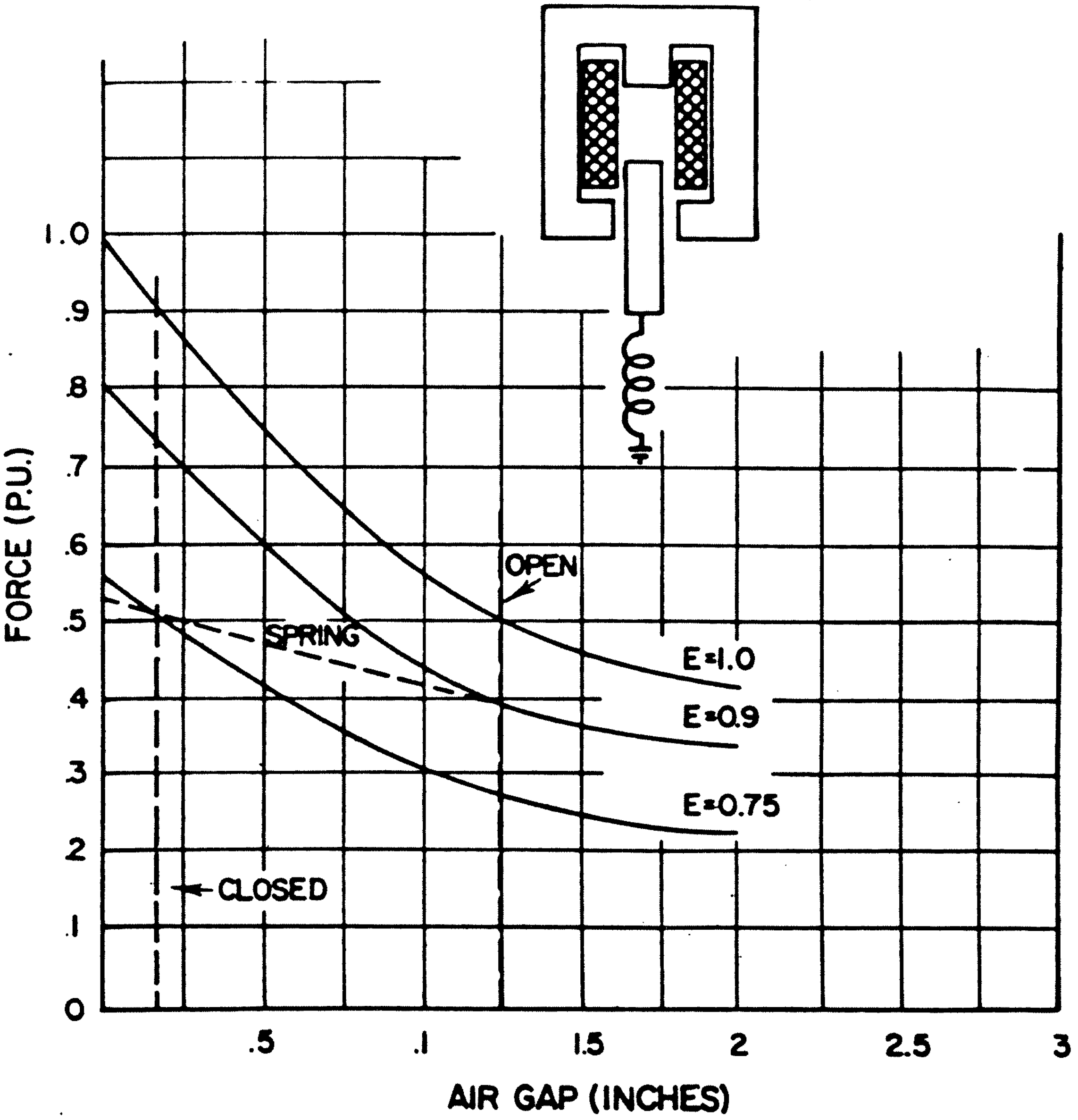


FIGURE 5 - TYPICAL FORCE VS. AIR GAP DIAGRAM FOR LONG STROKE ELECTROMAGNET SHOWING EFFECT OF CHANGES IN APPLIED VOLTAGE.

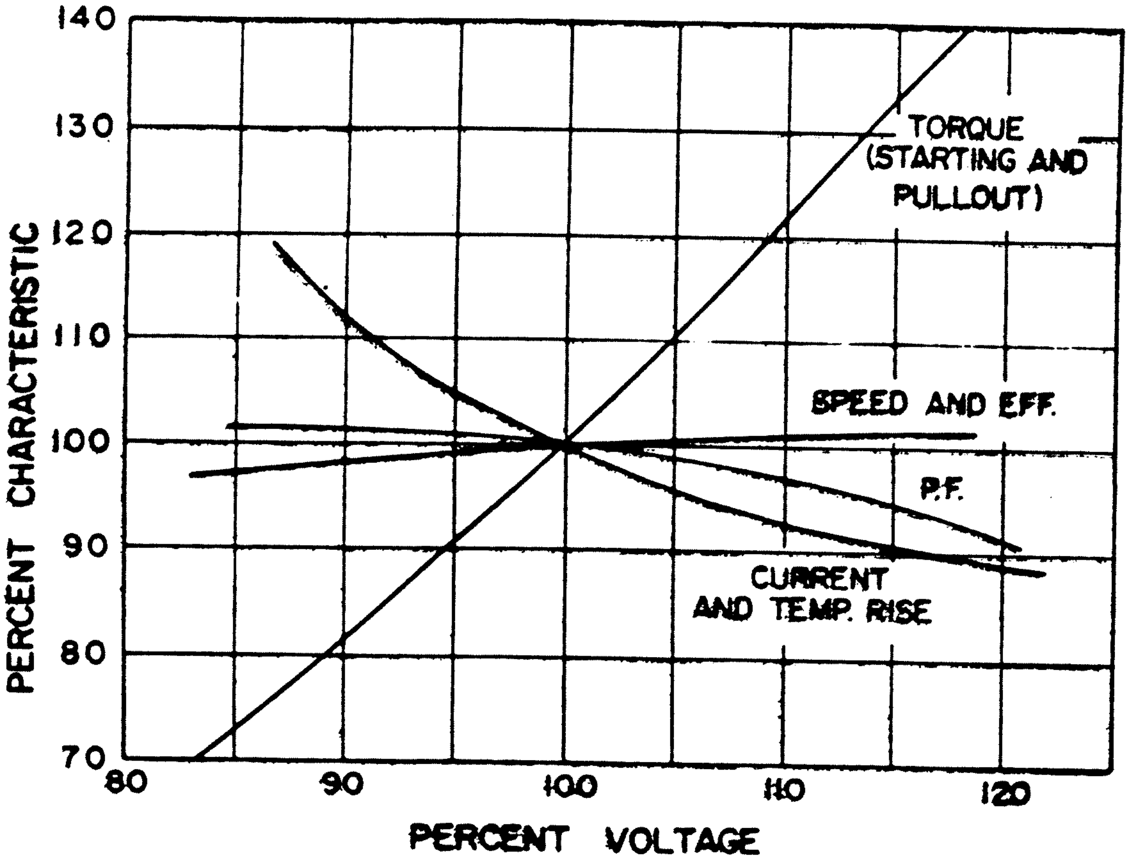


FIGURE 6 - EFFECT OF VOLTAGE ON THE CHARACTERISTICS OF A TYPICAL INDUCTION MOTOR.

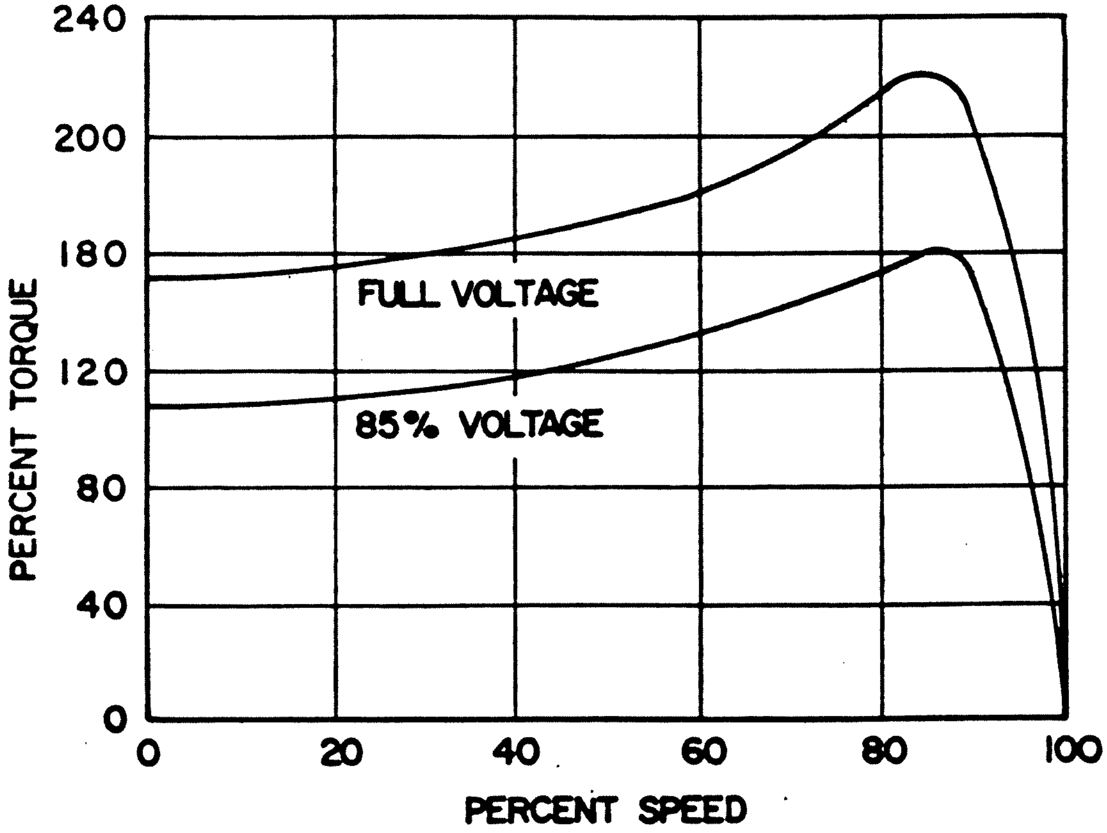


FIGURE 7 - SPEEP-TORQUE CURVES OF A TYPICAL INDUCTION MOTOR AT RATED AND AT REDUCED VOLTAGE.

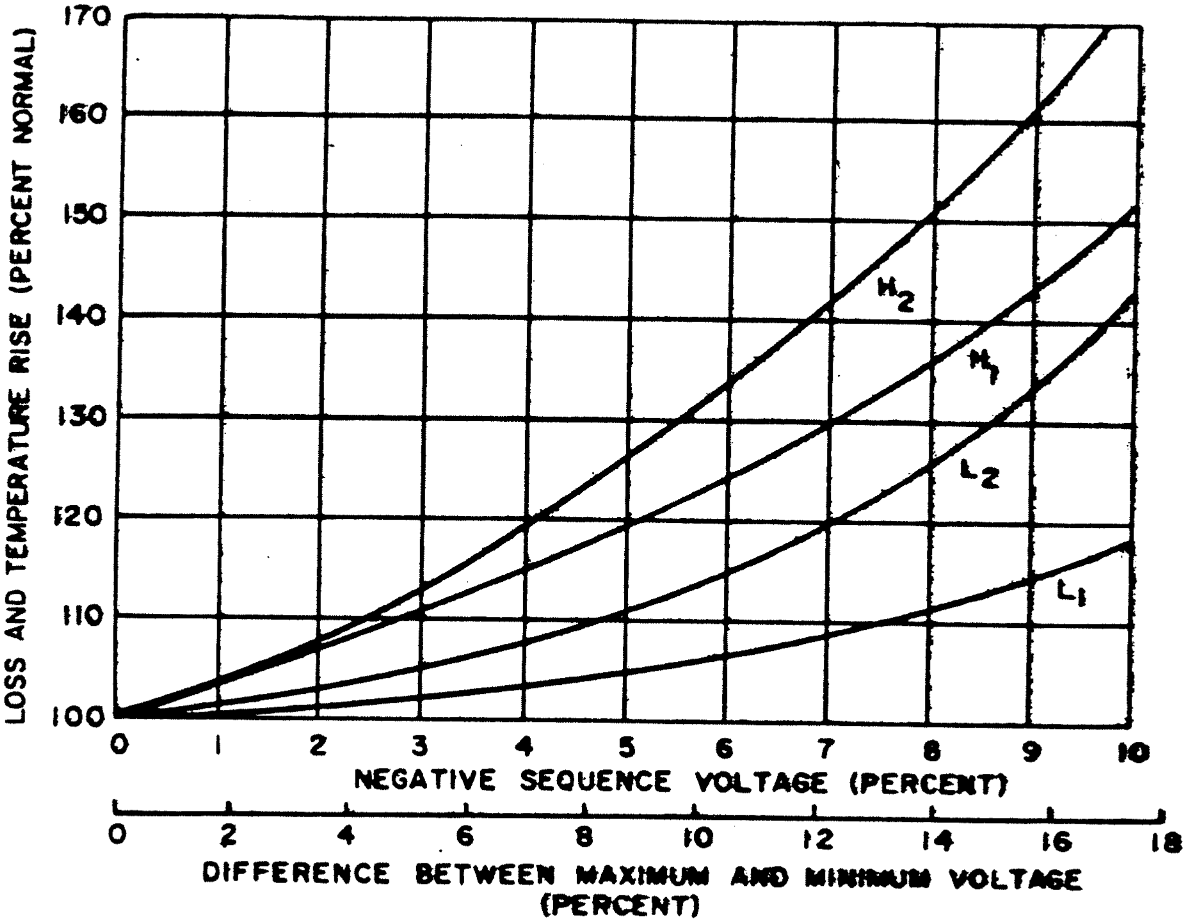


FIGURE 8 - EFFECT OF UNBALANCE IN APPLIED VOLTAGES ON THE LOSSES AND TEMPERATURE RISE OF INDUCTION MOTORS BASED ON POSITIVE SEQUENCE VOLTAGE EQUAL TO RATED VOLTAGE.

CURVE L_1 - TOTAL LOSSES IN SINGLE SQUIRREL CAGE MOTOR.
CURVE L_2 - TOTAL LOSSES IN DOUBLE SQUIRREL CAGE MOTOR.
CURVE H_1 - HOT SPOT TEMPERATURE IN SINGLE SQUIRREL CAGE MOTOR.
CURVE H_2 - HOT SPOT TEMPERATURE IN DOUBLE SQUIRREL CAGE MOTOR.

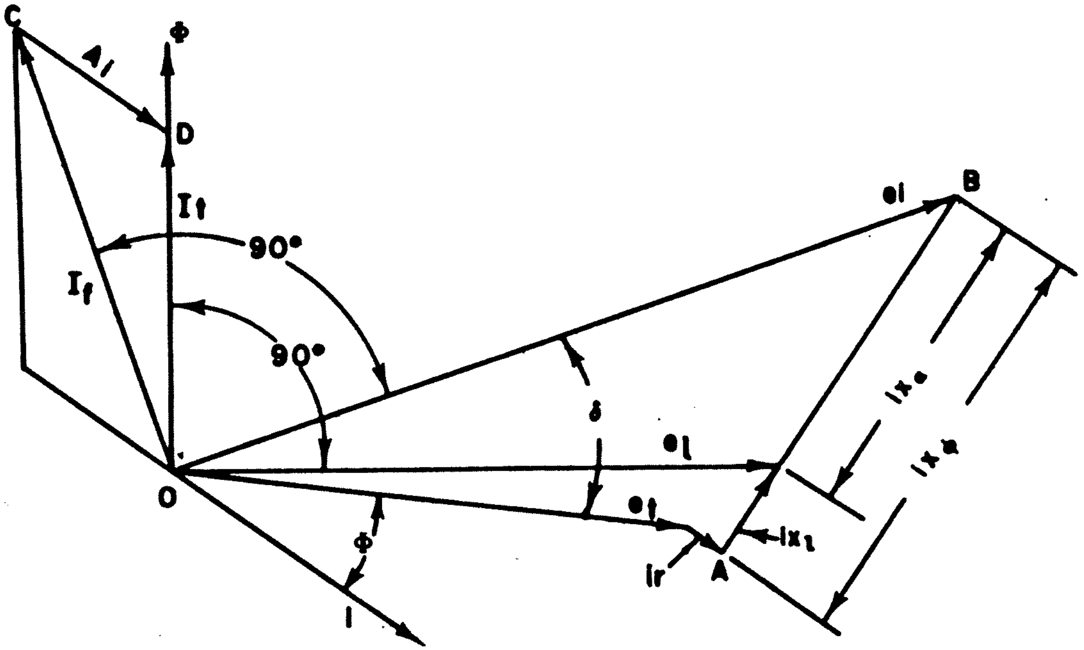


FIGURE 9 - SIMPLIFIED VECTOR DIAGRAM FOR NONSALIENT POLE, A.C. GENERATOR.

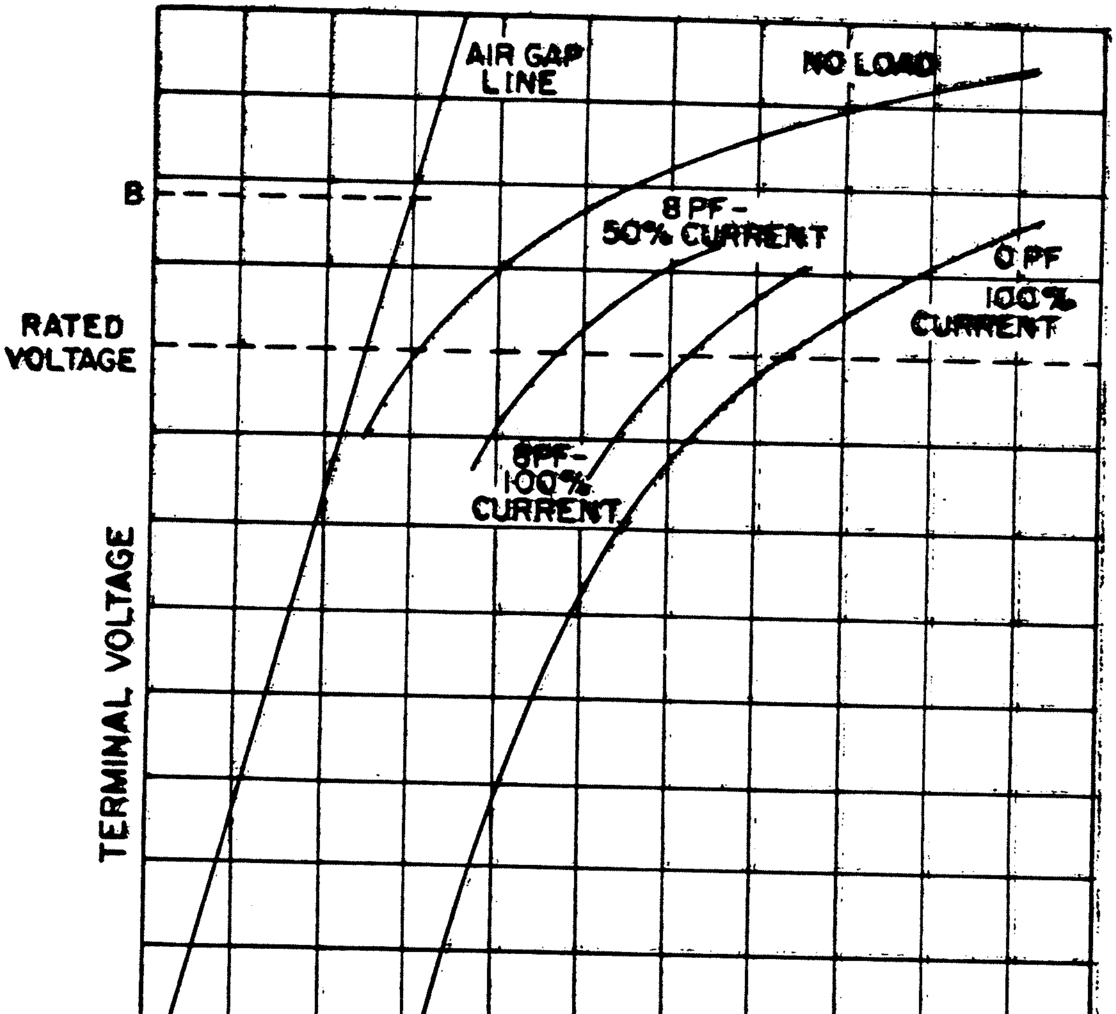


FIGURE 10 - CHARACTERISTIC SATURATION CURVES FOR AN A.C. GENERATOR.

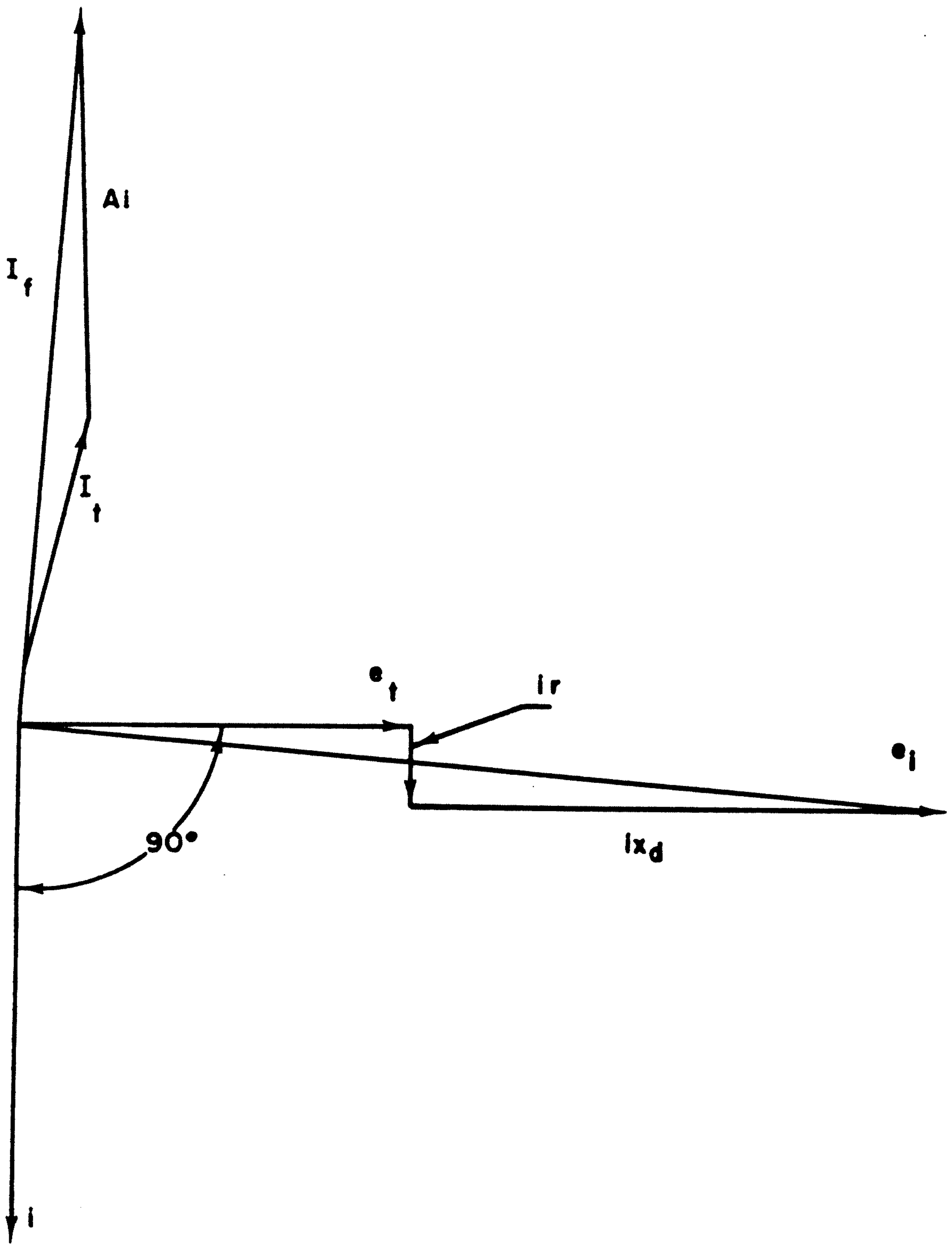
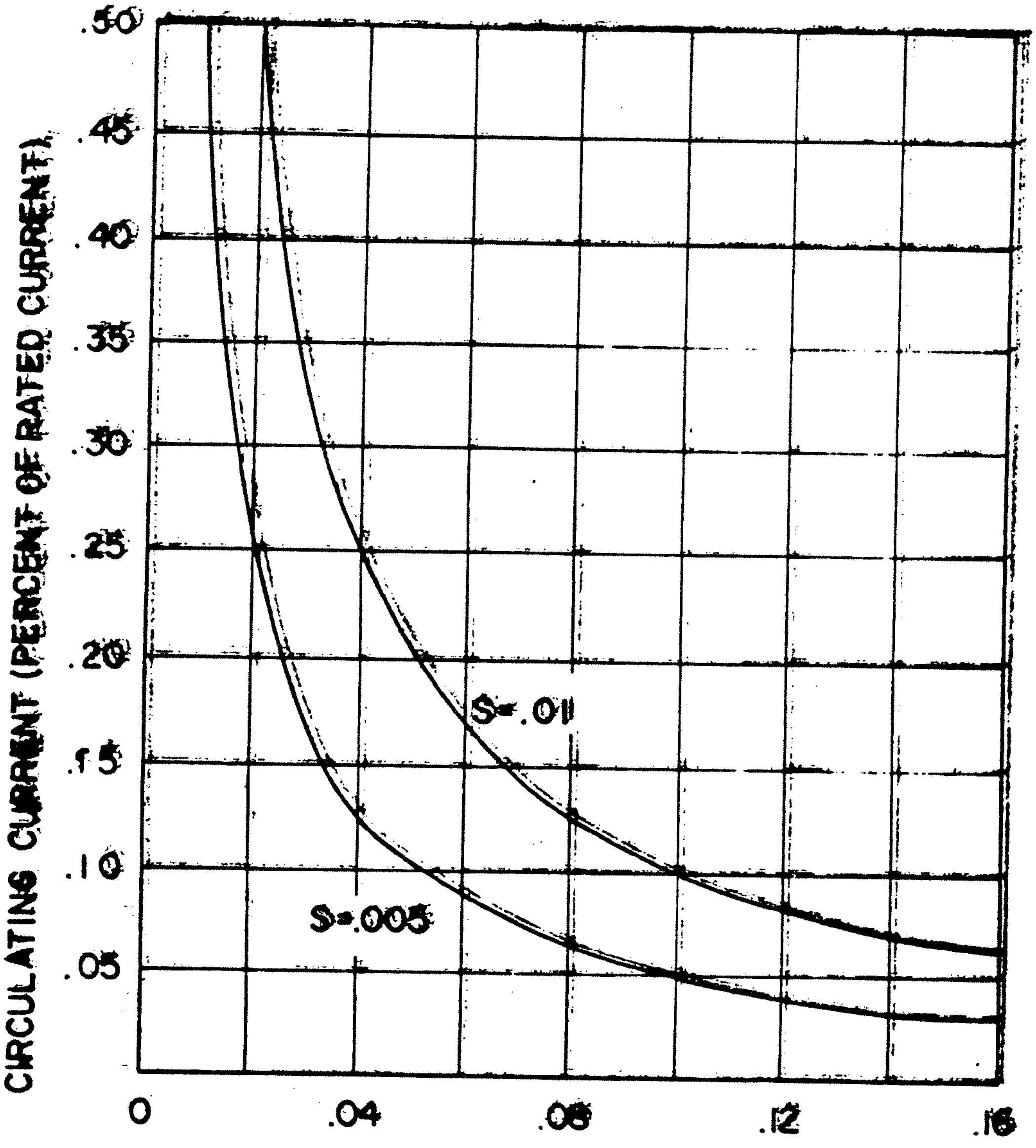


FIGURE 11 - VECTOR DIAGRAM FOR AN A.C. GENERATOR OPERATING AT ZERO POWER FACTOR LOAD.



REACTANCE COMPENSATION
(PERCENT DROP AT RATED LOAD, ZERO POWER FACTOR)

Figure 12 - EFFECT OF AMOUNT OF REACTIVE LOAD COMPENSATION ON MAGNITUDE OF CURRENT UNBALANCE BETWEEN TWO A.C. GENERATORS OPERATING IN PARALLEL EQUIPPED WITH INDIRECT-ACTING TYPE VOLTAGE REGULATORS. (S- REGULATOR SENSITIVTY IN PER UNIT.)

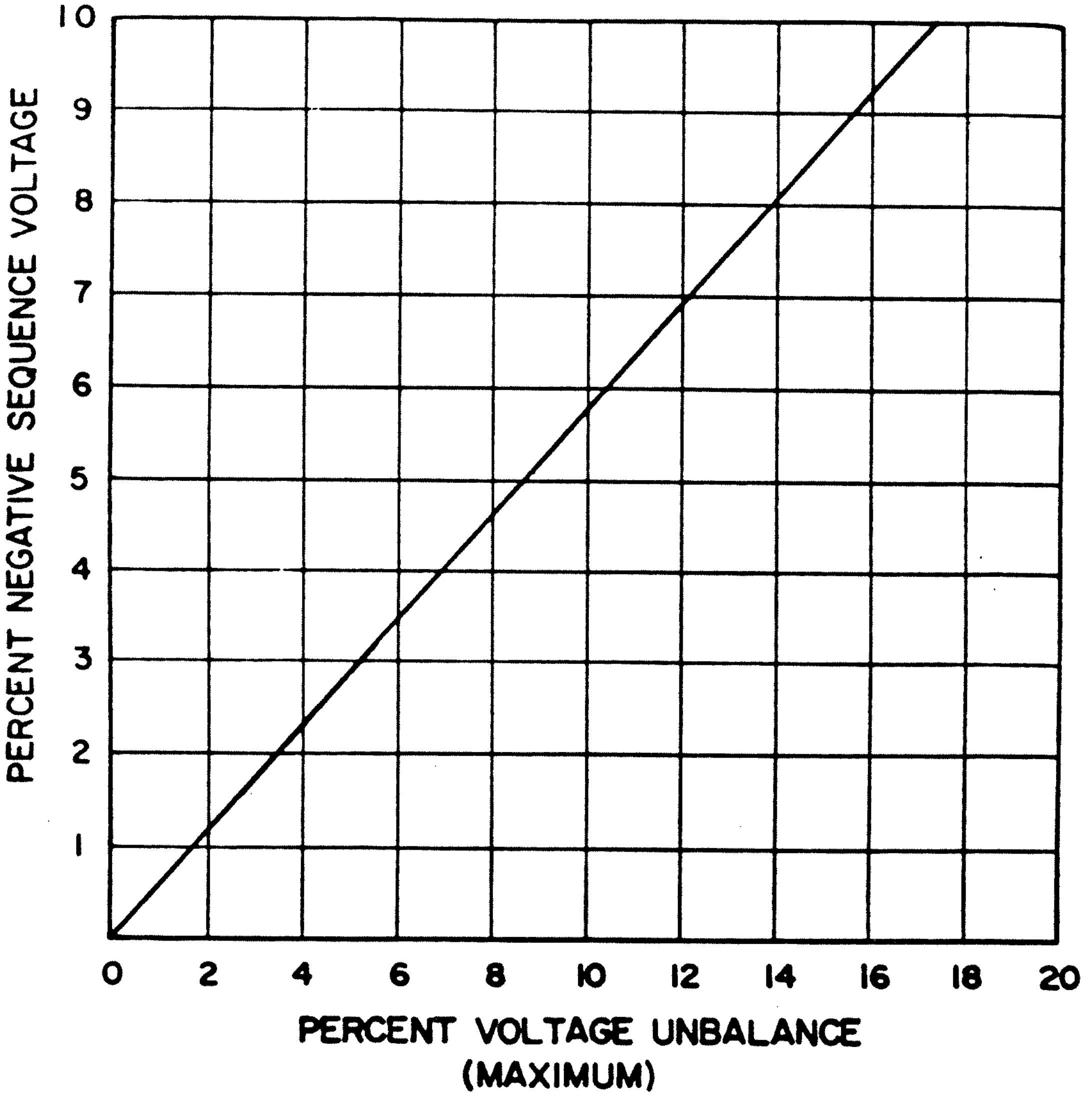


Figure 13 -RELATION BETWEEN MAXIMUM VOLTAGE UNBALANCE AND NEGATIVE SEQUENCE VOLTAGE WITH POSITIVE SEQUENCE VOLTAGE EQUAL TO RATED VALUE.

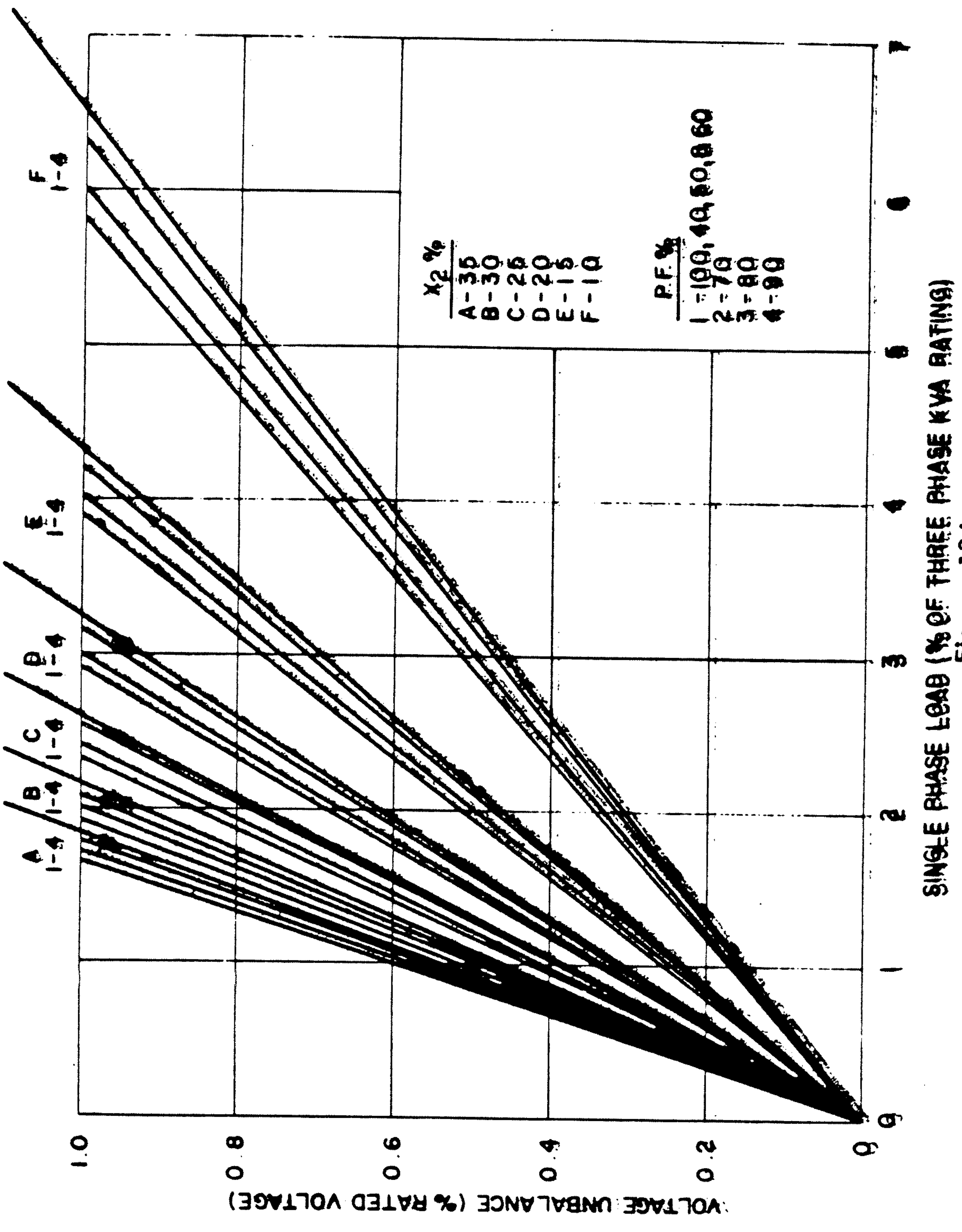

A
1-4
B
1-4
C
1-4
D
1-4
E
1-4
F
1-4
X2 %
A-35
B-30
C-25
D-20
E-15
F-10
P.F. %
1-100, 40, 50, & 60
2-70
3-80
4-90
0
1
2
3
4
5
6
7
SINGLE PHASE LOAD (% OF THREE PHASE KVA RATING)
0
0.2
0.4
0.6
0.8
1.0
VOLTAGE UNBALANCE (% RATED VOLTAGE)

Figure 13A

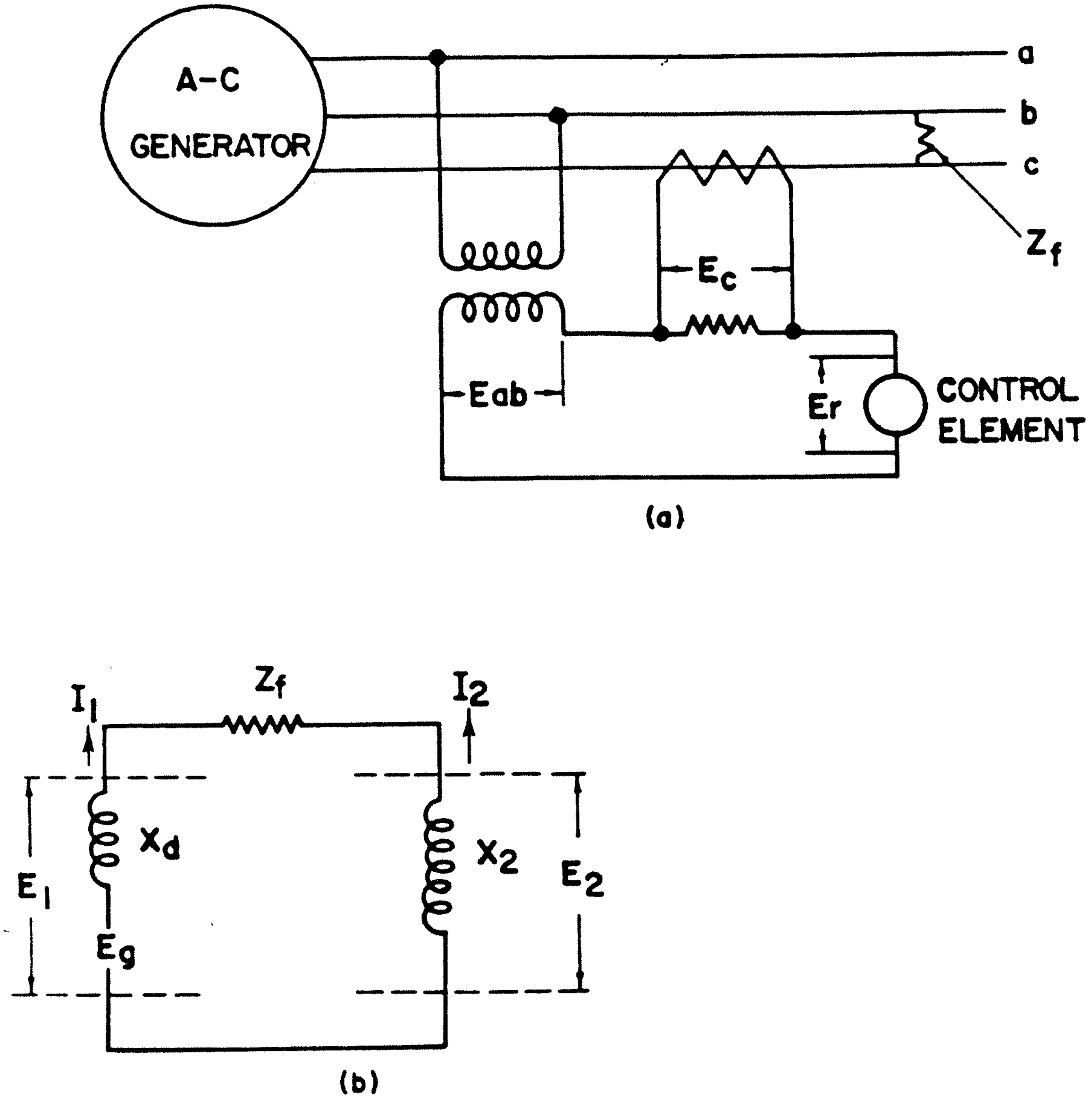


Figure 14 - (a) SCHEMATIC DIAGRAM OF A.C. GENERATOR EQUIPPED WITH SINGLE PHASE VOLTAGE REGULATOR AND CONNECTED TO SINGLE PHASE LOAD. (b) EQUIVALENT INTERCONNECTION OF POSITIVE AND NEGATIVE SEQUENCE NETWORKS.

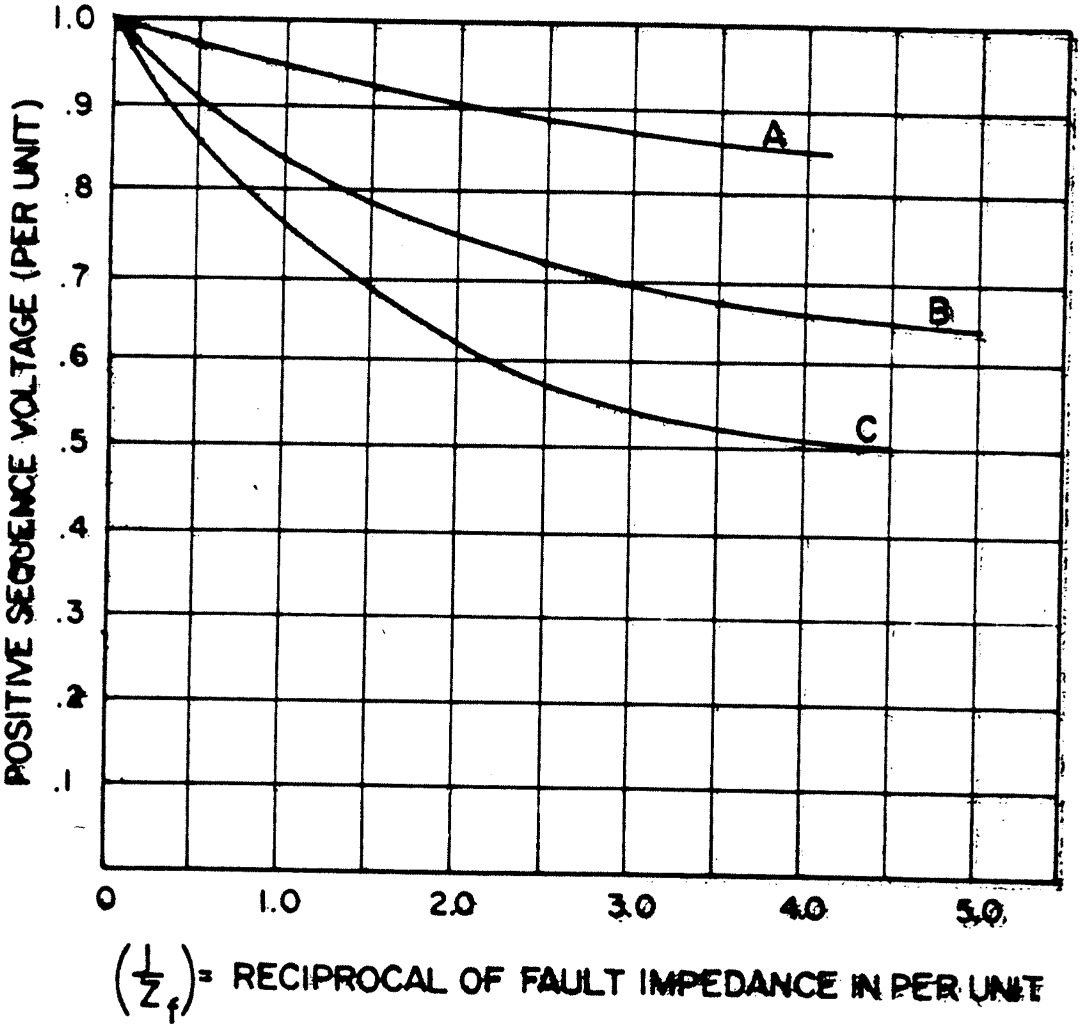


Figure 15 - RELATION BETWEEN SINGLE PHASE LOAD IMPEDANANCE AND POSITIVE SEQUENCE VOLTAGE OF AN A.C. GENERATOR EQUIPPED WITH SINGLE PHASE VOLTAGE REGULATOR AS SHOWN IN FIGURE 16.

CURVE A - THREE-PHASE REGULATOR WITH 5 PERCENT REACTIVE LOAD COMPENSATION AND REACTANCE LOAD.

CURVE B - SINGLE PHASE REGULATOR WITH 5 PERCENT REACTIVE LOAD COMPENSATION AND REACTANCE LOAD.

CURVE C - SINGLE PHASE REGULATOR WITH NO REACTIVE LOAD COMPENSATION AND RESISTANCE LOAD.

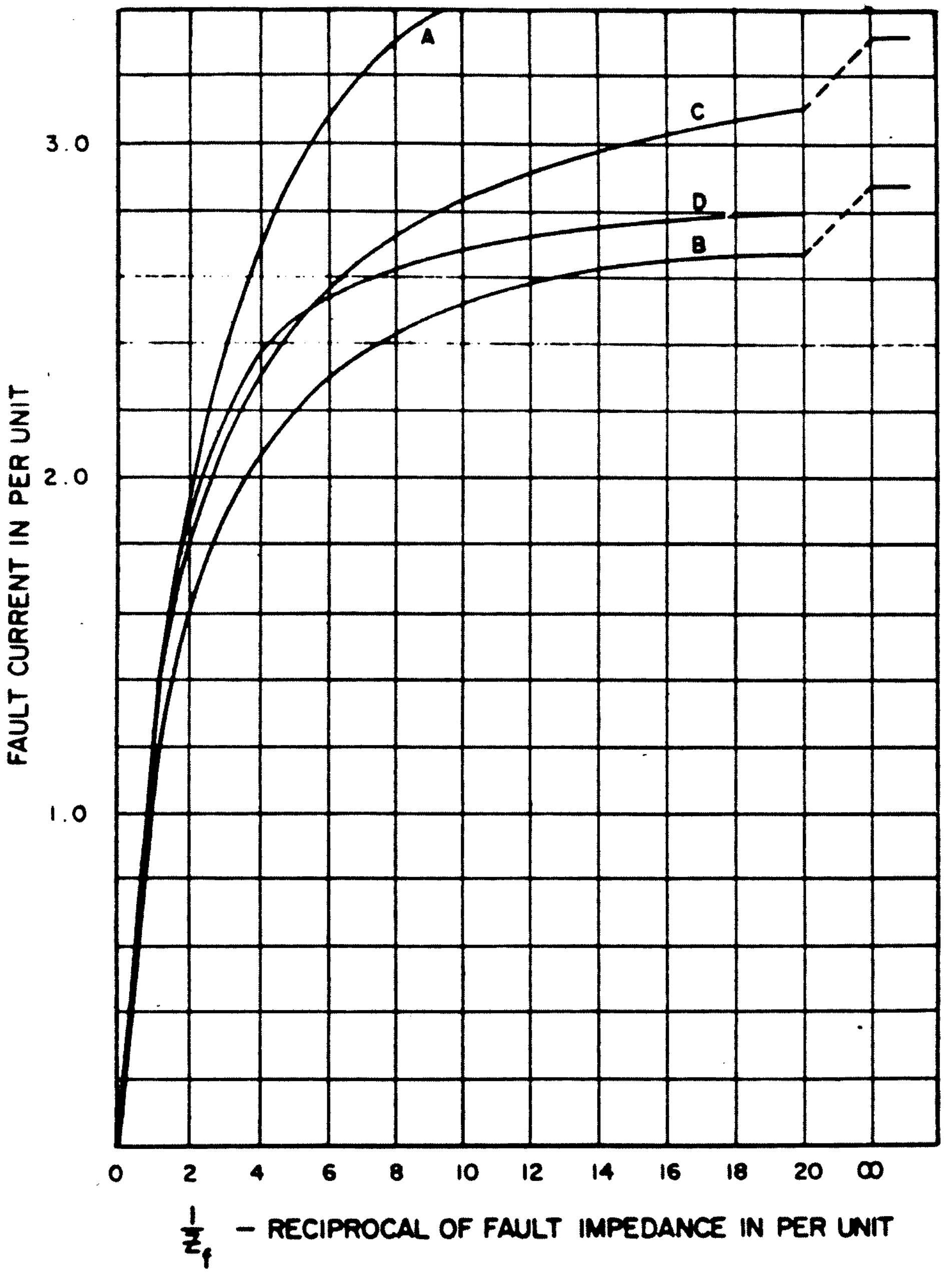


Figure 16-RELATION BETWEEN SINGLE PHASE LOAD IMPEDENANCE AND SINGLE PHASE LOAD CURRENT OF AN A.C. GENERATOR EQUIPPED WITH SINGLE PHASE VOLTAGE REGULATOR.

CURVE A- THREE-PHASE REGULATOR WITH 5 PERCENT REACTIVE LOAD COMPENSATION AND A SINGLE PHASE REACTANCE LOAD.

CURVE B- SINGLE PHASE REGULATOR WITH 5 PERCENT REACTIVE LOAD COMPENSATOR AND SINGLE PHASE REACTANCE LOAD.

CURVE C- SINGLE PHASE REGULATOR WITH NO REACTIVE LOAD COMPENSATION AND SINGLE PHASE REACTANCE LOAD

CURVE D- SINGLE PHASE REGULATOR (OR 3-PHASE REGULATOR) WITH 5 PERCENT REACTIVE LOAD COMPENSATION AND 3-PHASE REACTANCE LOAD.

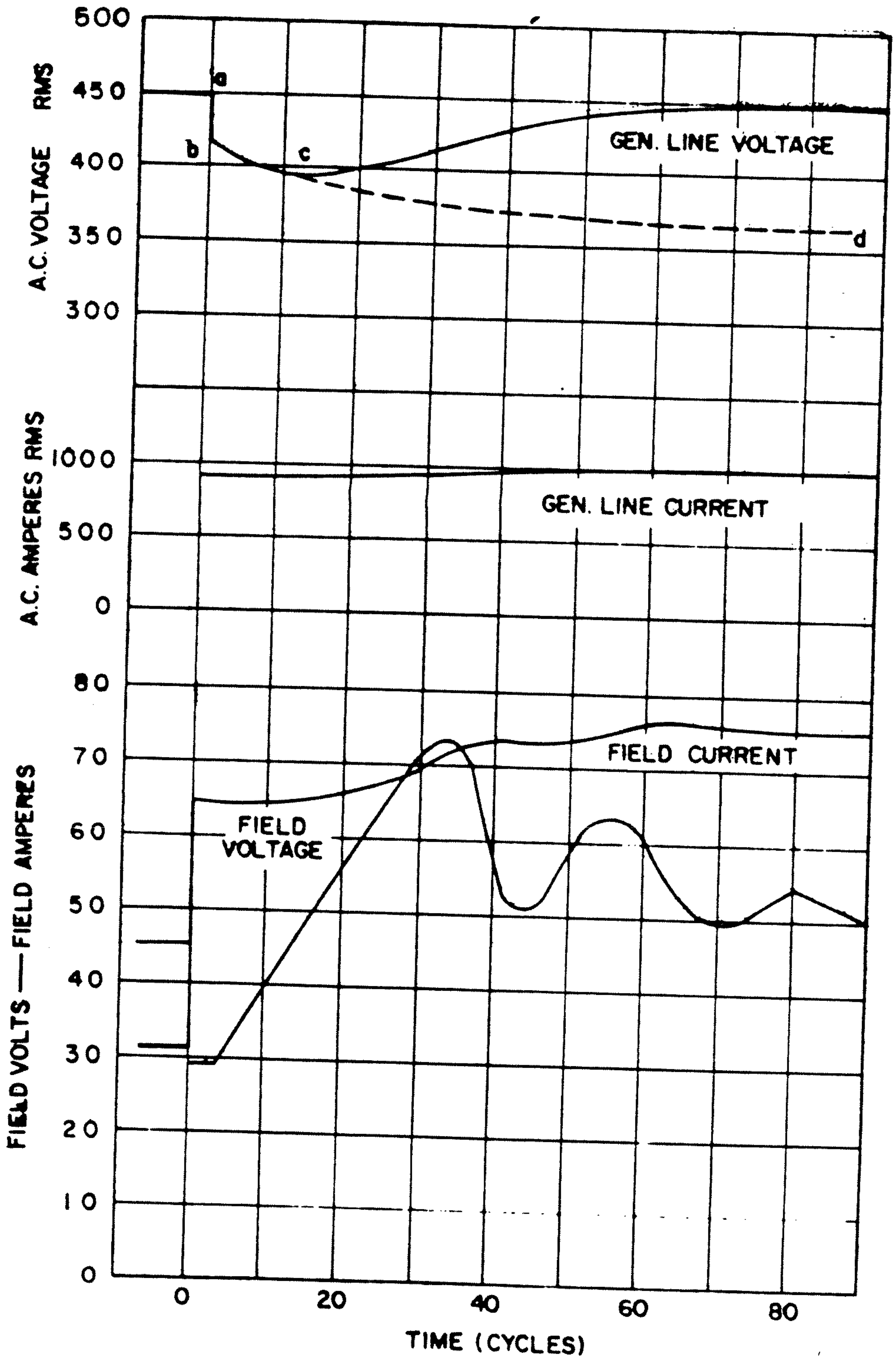


Figure 17 - Typical voltage transient for sudden application of a 2.0 per unit impedance zero power factor load to a ship service A.C. generator equipped with a direct-acting exciter field type voltage regulator.

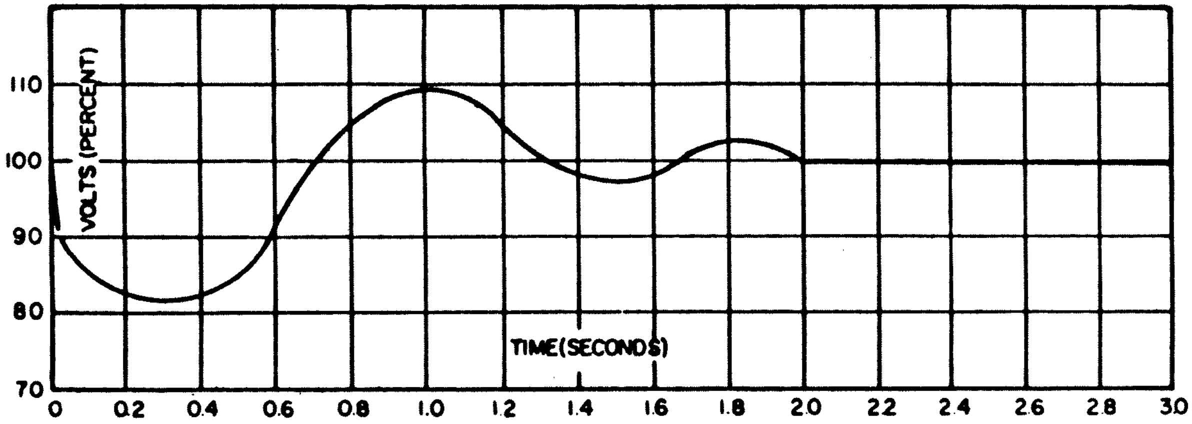
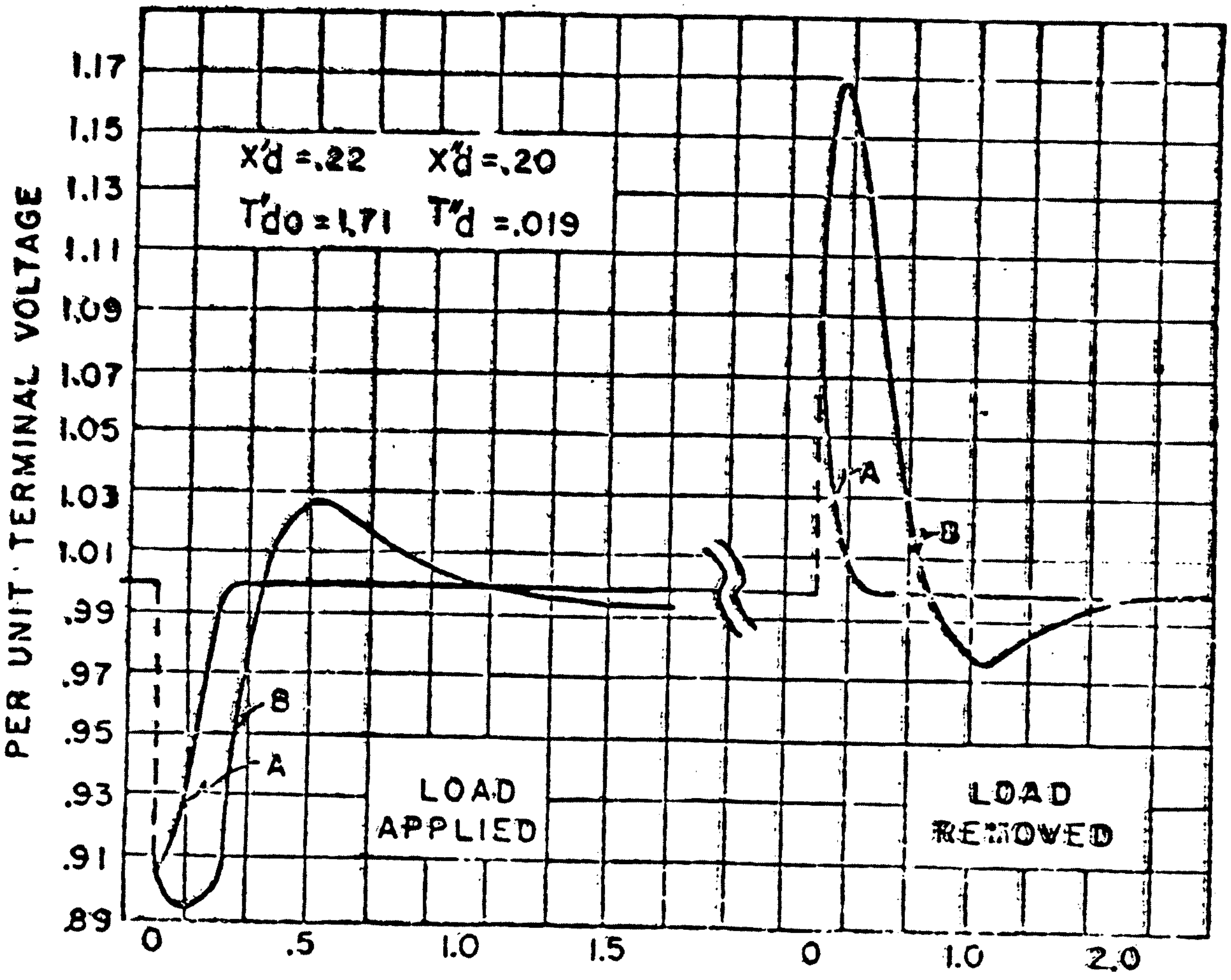


Figure 17A - Typical voltage transient (percent RMS instantaneous volts) For the direct-acting rheostatic type, the rotary amplifier type and the static scpt type regulator that operate in the transient range.



TIME IN SECONDS
TERMINAL VOLTAGE VARIATION, SUDDEN APPLICATION AND REMOVAL OF 2 P.U. IMPEDANCE, ZERO PF LOAD. WITH GENERATOR EQUIPPED WITH STATIC TYPE REGULATORS.

CURVE A STATIC SCR TYPE
CURVE B STATIC SCPT TYPE

FIGURE 17B

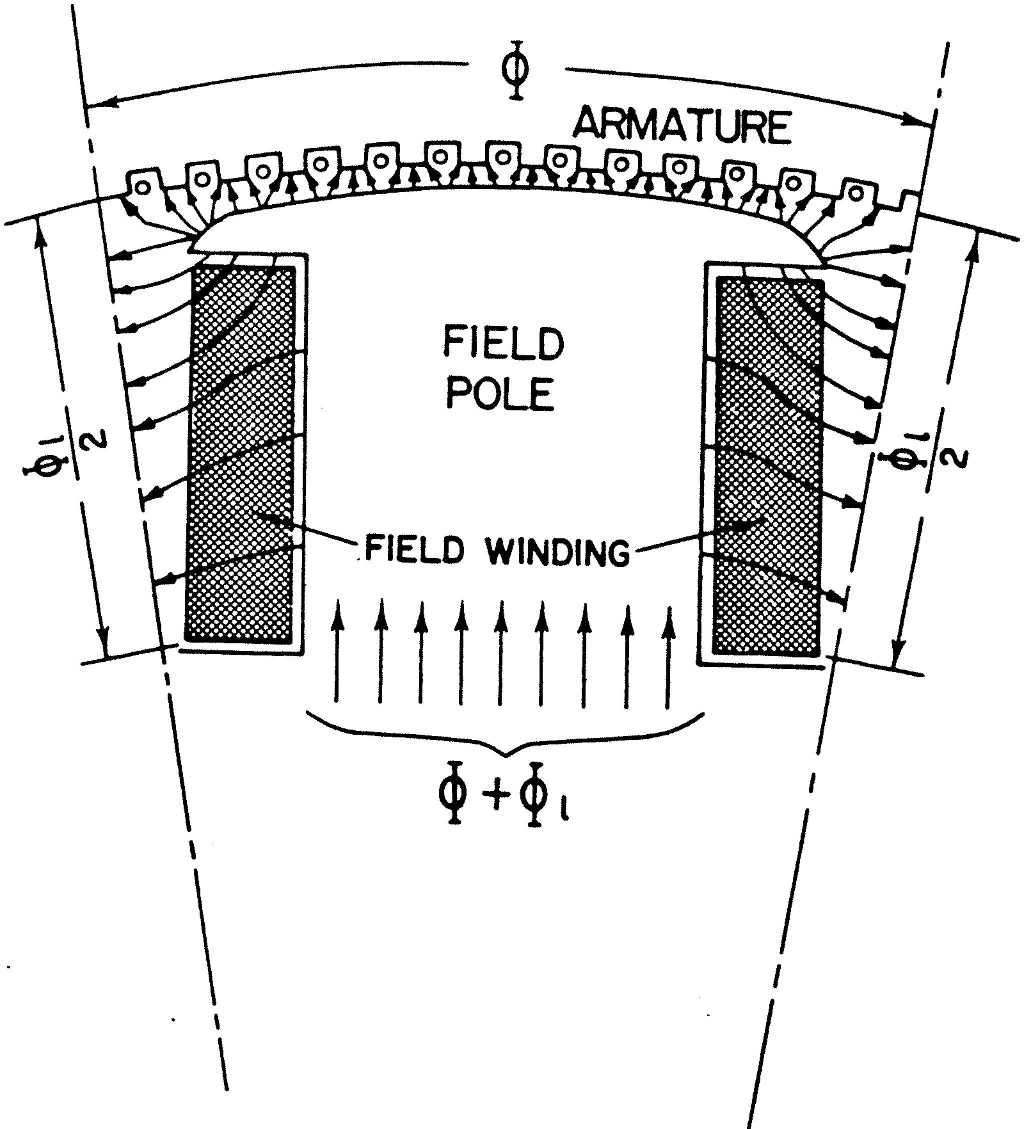


Figure 20 - AIR-GAP AND FIELD LEAKAGE FLUXES IN AN A.C. GENERATOR AT NO LOAD.

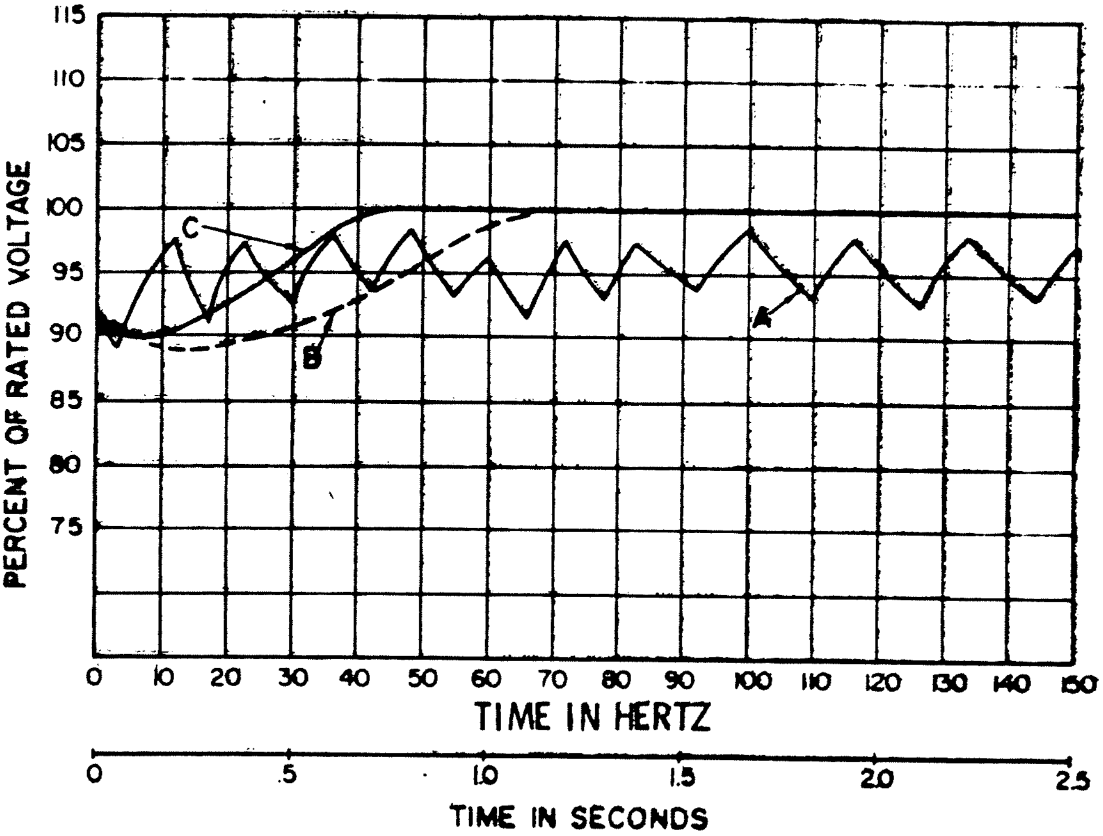


Figure 21 - COMPARATIVE PERFORANCE OF VARIOUS TYPES OF A.C. GENERATOR VOLTAGE REGULATORS.

CURVE A - INDIRECT-ACTING TYPE IN GENERATOR FIELD.
CURVE B - DIRECT-ACTING TYPE IN EXCITER FIELD.
CURVE C - ROTARY AMPLIFIER EXCITER TYPE.

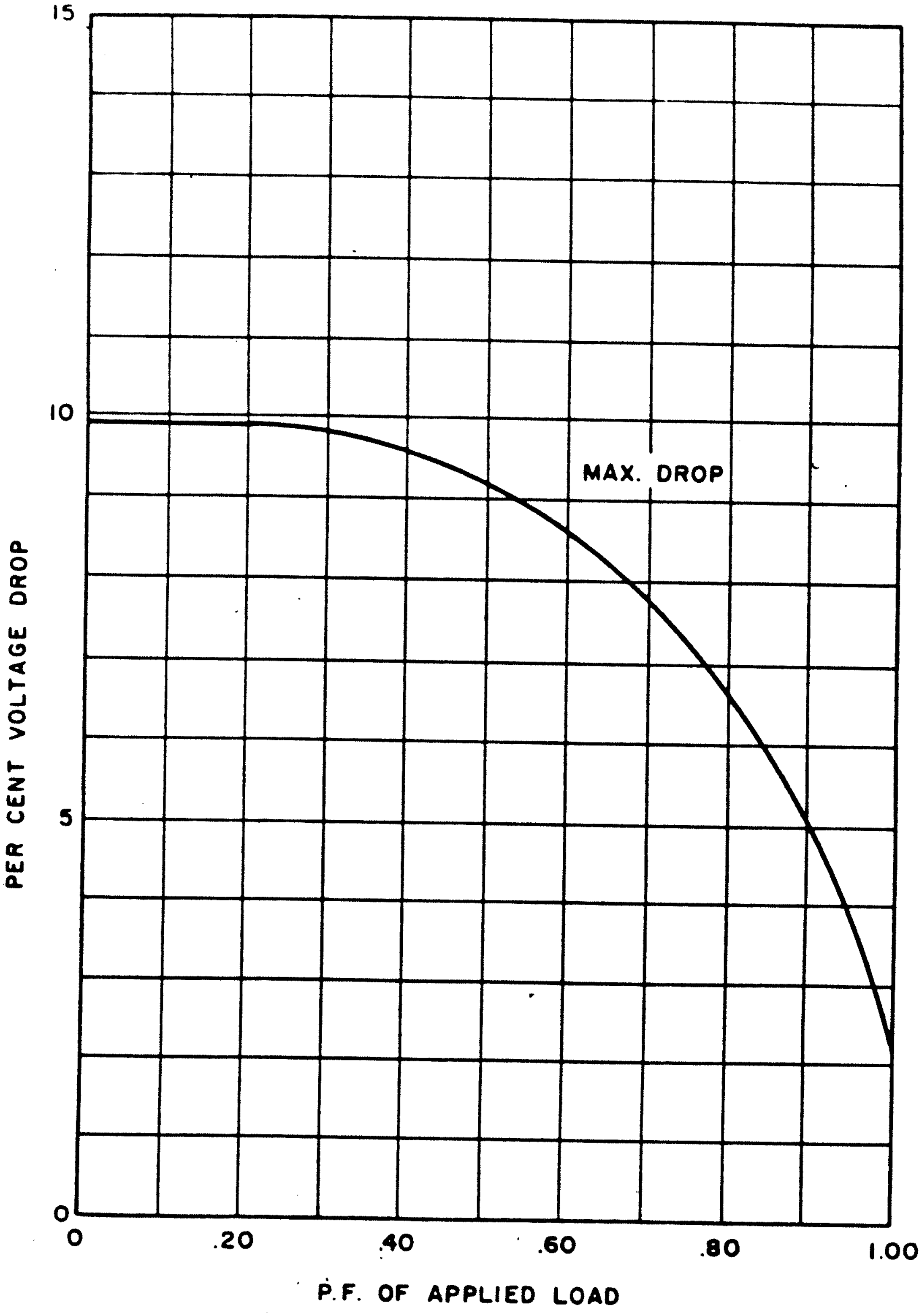


Figure 22 -TRANSIENT VOLTAGE DIP VS. POWER FACTOR OF SUDDENLY APPLIED LOAD

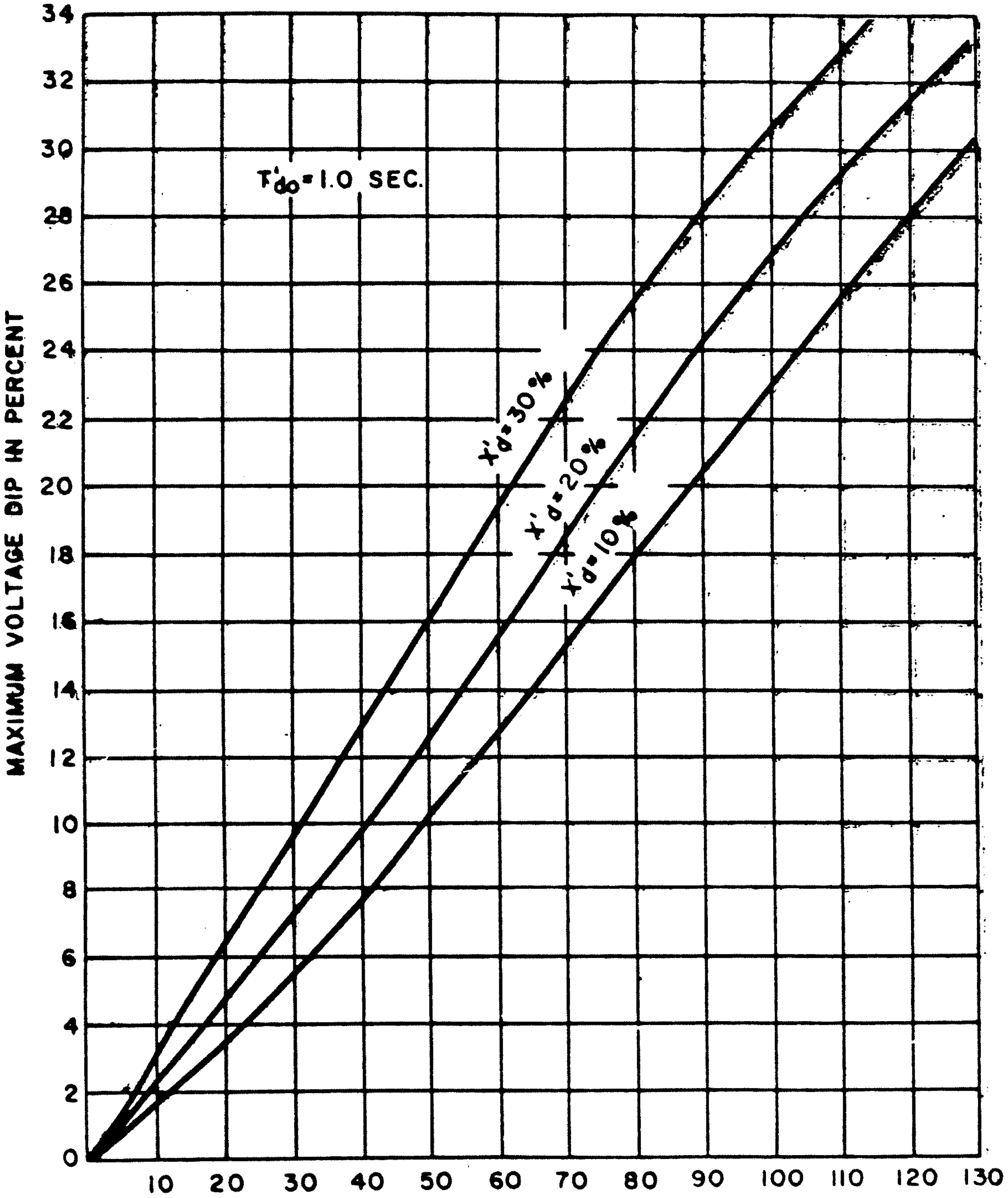
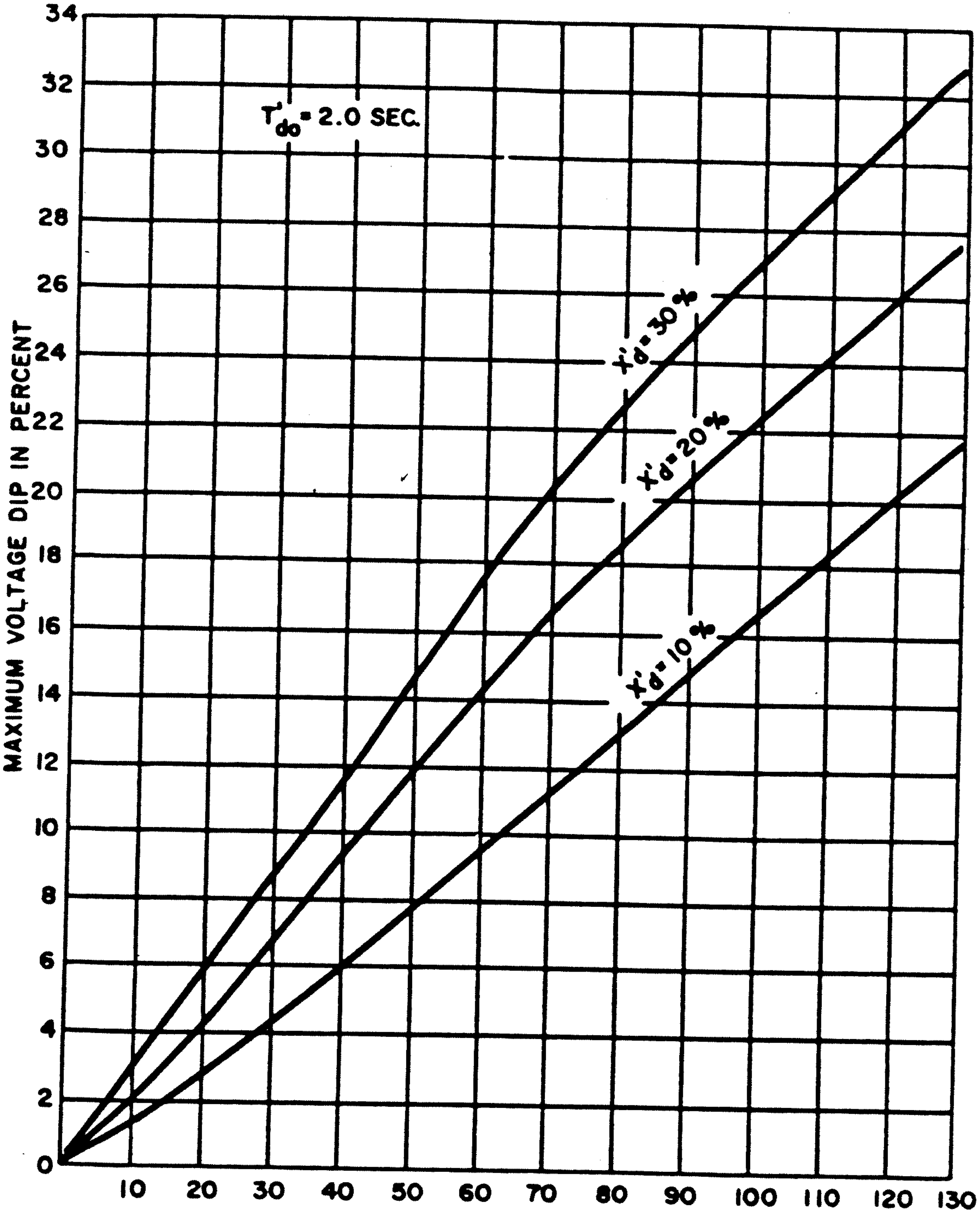


Figure 23-1 - TRANSIENT VOLTAGE DIP VS. SUDDENLY APPLIED LOAD FOR A.C. GENERATORS WITH VARIOUS TRANSIENT REACTANCES X'd, AND TRANSIENT OPEN CIRCUIT TIME CONSTANTS T'do



APPLIED LOAD (0.4 PF) IN PERCENT AT FULL VOLTAGE

Figure 23-2

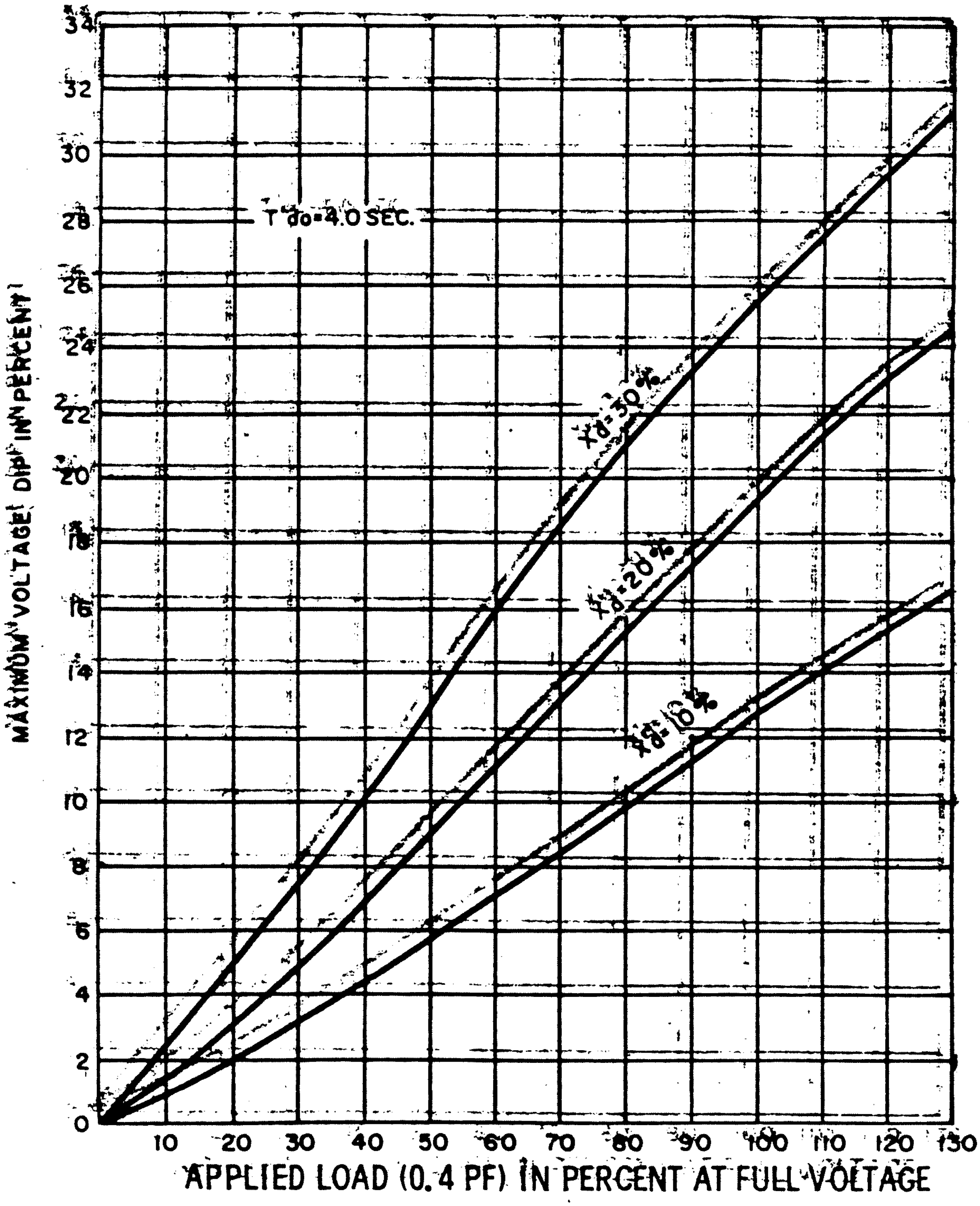

T'do=4.0 SEC.
X'd=30%
X'd=20%
X'd=10%
MAXIMUM VOLTAGE DIP IN PERCENT
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
32
34
10
20
30
40
50
60
70
80
90
100
110
120
130
APPLIED LOAD (0.4 PF) IN PERCENT AT FULL VOLTAGE

Figure 23-3

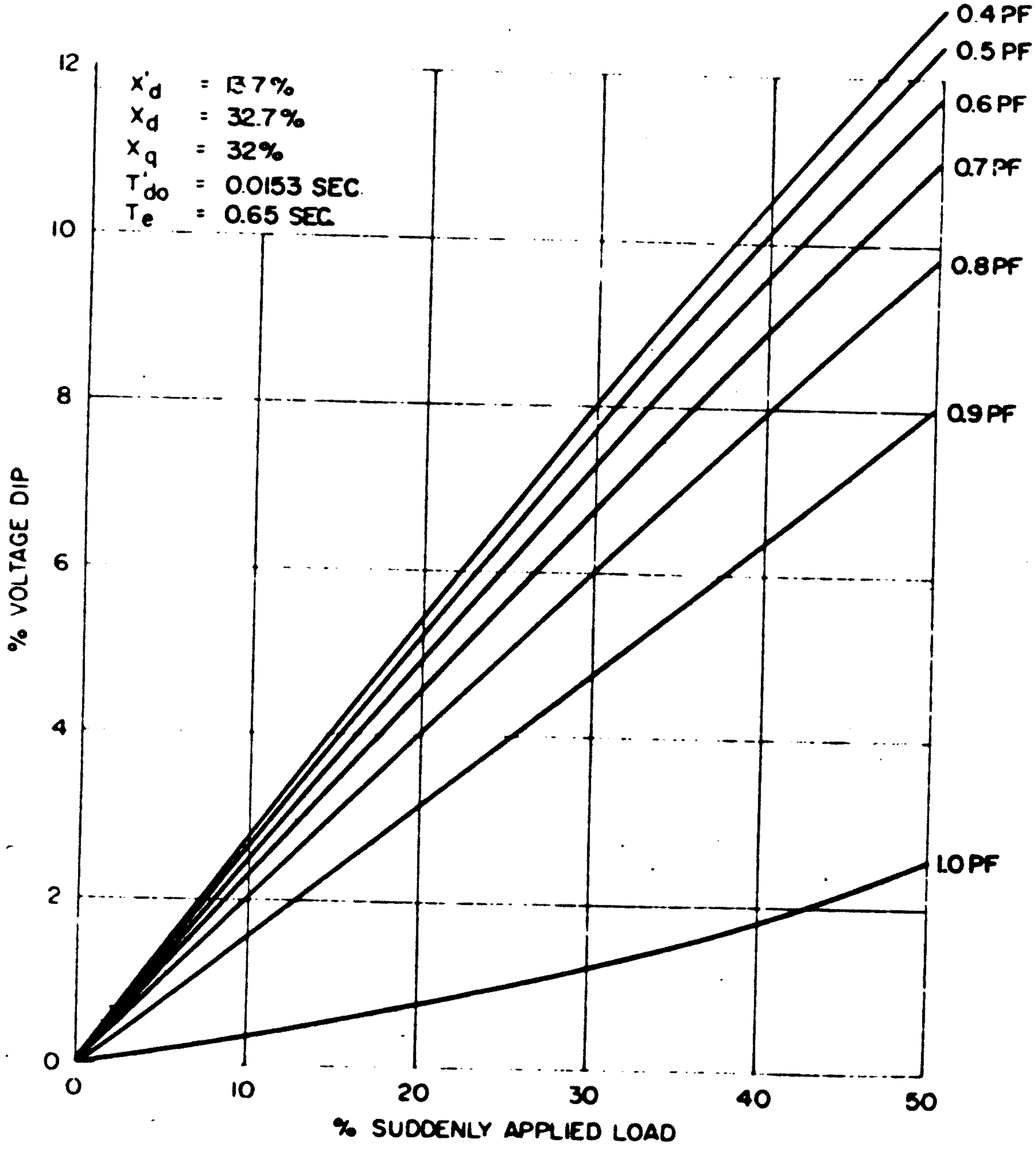

X'd = 13.7%
Xd = 32.7%
Xq = 32%
T'do = 0.0153 SEC
Te = 0.65 SEC
0.4 PF
0.5 PF
0.6 PF
0.7 PF
0.8 PF
0.9 PF
1.0 PF
% VOLTAGE DIP
0
2
4
6
8
10
12
0
10
20
30
40
50
% SUDDENLY APPLIED LOAD

Figure 23A-1

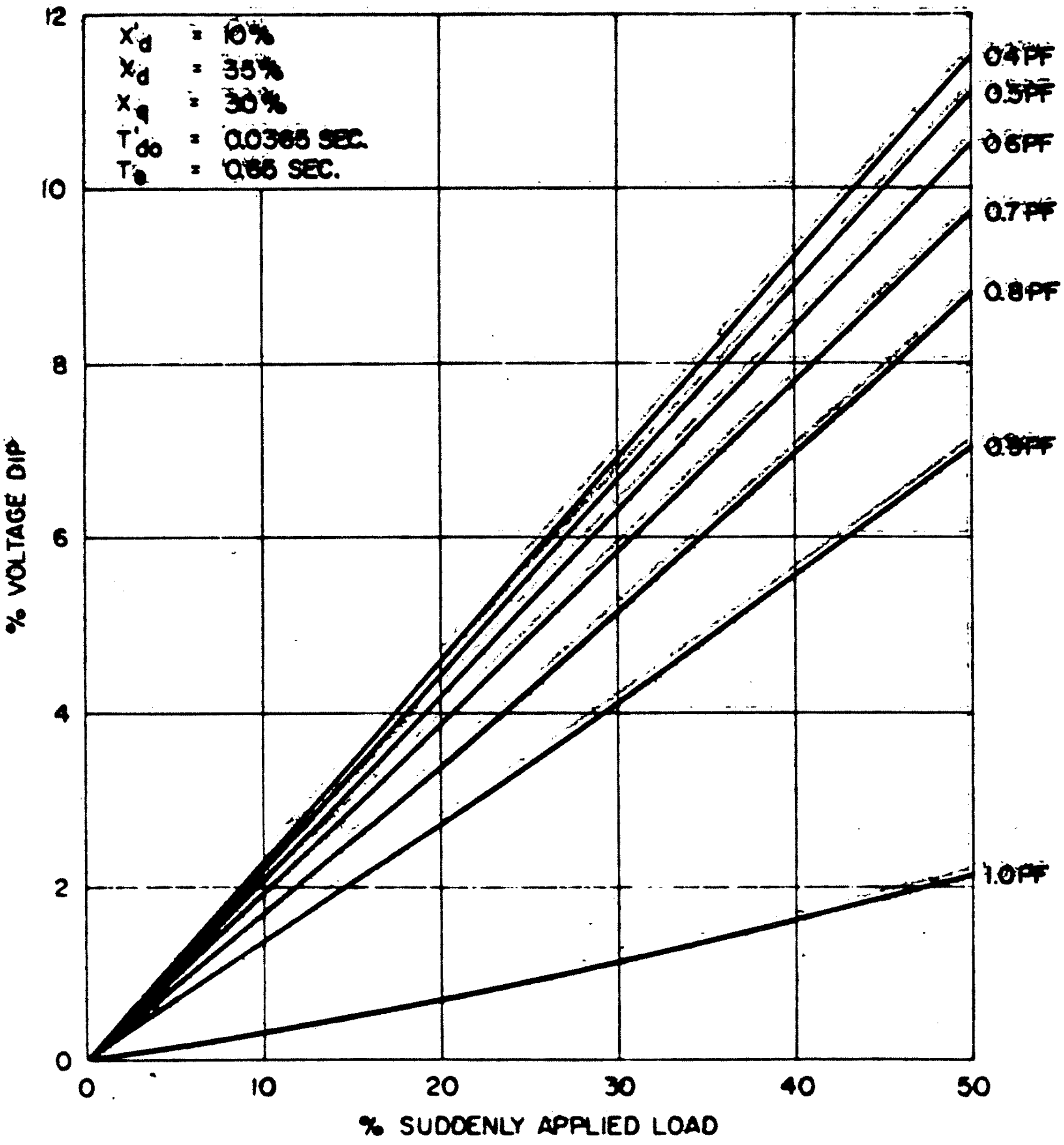

X'd = 10%
Xd = 35%
Xq = 30%
T'do = 0.0365 SEC.
Ta = 0.65 SEC.
% VOLTAGE DIP
% SUDDENLY APPLIED LOAD
0
2
4
6
8
10
12
0
10
20
30
40
50
0.4PF
0.5PF
0.6PF
0.7PF
0.8PF
0.9PF
1.0PF

Figure 23A-2

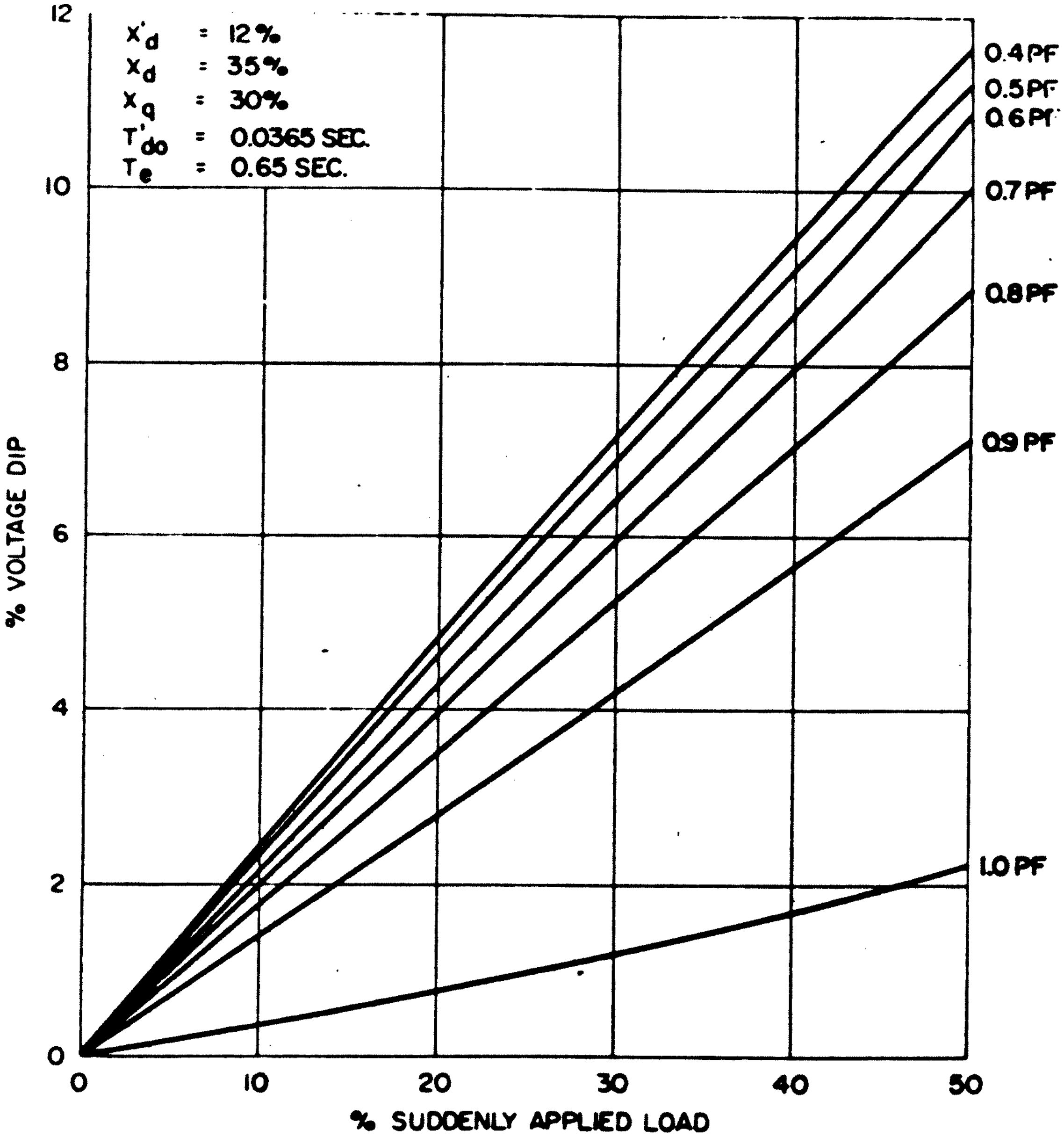

X'_d = 12%
X_d = 35%
X_q = 30%
T'_{do} = 0.0365 SEC.
T_e = 0.65 SEC.
0.4 PF
0.5 PF
0.6 PF
0.7 PF
0.8 PF
0.9 PF
1.0 PF
% VOLTAGE DIP
0
2
4
6
8
10
12
0
10
20
30
40
50
% SUDDENLY APPLIED LOAD

Figure 23A-3

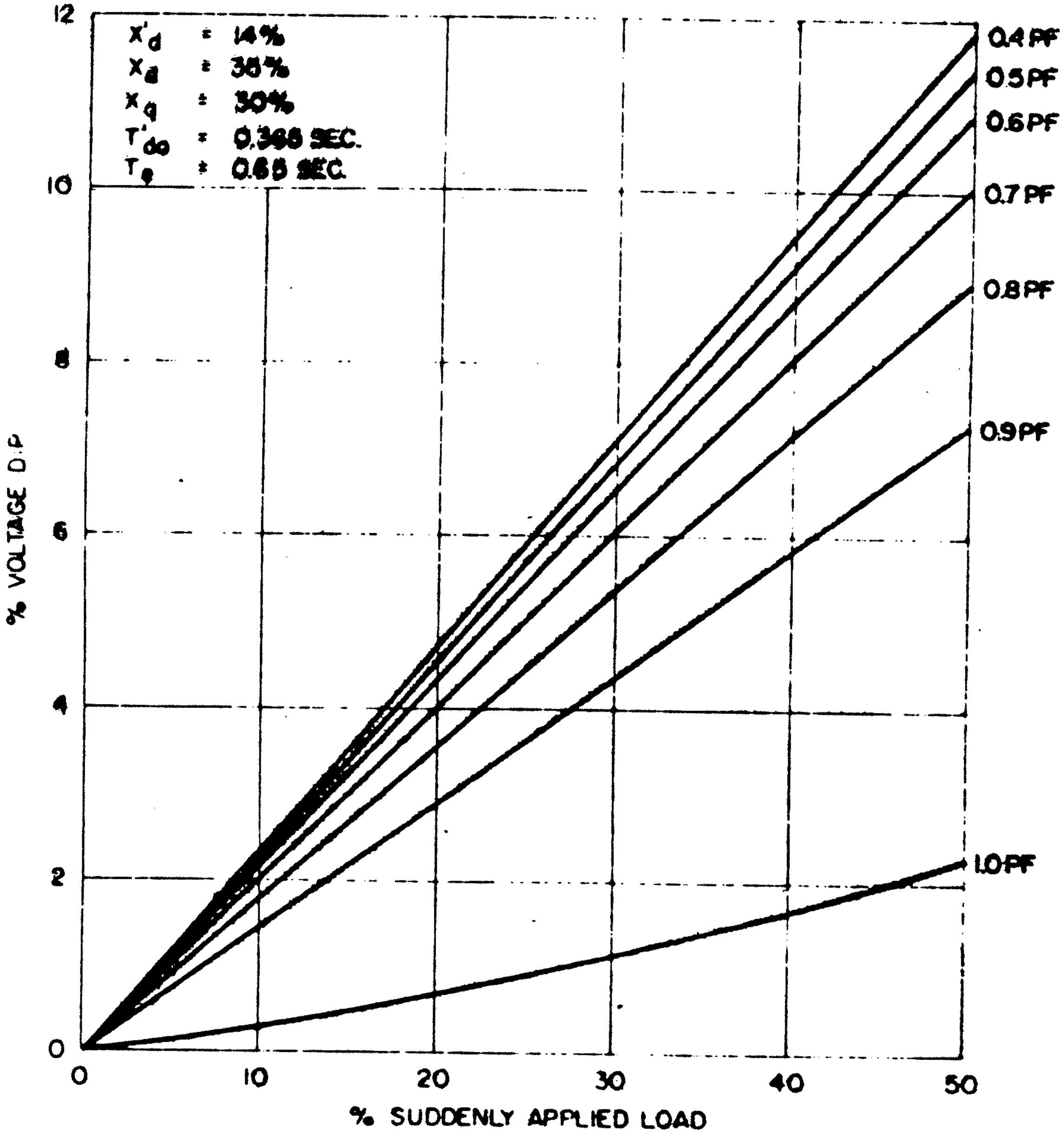

X'_d = 14%
X_d = 35%
X_q = 30%
T'_{do} = 0.366 SEC.
T_e = 0.65 SEC.
0.4 PF
0.5 PF
0.6 PF
0.7 PF
0.8 PF
0.9 PF
1.0 PF
% VOLTAGE DIP
12
10
8
6
4
2
0
0
10
20
30
40
50
% SUDDENLY APPLIED LOAD

Figure 23A-4

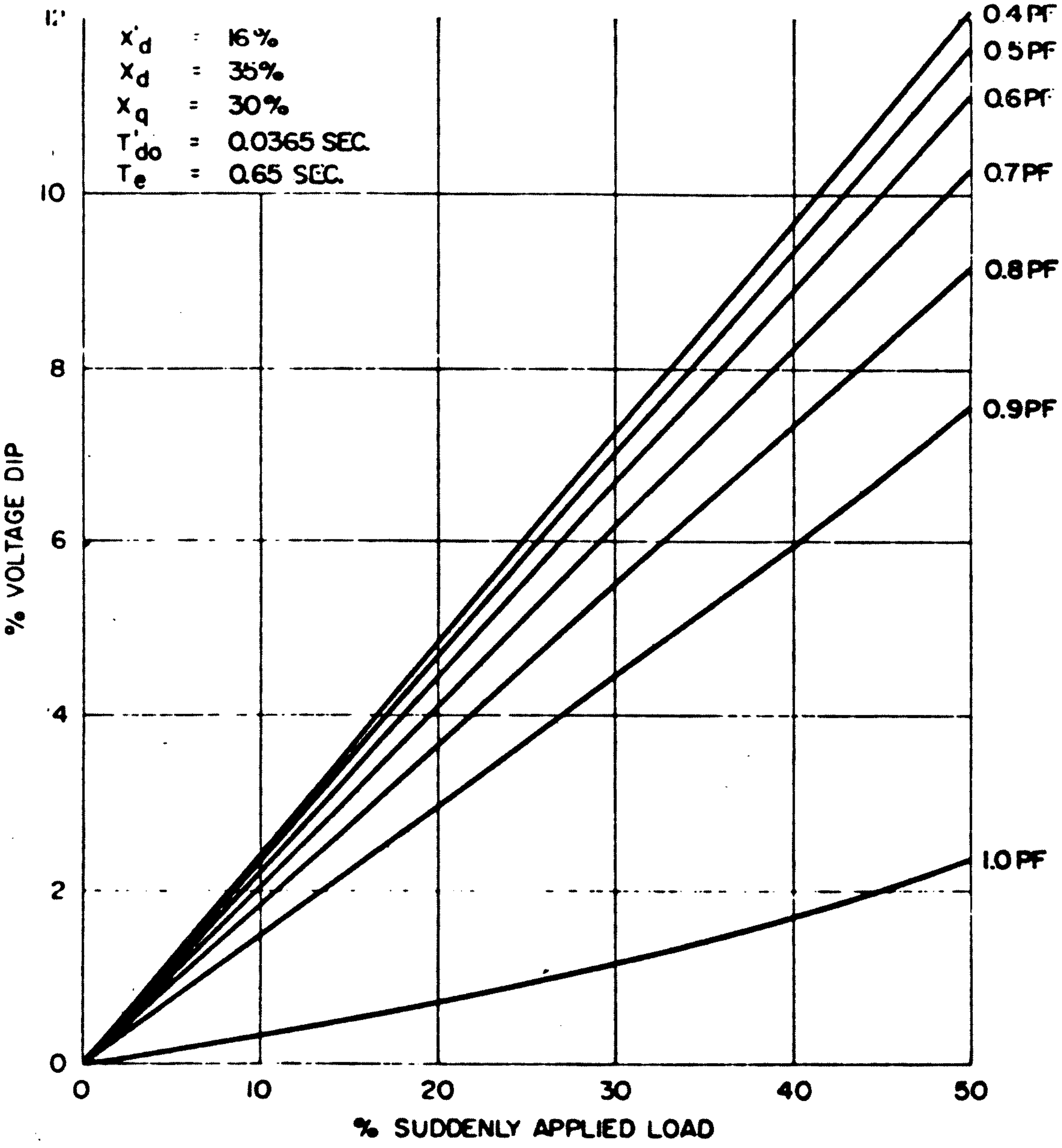

X'd = 16%
Xd = 35%
Xq = 30%
T'do = 0.0365 SEC.
Te = 0.65 SEC.
12
10
8
6
4
2
0
% VOLTAGE DIP
0
10
20
30
40
50
% SUDDENLY APPLIED LOAD
0.4 PF
0.5 PF
0.6 PF
0.7 PF
0.8 PF
0.9 PF
1.0 PF

Figure 23A-5

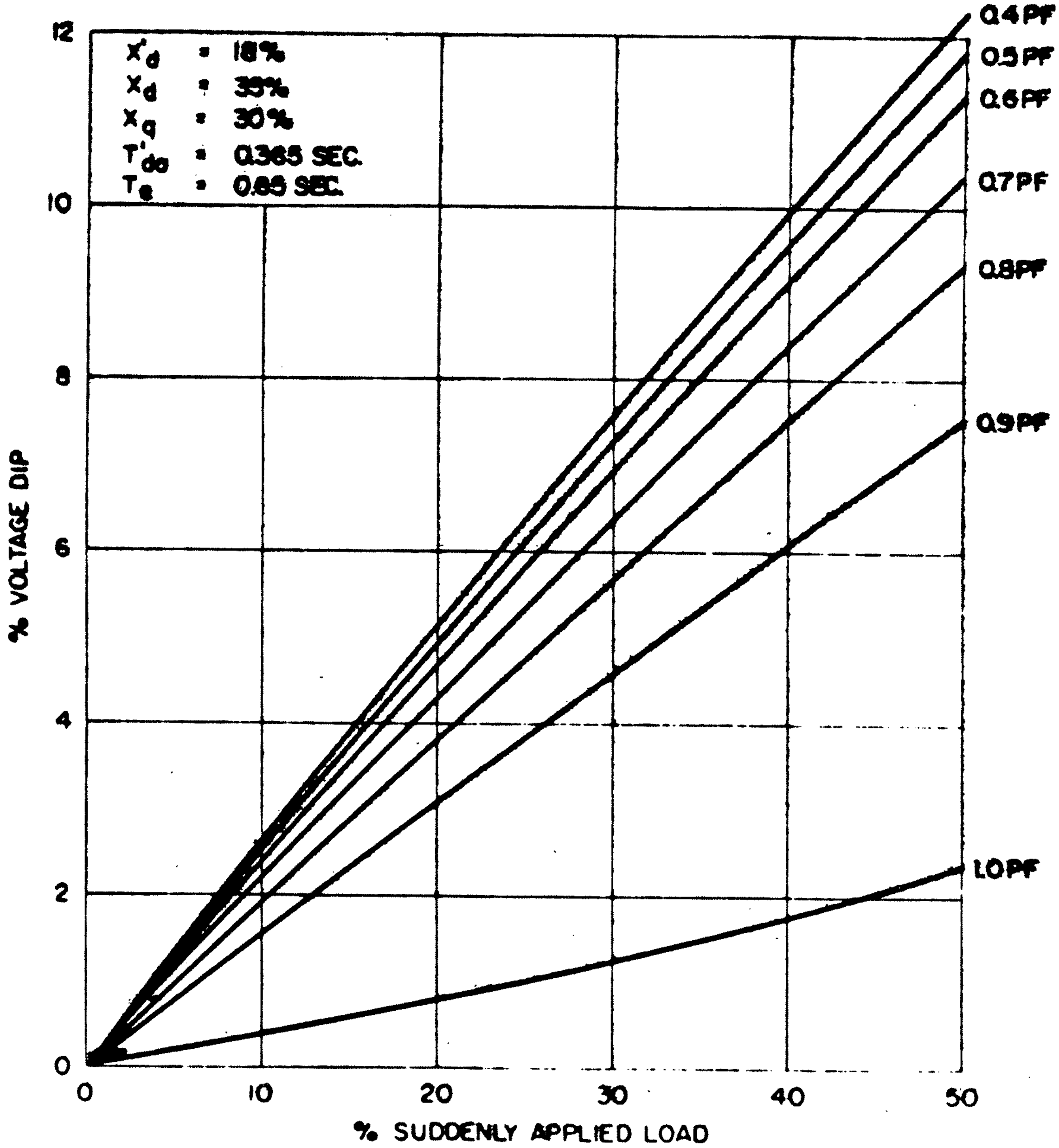
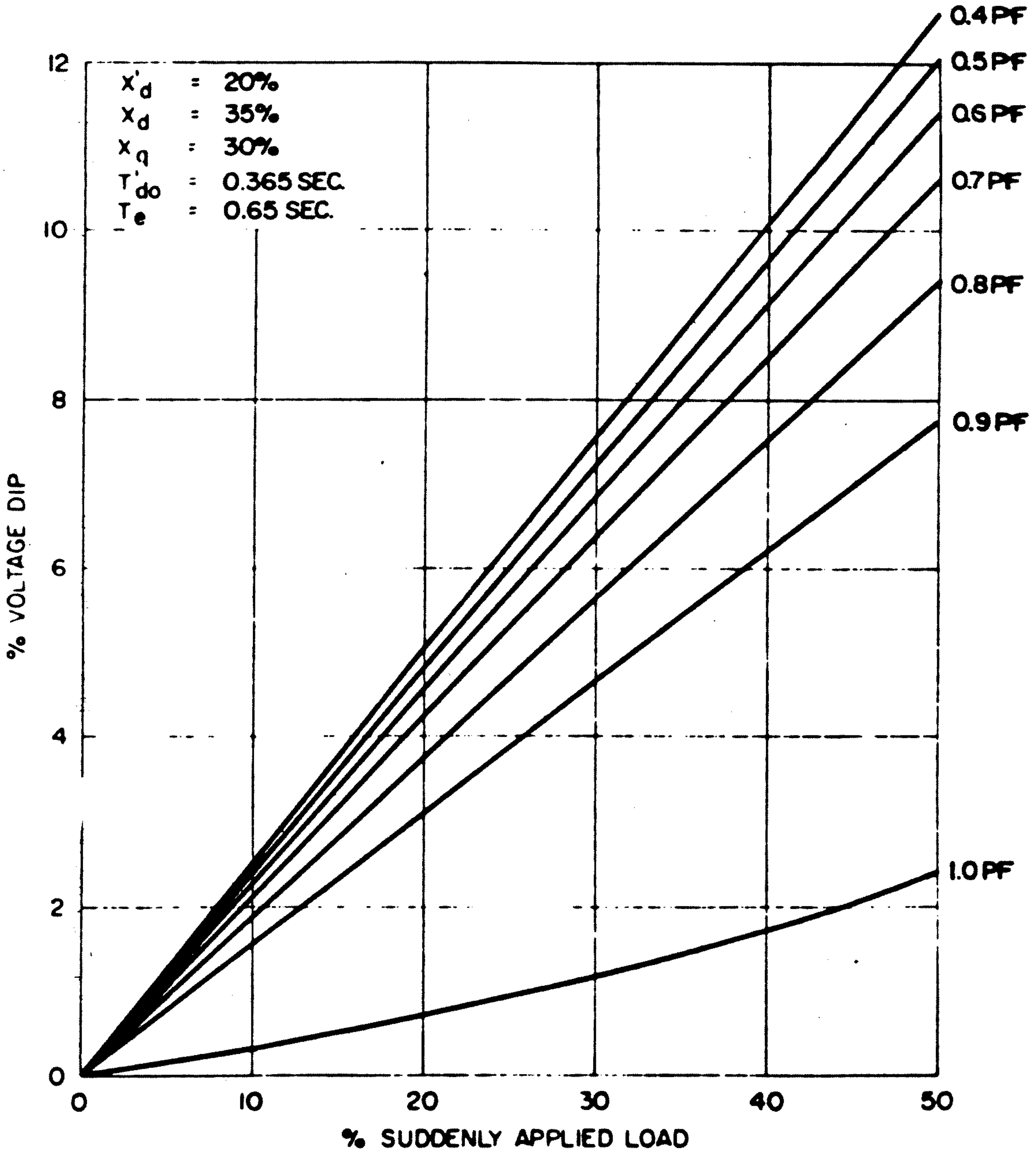

X'd = 18%
Xd = 35%
Xq = 30%
T'do = 0.365 SEC.
Te = 0.85 SEC.
0.4PF
0.5PF
0.6PF
0.7PF
0.8PF
0.9PF
1.0PF
% VOLTAGE DIP
0
2
4
6
8
10
12
0
10
20
30
40
50
% SUDDENLY APPLIED LOAD

Figure 23A-6



X'd = 20%
Xd = 35%
Xq = 30%
T'do = 0.365 SEC.
Te = 0.65 SEC.
0.4 PF
0.5 PF
0.6 PF
0.7 PF
0.8 PF
0.9 PF
1.0 PF
% VOLTAGE DIP
0
2
4
6
8
10
12
0
10
20
30
40
50
% SUDDENLY APPLIED LOAD

Figure 23A-7

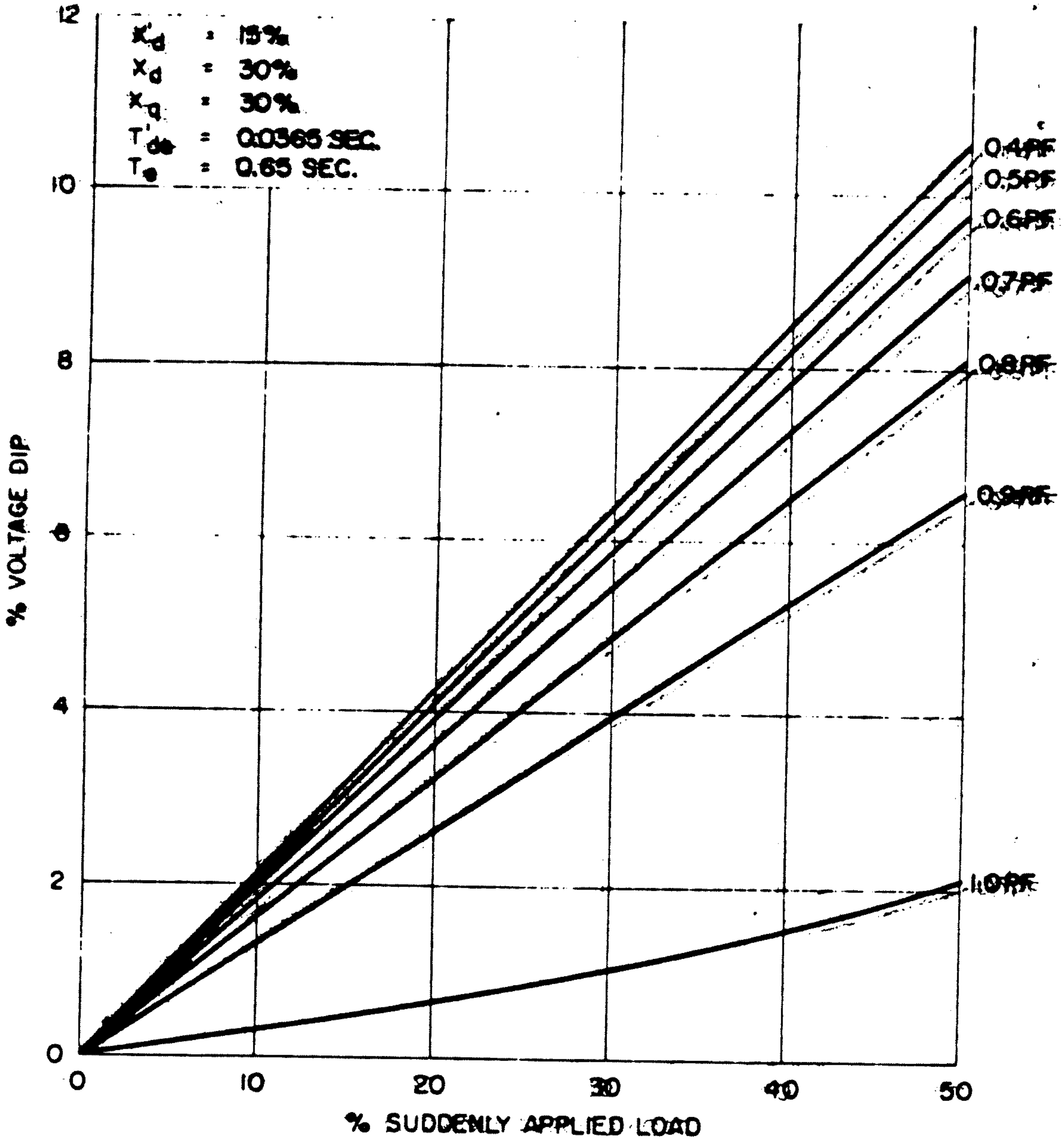

X'_d = 15%
X_d = 30%
X_q = 30%
T'_{do} = 0.0366 SEC.
T_e = 0.65 SEC.
0.4PF
0.5PF
0.6PF
0.7PF
0.8PF
0.9PF
1.0PF
% VOLTAGE DIP
% SUDDENLY APPLIED LOAD
0
2
4
6
8
10
12
0
10
20
30
40
50

Figure 23A-8

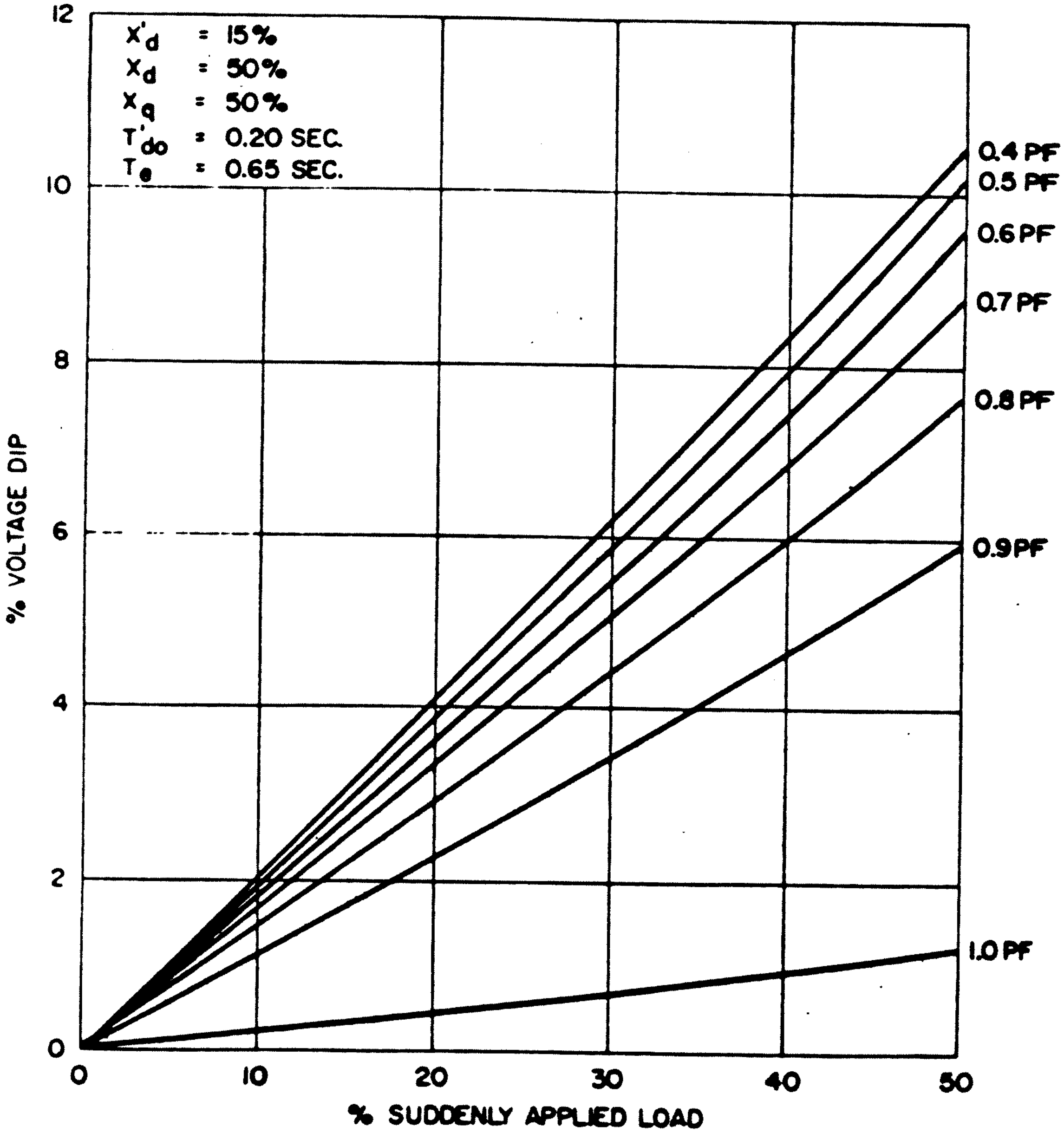

X'd = 15%
Xd = 50%
Xq = 50%
T'do = 0.20 SEC.
Te = 0.65 SEC.
0.4 PF
0.5 PF
0.6 PF
0.7 PF
0.8 PF
0.9 PF
1.0 PF
% VOLTAGE DIP
0
2
4
6
8
10
12
0
10
20
30
40
50
% SUDDENLY APPLIED LOAD

Figure 23A-9

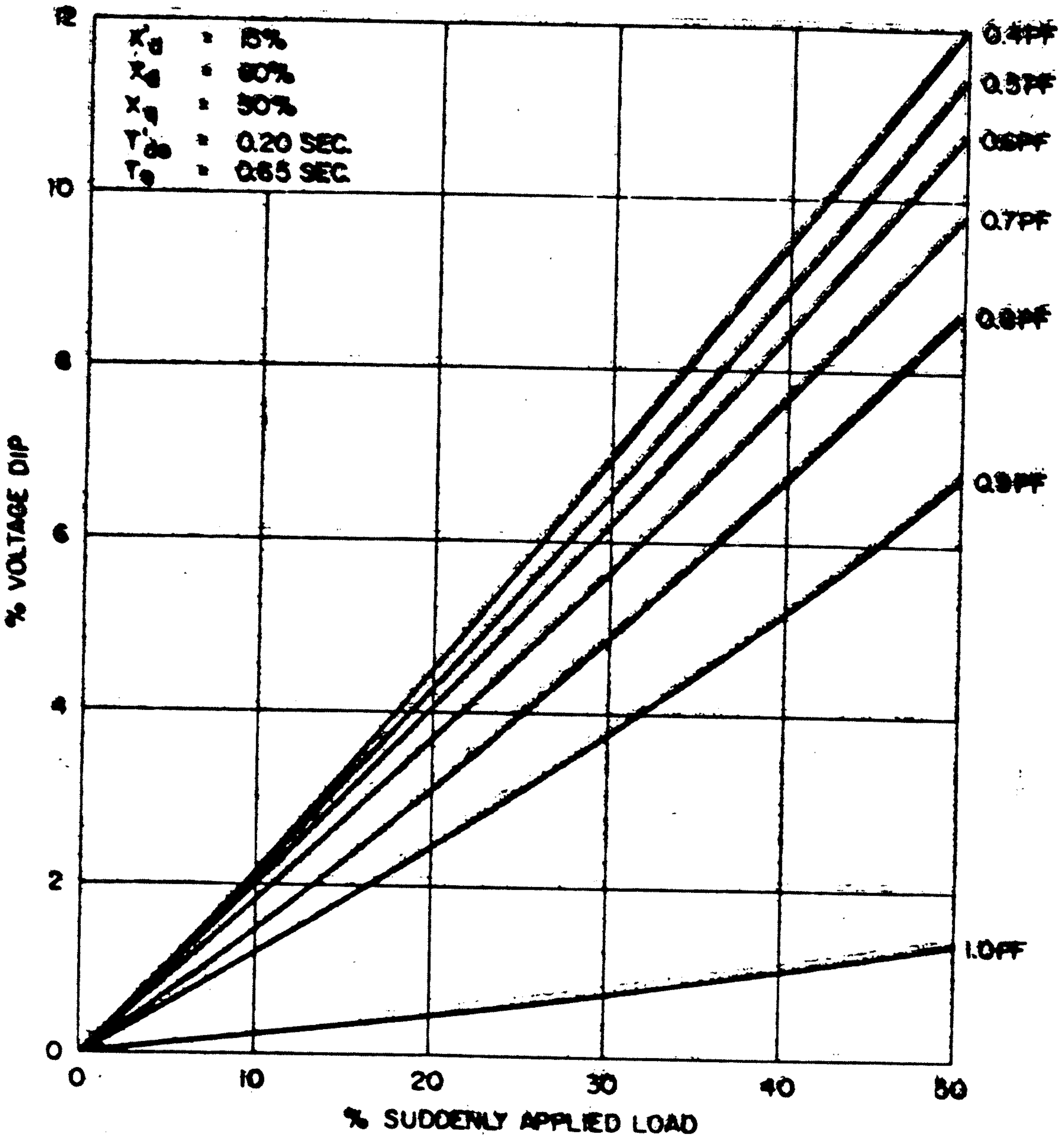


Figure 23A-10

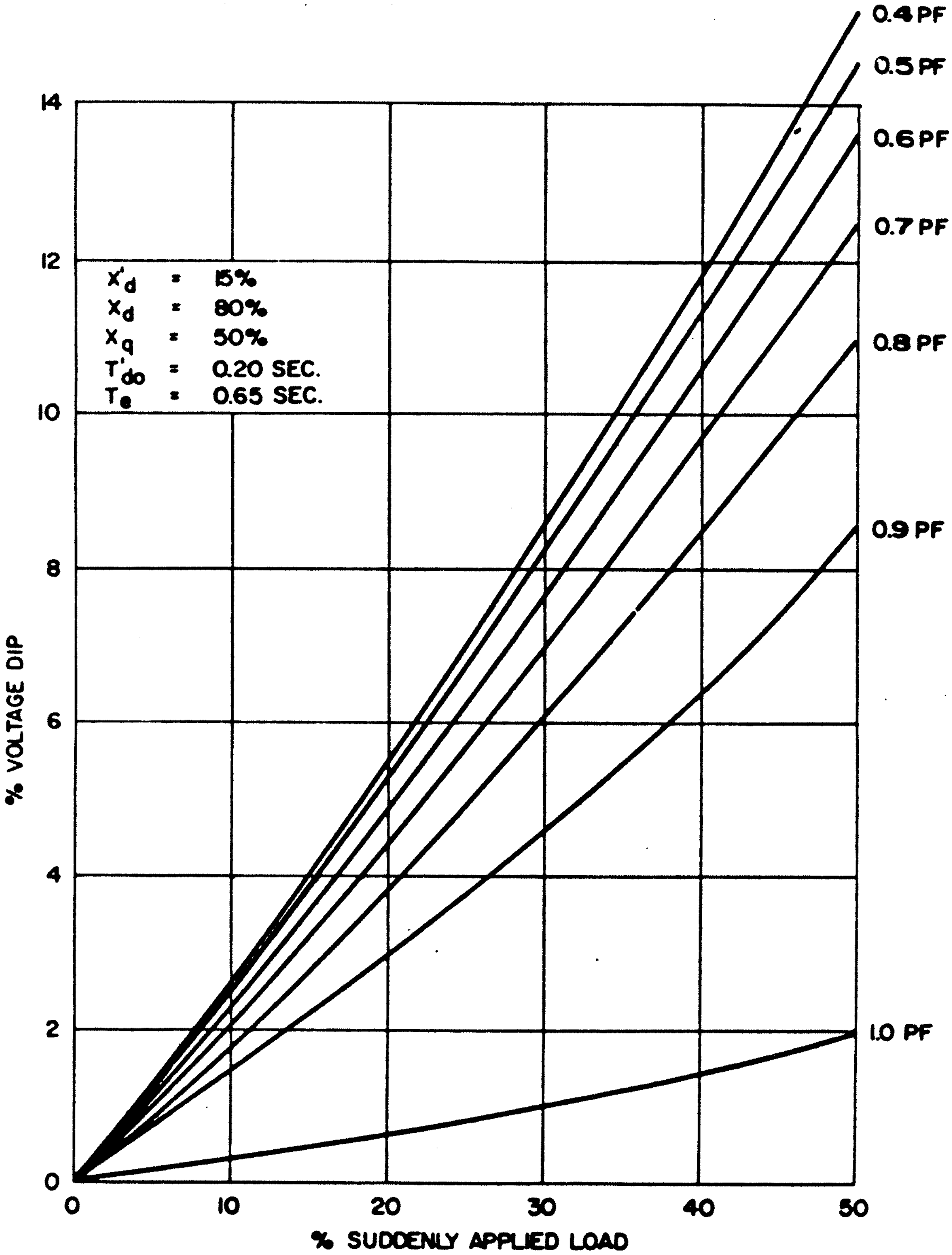


Figure 23A-11

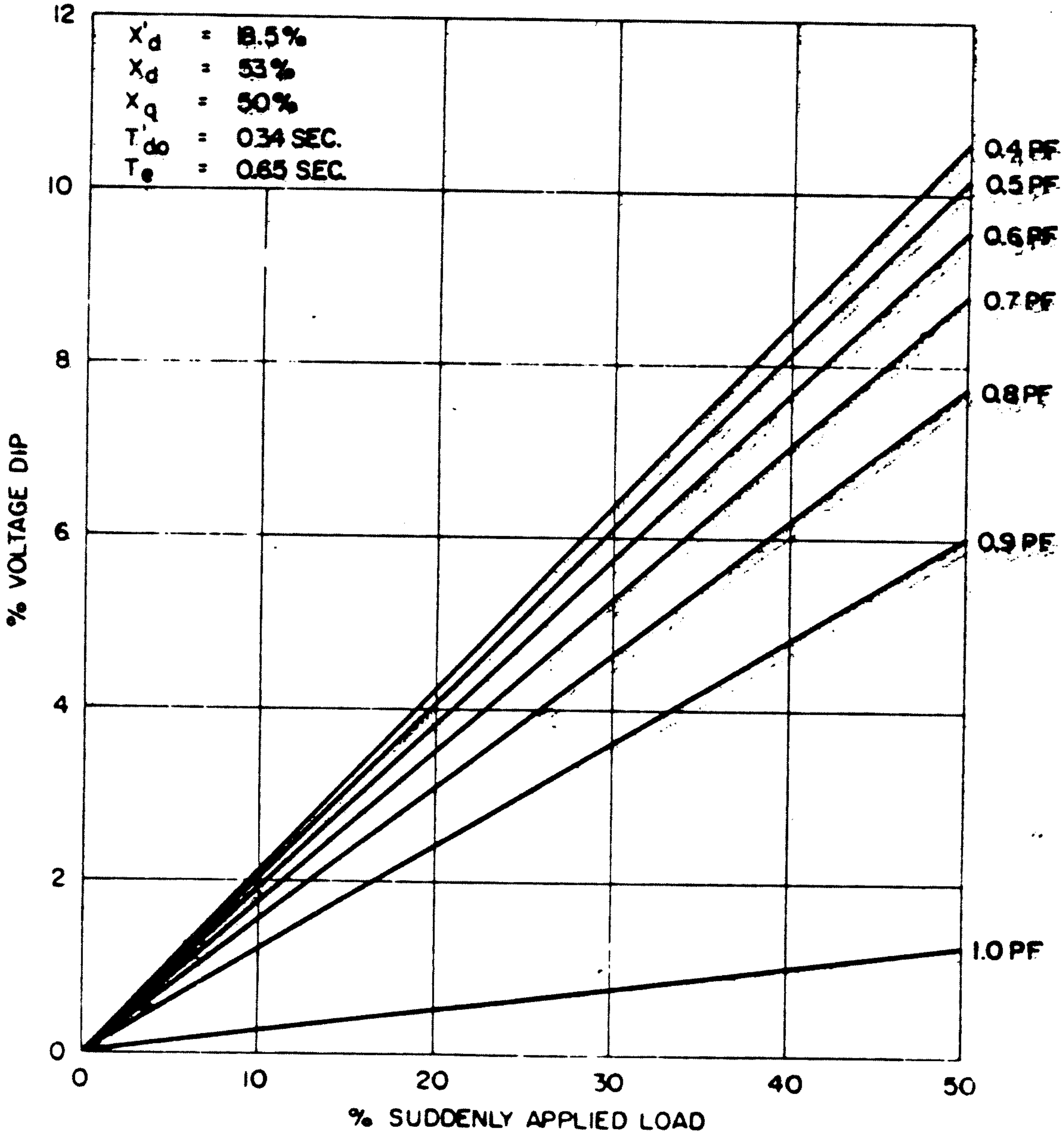


Figure 23A-12

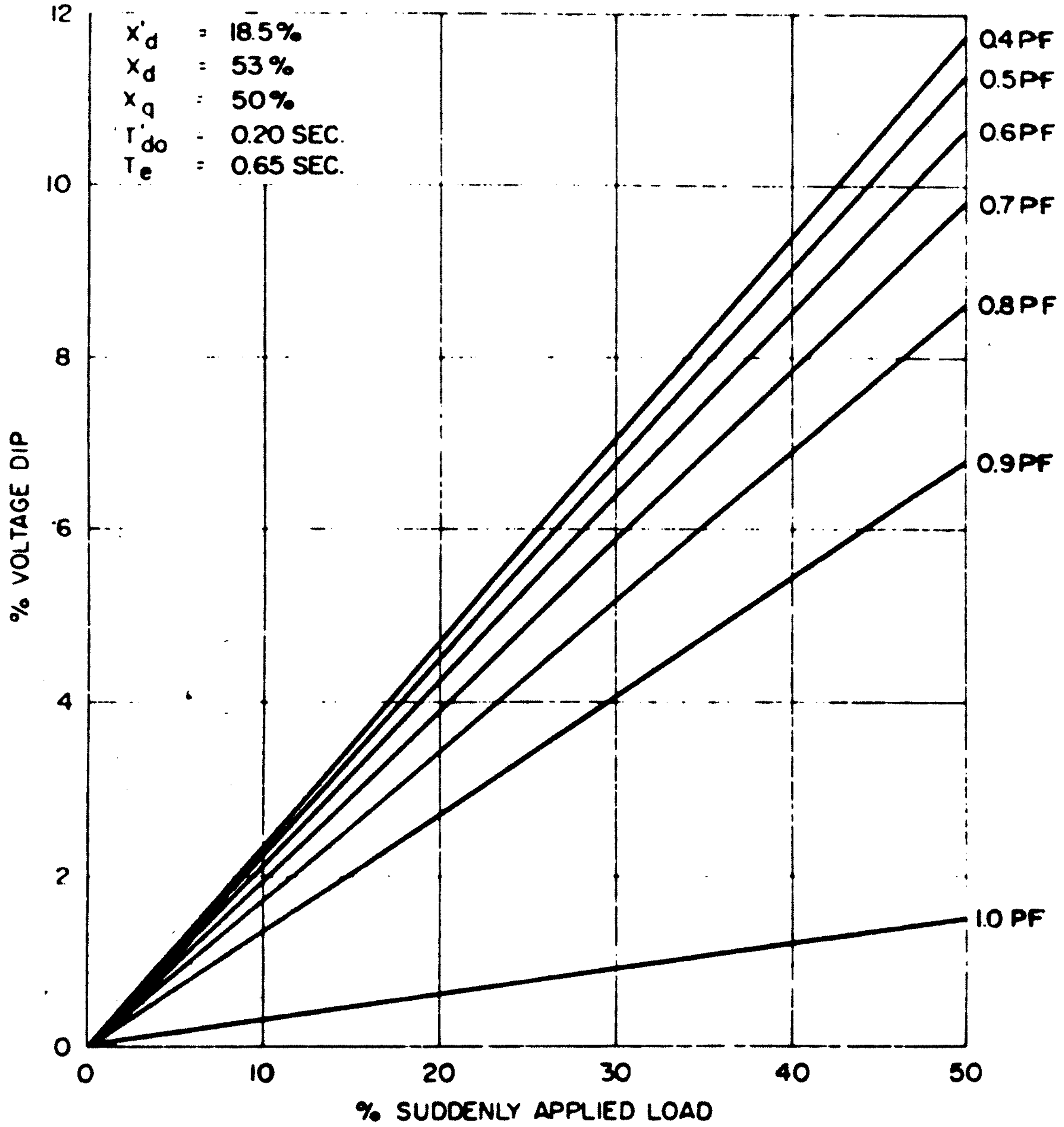


Figure 23A-13

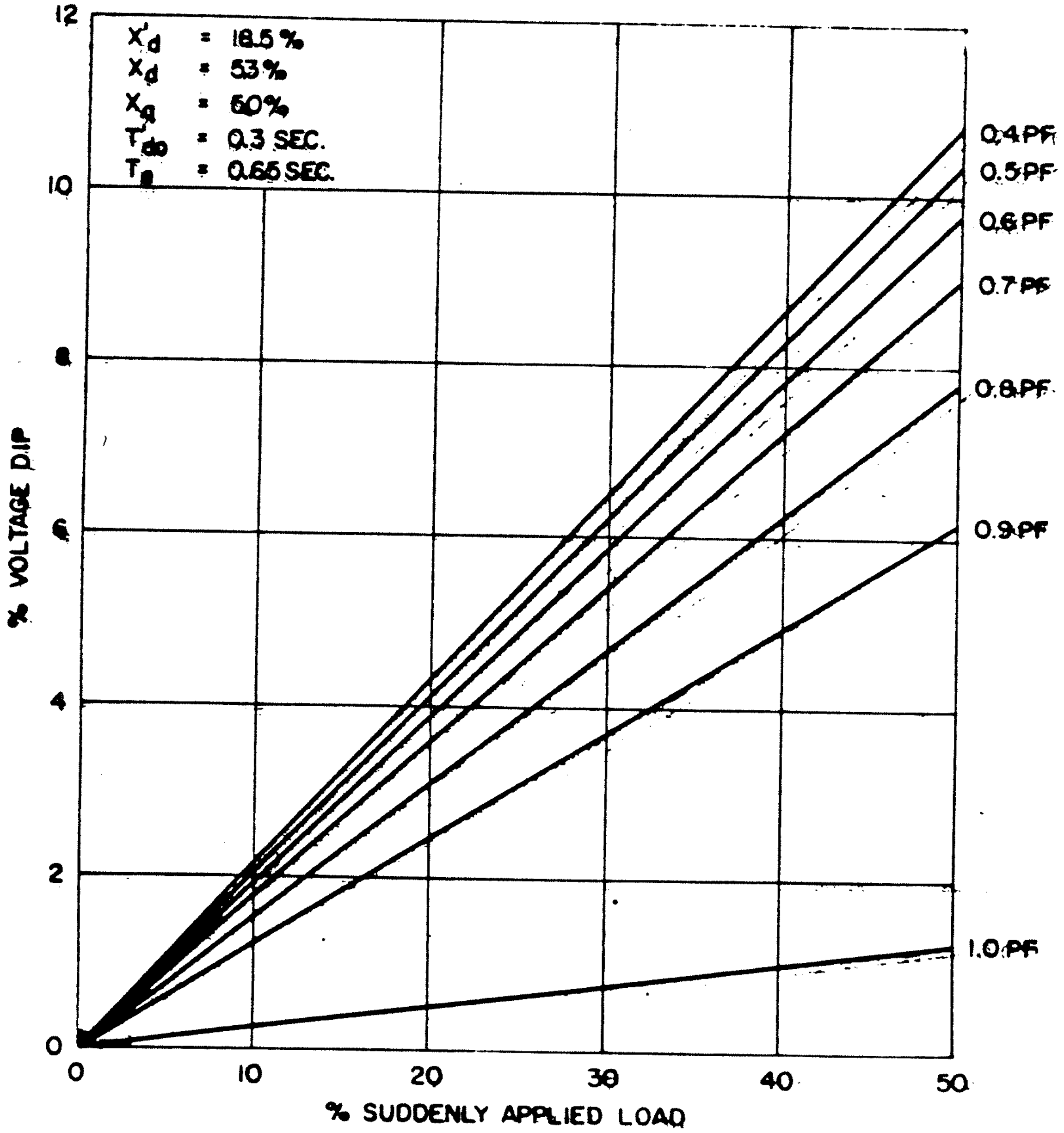


Figure 23A-14

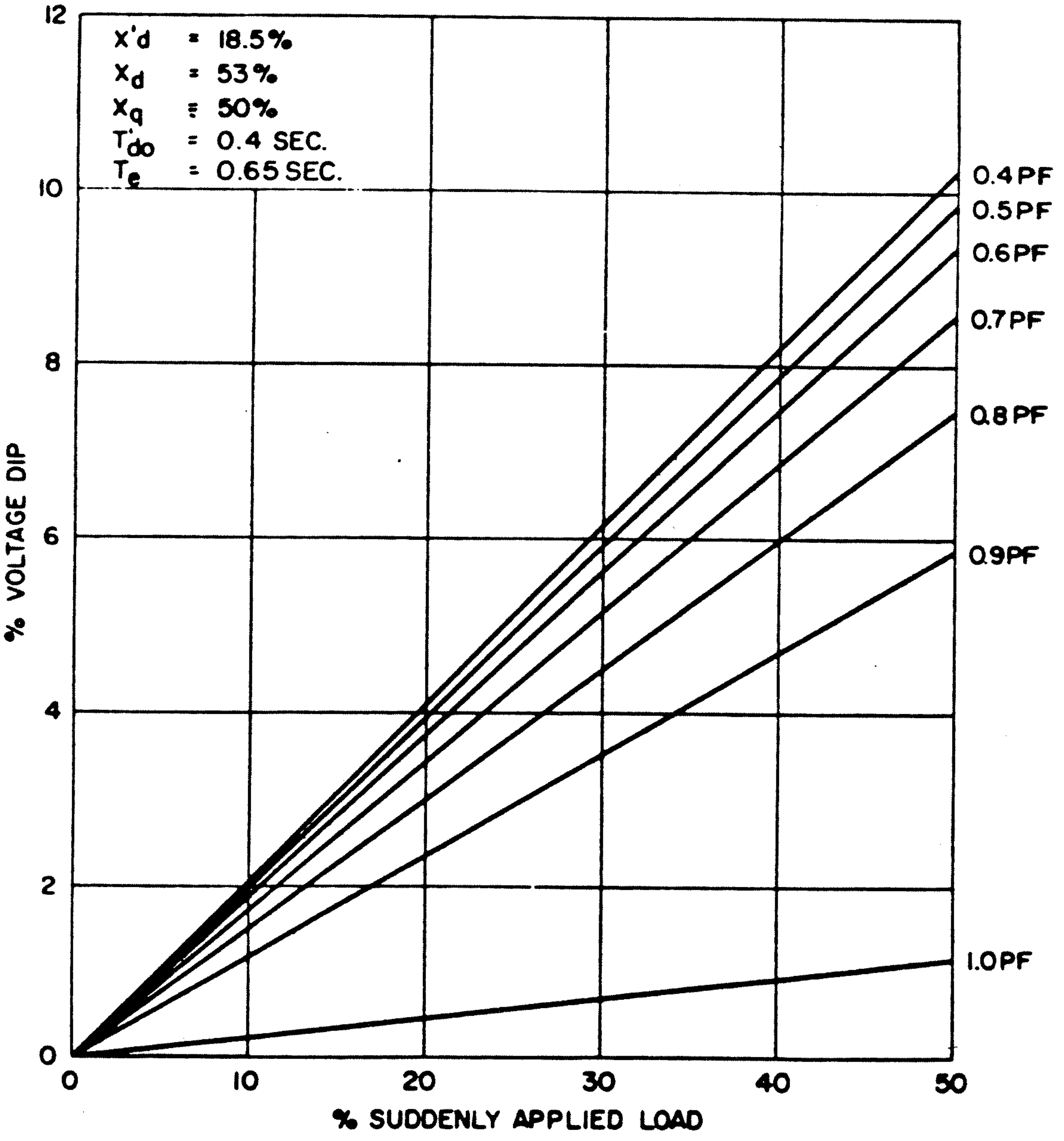


Figure 23A-15

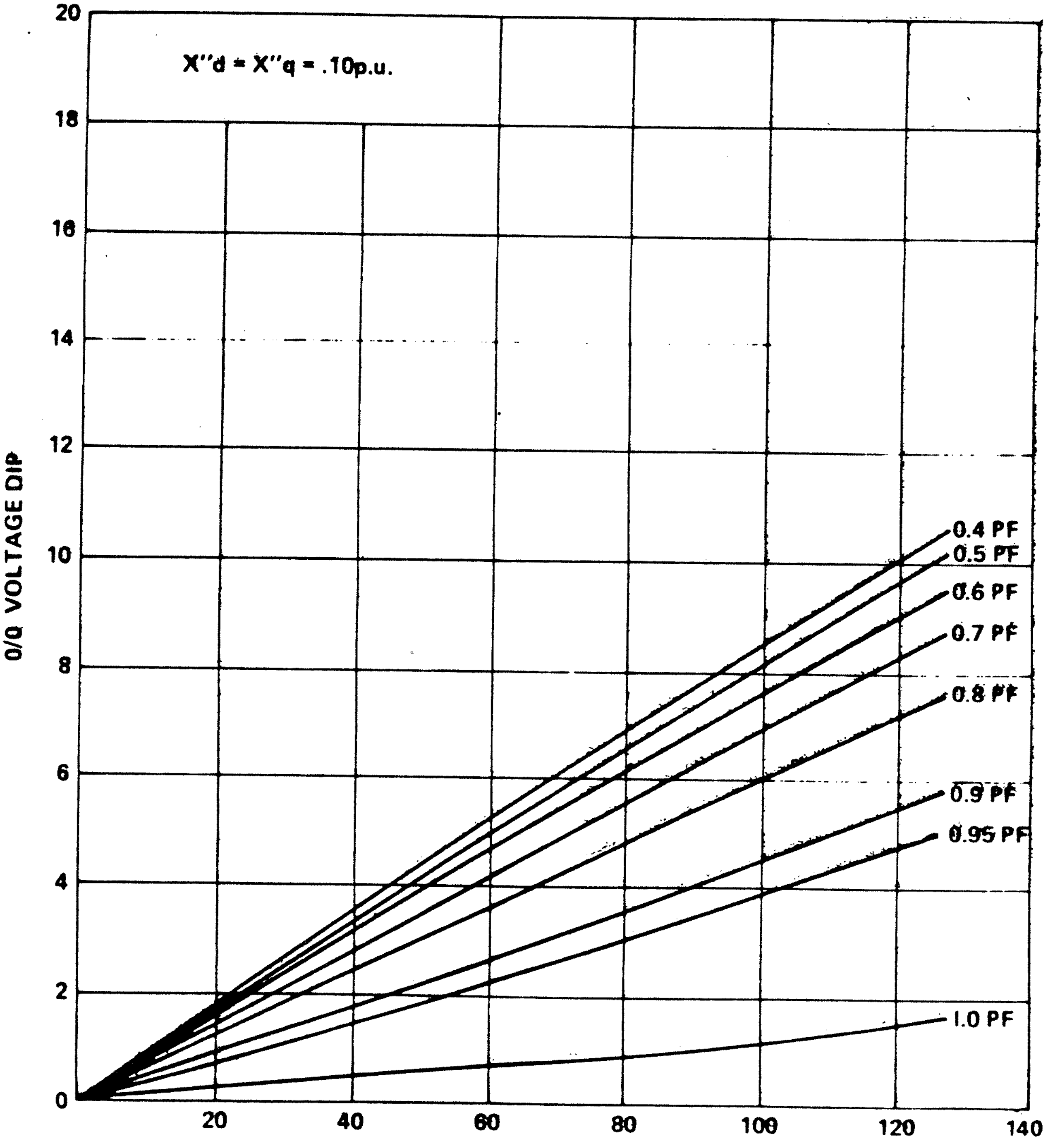

X"d = X"q = .10p.u.
0/0 VOLTAGE DIP
0
2
4
6
8
10
12
14
16
18
20
20
40
60
80
100
120
140
0.4 PF
0.5 PF
0.6 PF
0.7 PF
0.8 PF
0.9 PF
0.95 PF
1.0 PF
0/0 SUDDENLY APPLIED LOAD

FIGURE 23B-1

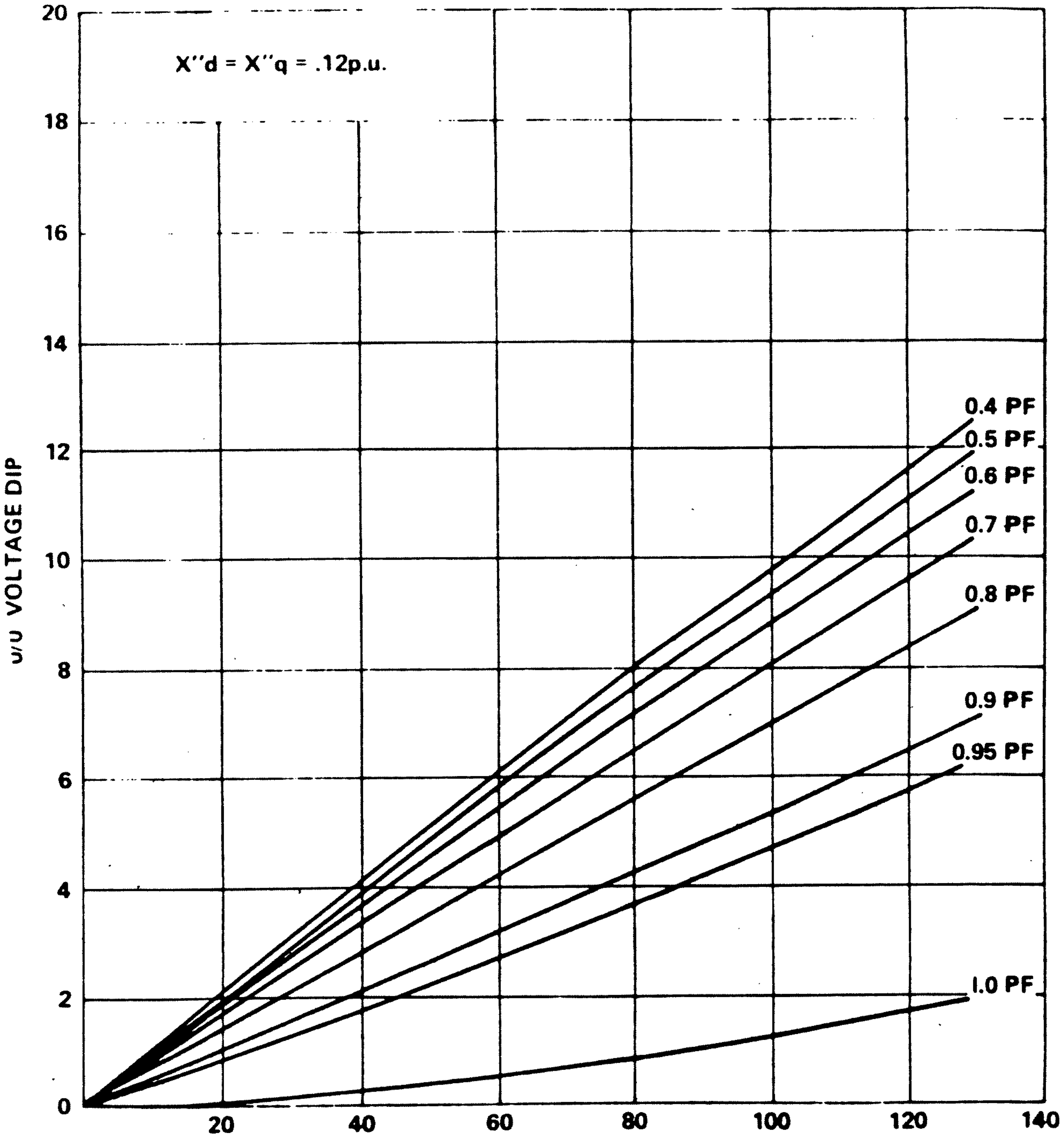

X"d = X"q = .12p.u.
0/0 VOLTAGE DIP
0
2
4
6
8
10
12
14
16
18
20
0/0 SUDDENLY APPLIED LOAD
20
40
60
80
100
120
140
0.4 PF
0.5 PF
0.6 PF
0.7 PF
0.8 PF
0.9 PF
0.95 PF
1.0 PF

FIGURE 23B-2

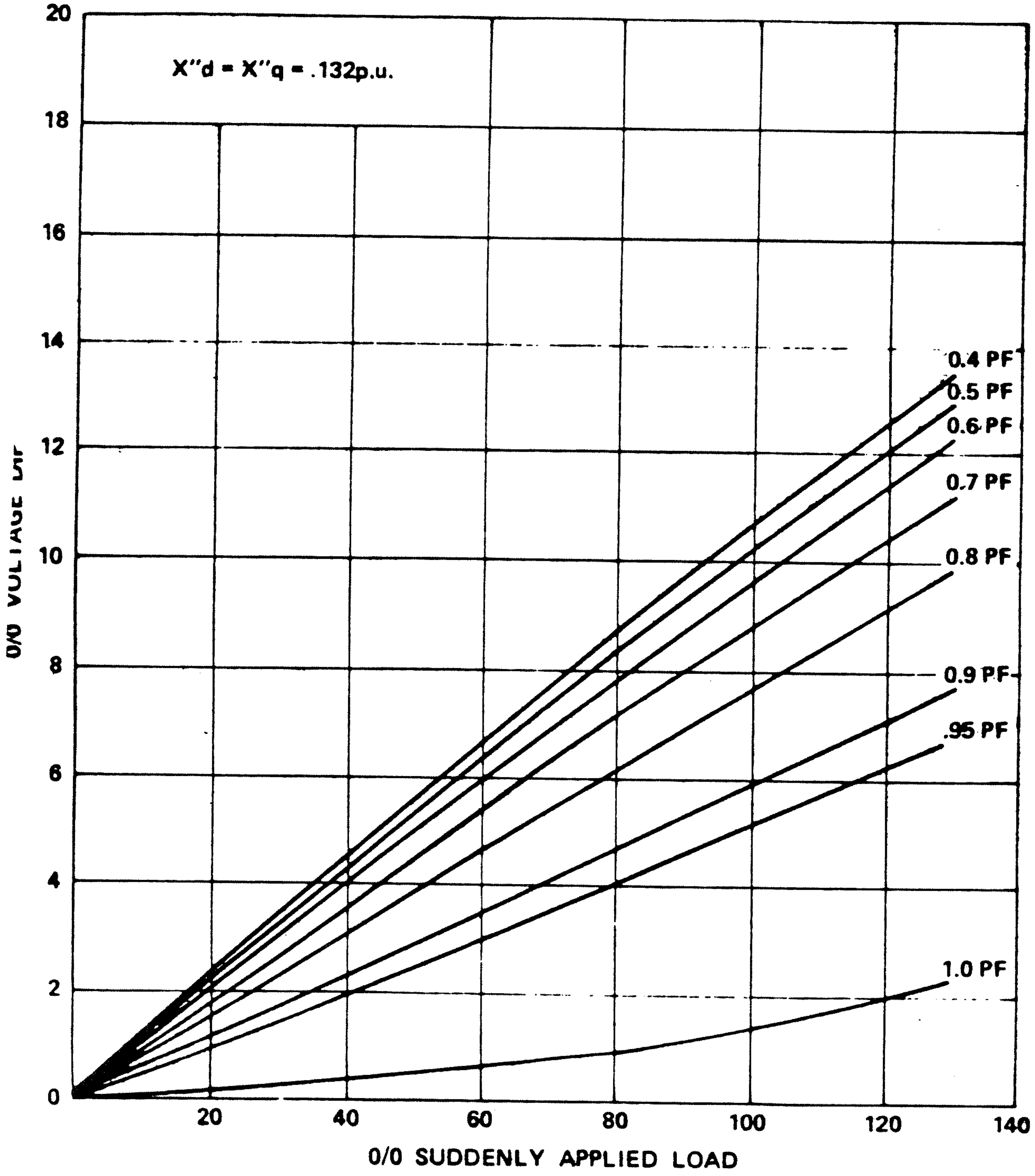
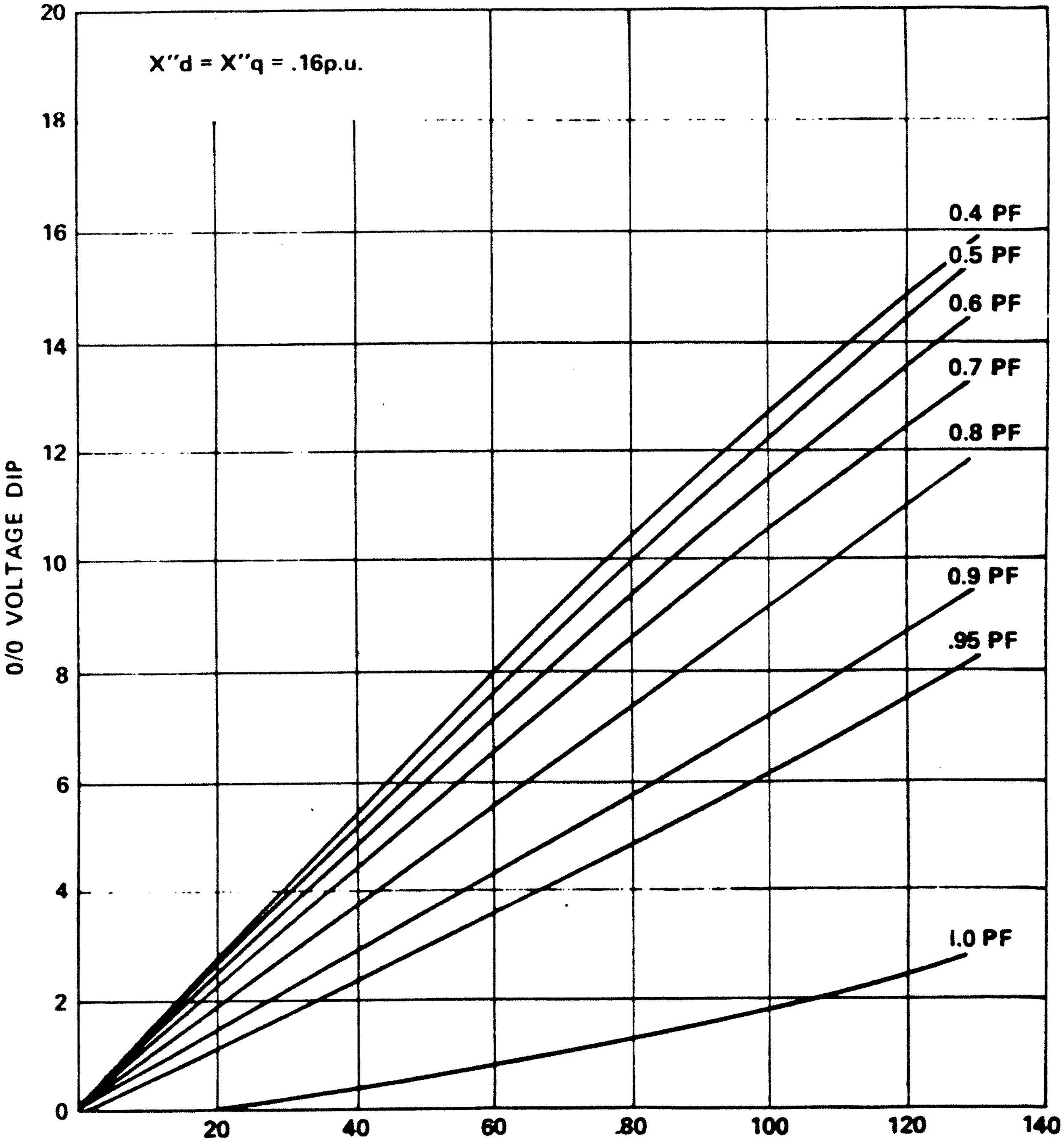

X"d = X"q = .132p.u.
0/0 VOLTAGE DIP
0/0 SUDDENLY APPLIED LOAD
0
2
4
6
8
10
12
14
16
18
20
20
40
60
80
100
120
140
0.4 PF
0.5 PF
0.6 PF
0.7 PF
0.8 PF
0.9 PF
.95 PF
1.0 PF

FIGURE 23B-3



X"d = X"q = .16p.u.
0/0 VOLTAGE DIP
0
2
4
6
8
10
12
14
16
18
20
0.4 PF
0.5 PF
0.6 PF
0.7 PF
0.8 PF
0.9 PF
.95 PF
1.0 PF
20
40
60
80
100
120
140
0/0 SUDDENLY APPLIED LOAD

FIGURE 23B-4

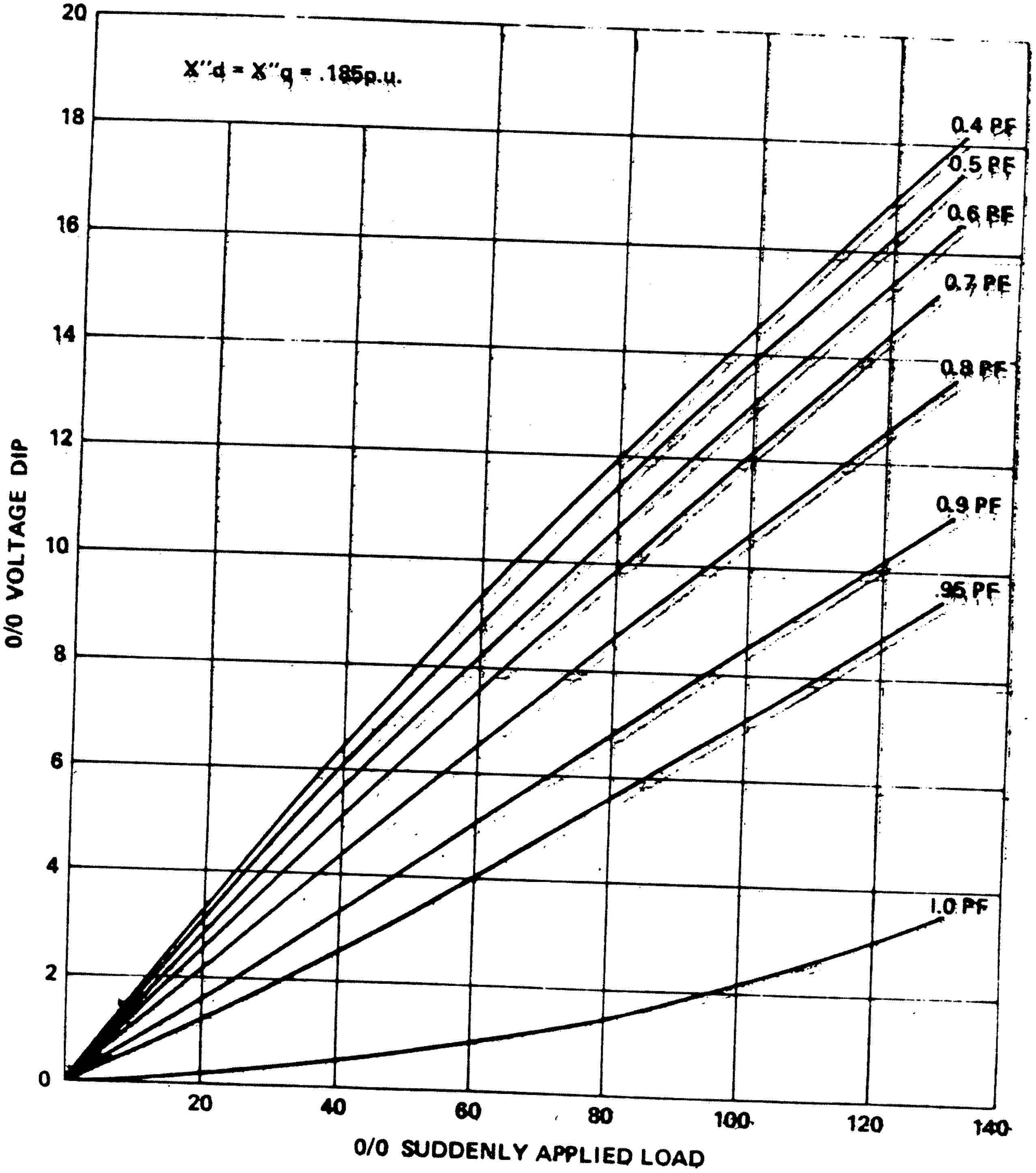

X"d = X"q = .185p.u.
0.4 PF
0.5 PF
0.6 PF
0.7 PF
0.8 PF
0.9 PF
.95 PF
1.0 PF
0/0 VOLTAGE DIP
0
2
4
6
8
10
12
14
16
18
20
20
40
60
80
100
120
140
0/0 SUDDENLY APPLIED LOAD

FIGURE 238-5

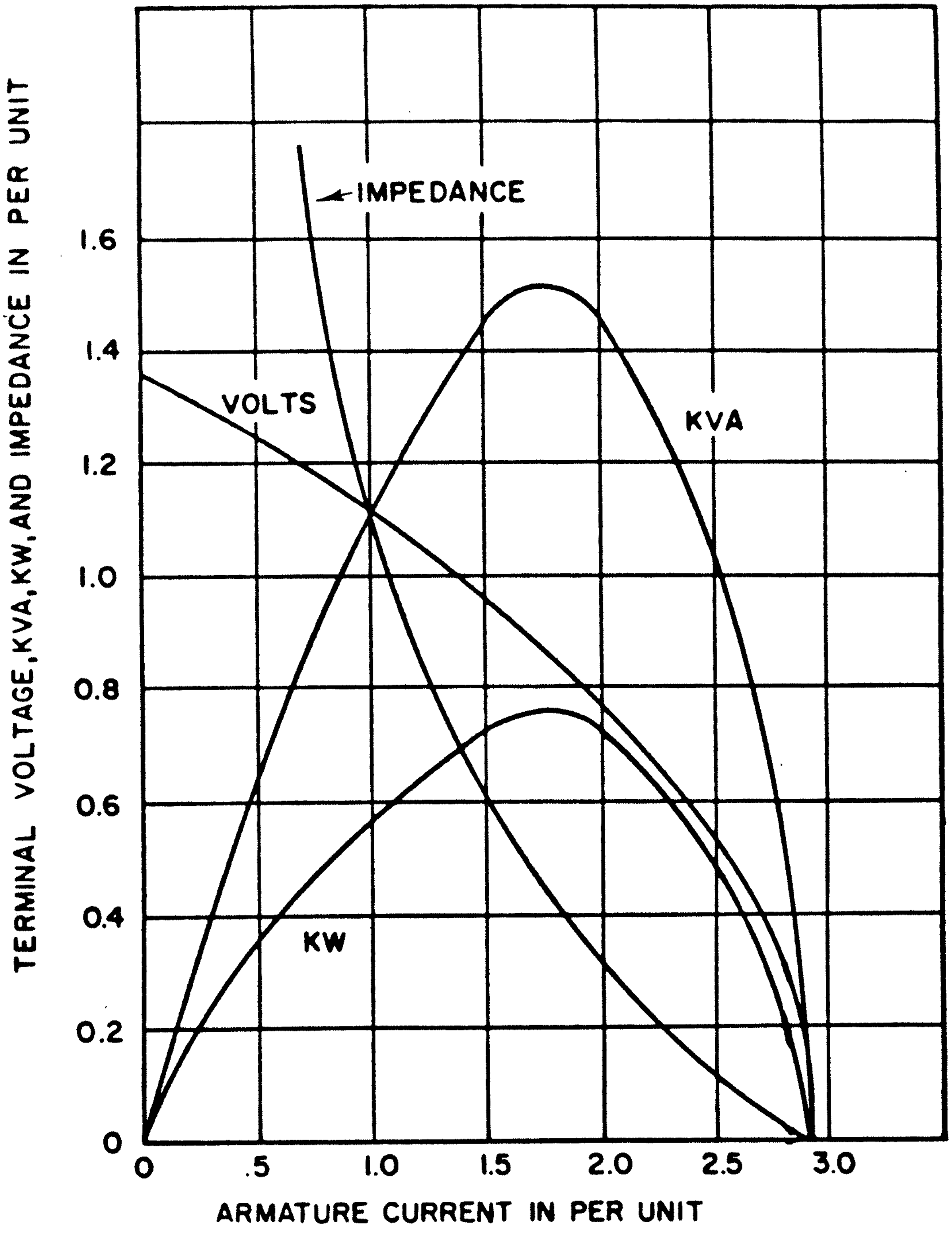
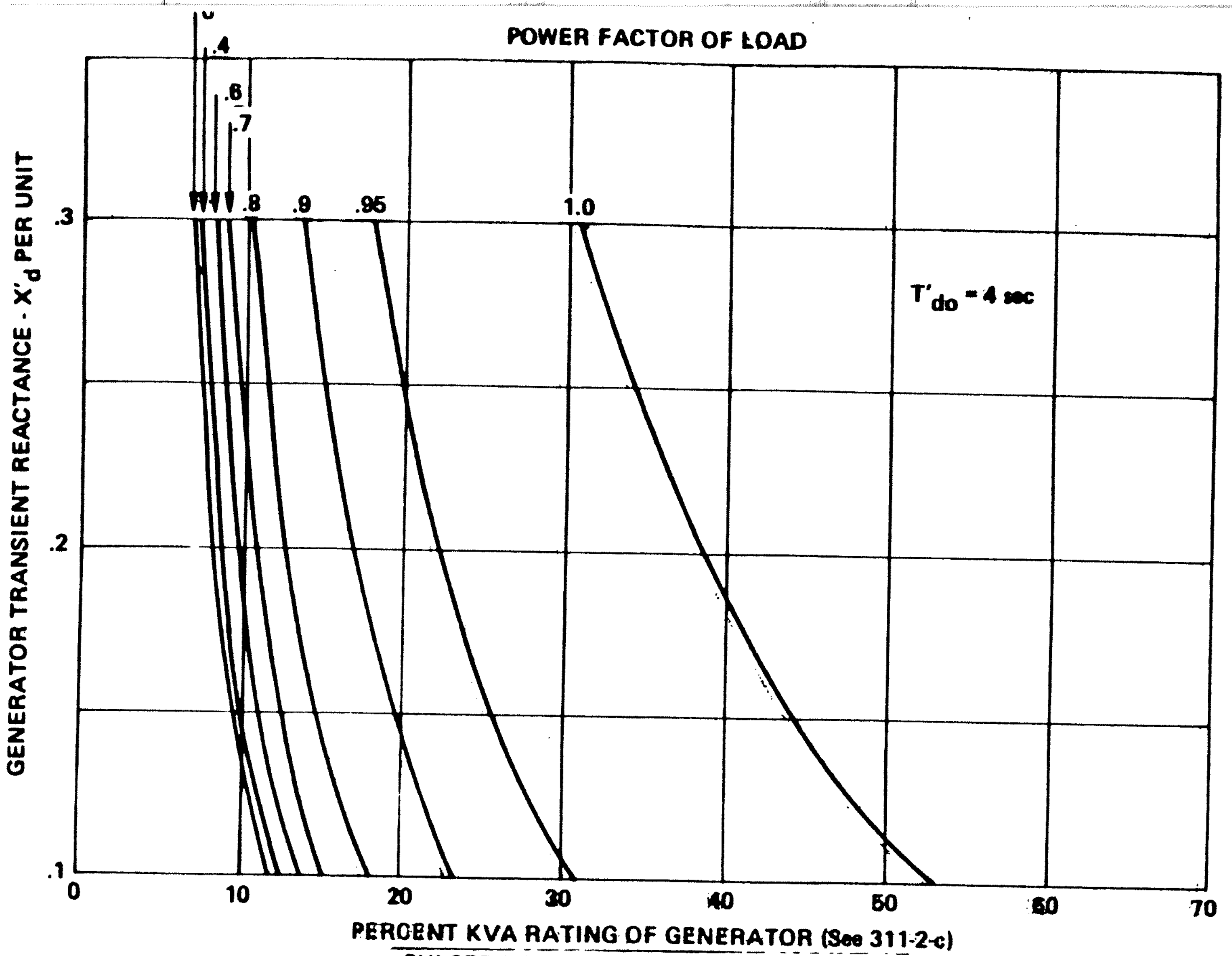
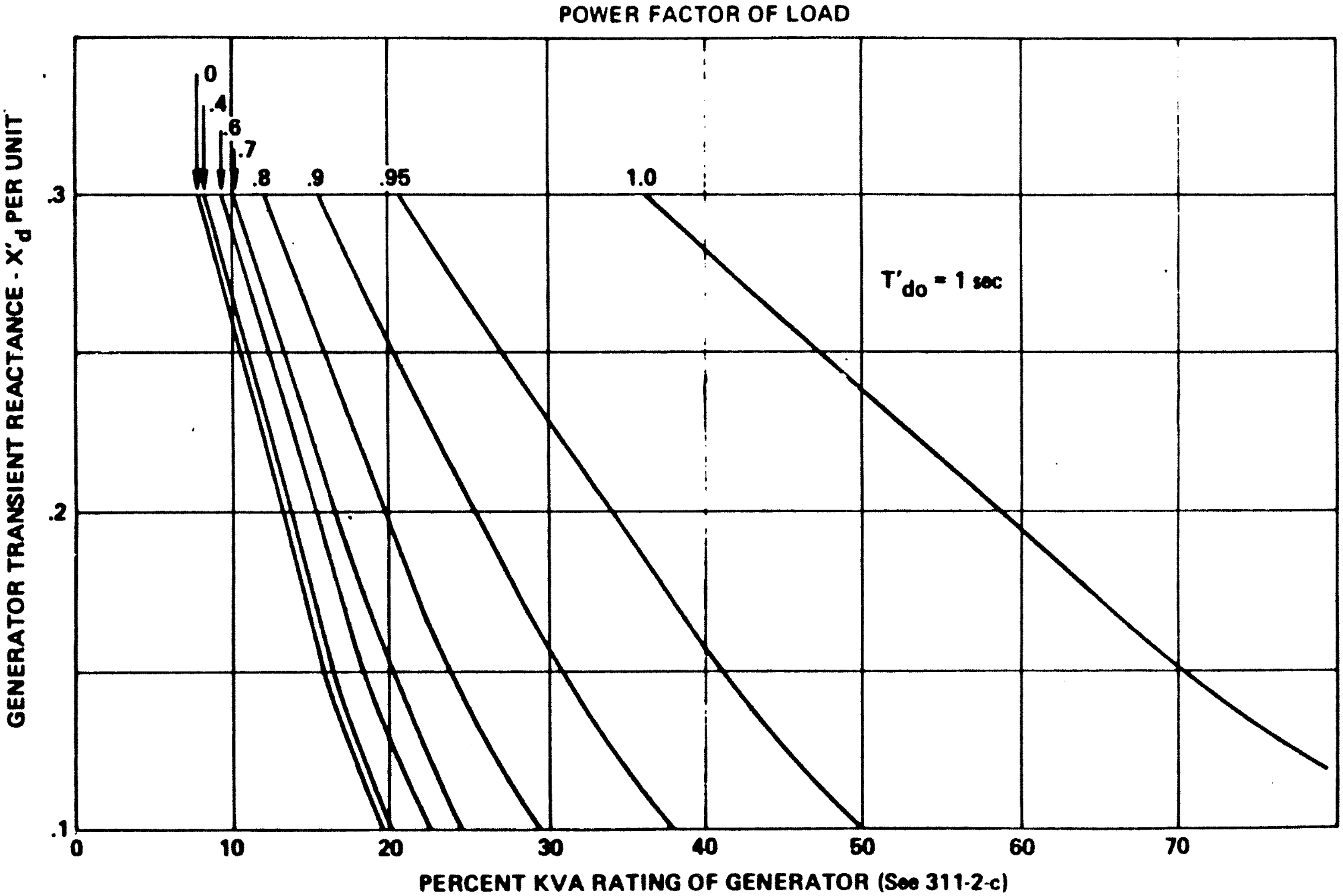


Figure 24 - RELATIONS BETWEEN ARMATURE CURRENT, TERMINAL VOLTAGE, KILOWATTS, KILOVOLT-AMPERES, AND LOAD IMPEDANCE FOR AN A.C. GENERATOR OPERATING AT CEILING EXCITATION OF 3.5 PER UNIT AND A FIXED LOAD POWER FACTOR OF 0.4 LOGGING.



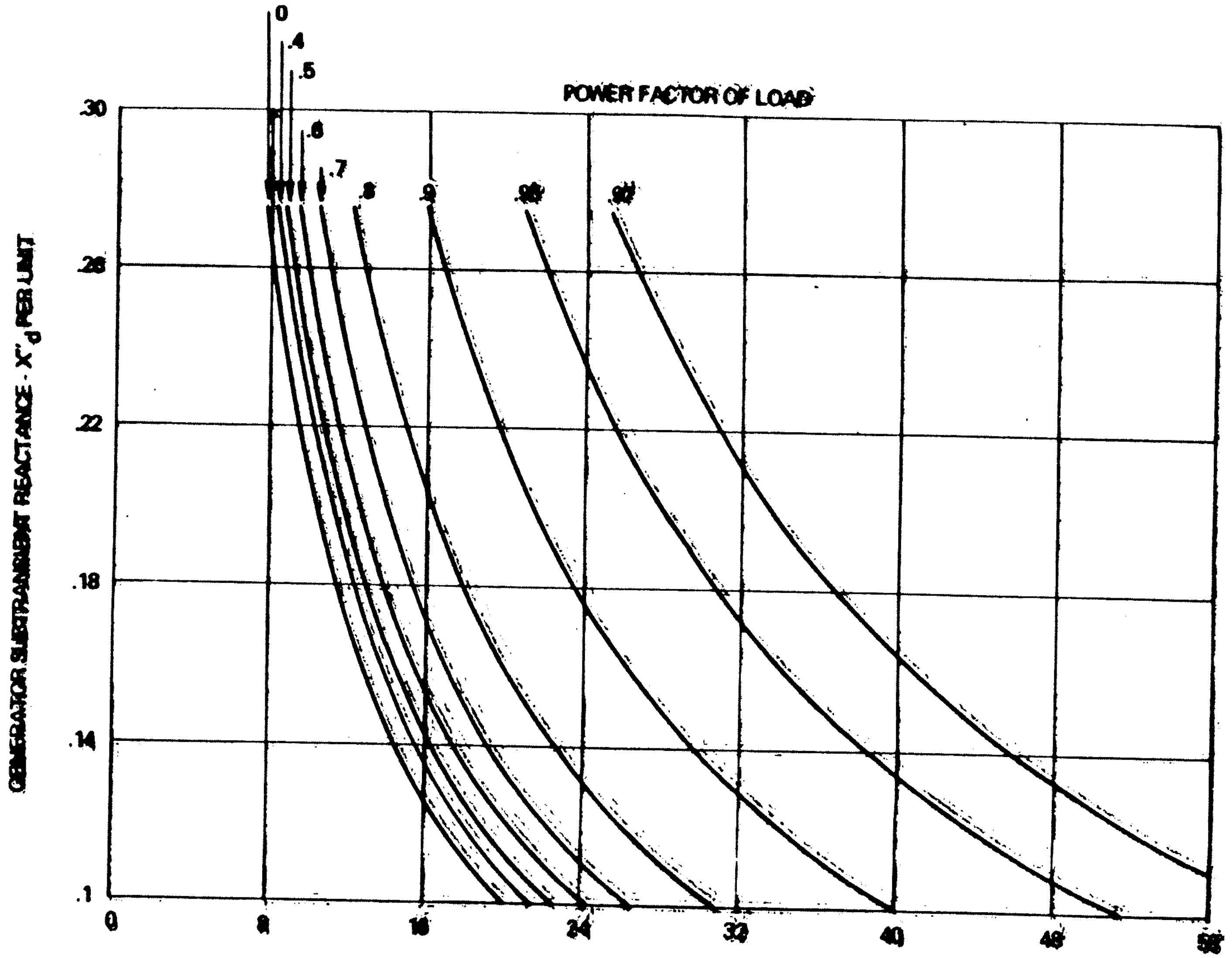
PULSED LOAD LIMITS TYPE I AND II POWER

FIGURE 25A



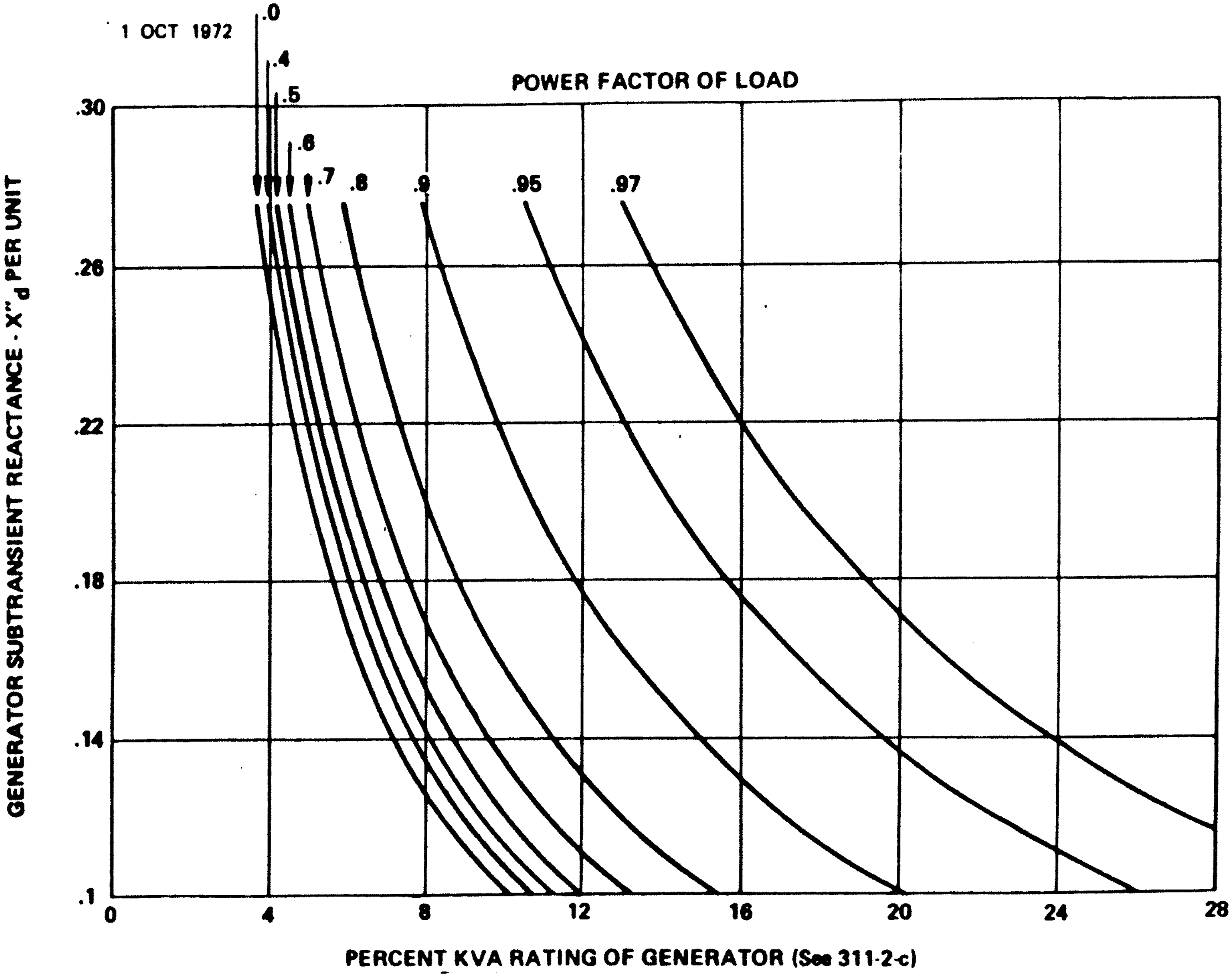
PULSED LOAD LIMITS TYPE I AND II POWER

FIGURE 25B



PERCENT KVA RATING OF GENERATOR (See 311-2-d)
PULSED LOAD LIMITS TYPES I AND II POWER

FIGURE 25C



PULSED LOAD LIMITS TYPE III POWER

FIGURE 25D

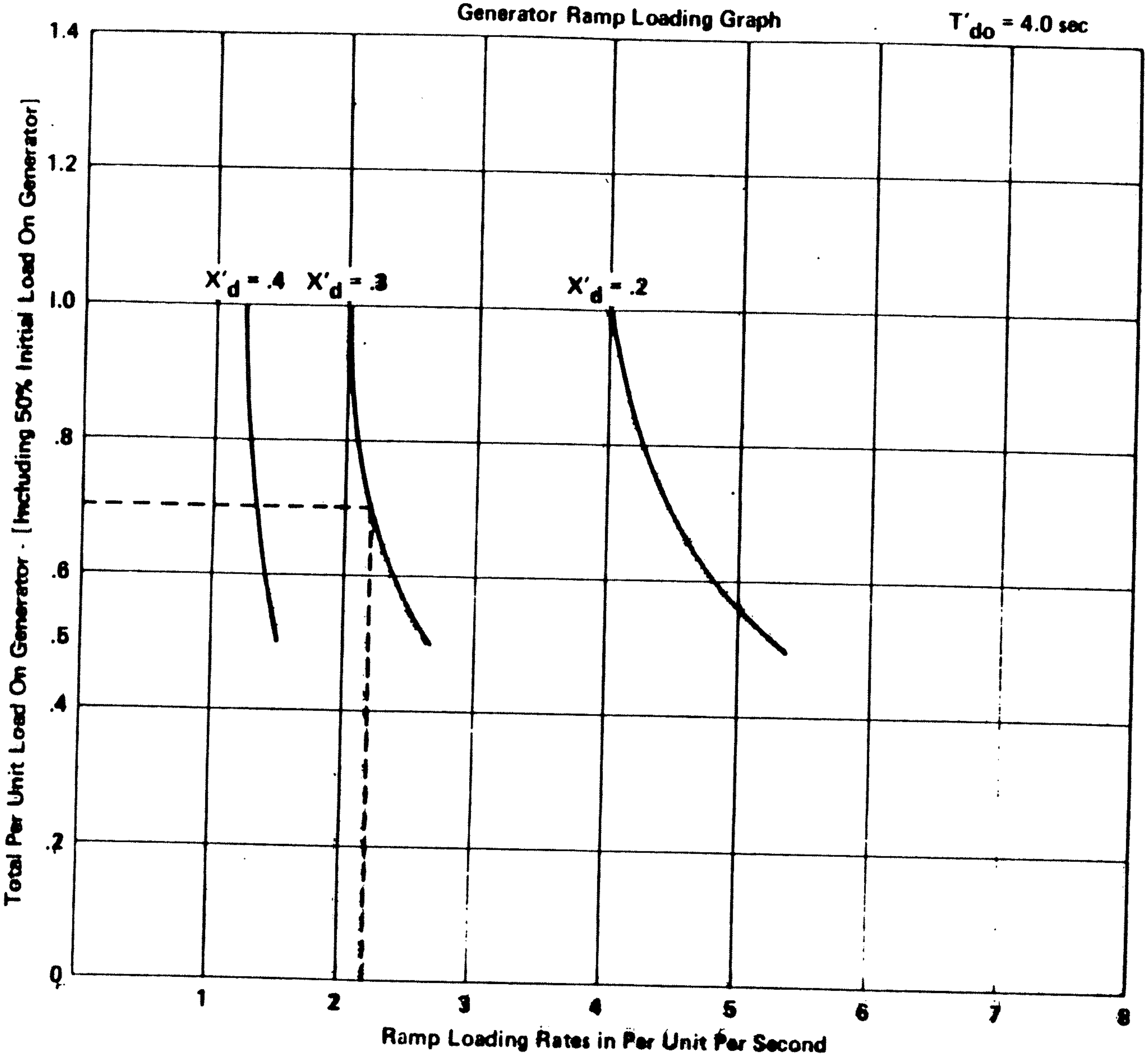

Generator Ramp Loading Graph
T'do = 4.0 sec
X'd = .4
X'd = .3
X'd = .2
1.4
1.2
1.0
.8
.6
.5
.4
.2
0
1
2
3
4
5
6
7
8
Total Per Unit Load On Generator - [Including 50% Initial Load On Generator]
Ramp Loading Rates in Per Unit Per Second

Figure 26A

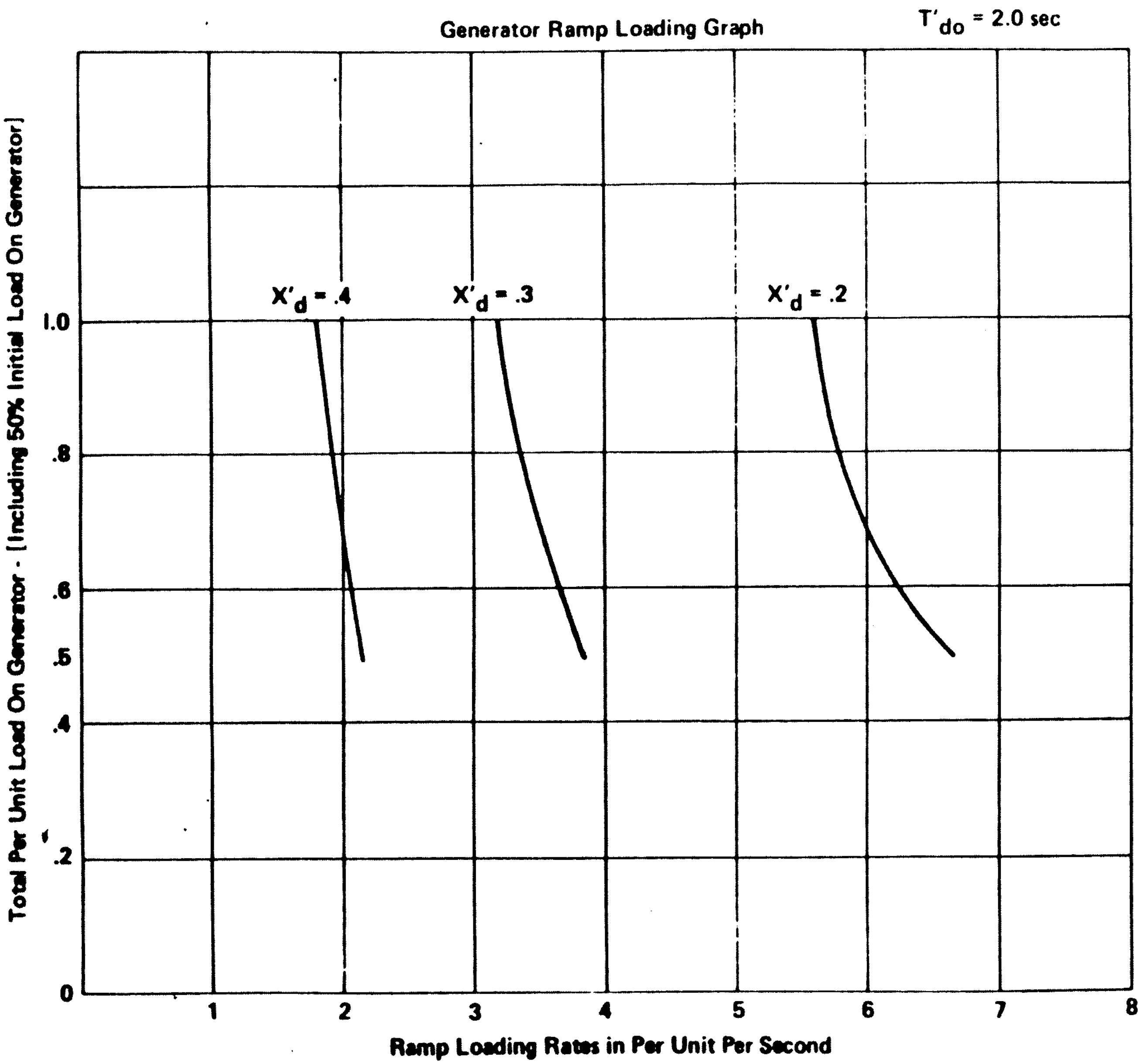

Generator Ramp Loading Graph
T'do = 2.0 sec
X'd = .4
X'd = .3
X'd = .2
Total Per Unit Load On Generator - [Including 50% Initial Load On Generator]
1.0
.8
.6
.5
.4
.2
0
1
2
3
4
5
6
7
8
Ramp Loading Rates in Per Unit Per Second

Figure 26B

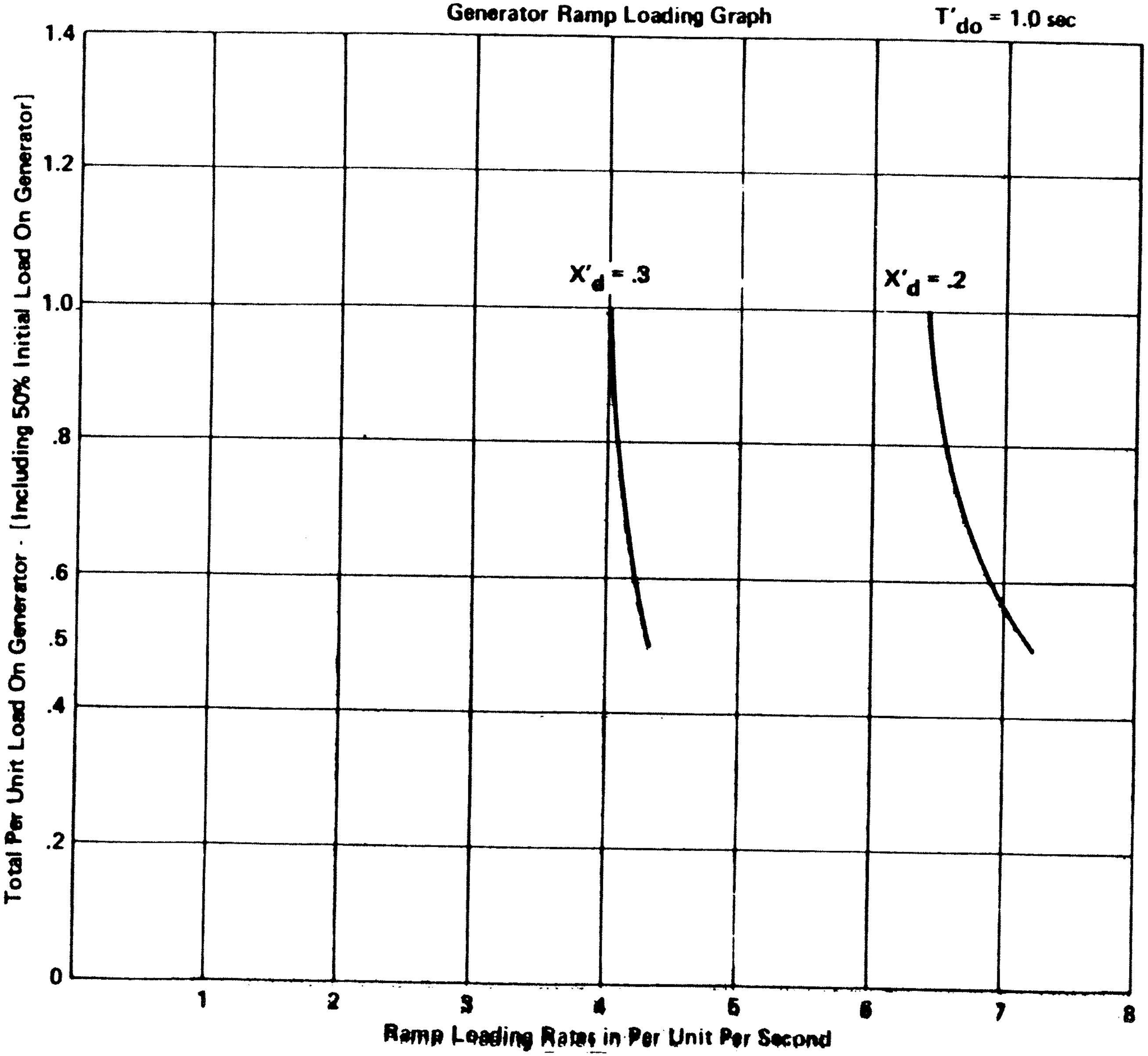

Generator Ramp Loading Graph
T'do = 1.0 sec
Total Per Unit Load On Generator - [Including 50% Initial Load On Generator]
1.4
1.2
1.0
.8
.6
.5
.4
.2
0
X'd = .3
X'd = .2
1
2
3
4
5
6
7
8
Ramp Loading Rates in Per Unit Per Second

Figure 26C