PROTECTIVE REACTORS FOR FEEDER CIRCUITS OF LARGE CITY POWER SYSTEMS*

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ABSTRACT OF PAPER

This paper outlines the use and limitations of protective reactance coils in feeder circuits. When no feeder reactors are used, doubling up the station capacity increases the number and severity of short circuits. The insertion of feeder reactors cuts down the severity of a short circuit and practically renders the effect local, so that beyond a certain point additional generator capacity does not appreciably increase the severity.

Curves are given showing what the effects of feeder reactors are, with and without bus reactors, for generators of various reactances. The advantages that might be gained by parallel operation of feeders are discussed and the difficulties to be encountered are pointed out.

INTRODUCTION

IN a paper entitled "Protective Reactances in Large Power Stations" presented at the 1913 midwinter convention of the Institute, the authors discussed the use and limitations of current limiting reactors in generator circuits and in power station busbars.

It was shown in that paper that, on a radial feeder system, the use of busbar reactors tends to confine the disturbances from a short-circuited feeder to that section of the busbars to which the feeder is connected. It was also shown, in one example, that the use of 3 per cent feeder reactors reduced the amount of current flow into a feeder short circuit to 1/4 of what it would be without feeder reactors.

It is the purpose of this paper to discuss, in greater detail, the use and limitations of reactors in the feeder circuits of large city power stations.

The methods of deriving the curves of this paper are the same as are given in the appendix to our earlier paper. Where reference is made to maximum values this refers to maximum r.m.s. values and not to maximum instantaneous values.

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Transient effects are not taken into account by these curves. The transient effects can be derived from the r. m. s. values.

THE NEED OF FEEDER REACTANCES

Consider the case of a 225,000-kv-a. power station which generates electricity at 11,000 volts. Such a station would have, say, 80 feeders each rated at 5000 kv-a. If these feeders average three miles in length there would be a total of 240 miles of feeder cable installed. If on this system there are five break-downs per 100 miles per year, then there might be expected a total of 12 break-downs per year on the system, or an average of one break-down per month.

If the station capacity and the number of feeders are increased 50 per cent and the average length of feeder increases $33 \frac{1}{3}$ per cent, then the break-downs will average two per month. If all of the feeder cables are tied directly to the power station busbars and no reactors are used in either feeders or busbars, heavy short circuits occurring within a mile or so of the power stations would be felt over the entire system, and might be felt with troublesome severity even when occurring at greater distances from the power station. At times of light load, few machines are running and the portion of the short circuit kilovolt-amperes carried by each machine on the system might easily be several times the normal load rating of each machine. Evidently one or two such general disturbances per month could not be tolerated. Properly designed feeder reactors limit the amount of short-circuit current in a feeder to such an extent that the effect is local.

CURVES

In order to study the effects of different values of feeder reactance a number of curves has been plotted.

Curve sheet 1 shows the relation between the equivalent kilovolt-amperes in a short circuit and the station capacity in kilovolt-amperes for six different values of feeder reactance when no bus reactance is used. The generators in this case have 12 per cent inherent reactance.

Curve Sheets 2 and 3 show similar sets of curves which differ from the curves on Curve Sheet 1 only in the values of inherent generator reactance, which are chosen at 10 per cent and 8 per cent respectively.

The points of special interest shown by these curves are:

(a) With infinite generator capacity the equivalent kilovolt-

amperes in a short circuit vary inversely as the reactance in the feeder circuit.

CURVE SHEET No. 1—CURVES SHOWING VALUES OF SHORT CIRCUITS IN TERMS OF KV-A. WITH FEEDER REACTORS OF VARIOUS PER CENTS—INHERENT GENERATOR REACTANCE 12 PER CENT WITHOUT BUS REACTORS—5000-KV-A. FEEDERS.

(b) The equivalent kilovolt-amperes in a short circuit with infinite generator capacity are the same for the three sheets of curves.

(c) The kilovolt-amperes in short circuit increase more rapidly per kilovolt-ampere of station capacity for a small station than for a large one.

CURVE SHEET NO. 2—CURVES SHOWING VALUES OF SHORT CIRCUITS IN TERMS OF KV-A. WITH FEEDER REACTORS OF VARIOUS PER CENTS—INHERENT GENERATOR REACTANCE 10 PER CENT WITHOUT BUS REACTORS—5000 KV-A. FEEDERS.

A comparison of similar curves on the three sheets shows that the variation in generator reactance does not greatly affect the curves. Curve Sheet 4 shows the four curves for 3 per cent (of

5000 kv-a.) feeder reactance replotted on the same sheet for generator reactance of 12 per cent, 10 per cent, 8 per cent and 6 per cent, respectively. By comparing the curve for 6 per cent

CURVE SHEET NO. 3—CURVES SHOWING VALUES OF SHORT CIRCUITS IN TERMS OF KV-A. WITH FEEDER REACTORS OF VARIOUS PER CENTS—INHERENT GENERATOR REACTANCE 8 PER CENT WITHOUT BUS REACTORS; 5000 KV-A. FEEDERS.

generator reactance with that for 12 per cent generator reactance the small effect of the generator reactance on the curves is evident.

Curve Sheet 5 shows the relation between equivalent kilovolt-amperes in a short circuit and station capacity in kilovolt-ampere with 10 per cent generator reactance and 3 per cent (of 5000 kv-a.) feeder reactors under two conditions. Under one condition no bus reactors are used. Under the other condition 12 per cent (of 25,000 kv-a.) bus reactors are used. The points of interest here are, that where 12 per cent bus reactors and 3 per cent feeder reactances are used, the equivalent kilovolt-amperes in a feeder short circuit becomes practically constant at 125,000 kilovolt-ampere station capacity, and any further increase in station capacity has no appreciable effect in increas-

CURVE SHEET No. 4—CURVES SHOWING VALUES OF SHORT CIRCUITS IN TERMS OF KV-A. WITH 3 PER CENT FEEDER REACTORS AND VARIOUS GENERATOR REACTANCES WITHOUT BUS REACTORS—THREE-PHASE SHORT CIRCUITS—5000 KV-A. FEEDERS.

ing the short-circuit kilovolt-amperes. Where no busbar reactors, but 3 per cent feeder reactors are used, the short-circuit kilovolt-amperes increase until with infinite generating capacity they become 167,000 kilovolt-amperes.

Interpreted in another way, when the busbar reactors are used the feeder reactors absorb 75 per cent of the voltage and therefore give a 25 per cent drop in voltage on the section of the busbars to which the feeder is connected under the worst conditions of short circuit. This means that all of the feeders connected to that section will suffer a momentary drop in voltage of 25 per cent. Where no busbar reactors are used, the feeder reactor

on the defective feeder will, under the worst conditions, absorb 100 per cent of the voltage and will pass 40,000 more kilovolt-amperes, but the voltage of the other feeders on the system will not be appreciably affected. If there were no possibility of a short circuit on the busbars or between the busbars and the feeder reactors and no possibility of a failure of the generator windings or connections between windings and busbars, it is evident that the use of feeder reactors alone is preferable to the combination of feeder reactors and bus-bar reactors, but with these live possibilities of trouble always present, busbar reactors should be considered. Whether or not they should

CURVE SHEET NO. 5—CURVES SHOWING VALUES OF SHORT CIRCUITS IN TERMS OF KV-A. WITH 3 PER CENT FEEDER REACTANCES, 10 PER CENT GENERATOR REACTANCES—WITH AND WITHOUT 12 PER CENT BUS REACTANCES—5000-KV-A. FEEDERS.

Bus reactance rating based on 25,000 kv-a. Bus reactances located between adjacent generating capacities of 25,000 kv-a.

be adopted depends upon the particular conditions of the system under consideration. It is evident that a very large power station without either bus reactors or feeder reactors is liable to short circuits which will endanger apparatus and service, due to the practically unlimited concentration of power in the short circuits.

EFFECT OF FEEDER REACTORS ON VOLTAGE REGULATION

At 0.8 power factor a 3 per cent feeder reactor will cause a voltage drop of approximately 1.8 per cent, at 0.9 power factor, a drop of approximately 1.3 per cent, at 0.95 power factor a

drop of approximately 1.0 per cent, and at 0.98 power factor a drop of approximately 0.6 per cent.

In large city power stations such as have been considered, there is always a considerable amount of synchronous apparatus in operation at a high power factor and the voltage drop due to 3 per cent reactance in their feeders will be low.

THE PARALLEL OPERATION OF FEEDERS

The paralleling of a-c. feeders on a set of busbars at the substation end and the tying together of the different substation buses by means of tie feeders between substations would be highly desirable on most of our large city systems, if it could be safely accomplished. Such a method of operation would allow maximum facility in the interchange of power between various parts of the system, with a minimum amount of cable; the cables between the power station and each substation would be more evenly loaded and the total number of cables could be reduced. Because of the cables between substations, the necessity of idle reserve cables between power station and substations would be eliminated. During the period of peak load on a given substation, power would flow in over the tie cables from substations not carrying their maximum loads; and later when the conditions of peak were reversed the flow of power would be reversed.

THE EFFECT OF REACTANCE COILS ON THE PARALLEL OPERATION OF FEEDERS

To assist in the study of the amount of short-circuit current which can flow into a fault, the series of curves on Curve Sheet 6 was plotted. These curves can be applied to approximate the amount of short-circuit current into a fault on the busbars of a power station where busbar reactors are used, or to approximate the amount of short circuit current into a fault on or near the substation busbars where several feeder cables are connected in parallel on the substation busbars with busbar reactors between them.

As applied to the case of a power station, one or two examples will be cited. Assume the case where the ratio of generator reactance to busbar reactance (a/b) equals $1/3$. The corresponding curve is almost constant with three running generators. This means a short circuit on any section of the busbars is practically maximum when the generator on the same section and one generator on each adjacent section are in operation, and the addition of more generators to the system will not appreciably increase the amount of short-circuit current.

Where the busbar reactance and generator reactance are equal ($a/b = 1/1$) the maximum value of current is nearly reached with five generators running.

In applying the curves to a substation consider the following concrete example:

Consider a case in which the inherent reactance in each feeder

equals 1 per cent, artificial reactance equals 3 per cent, and bus reactance equals 3 per cent, all based on 5000 kilovolt-amperes. Then if a short circuit occurs on or near the substation busbars the kilovolt-amperes flowing in over the short-circuited line equal $\frac{5000}{0.04}$, or 125,000 kv-a. $a/b = 4/3 = 1.33$. From curves, by

interpolation, $x/y = 0.75$. Hence, the kilovolt-amperes flowing over each adjacent bus reactor equal $0.75 \times 125,000 = 93,750$ kv-a. and the total kilovolt-amperes flowing into the fault $= 125,000$ kv-a. $+ 2 \times 93,750$ kv-a. $= 312,500$ kv-a.

The 93,750 kv-a. flowing in over each bus reactor are composed of two components, one flowing in over the second reactor and the other over the adjacent line. These also bear the relation to each other of $x/y (= 0.75)$. Hence, over the second reactor there flow in 40,180 kv-a. and over the adjacent feeder 53,570 kv-a.

In this case with 125,000 kv-a. flowing into the fault from the feeder on the same section with the fault, and 53,570 kv-a. over each adjacent feeder, it is probable that all three of these feeders will go out at once and these will be followed by the other feeders in the substation.

Consider another case in which the total reactance in the feeder is as high as 10 per cent, and the bus reactance is also 10 per cent. (Both based on 5000 kv-a.). Then, in case of a short circuit on or near the substation busbars, the kilovolt-amperes flowing in

over the line equals $\frac{5000}{0.10}$ or 50,000 kv-a. $a/b = 1$. From the

curve, $x/y = 0.62$. Hence, kilovolt-amperes flowing over each adjacent bus reactor $= 0.62 \times 50,000 = 31,000$, and the total kilovolt-amperes flowing into the fault $= 50,000 + 2 \times 31,000 = 112,000$ kv-a.

The 31,000 kv-a. flowing in over each bus reactor are composed of x and y components bearing the relation $x/y = 0.62$. Hence, over the second reactance there flow in 11,850 kv-a. and over the adjacent feeder, 19,150 kv-a.

In this second case 50,000 kv-a. flow in over the feeder connected to the faulty section of the busbars, while 19,150 kv-a. flow in over the adjacent feeders. It is therefore probable that with the ordinary relay setting, all three of these feeders will go out at nearly the same time and that these will be followed by others. Furthermore, such large reactors in feeders and substation busbars would have a serious effect on the voltage regulation of the system, and would in a large measure defeat the purpose of their installation, viz., to permit the free interchange of power between different parts of the system.

Another arrangement of feeder reactors would be to place reactors at both ends of the feeders and omit the reactors

from the substation busbars. This scheme would be more objectionable than the one discussed above, because a short circuit on the substation busbars would be fed by the several feeders in parallel, and, if these feeder circuits were all alike, the kilovolt-amperes flowing into such a short circuit would be directly proportional to the number of feeders connected to the substation busbars.

Several power stations of about 50,000-kv-a. generating capacity are operating today with feeders tied together at the substation end. In several of these stations it has been noticed that a severe feeder short circuit usually trips out several feeder switches and sometimes causes a general interruption to service.

The above analyses show that even on feeders from a very large generating station, feeder reactors of moderate size effectively limit the amount of current flowing from the power station end into a short circuit on the feeder. On the other hand if this feeder is one of a number of feeders connected in parallel at the substation end, a short circuit will have a back feed from all of the other feeders connected to the substation busbars. The amount of kilovolt-amperes flowing over these other parallel feeders is likely to be sufficient to trip out part or all of the oil switches on these circuits.

SUMMARY

In a large city power system, the miles of underground cable and consequently the cable faults increase at a faster rate than the generating capacity. The severity of short circuits also increases with increased generating capacity. Feeder reactors are particularly effective in reducing and localizing the effect of such short circuits. When properly proportioned feeder reactors are used, an increase or decrease of generator reactance has only a limited effect on the amount of kilovolt-amperes flowing into a fault. Bus section reactors in the generating station in connection with feeder reactors still further reduce and localize these effects, even when it might be more desirable to distribute their effect if other conditions permitted.

It would be desirable for many reasons to operate feeders in parallel at their substation ends, but such operation tends to increase greatly the kilovolt-amperes flowing into a feeder short circuit and to cause other feeders besides the one affected to trip out when overload relays with the usual settings are used.