

DISCUSSION ON "THE USE OF POWER LIMITING REACTANCES WITH LARGE TURBO-ALTERNATORS," "SOME RECENT TESTS OF OIL CIRCUIT BREAKERS" AND "DEVELOPMENT OF THE MODERN CENTRAL STATION." CHICAGO, JUNE 27, 1911.

**John W. Lieb, Jr.:** Once again we are indebted to Dr. Steinmetz for a splendid and acute analysis of what is essentially a practical problem. With that keenness of discernment which we have been accustomed to expect from Dr. Steinmetz, he has touched upon a number of vital points which are of momentous interest to the present and the future of central station work. In the papers of Messrs. Schuchardt and Schweitzer, and in the paper of Mr. Merriam, we have notable instances of the method of applying scientific research to the investigation and solution of electrical problems, and the Institute is to be felicitated in having before it the details of these tests as affording material for thought.

In Mr. Schuchardt's paper he refers to the points to be determined by the tests which were made, indicating as the first, the instantaneous short circuit current of turbo-generators without external reactance. These questions referred to by Dr. Steinmetz and the other authors are matters which have been given careful consideration by the New York Edison Company, for instance, as another of the companies having these large problems to deal with, and this first element was one of the first questions which presented itself for investigation; and it was found that there was a considerable and wide variation as between types of generators, particularly turbo-generators, in this matter of internal reactance. There were tests made between types of generators as to the amount of internal reactance, amounting to as great a difference as two to one. It has therefore, opened a new light as to the possibility of control within the generator itself of the application of an increased amount, by and within the practical limitations which the applications permits, of internal reactance, and by an increase of internal reactance you make it possible to limit the amount which need be applied externally.

It is difficult to conceive of the tremendous disturbance that takes place on a large interlaced system by short circuits in feeders or failure of generators. With ten, twenty, or thirty substations distributed over vast areas, having hundreds of synchronous machines working in parallel, the disturbance and throwing out of synchronism of this vast number of units, and the enormous difficulties involved in starting up these different substations widely separated, present unique problems, and it is therefore well worth most careful consideration to reduce the possibilities and the effects which these enormous concentrations of power in local disturbances may call forth.

The concentration of power for economical reasons in these huge power plants, the dependence for vast industrial enter-

prises and for our transportation systems, as well as for lighting and industrial power, make it absolutely essential that they shall be protected against disturbance, and that every possible precaution should be taken, which experience or ingenuity can provide, against irregularity in operation, because if these huge systems are going to be subjected to disturbance and interruption of service, we shall have reached a point where something radical will have to be done; but very fortunately with these elements which are brought before us, and other elements which are not here referred to, we can feel sure that the future provides fairly safe guarantees against interruption of service which produce very serious results in a community served by these vast enterprises. I am sure that we are very much indebted to the gentlemen of the Commonwealth Edison Company for having laid before us in great detail the results of their tests and experiments, with a view to arriving at a satisfactory solution of these problems, and to Dr. Steinmetz for having put his finger on the essentially important elements which are such prime factors in the development of the modern central station industry.

**M. H. Collbohm:** Mr. Merriam has presented us with very valuable data on the operation of oil switches designed for severe service conditions which data have been obtained from actual tests.

I note, however, that all these tests have been made on an oil switch type employing the vertical break. It would have been very instructive if the test had also been made on a switch of the horizontal break type in order to allow comparison between these different constructions.

It seems to me that the horizontal break oil switch would offer greater prospects for successful operation under severe conditions for the following reasons:

1. The break occurs in the lower part of the tank with a considerable head of oil above the break, in contradistinction from the vertical break where the arc starts nearer to the surface of the oil. This seems to be of great importance considering that the arc is most vicious at the moment of separation of the contacts when the current has its greatest value.

2. The horizontal movement of the thin switch blade through the oil combined with the tendency of the arc to rise vertically causes this arc to continually come into contact with fresh and cool oil layers thus extinguishing the arc sooner than would be possible in the vertical break switch where the arc tends to maintain its original vertical position. The break in the vertical type must therefore be considerably longer thus rendering this type of oil switch materially more expensive for the same rupturing capacity.

3. The knife blade form of contact pieces insure a more positive contact in the clips than can be obtained by the wedge or butt contacts usually employed in the vertical break switch for higher voltages.

The speaker has had experience with both types of switches on high tension lines and feels it his duty to express his satisfaction with the cheaper horizontal break oil switch which has opened without trouble several short circuits without the dampening influence of reactive coils.

The main advantage claimed for the vertical break type, *viz.*, the opening by gravity does not seem to the speaker to be superior to the opening by springs. The latter can be adjusted for a more rapid operation thus increasing the effectiveness of the switch. The gravity break type in the speakers experience in one instance failed to establish good contact in closing resulting in the partial burn off of the contact clips and carbonizing the oil.

In regard to the rupturing capacity of the oil switch in general I would like to be informed what the considerations are for giving the same switch type a higher rating on lower voltage than on higher voltage, as given by some manufacturers, catalogues. Ordinarily one would expect greater damage to the switch at lower voltage due to the greater  $I^2 R$  energy in the rupturing arc. The speaker in laying out the switchboard for a 16,000-kw. hydroelectric station interconnected with others of still higher rating, suggested the use of a high generator voltage in order to lessen the possibility of trouble to oil switches under short circuit conditions but was informed by the switch manufacturer that the standard voltage of 2,300 volts would be preferable.

As the speaker at that time could not get a satisfactory explanation for this advocating a lower voltage he would appreciate very much to learn at this time the reason for this method of rating oil switches.

Dr. Steinmetz in his paper has given a very interesting exposition of the development of the present alternating current central station from the old direct current plant with particular reference to the external reactance coil as one of the characteristic protective features of the modern large sized plant. The development of this protective device was brought about by the desire to overcome the danger from the enormous short circuit current in the system, particularly in a plant with synchronous turbo-generators.

The question arises in my mind whether this heavy short circuit current could not be materially reduced by other means, possibly in addition to the proposed choke coil. The present practice of sacrificing regulation in the synchronous machines in order to reduce the short circuit current, is only a small help, and it seems that the liberal use of induction generators with their characteristic low short circuit current would aid very materially in bringing about the desired result, both as regards reduction in short circuit current as also absence of necessity for running synchronized.

This type of machinery has already been successfully installed in combination with low pressure steam turbines, and it seems

that the equipment of a whole station with induction generators specially designed for a small magnetizing current in connection with synchronous motors floating idle on the system for furnishing this magnetizing current would make a feasible arrangement. The synchronous motor in such installations would have the appearance of an unproductive piece of apparatus, but for the advantage it offers by rendering the respective plant independent from any other synchronous station, its use appears justified. It might thus be considered to be in a same class with the frequency changer.

In such a system the throwing together of stations slightly out of phase may not cause nearly as heavy a shock as if both stations were equipped with synchronous machines only. The last problem stated by the author at the end of his paper, *viz.*, synchronous operation of different stations would then also find its solution.

Aside from city steam stations this induction generator type would also be of considerable advantage in a system of interconnected hydroelectric plants where it could be installed at stations of secondary importance, furnishing power only and leaving the regulation of the system to a synchronous generating station. The installation of a synchronous motor in connection with the induction generators would again render this secondary plant independent from the main station as regards regulation. Such a plant could always be run at highest efficiency, possibly without the use of hydraulic governors and could utilize the total stream flow at nearly all times without the expensive provision of a storage reservoir.

Aside from the development of the reactive coil as a protective feature of a high capacity low tension steam station there have been made developments on other protective devices serving a different purpose in stations of high voltage character, and which may perhaps properly be mentioned in discussing station development:

The aluminum arrester, although it has failed several times in the speaker's experience to perform its function without being destroyed itself by mere internal disturbances in the system, represents nevertheless a considerable improvement over the older types.

In addition to the use of this arrester the speaker has advocated and put into successful operation a scheme of additional protection to station apparatus consisting in the use of solid non-coated iron wire of high permeability for station wiring, extending from the high tension transformer taps to the point where the arrester connections tap on the transmission line, which should preferably extend to the first tower outside the power house. The advantage of this scheme lies in the greatly increased ohmic resistance which the iron wire, due to the skin effect, offers to any high frequency surge such as lightning. The choke coil in particular, representing quite a length in the con-

ductor, should be of soft Swedish iron. This scheme of using iron wire choke coils appears also to get into favor in Europe judging from a bulletin of a responsible European manufacturer of such coils recently received by the speaker.

The usual danger from high voltage building up on the reactance of the series transformer by any high frequency disturbance has been overcome by an arrangement of the speaker of shunting a small electrolytic cell across the high tension terminals of the series transformer.

Inasmuch as the skin effect of the iron wire was sought as an additional choking effect for protecting station apparatus, it had on the other hand to be removed from the path of the lightning discharge, particularly the overhead ground wire on the transmission lines was investigated by the speaker in 1909 with the result of recommending copper clad steel for ground wire purposes instead of steel which had been used exclusively before. Subsequent high frequency tests made at the University of Wisconsin on iron and copper wires have proven the speaker's arguments in favor of copper.

All the before mentioned schemes for additional protection to station apparatus have been tried out on one of the hydroelectric transmission plants built by the speaker and have worked out to entire satisfaction. This particular plant (of the Northern Hydroelectric Power Co. at High Falls, Wis.) has experienced many severe lightning storms which caused the arresters to act very frequently but there has never been the slightest damage to any of the apparatus.

A further development in lightning arresters has recently been made in Europe where a number of prominent central stations have been equipped with arresters consisting of one or more banks of condenser elements shunted by a grounding choke coil. The condenser battery acting on high frequency disturbances of any voltage, even of a very low value to which the electrolytic arrester would not respond, while the choke coil takes care of accumulated static. This arrester is reported to have given excellent results.

There are some minor details which have recently undergone development and which when taken as a whole may exert a marked beneficial influence upon the safety of central station operation.

The instrument and control panels in a large station become so numerous as to be difficult to oversee, and a reduction in their number and a clear distinction between the various instruments and panels becomes very desirable. The voltmeter and ammeter for the generators may be omitted from the respective panels and one instrument of each kind placed on a swinging bracket to serve for all the various machines by providing a receptacle and plug for each of the respective panels. A wattmeter and power factor indicator is generally sufficient for the control of the generators. If curve drawing instruments are

used they may serve at same time as indicating instruments thereby rendering this latter instrument superfluous. A duplicate transmission line may be equipped with one wattmeter only by paralleling the secondaries of the respective current transformers.

The panels and the instruments should preferably be black and the instruments have their designation printed in bold types upon their scales, such as "Volts—Amperes—Watts, etc.," the graduation of the scales should be in decimals to facilitate reading. Only instruments with flat glass covers should be used to avoid the disturbing effect on the curved glass covers of the usual horizontal edgewise instruments. The illumination for the board should be accomplished by diffused light from well above the board in order to have no reflex whatever from the instruments.

The individual panels should be marked by genuine enameled name plates which do not oxidize or fade as in the case of the usual copper or paper name plate. Each circuit or group of circuits should be provided with a blue signal lamp above the board to operate in conjunction with the alarm bell in order to indicate immediately the circuit in trouble.

The above precautions may appear insignificant to the designer but they are of real value to the operator and consequently to station safety.

Besides in the Central station proper there have also been made developments in other parts of the system notably the transmission line. I wish to mention only the flexible type of transmission tower and quite recently the appearance of the composite transmission cable consisting of aluminum or copper strands and a steel center of very high elastic limit. By this arrangement the elastic limit of the composite cable is considerably increased, allowing of a wider spacing of towers with consequent reduction of cost in line construction.

**D. B. Rushmore:** In the President's Address this morning and in the papers which have been presented, we have the problem of disturbance from increasing magnitude—a problem most universal in the present age in social, political, industrial and engineering life. In designing for any particular condition, a design is made to meet the major point under consideration. We design machines, power plants and power transmission systems for operation, but a compromise must always be effected in considering the factors involved when we take into consideration the emergency conditions.

In the discussion that we have had on these conditions of central station operation are involved one example of a change taking place in power transmission systems, and in what are becoming very large stations for industrial power use. The magnitude of individual pieces of apparatus is increasing, the magnitude of stations, and of systems, and very largely of a number of stations tied together. While in so many of our old

problems the boy, as it were, has been relatively harmless, the young man as he appears now, older, larger, stronger, and more powerful is becoming a more disturbing factor, and we have yet to look ahead to the full grown man, to the power systems that are going to cover very much larger areas than at present, and be of very much larger capacity.

In designing apparatus for these conditions a compromise is necessarily effected, and the illustration we have had of placing reactance outside of the machines, allows in many cases a better machine to be designed. While the machine has to be designed for operation, occasionally the best of machines have to be repaired, and to place a large internal reactance in machines involving high, true self induction means, as a rule, increased difficulties in repairing machines.

To bring before the Institute one problem as yet unsolved, we have had for years in hand the development of an automatic resistance which will protect the circuit against high voltage. This has been done in the aluminum lightning arrester, which in itself essentially is an automatic resistance varying with the voltage. What we need now is an automatic reactance varying with the current, something not yet obtained, and something which is well worthy of the best study of inventors. I think that such a thing is possible, as well as likely. It has not yet been developed with sufficient rapidity to handle the problem of these large instantaneous short circuits. We must also consider that any change in condition is to be met with other changes and in connection with systems possessing large capacity or induction, all additional reactance brings with it certain possibilities which ought to demand a very much larger use of protective apparatus.

**C. W. Stone:** Last year at a meeting the point was raised in regard to the ultimate capacity of oil switches. In the paper by Mr. Cheney of Philadelphia, there was some question raised about the ultimate capacity of oil switches, and the suggestion was made that it was possible that we would need a new type of switch in order to handle these large capacities. I think the paper by Messrs. Schuchardt and Schweitzer demonstrates that by the use of reactances and the use of the larger 10 in. oil pot switches we do not need a complete redesign of the switches. The switches are large enough even to handle such systems as the Commonwealth Edison Company, and instead of being limited by the switch, it is perfectly possible to still increase the ultimate capacities of our stations.

Before I stop, there is one thing I think I should bring out, and that is I think we owe a very great debt of gratitude to the officials and engineering organization of the Commonwealth Edison Company for the very thorough way in which they have carried out these tests. There are very few places in the country where such a complete and fundamental investigation of the shocks to systems under short circuit could be made as thor-

oughly as they were made by the engineers of the Commonwealth Edison Company in Chicago, and I think that the whole engineering profession should feel a debt of gratitude for this paper by Messrs. Schuchardt and Schweitzer, reporting on these tests.

Mr. Merriam in his paper points out that with the 10-in. oil pot the strains or pressures are reduced to about one-third or one-fifth of what they were with the 8-in. pot. I think that is a fundamental point. One of the previous speakers mentioned the possibility of using a horizontal break. I think he lost sight of one of the fundamental principles which has been employed so generally in the type of switches described in the paper and that is by using the vertical break, it is possible to so adjust the baffles in the switch as to confine the pressures around the arc, and thus extinguish it more readily. This is difficult to do in a horizontal break type of switch. I think if the engineers here give this matter attention, they will be convinced that the vertical break, with the type of baffling usually employed, has greater possibilities for large capacities than any other type yet proposed.

There is another point. Mr. Merriam in his paper refers to the small amount of oil which is thrown out after repeated short circuit. I think many engineers in witnessing some of these tests would have said that the amount of oil thrown out was excessive. Complete tests were made to find out how much oil could be thrown out, and the switches were opened under short circuits time after time, without changing the oil, and then the amount that had been thrown out was measured and it was found that only about five per cent had been thrown out. To be sure, it is not a dangerous amount, and yet it does demonstrate that it is advisable to install these switches in fire-proof compartments, such as brick, concrete or soapstone.

Mr. Lieb brought out the point about the possibility of the increase in the internal reactances in the generators. It is perfectly possible to design generators with higher internal reactance, but you will always sacrifice something.

I do not think that a generator with twice the internal reactance of the present machines, such as those under test, would have as big a factor of safety as the generators which are now in operation. I think also the point should be brought out that the high internal reactance generators will not accomplish what the generator with the external reactance will accomplish, and that is this—with the external reactance, in case of damage to the generator, due to the breakdown of some coil, the amount of short circuit current which can flow into the generator is limited by the reactance which is in series with it. If the generators were built for high internal reactance, and external reactance not used, the effect of the internal reactances on the generator which was damaged would be entirely eliminated, and the amount of short circuit current which could flow into that generator at that time would only be limited by the internal reactance of the other machines operating in parallel.



I think, therefore, what we should aim to do is to make the generators as safe as possible, and then protect them and the system and the oil switches by means of the external reactances.

I think another very interesting point brought out by Messrs. Schuchardt and Schweitzer is that after repeating short circuits, nearly 150 of them, there was absolutely no damage to the generators, no displacement of the coils, no displacement of the field structure or the shafting of the machine. I think that demonstrates the desirability of the reactance about as well as any point that has as yet been brought up.

**B. G. Lamme:** Two of the papers presented this morning have brought out the fact that reactances are advisable in the protection of large capacity alternating current generators. I fully agree with the authors of the papers on this point and have held a similar opinion for several years. Experience shows that, in commercial operation, sooner or later short circuits will occur on all generating systems, especially if they are of high voltage; and if the machines are of very large capacity the stresses exerted by the short circuit current will be so great that there must be some means provided for limiting the maximum current.

An interesting point to me in the paper by Messrs. Schuchardt and Schweitzer is the amount of reactance which they found advisable. From their tests they found that a reactance which limited the maximum current to 14 times normal was satisfactory. That is an interesting figure, for it is the one which we had reached as the limit, in our experience with large generators. We found that when we could keep the current down to 12 or 14 times normal current on dead short circuit there was very little, if any, difficulty in bracing the end windings to stand the shock. We also found that, in a great many cases, there was no difficulty in getting that amount of reactance in the machine itself without making an abnormal design.

However, that question depends somewhat on other features than on the construction of the winding itself. The speed comes in as an important condition. For instance, if you have a moderate speed turbo generator of large capacity it may require an abnormal design to obtain a high reactance inside the machine itself. If you double the speed, and thus cut the number of poles in half, you may find it difficult to obtain a low reactance in the machine. As the speed is increased and the number of poles is decreased the reactance naturally tends to increase and if the speed is made sufficiently high the machine can have sufficient reactance in itself to limit the short circuit current to a satisfactory value. That being the case, no external reactances will be required in such machines. For example, if a 10,000 to 15,000 kw., 25 cycle machine is made with two poles, 1,500 rev. per min., the internal reactance would naturally be very high. Also, if the same capacity machine for 60 cycles has four poles and operates at 1,800 revolutions, a fairly high internal reactance can readily be obtained. My experience with such

machines has been that there is little or no occasion for adding reactances outside the machine.

Furthermore, in these high speed machines it does not appear to complicate the machine, or increase its cost, to obtain sufficient internal reactance. In such machines a comparatively small number of coils of large size will naturally be used and such construction tends at once toward high reactance.

One fact, which should be considered in the use of reactance, is that the higher the reactance in circuit the higher the machine will be worked for a given terminal voltage, or the lower the terminal voltage with a given generated e.m.f. In other words, the addition of reactance in the circuit directly tends to decrease the available output of the machine.

On the other hand, the conditions which tend toward increased output in the machine itself also tend toward increased internal reactance, relatively, and it may be assumed that, if the machine is constructed for high internal reactance, in many cases it can also be constructed for very high output. This interrelation of high internal reactance and high output can be illustrated in a rather simple manner. Assume, for example, that with a given number of armature slots, the ampere turns per slot can be doubled, by changing the proportions of the slots, and by various other arrangements. It is obvious that the reactance of the machine as a whole would either be increased slightly, or at least, would not be decreased. However, the output would be very materially increased and in consequence the maximum short circuit current on the machine would either be decreased or would be no greater than before, while the normal current would be increased. In consequence, the machine with increased output would have no worse short circuit conditions than before, or the conditions might even be materially improved due to increased reactance. The problem therefore turns purely upon questions of design, such as obtaining high ampere turns per slot, while at the same time avoiding excessive eddy current losses and heating in the slot conductors. Greater refinements in the proportioning of the windings are now being carried out than were thought necessary only a few years ago.

For parallelling large alternating current systems, low reactance is not a necessary condition, but relatively low resistance is required. Experience has shown that there is a certain limiting resistance which can be used, above which instability of operation will occur. The limiting value of that resistance is, to a certain extent, a function of the construction of the machines themselves. For instance, if the synchronous machines have large cage dampers on their fields, the resistance between the machines can be higher than with undamped machines. In some tests made a few years ago it was found that with an ohmic drop corresponding to 20 per cent of the terminal voltage of the machine, instability was reached with the very best damper which could be put on the field. With less damping action

a lower resistance produced instability. If, therefore, a 25 per cent to 50 per cent overload condition is to be considered, then at normal load, only from 10 per cent to 12 per cent ohmic drop is permissible between the machines.

At the same time that the above tests were made for limiting resistance drop it was found that a very high reactance could be used between the machines without producing instability. The tests showed that the amount of reactance permissible was far greater than that required to limit the maximum current to a safe value in case of short circuit.

There is one point not brought out in Mr. Schuchardt's paper and that is that the damage to the winding is not merely a function of the maximum current but is also dependent upon the duration of the short circuit and also upon the number of short circuits which may occur. In connection with the New Haven Railway generators, where we had to add reactances to reduce the shocks on the machines and system, it was found that an individual short circuit apparently produced but little damage to the armature windings, but in the preliminary operation of the system, as many as 25 to 30 short circuits occurred per day, and, even with such frequent short circuits, the winding was found to stand up for months before a breakdown would occur. Also, as these machines were equipped with very heavy dampers the maximum short circuit current would hold up to practically highest value for 25 to 30 alternations, which was found to be a much more severe condition than where the short circuit was of much briefer duration. The results indicated that it was the continued hammering of the insulation by the short circuit stresses which did the most damage, and not the individual shock.

A remedy applied for this condition on these machines was the use of reactances in the circuits from the machines. These were of the iron-core type and have proven very effective. At normal load the iron is worked at such a low induction that the maximum current on short circuit will just about saturate the core. When so proportioned, an iron reactance is apparently as effective as an air-core reactance and has very little external stray field. I will say, however, that in constructing this reactance a large internal air gap is allowed—about 5 in., so that it is, to a certain extent, an air-core reactance with an iron enclosing circuit.

In these New Haven machines it was found that a reactance allowing 15 times normal current was not sufficient to protect the machines, and it was necessary to put in reactances sufficient to reduce the current to seven or eight times normal. However, the conditions were abnormal, as the output of the machines was single-phase current which required heavy cage dampers on the rotor fields in order to suppress the magnetic pulsations due to the single-phase armature reaction. With these heavy dampers the short circuit conditions were very much worse

than those encountered in ordinary generators of the same capacity. Experience with other types of machines has indicated that if sufficient reactance is supplied either internally or externally, to limit the current to about 12 times normal, it will protect the usual types of machines.

**W. L. Waters:** The tests made at the Commonwealth Edison Co., and the system of protection there worked out, are similar to those carried out three years ago by the Westinghouse Company, in connection with the Cos Cob Power Station of the New York, New Haven and Hartford R.R. Co. At the time the single phase equipment was being installed, this power house was subjected to a continuous series of short circuits due mainly to the non-selective action of the circuit breakers; these short circuits sometimes occurring as frequently as 25 or 30 per day, and varying in intensity from a dead short circuit to one at the

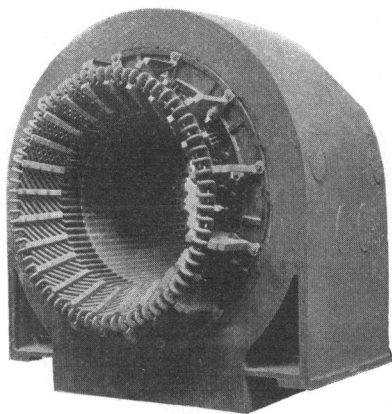


FIG. 1

end of a line having 5 per cent resistance drop. The system of protection worked out for that power station was:—an improved system of armature coil bracing on the turbo generators; the connection of a 9 per cent iron cored choke coil permanently in series with the line; and series or relayed oil switches, which in cases of short circuit introduced resistance into the line, thus decreasing the magnitude of the short-circuit current and raising its power factor before finally opening the circuit. This selective circuit breaker action and somewhat elaborate system of protection was installed on account of the exceptionally severe conditions of operation, and it is probable that some less complete arrangement such as that employed by the Commonwealth Edison will afford ample protection for the average power station.

The system of armature coil bracing for the turbo generators is shown in the accompanying illustration Fig. 1. It will be

seen that it consists of heavy wood blocks clamping the winding to metal brackets by means of insulated bolts. This bracing can be made as rigid as desired, and has the advantage of being permanent, as it does not deteriorate with time like the rope or twine lashing sometimes used. Numerous tests have been made on generators equipped with this system of bracing, by short circuiting when excited to 30 per cent above normal voltage, and in no case has any movement of the coils been noted. In fact the shock of the short circuit seems to be felt more on the frame of the generator than on the winding.

The Westinghouse tests above referred to, which were oscillograph records made to determine the effect, on the generator short circuit current, of including various types of self induction in the circuit, were made in 1908 on 2,000 kw.; 500 kw. and 300 kw. generators, tests being made at 60 and 25 cycles, both with and without dampers on the field magnets. The majority of the tests were made single-phase as it was found impossible to obtain consistent results on three-phase tests because of variation in the time of closing for the short circuiting switches in the three phases. The results of tests checked up well with theoretical calculations; the actual shape of the short current waves being found to be dependent on the power factor of the short circuit and the phase of the current at the instant the short circuit was closed. Under the worst conditions, the current wave immediately after closing the short circuit lay entirely on one side of the zero line, and the maximum peak had a value double that figured by dividing the e.m.f. of the generator by the impedance in circuit. Under the most favorable conditions, the current wave was at all times symmetrical with regard to the zero line, and the maximum peak was approximately the same as the value obtained by dividing the e.m.f. by the generator by the impedance in circuit.

Referring to the relative advantages of auto-transformers, iron choke coils, and air choke coils, for installation in a power station to protect against lightning, surges, and short circuits, it would seem that they all have both advantages and disadvantages; provided in all cases any iron cores used are worked at a sufficiently low magnetic density, so that they do not become saturated at the maximum peak of the short circuit current. An auto transformer, if built with a sufficiently high leakage reactance will undoubtedly afford protection, but it is expensive and is a constant source of loss. A 12,000-kw., three-phase, 25-cycle 4,500 to 9,000-volt auto-transformer will have a full load efficiency of about 99.25 per cent, while the efficiency of a 12,000 kw. 9,000-volt turbo-generator is practically the same as the corresponding 4,500 volt machine, so that this 0.75 per cent loss in the transformer is not compensated for in anyway. If we assume the generator operates 50 per cent of the time and that energy costs 0.4 cent per kw-hr., this auto transformer results in an annual loss of \$1,570 which capitalized at 8 per cent represents \$20,000.

In regard to the relative desirability of air and iron choke coils:—an air choke coil is appreciably cheaper in first cost, but possesses the disadvantage of a strong external magnetic leakage field which is liable to effect the instruments and to produce mechanical stresses or heating in surrounding objects. It has also been found from experiment that an iron choke coil is less liable in a short circuit to produce the distorted current wave located entirely on one side of the zero line which was above referred to. So that as a result of this it would seem that an iron choke coil, provided there is no saturation at the high current values attained on short circuit, is somewhat more effective in reducing the maximum current on short circuit than would be an air choke coil having the same impedance for steady values.

**John J. Frank:** In the discussion of the papers by Mr. Merriam and the paper by Mr. Schuchardt and Mr. Schweitzer I will endeavor to confine my remarks to that of the designing engineer, on the current limiting reactance which forms such an important part of both papers.

Neither paper, I believe, intends to convey the impression that every distributing system great or small should be provided with a current limiting reactance as a positive insurance to the elimination of all the troubles experienced by the operating engineer.

Where the impedance of the generator and the transformers is small the introduction of a current limiting reactance will no doubt, relieve the system to a great extent of both mechanical and electrical strains. This is supported not only by the papers presented but by the experience of the Consolidated Gas & Electric Co., of Baltimore, who installed a reactance for the protection of a 5,000-kw., 13,200-volt 25-cycle turbo generator. The particular causes of excessive current are short circuits between the lines, bus bars and generator leads, and grounds on Y connected systems with grounded neutral. The possible effects in mechanical strains upon connected apparatus can best be understood by reference to the strains in a transformer.

Take for illustration a 5,000 kw., three-phase transformer, having delta connected primaries supplied with 9,000 volts, 25 cycles. The normal current in the windings is 185 amperes; the measured reactance of the windings is 2.3 per cent. With the secondary windings short-circuited and constant terminal voltage impressed upon the primary windings, the current flowing

in the latter would be  $\frac{185}{0.023} = 8050$  amperes. The distance

between their magnetic centers is 1.7 in. = 4.32 cm.

The mechanical work of the magnetic forces of a circuit in which current is flowing is

$$W = \frac{I^2 L}{2} \quad (1)$$

Where  $I$  is the measure of the current and  $L$  the inductance of the circuit. This quantity is analogous to the energy of a static charge,  $\frac{C E^2}{2}$ , and to the energy of motion,  $\frac{M V^2}{2}$ .

If  $F$  is the force in grams produced between primary and secondary windings, and  $l$  the distance between their magnetic centers, the mechanical work done in moving one set of coils through the distance  $l$  against the force  $F$  would be

$$\begin{aligned} W &= F \times l \text{ g.-cm.} \\ &= F \times g \times l \times 10^7 \text{ joules.} \end{aligned} \quad (2)$$

Hence, substituting (1) and (2)

$$Fl = \frac{I^2 L}{2 g} 10^7 \text{ g.-cm.} \quad (3)$$

and

$$*F = \frac{i 2 L}{2 g l} 10^7 \text{ g.} \quad (4)$$

which is the mechanical force existing between the primary and secondary windings of a transformer at the short-circuit current  $i$ .

At short-circuit, the total supply voltage  $e$  is consumed by the leakage inductance of the transformer, therefore:

$$e = 2 \pi f L i \quad (5)$$

Hence, substituting (5) in (4) gives

$$\begin{aligned} F &= \frac{e i 10^7}{4 \pi f g l} \text{ g.} \\ &= \frac{812 e i}{f l} \text{ g.} \end{aligned} \quad (6)$$

Inserting the values of  $e$ ,  $i$ ,  $f$  and  $l$  in (6) we have,

$$\begin{aligned} F &= 545 \times 10^6 \text{ g.} \\ &= 1,200,000 \text{ lb.} \\ &= 535 \text{ tons.} \end{aligned}$$

This force is exerted between the six faces of the three primary coils and the corresponding faces of the secondary coils; and thus on every coil there is exerted the force

$$\frac{F}{6} = 89 \text{ tons.}$$

This is the average force, which varies between 0 and 178 tons, and thus reaches an enormous value.

If we denote the leakage reactance of a transformer by  $x$ , substituting  $i = \frac{e}{x}$  in (6) gives as the short circuit force at maintained terminal voltage  $e$ , the value

$$F = \frac{e^2 10^7}{4 \pi f g l x} = \frac{f l x}{812 e^2} \text{ g.}$$

That is, the short circuit stresses are inversely proportional to the leakage reactance of the transformer. It follows, therefore that on systems of very large powers safety requires the use of high reactance.

In order that a reactance shall protect, its voltage characteristic should be a straight line; that is, it should be proportional to the current flowing. The following empirical formula has been followed in the design of such coils.

The voltage induced in a coil in a magnetic field is

$$E = \frac{4.44 \phi f T}{10^8} \quad (7)$$

in which  $\phi$  is the flux enclosed by the conductor,  $f$  the frequency in cycles per second, and  $T$  the number of turns. The flux produced by a solenoid or coil without an iron core is

$$\phi = \frac{I T d}{K} \quad (8)$$

in which  $I$  is the current in the coil,  $T$  the number of turns,  $d$  the inside diameter, and  $K$  an empirical constant which equals

$$K = 0.125 + 0.28 \frac{L}{D} \quad (8a)$$

where (see Fig. 2)  $L$  is the length and  $D$  the mean diameter of the solenoid. Substituting (8) in (7)

$$E = \frac{4.44 I T^2 d f}{K} 10^8 \quad (9)$$

and

$$T = 4750 \sqrt{\frac{K E}{I d f}} \quad (10)$$



The latest expression of the designer is shown in the accompanying illustrations Figs. 1 and 2. The core consists of a cylinder of concrete in which are imbedded anchor plates for clamping bolts.

Radial strips of wood treated to give greatest possible insulation are attached to the core and are provided with grooves into which the conductor is wound. The conductor consists of bare stranded cable and is wound in one continuous piece as shown in the photograph so that eddy currents which might heat the solder or brazed joint in the center of the winding is eliminated. The end turns are given increased space over the average allow-

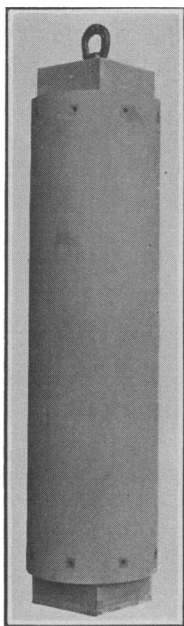


FIG. 1

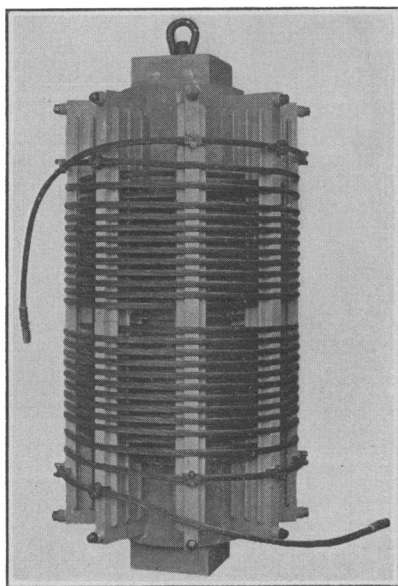


FIG. 2

ance to afford better reliability against electrical or magnetic shocks to which it may be subjected. In addition the conductor on the last turn at each radial support is clamped to further increase the rigidity of the coil. That the reactance operated satisfactorily in the tests made is brought out in the two papers. In order to facilitate cleaning and inspection, the cores and wooden radial supports are given a coat of cream color enamel paint. All of the bolts, nuts, and clamping members are made of brass rather than steel, to eliminate any heating due to the concentration of the flux which would be induced by a magnetic material.

**Louis A. Ferguson:** I would like to know whether Mr. Lamme desired to convey the impression that it would be better to use machines of high reactance rather than external reactance? My reason for asking that question is because he made the statement, if I heard him correctly, that by using machines of high reactance you could increase the output, by using a large number of coils per slot.

Our experience here in Chicago has been rather the other way; that is, we have found with our earlier large machines that there was considerable heating, and that the output for the capacity of the machine was limited, and it was necessary, in order to obtain the desired output, to reduce the number of coils per slot, and for this reason, because of the two statements going together, I would like to have him state whether in his opinion it is better to use machines of high reactance, or machines of low reactance, and external reactance connected therewith.

In replying to the question I would suggest that Mr. Lamme confine his remarks to the large machines, such as the 12,000 to 20,000-kw. and leave out of consideration the small machines of say, 1,000 to 2,000 kw.

**B. G. Lamme:** In machines of large capacity, such as turbo-generators, it is advisable and practicable to obtain large internal reactance by suitable design. If you can increase the number of ampere turns per slot you will tend to increase both the output and the reactance of the machine, and therefore the percentage of current on short circuit will be relatively decreased. In practice it will be found that high reactance machines are generally of relatively high output for given dimensions.

As to the matter of increasing the number of ampere turns per slot, that is a question of design principally. The difficulty with high ampere turns per slot is principally from eddy currents due to local flux conditions in the slot. Very much can be gained on this point by careful design and there is evidence that we can go much further in this regard than we have yet gone.

I think the whole tendency in turbo-generator design is toward the largest number of ampere turns which can be gotten into the armature, without increasing the dimensions, and such increase in ampere turns will also be accompanied by increase in reactance. I am in favor of putting as much reactance as possible into the machine itself up to the limiting amount required, and whenever a sufficient amount for protection cannot be put into the machine itself, then put the remainder outside. I do not favor making the internal reactance as low as possible and putting high reactances outside for I believe that this is a relatively expensive method of procedure.

**R. B. Williamson:** This paper has demonstrated very clearly the desirability of a certain amount of reactance in connection with large turbo-generators. This reactance may be external as in the present case, or it may be in the machine itself, provided

the design is such that a high reactance winding can be used without making a less desirable design in other respects. High reactance in the generator itself means a high specific loading for the stator (*i.e.*, high value of the number of ampere-conductors per slot or per inch of periphery.) In large turbo-generators, most of the heat liberated in the stator copper must pass through the insulation and into the stator iron before it can be carried off, *i.e.*, the cooling effect of the ends of the coils is comparatively slight. In order, therefore, to limit the internal heating of the stator coils, an increase in the number of conductors per slot must be accompanied by other changes in the design, in order to limit this heating. This is particularly true in high voltage generators where the heat has to pass through a considerable thickness of insulation.

Since it is clearly desirable to have a certain amount of reactance in order to avoid the disastrous effects of short circuits on large units, and, since a high reactance involves poor inherent regulation, it follows that close inherent regulation should not be specified for such units. Moreover, it is now general practice to take care of the voltage regulation by means of automatic regulators, so that there is no great necessity for close inherent regulation.

Another point to be considered is that, other things being equal, high speed machines are more likely to be damaged by heavy short circuits than low speed ones. The internal reactance of the high speed generator will usually be less than that of the lower speed machine, but even assuming the same reactance in each case, the coils in a high speed generator span a greater angle, hence the projecting ends of coils are correspondingly longer and more difficult to support securely.

**Clarence P. Fowler:** In addition to the superior features mentioned, by Dr. Steinmetz, of direct current as compared with alternating current for supplying electrical energy to the congested portions of our larger cities, the following inherent advantages of the former system for this class of service, have been doubtless, in no small measure, responsible for the persistence of this system, (through the use of alternating current-direct current conversion apparatus) to the exclusion of alternating current supply:

*a.* With direct current available, special devices are unnecessary for charging small storage batteries, such as used in automobiles, etc.

*b.* As most isolated plants for office buildings, etc., are of the direct current type, the use of direct current distribution at once facilitates, the installation of breakdown service connections for such plants.

*c.* With alternating current distribution there is considerably more high tension feeder copper required per maximum kw. than with the alternating current-direct current system and as high tension cables cost vastly more per lb. of copper than low tension

cables, it is evident that there will be quite a marked saving in this direction in favor of direct current distribution.

d. There is also quite a difference in favor of the maintenance of low-tension cables as compared with high-tension cables and even assuming equal life for each, the scrap value, at the time of removal, would be perhaps 35 per cent to 50 per cent lower for high tension than for low tension cables.

The analogy drawn between the necessity for the use of reactance in connection with our modern high voltage, high-power systems, on the one hand and the resistance of lines, feeders and mains of the older and smaller direct current systems, on the other, is interesting.

The use of reactance, as an adjunct to the operation of synchronous apparatus, as a means of affecting voltage regulation has been fully appreciated, for some time past. In 1905 the writer discussed, the possibilities of the use of reactance, for this purpose, and showed by means of waves, giving the relative phase relations of e.m.f. and current, that the inductive voltage, across a reactance, could be made additive to or subtractive from the delivered line voltage, depending upon the intensity of field charge of the connected synchronous apparatus.

It is, however, only comparatively recently that the power-limiting capabilities of reactances have come to the fore. This, no doubt, has been largely due to the marked movement toward consolidation and concentration, in the central station industry, resulting in unified systems of gigantic proportions, the loads upon which may fluctuate suddenly through a wide range or still worse, short circuits on such high-powered systems may give rise to rushes of current, the volume of which was hitherto unknown, in previous systems. The change that has taken place in the size of central stations will be apparent, when it is noted that the U. S. Department of Commerce and Labor, reports that the average size of central station grew about 72 per cent, in the five year period from 1902 to 1907.

The violent forces acting upon generating transforming and switching equipment resulting from short circuits, on high-powered systems, have, in many instances, manifested themselves in no uncertain way, in the complete destruction of the switching equipment and oftentimes with considerable damage to generating and transforming equipment, in the absence of power-limiting reactances. With the practical elimination of the reciprocating engine from these large stations and the substitution therefor of the steam turbine, a type of apparatus has been introduced the construction of which is peculiarly susceptible to mechanical strains, due to sudden surges of current of large volume. This condition in the turbine, results from the comparatively few poles employed and the consequent relatively greater throw of armature coils, and resulting lack of rigidity of the armature conducting structure. To add to the rigidity of the armature coils, various forms of coil supports, brackets,

etc., have been devised, and while this method of construction has greatly aided in preventing distortion of the armature winding, it is evident the method of removing the cause of the trouble through use of properly designed reactances offers one of the most satisfactory solutions of this problem. In fact, one of the largest and most important examples of steam railroad electrification in this country, has found the use of just such reactances a most indispensable aid in the safety and reliability of its power supply apparatus.

**P. Junkersfeld:** The three papers presented at this session are either based upon or suggested to a large extent by the tests referred to as having been made in the plants of the Commonwealth Edison Company of Chicago. The need for making this long series of tests at considerable risk and expense was brought about by a unique situation. A very large amount of electric power supply business had been obtained and to serve this, there had been installed sixteen (16) large turbo-generators aggregating 204,000 kw. all in a little less than five years. The rapidly increasing responsibility to the consuming public of operating this unusual equipment and the large system of which it forms a part, together with the need of providing additional equipment of still greater capacity and better economy, made it absolutely necessary to make a most thorough experimental investigation and to secure the most positive information on this fundamental feature of reactance in a large system. As a result of these tests the previous tentative plan of installing 6 per cent reactance for each of the remaining thirteen (13) turbo-generators having a frequency of 25-cycles was finally approved and also the plan of installing a limited amount of reactance in each of the two tie lines connecting the Fisk and Quarry Street Stations.

I wish to express appreciation of the careful thought and much extraordinary effort on the part of all the engineers of the manufacturing and operating companies who were in any way connected with these tests, and particularly also to Dr. E. J. Berg and Dr. Chas. P. Steinmetz who gave thereto a very large amount of personal attention.

As a matter of reliability of service, the localization of the effect of breakdowns of whatever nature will probably always be the most important problem. On the one hand there is frequently the temptation to install a still larger amount of protective apparatus which may in itself occasionally cause trouble. On the other hand other methods of securing greater reliability such as independent lines or sources of supply, multiplication of lines, sectionalized operation to a greater or lesser extent, etc., may involve greater expense than is commercially justified.

Referring now to Mr. Lamme's statement, as I understand him, that repeated short circuits do more damage than individual short circuits: In our experience it is the individual short circuit on the high tension system that causes the damage, and

which in most cases is so severe that the particular unit or element affected must be repaired or overhauled before it can be again put into service.

At the Annual Convention last year, the discussion of Mr. Cheyney's paper on "Oil Switches" by myself and others indicated a lack of confidence and brought out the fact that very little improvement had been made in oil switches for several years. Tests made during the past year, some of which are included in Mr. Merriam's paper, have indicated the necessity of several improvements in every type and make of oil switches that were tested. They are improvements in oil diverters and baffles, proper reinforcement of various kinds of oil vessels, effect of size of oil vessels, speed of opening, length of break, effect on oil of repeated short circuits and so on. These improvements are in a structural sense of a minor nature, but of much importance in securing more satisfactory and reliable operation of oil switches, and hence I believe we are now justified in placing more confidence in oil switches than before. There is, however, still ample room for further improvements.

It was demonstrated during the Chicago tests that it is not necessary in future that such short circuit tests be made in a large steam turbine driven power house in order to be conclusive as all of the destructive power in such short circuits was found to be due to the stored energy in the generator and none of it to the amount of steam back of the turbine. The tests and investigations described principally in the paper by Messrs. Schuchardt and Schweitzer can, therefore, now be continued in the test rooms of manufacturers as a large generator brought up to speed slowly by a comparatively small motor or prime mover will answer equally as well for further experimentation and at very much less risk and expense.

**C. P. Steinmetz:** In concluding I wish to say that the oil circuit breaker is one of the most common and most important pieces of apparatus, and at the same time its method of operation is least understood by most engineers, and modifications of it are still continually suggested, based on theoretical considerations, largely erroneous. We must realize that the operation of the oil circuit breaker is not based on any oil circulation, but is based on the control of the explosive forces developed at the break, for extinguishing the arc, and you can easily realize, then, that the concentric gun barrel type of switch has advantages which no other type has as yet been able to approach.

Regarding the induction generator, I have always been very much in favor of it, and I believe it is a very useful machine; and in a central station having an excessive momentary short circuit current, the addition of the induction generator reduces the percentage of short circuit current, since this machine does not add to the short circuit current. But you must realize that you could get the same effect by using generators with lower regulation. Thus, if you consider the station as a whole,

there is little difference between a synchronous generator station and an induction generator station, regarding the momentary short circuit current. Every station depends in its excitation on an independent direct current excited field, in one case the synchronous alternator field, in the other case the synchronous motor field, which gives excitation to the induction generator. If you use for the excitation of the induction generator station the converters, synchronous motors, and frequency changers scattered over the system, as these are slow speed machines of low momentary short circuit current, you can materially reduce the short circuit current, but you throw the control of the system away from the generator station into the hundred or more isolated machines, all of which combine in controlling the generating station, and that is not practicable. If you have synchronous motor exciters floating on the system at the induction generator station, economy requires just as high speed machines as our present synchronous turbo-alternator, that is, machines with just as high momentary short circuit current, and you gain practically nothing; and therefore, while the induction generator is a very valuable machine in many instances, the problem of momentary short circuit current is not solved by it. The main field for the induction generator, in my mind, is in the secondary generating stations of hydroelectric systems, as it becomes possible thereby to control voltage, load and frequency of the system from a few main generating systems; the installation control and operation of the smaller induction generator stations becomes greatly simplified, and it becomes feasible to utilize smaller water powers, which could not be economically developed by synchronous machinery.

The last point I wish to bring up is the question of internal reactance as against separate reactance in the generator. That is a question which needs no further discussion, but is ancient history. The development of the generating station has long advanced beyond it. We know we must have power limiting reactance in the individual generator, and it is merely a constructive question—a question of design, whether we put it inside the alternator or outside of it, or whether we make the most economical combination possible, put into the machine as much reactance as possible without sacrificing the quality of the machine, and then put the rest of it outside of the machine.

But even if we had generators with a momentary short circuit current five or six times full load current, that would not solve the question of the operation of the present systems, because if the system is large enough, 100,000, 200,000 or 500,000 kw., you reach a limit where the operation becomes unsafe, even with power limiting generator reactances.

That is where the development has arrived, to put power limiting reactances in the bus-bars. This is really the most essential advance. In the last few years we have come to larger and larger systems, and consequently greater difficulties of

operation. Apparatus which was satisfactory in a 50,000-kw. station became unsuited to the operation of a 100,000-kw. station, and apparatus which had been employed in a 100,000-kw. station will become inoperative at 500,000 kw. That was not the case in the old Edison direct current system. There, if you joined generating stations together, there was no material increase of danger, no decrease of safety, because the whole system was limited by the resistance of lines and feeders. Thus the effect of a short circuit was practically the same, whether the station was alone, or other stations were tied to it; that is, there was that feature that the danger did not increase with the increase of the system. That is the most important feature which modern development has arrived at in these alternating current systems, that by breaking up the bus-bars and tie-feeders by reactances, the danger and difficulty of operation, the strain of switches and apparatus, does not increase with any further increase of the system, and the 100,000-kw. system is just as safe or dangerous as the same system will be if extended to 500,000 or 600,000 kw. capacity. That is the great development beyond the power limitation of the generator—the use of power limiting reactances in the bus-bars, which makes an unlimited extension of the system possible without any increase of danger.

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