DISCUSSION ON "THE REGULATION OF DISTRIBUTING TRANSFORMERS", "TEMPERATURE GRADIENT IN OIL IMMERSSED TRANSFORMERS", "DISSIPATION OF HEAT FROM SELF-COOLED, OIL FILLED TRANSFORMER TANKS", "PROBLEMS IN THE OPERATION OF TRANSFORMERS", PITTSFIELD FEBRUARY 15, 1911.

W. S. Moody: I will not attempt to contribute to any of the discussion, but I wish to point out one idea that has been specially in my mind in connection with the papers that have been presented this afternoon. Most apparatus, whether electrical or otherwise, requires some arbitrary or empirical formula to be used in its design. Transformers, among electrical apparatus, are, I believe, as little subject to these "cut and try" methods as any other class of apparatus, except for two characteristics that have been brought to the front in the discussion this afternoon—*viz.*, the calculation of the dynamic forces that must be resisted, and the predetermination of temperature rise.

For the first, we now have in the formulae recently developed the means of knowing what these forces are, and with this knowledge, taking care of them is a relatively simple matter.

When sufficient mechanical support has not been furnished for transformer windings, it has been due to an under-estimate of what these forces are likely to be, rather than any special difficulty in providing proper supports when the actual force to be encountered is known.

With reference to the second point—*viz.*, temperature rise, there has been a great lack of definite data. We can calculate a new transformer in nearly every other characteristic with great accuracy, but if the design is radically new, one could not, in the past, tell what the real capacity would be with a given temperature limit until tests were made.

Having determined the temperature by test, it is usually necessary to re-proportion the parts once or more to obtain the desired characteristics on the re-rated design.

To predetermine temperature rise one must consider a vast number of details, such as are considered in Mr. Weed's paper, and which have previously been neglected or allowed for in a very arbitrary way.

With such formulae as are discussed in Mr. Harper's paper, and such data and formulae as are considered in Mr. Weed's paper, I feel that there is no further excuse for the use of any "cut and try" methods being pursued in transformer design.

Henry Pikler: The papers we have just heard as some of the papers we heard earlier, interest probably the designing engineer more than the operator, since after all the operating engineer is satisfied if the apparatus in service fulfills the requirements of guarantees attached to it.

As to the various papers, Mr. Allen's paper on the "Regulation of Distributing Transformers" is a very able and clear presenta-

tion of the relation between resistance and reactance in the regulation of the transformer. A great many examples have been worked out and various formulas given to calculate the regulation, but in general I dare say I do not find the broad point of view from which the influence of both the reactance and the resistance could be clearly pictured. The following may be a clearer and simpler presentation of the facts: The regulation depends upon the mutual relation between resistance and reactance in the transformers; at loads of unity power factor the regulation is approximately equal to the resistance drop, and at loads of zero per cent power factor, it is approximately equal to the reactance drop; at power factors between the two, the regulation will be found between these two figures that is the resistance drop and the reactance drop combined.

Towards the end of the paper a method is given whereby good regulation may be obtained in transformers intended to be used for three wire distribution, lighting transformers. At this point it may be said with probably greater simplicity: In small size lighting transformers the resistance is the predominant component of the impedance. In larger transformers the reactances is of larger amount. Therefore, when we want to connect various parts of the transformer windings into parallel, so as to obtain proper three wire distribution and at the same time best regulation, in small transformers equal resistances in large transformers equal reactances should be connected in parallel.

I consider one of the most interesting papers, presented to us, that by Mr. Green on "Problems in the Operation of Transformers". Anybody who has had a chance to install transformers, to observe them in operation and to note the various phenomena in connection with them will appreciate the complexity of these phenomena and the difficulty of their clear presentation.

One of the most frequent sources of troubles in connection with transformers is their installation. At this point I wish to call attention to the fact that while almost always the transformer is tested at the factory of the manufacturer, in the presence of a representative of the customer, afterwards the transformer is installed frequently by the customer himself. The transformer is often found satisfactory in every respect at the factory, yet, at its installation breakdowns are not infrequent. Causes of this may be various and I shall refer to them later on, but I desire to use this occasion for suggesting the adoption of some rules, if that is at all possible, whereby the customer be held responsible for injuries to the transformer when he does the installation after having tested and accepted the transformer at the factory. The manufacturer should be held responsible only when his representative does the installation.

The causes of the breakdowns in transformers may be divided into two great classes. (1) Internal causes in the transformer itself. (2) External causes.

1. As to the internal causes I believe that defects in design, electrical construction, insulation, will show up at the factory if the apparatus be tested rigidly. At the same time there may be defects in the manufacturing which develop a weakness in the transformers only after it has been installed and operated for some time. At the present time the use of solid compounds for impregnation of the windings is almost universally adopted. The solid compound marks a great improvement in the modern transformer because it makes those mechanically weak coils of which we heard so much this afternoon, stronger by cementing together the turns and the insulation between turns and layers in the winding. At the same time the application of this solid compound is not so easy as it may look at first glance. If not done properly there may be found bare spots in the winding which have not been reached by the compound. At such places the mechanical wear and the dielectric stresses combined may create injurious effects in the course of time.

Also improper drying out before installation may be the cause of a breakdown.

One very good point brought out in this paper which I believe hits the nail on the head as regards internal causes, is the suggestion that the electrostatic capacity of the parts of the transformer should be small.

It is very interesting to follow the history of the design of transformers and of the means suggested for their protection. Years ago we heard that the weakest element in a transformer were the first turns and they ought to be protected most carefully by insulating them more than other parts, it was earnestly recommended to put a choke coil in series with the transformer or use the choke coil internally or even to develop the first few turns as a choke coil. *Now* we hear that it isn't so much between the first turns where the breakdowns occur but between other turns or parts of one winding. It would be very interesting to take oscillograms for the purpose of obtaining the voltage distribution between the various parts of the transformer winding under various conditions as switching surges, etc.

Again in this paper we find reference to forces in transformers arising on short circuits; it is suggested that the transformer be designed with sufficiently high reactance in order to reduce the short circuit currents, and the resulting forces. At this occasion I wish to say that contrary to the statements made by previous speakers that the low regulation of the transformer is chiefly due to the customer's demands for such, my findings are different: Low regulation is a natural sequence in transformers of large sizes; with the generally adopted principles of design and the economic utilization of materials, we cannot help but obtain a decreasing reactance with increasing output. Furthermore, we mustn't forget that it is not the per cent reactance that should be considered in this problem but it is the numerical value in ohms. To make a large transformer of high reactance is not

so simple as it may seem at first glance. A high reactance transformer means an expensive transformer. It means a transformer with many more ampere turns than in a low reactance transformer. More ampere turns means more copper and copper is an expensive material; besides copper requires winding space, hence a bigger iron core, in other words a larger and a more expensive transformer. On the other hand, if the high reactance be created by increasing the space between primary and secondary windings, we again get a larger winding space and larger core; in addition a tremendous self inductive field will be developed between these windings which is conducive to high eddy currents, heating and a reduced efficiency.

2. As to the external causes of breakdowns I wish to emphasize very strongly that in this respect the entire power system must be considered from the prime mover to the distributing apparatus. Concentrated condensers in parallel with the transformer created by neglect of grounding supports of high tension wiring, switching apparatus, etc., can pile up tremendous voltages on the system which may find an outlet into the transformer. Analogously concentrated choke coils may also be detrimental in the case of great variations in currents. Defective governors of prime movers, variations in speed and voltage, high winds which bring line wires on poorly constructed transmission systems in oscillation, improperly installed protective apparatus, surges of all kinds in connection with concentrated condensers as described above are the most frequent sources of breakdowns of transformers. Therefore before installing a transformer particularly on a high voltage long distance transmission system everything ought to be reviewed from the point of generation of the energy to the point of distribution.

As to the paper on "Dissipation of heat from self cooled oil filled transformer tanks", again I do not find that broadness I looked for on this subject; although I must say that the paper presented by Messrs. Frank and Stevens is very valuable particularly for the many tests and numerical results given: In self-cooling transformers we find a great disadvantage results from the fact that the surface of the tank is not uniformly efficient. The useful surface is almost entirely the upper one; the lower portion depending of course on the proportions of the tank, is quite useless. Before we start to adopt various artificial means for increasing the radiating surface of the tank, we should first take advantage of the surface we already have, that is, make it as nearly uniform in efficiency as possible. There is one transformer tank that meets this requirement, this is the one with the external return pipe connections between top and bottom. This tank does not represent a novel idea; about eight years ago the Stanley Electric and Manufacturing Company—Mr. Chesney who is present will probably remember—had some transformer tanks in the shop of exactly that type, this type of tank was abandoned, however, on account of the excessive cost,

and the difficulty at that time in making the welding between the coil and the tank.

In comparison with the European practice it ought to be pointed out that European transformer designers and makers are far ahead in making self-cooling transformers and tanks, and it is not unusual that capacities as high as 3,000 kw., or over are made for self-cooling purposes. One reason for this may be that the European standard for the rise of temperature is 20 to 25 degrees higher than the American standard. I personally think that our temperature limitations are too low, particularly in view of the great improvements made in insulating materials during recent years. I think it would be absolutely safe to allow a temperature rise even as high as 60 degrees instead of 40 degrees, even in the over-heated power station.

E. G. Reed: Mr. Pikler has just made the statement that the European practice in regard to self-cooling transformers is superior to that in this country, referring to the size of units which can be cooled in this manner. The above statement should not be permitted to go unchallenged, as we are to-day successfully building in this country, transformers of this type up to as high as 3000 kv-a. capacity. The method of cooling employed is to provide oil tubes external to the transformer case through which the hot oil flows, being cooled in passing. This is a distinct advance in the art of transformer design. Such self-cooled units find their use, for example, in isolated substations where water for cooling is very difficult to secure and where it is desirable to dispense with an attendant.

Just a word in regard to Mr. Allen's paper: It seems to me that the most important point in this paper is the suggestion of the standardization in the method of calculating regulation on the basis of not taking into account the exciting current. If this method is correct, and I think it is, as it lines up with the Institutes' definition of regulation it should be generally adopted.

Louis F. Blume: Before regulation was defined by the American Institute of Electrical Engineers, it was proper to include exciting current in its calculation for transformers, because then by regulation, was understood the total drop at full load in the transformer from primary applied to secondary terminal voltage. When the Institute defined regulation as the difference between no load and full load primary voltage the consideration of exciting current became negligible. Thus, as Mr. Allen points out, the only influence of exciting current upon regulation lies in the fact that at no load it is greater than at full load. This difference, however, being so very small, is only of theoretical interest.

E. A. Wagner: The paper by Mr. Allen is typical in showing that the transformer engineer does do things accurately. Our worthy President intimated that transformer engineers did not get very close in their calculations, but rather guessed at them. Mr. Allen shows several formulae for the calculation of regula-

tion, and in these several formulae he works out to hundredths of one per cent. I think it is a matter of choice, no matter which formula you take, and I know that there is considerable discussion at times as to the method of calculating the regulation and working it down to very fine quantities, and I believe it is within the province of the Institute to make a recommendation as to some definite formula, so that in the case of a discussion between a consulting engineer and a manufacturer as to the method of calculating the regulation, there is something to refer back to.

It may be true that the formulae would be subject to such discrepancies as stray exciting current or magnetizing current might produce—you might want to segregate them—but I do not think that has any direct bearing on the matter, and I want to make a recommendation that this matter of having some recommended formulae for calculating regulation be taken up by the Standardization Committee.

In regard to Dr. Steinmetz's paper, which I did not discuss previously, would state that I had occasion a number of years ago to see an actual demonstration of the forces or stresses which followed from a short circuit. It happened at Niagara Falls, and was a case of 200 kw. transformer subjected to short circuit, and it showed that the busbar winding, which was about one-half in. by two in. was strained and actually forced and distorted out of place, and at the same time, due to the same causes, the cables in the alley running from the power house were thrown off the rack—that was an actual demonstration and showed at that time that these stresses did take place.

In regard to the paper by Messrs. Frank and Stephens, on the dissipation of heat from self-cooled oil-filled transformer tanks, my experience is in accordance with theirs. I think you will obtain about 50 per cent, make the figure a constant of 50 per cent, less watts per square inch, with a corrugated sheet steel tank than with a plain cast iron tank, and I have tried to follow that out carefully, and find that the practice agrees very closely with their curves. I think that the tendency to run to very deep narrow slots will give us dead air pockets, and believe the best results will be obtained by slots or corrugations having ratios of a depth not more than twice the opening. I have not made any attempt to calculate this and arrive at a mathematical conclusion, but as a matter of practice find that the above general rule gives the best results. I do not think that good results will be obtained from the boiler tube tank, because I have tried schemes of pumping hot oil into the bottom of the tank, and *vice versa*, taking cold oil from the bottom, and circulating it from the top, so that the surface of the tank reaches the same temperature throughout—under these conditions, the lowering of temperature with a transformer having a 40 degree rise without the circulation, my tests showed we gained one or two degrees lower rise which is not enough to warrant the additional complications which this system involves.

C. A. Adams: Referring to sketch H of Mr. Green's paper, it may be of interest to show why there must be a 3rd harmonic in the transformer flux and induced e.m.f., with three-wire star connected primaries, and secondaries on open circuit.

It has often been shown that a sinusoidal flux in a closed iron magnetic circuit such as that of the ordinary transformer, requires a magnetizing current with a considerable 3rd and a lesser fifth harmonic. But a third harmonic current cannot flow in a three-wire, three-phase, star connected system, since the third harmonics in the three wires are in phase when counted positive in the same direction along the line, and would therefore be all flowing towards the star neutral at the same instant, which is obviously impossible without a neutral return wire.

Assume the secondaries on open circuit, and neglect the fifth and any higher harmonics. The currents in the three trans-

FIG. 1

former primaries will then be sinusoidal. Neglecting eddy currents, the relation between the m.m.f. and the flux is given by the hysteresis loop of Fig. 1. The sinusoidal magnetizing current or m.m.f. is plotted against time in Fig. 1. In both curves, time is indicated by the arrow-heads. The flux-time curve, derived in an obvious manner from the hysteresis loop and the m.m.f. time curve, is curve *B* of Fig. 1. The fundamental of the flux curve is shown in curve *B*, and the residual or higher harmonics in curve *B_{3, 5, etc.}*. From this it is clear that there is very prominent third harmonic in the flux curve, which increases with the maximum density.

Thus on open secondary circuit, there is a pronounced third harmonic in the flux and therefore in the primary and secondary e.m.fs. It is obvious that these third harmonic e.m.fs. in the primary phase or star e.m.fs., do not affect the line e.m.f., the

wave-shape of which is determined by the supply alternator. (The two third harmonic e.m.fs. connected in series between any two primary lines are 60 degrees apart in fundamental degrees, when counted positive from line to line through the star neutral, and therefore 180 degrees apart in third harmonic degrees. They thus neutralize each other and do not appear in the line e.m.f., but merely cause a rotation of the star neutral point).

If now the secondaries be closed, either in simple delta or diametrically to a six-phase converter as indicated in Mr. Green's sketch H, the third harmonic, unless exactly neutralized by some third harmonic dynamic e.m.fs. in the converter, will produce third harmonic currents in the secondaries, the m.m.f. of which will tend to oppose their cause, namely the third harmonic fluxes in the transformer cores, *i.e.*, these third harmonic currents in the secondaries will act as exciting currents, will tend to supply the primary deficiency in this respect, and to restore the flux to the sinusoidal form. This restoration will obviously take place up to the point where the third harmonic secondary e.m.fs. are just sufficient to drive the necessary third harmonic exciting currents through the local (internal or leakage) impedances of the secondaries, and of the converter. As these third harmonic e.m.fs. are very small, the flux will be practically sinusoidal when the secondaries are connected as in sketch H.

It has often been stated that the design of electrical machinery is an *art* rather than a *science*, and while there was doubtless much of truth in the statement when it was made, the application of scientific methods to a rapidly increasing number of design problems is bringing about a condition not accurately described by the above mentioned statement. As one much interested in this particular evolution, I wish to congratulate Mr. Weed on his paper, which is a step in the right direction. Of all the problems connected with the design of electrical machinery, none is at present handled in a more crude and superficial manner than the very vital problem of temperature rise. To be sure, from the standpoint of scientific accuracy, the problem is hopelessly complex, but there is much room for improvement before we begin to approach that ideal, and every step means more rational and more economical designs.

A. E. Walden (by letter): Mr. C. E. Allen's paper on "The Regulation of Distributing Transformers" is very interesting, and is in line with the method the writer has been employing for over eight years for selecting transformers for power service. The small transformers were tested with actual load, both with lamps and choke coils, obtaining actual drop directly. The manufacturers' claimed regulation is shown in the chart for three types of transformers, two using the old iron or steel, and one the new steel, and the method of selecting to get the best regulation. Actual tests taken have given better regulation than claimed by most manufacturers.

Mr. Allen's paper does not bring out very clearly the resultant loss in feeders due to poor regulation, with consequent voltage and power increase at the generating station, and the increased power required at exciter, due to lower power factor in the motors or transforming devices. In the operation of generating station and the distribution system of to-day, considering the size, the condition of low power factor deserves more attention that it has heretofore been given.

In a large distribution system at low power factor, such as is usually found with induction motors, the feeder loss with an increased drop of three or four per cent in transformers will be found to be considerable in the aggregate. In a generating station of 8,000 h.p., which the writer inspected recently, the power factor was below 70 per cent during the day, due to the

fact that the load was nearly all motors. This will increase this loss considerably over iron loss.

It should be noted, further, however, that the regulation of transformers tends to improve slightly with power factors below 60 per cent.

Will Mr. Allen kindly explain what the increases in cross-section of the cores would be, also increase in weight per cent, to improve the regulation to that shown by curve No. 1. Also approximately what would be the increase in transformer cost if this was done, or could be done without changing the number of turns of the copper?

Ralph D. Mershon: I am sorry I have not had an opportunity to study these papers. I am especially interested in the paper by Mr. Weed and in that by Messrs. Frank and Stephens,

not only in their bearing upon transformer design but also in connection with other engineering work where almost exactly similar problems arise relative to cooling. There does not seem to be much published data applying to this problem, and in some cases where I have required data I have been helped out by information furnished by some of my friends engaged in transformer design. But the information they could furnish was not nearly as comprehensive as would be generally desirable.

Figs. 5 and 7 of the paper by Messrs. Frank and Stephens show corrugations of such form that the section of the air space within the corrugation is greater than the corresponding oil space. I should like to ask the authors whether they have arrived at a method of determining the relation between these sections for the best result and if so what that method is.

There is another feature of the problem somewhat similar to that of the relation between the sections of the air and oil spaces in the corrugations. That is the best relation between the areas of tank surface exposed to air and oil respectively. Suppose we have a cast iron tank, for instance, having ribs on the inside and ribs on the outside. We may make the ribs on the inside and outside of different depths so that, within limits, we may vary the relation between the area of the tank in contact with the oil and the area in contact with the air. Now it would seem to me that the temperature drop to transfer a given amount of heat from the oil to a given area of tank surface would be less than that required to transfer the same amount of heat from the same area of tank surface to the air and that, therefore, less area would be required on the oil side than on the air side. It would be interesting if the authors could give us data bearing upon this point.

FIG. 1

It is not necessary to have a cast iron tank in order to control the ratio between the inside and outside areas. It can be done in a corrugated tank by collapsing some of the corrugations as in Fig. 1 and at the same time the relative sections of the spaces included in the corrugations can be controlled as indicated in the paper.

C. W. Stone: I have one or two questions in mind that I would like to ask—one is in relation to Mr. Allen's paper. Fig. 9 shows a transformer which he calls a distributed shell type transformer, and Fig. 12 shows a core type of transformer. I do not see the difference. I wonder how he got at the name distributed shell type transformer. Apparently they are both core type. I think Mr. Allen could have brought out more prominently the increased cost of the transformer, and that bears out the point Dr. Steinmetz referred to, that the customer forces the price of the transformer down. If he has not done it, the manufacturers competing for the business have done it, which amounts to the same thing.

Mr. Pikler spoke of the breaking down of the transformer oc-

curing inside the transformer, in other places than the end turns, and he suggested this matter should be investigated. It has been investigated by the oscillograph with interesting results which will be brought out later in another paper.

I notice a point in Mr. Green's paper which I think is particularly interesting to all designing engineers as well as operating engineers, in referring to the percentage of puncture between high-tension and low-tension windings, or between the windings and laminations, as being negligible, as compared with the percentage of punctures between turns. That is based on years of experience after many investigations of burn-outs of transformers I do not think it is often given consideration.

Another point that Mr. Green makes is one that operating engineers overlook—they seem to think, if they put a lightning arrester on the line, they are free from trouble, and that if the transformer breaks down it is due to a defect in the transformer. I want to point out that the best type of lightning arrester that can be conceived will not protect the transformer, particularly if they are switched on the high-tension side. There will be internal surges which will break the transformers down, regardless of the lightning arrester. Put on all the lightning arresters you can get and then put on some more, and it will protect you from surges outside, but will not save the transformers. You must provide proper switch transformers, and particularly avoid switch transformers on the high-tension side or else you will have a breakdown.

Another point which Mr. Green makes is the question of external reactance. I am a great believer in external reactance. I am also a believer in internal reactance. I think it is a good thing to have, the more the better. I think as the systems grow larger and larger there is less need for what is called good regulation. The diversity factor which is coming into our central station work to-day means that our transformers are loaded a greater proportion of the time—consequently there is less need for the best regulation; on the other hand, as our diversity factor does come into the operation of our systems, our systems become larger and there is a greater need for reactance. Reactance in the transformer itself does a certain amount of good; reactance external to the transformer does still more good. I think that is also true in regard to generators. And I think it is a subject which should be considered in all large stations and provision should be made for the installation of external resistance, if not at the time of the installation of the transformers, at some later time.

I think there is something in Mr. Wilson's suggestion, and I would suggest that the Standards Committee take up the point, and that is the question of the temperature rise of transformers, particularly water-cooled transformers—should they be based on the air test, or should they be based on the water test. I think these two factors are important and should be considered, and they are not now considered in the Institute rules.

E. F. Alexanderson: In the design of any electric machine which is cooled by an effective system of forced ventilation the greatest problem is to predetermine the temperature gradient between the conductors and the ventilated surfaces. After the heat has been carried to a metal surface it can easily be carried off by the air. As an illustration, I wish to mention a convenient method to determine the heat radiation in machines cooled by air holes running crosswise through the laminations of the core. As result of test of various machines the watts per square inch radiated on the duct can be expressed:

$$\text{Watts per square inch} = 1 + \frac{\text{velocity of air}}{1000}$$

The velocity is expressed in ft. per min. based on 75 degrees rise of the conductors and a temperature rise of 35 degrees to 40 degrees including incoming and outgoing air. The formula is, of course, only a thumb rule, but I wish to point out the magnitude of the quantity. If the velocity of the air is 2000 ft. per min. the radiation is 3 watts per square inch or 10 to 20 times as great as the figures mentioned for exposed coils in transformer design. This indicates that the largest temperature drop is in the insulation.

There is another circumstance that points to some peculiarities of the heat conductivity of insulation. The behavior of some transformers indicate that the temperature rise of a ventilated coil increases faster than the watts per sq. in. In other words, the heat conductivity changes considerably with the temperature. In view of this the question would seem pertinent, what is the heat conductivity of the various insulating materials, and I believe it would be of benefit for machine design in general if rules for determining the heat conductivity of insulation materials received as much attention by the Institute as similar data for dielectric strength.

Henry A. Pikler: I want to refer, in a few words, to the remarks made by Mr. Stone—he pointed out two things, one is the switching of the transformers on the high tension line; he desires to have some method devised and adopted whereby this could be avoided; in other words, he wants to see some rules introduced and accepted by the customer or the operator that transformers should not be thrown directly in the high tension line; the other thing that he pointed out, is that the introduction of reactance outside or inside is desirable. It is very interesting to note how intimate the relations between these things are. As to the first point, I do not think that is feasible. I cannot imagine any way whereby we could avoid throwing the transformer on the high tension line directly, except by shutting down the power entirely, if this transformer be the first transformer at that point. If we insert reactances in the circuit—let us say,

more generally speaking, a series impedance, the result will be the distortion of the sine wave generated by the generator, at the terminals of the transformer.* This, of course, is quite serious, because we want to avoid the higher harmonics. With the introduction of the reactance, particularly at the moment of throwing on a transformer on the line, we will introduce these higher harmonics in a greater measure, than if we do not use the series reactance outside of the transformer circuit. And if the series reactance does not cause this then this proves its ineffectiveness for the purpose it was intended for.

C. P. Steinmetz: Regarding the remark made by Mr. Stone on the undesirability of high tension switching, I desire to endorse it, and still more particularly to draw attention to one interesting feature. We very often have done, and still occasionally do, things which we should not do, but we do them because we do not know any better, and as result, apparatus occasionally broken down by some mysterious phenomenon,

FIG. 1

which would not have been mysterious but for lack of knowledge. One of these things is the high tension switching. It has to be done, and will be done, but the less we do it the better it will be. We never realized this until we had the oscillograph on the high tension switch on very high voltage, long distance lines. It is easy to specify and say you must do it—certainly some time you may do it—but after looking at the oscillogram you will realize that the more we avoid high tension switching, the better it will be for the apparatus. In Fig. 1 is shown the oscillogram of a cumulative oscillation, resulting from high tension switching. Not shown in this oscillogram is the momentary and extremely local very high frequency traveling wave starting the oscillation, which is estimated of a frequency of two million cycles, and measured by its disruptive effects.

*H. A. Pikler, effect of series resistance in the primary circuit of a transformer. *Electrical World and Engineer*, 1903, p. 218.

Now, in regard to reactance, the place for high reactance is not in the high voltage line, where the high tension switch is objectionable. When you have a line in which you have to go to 100,000 volts, you are fairly certain there will be a voltage drop of ten per cent or more, whether the transformer has a high or low reactance, because the power which can flow through the transformer is limited. It is in those systems where the power is unlimited and the drop is negligible, a different class of systems, where the destructive effects of low reactance have been conspicuous.

When you speak of reactance, however, one thing must not be overlooked. If you say, a four or six per cent reactance is desirable for safety, that means you must have the reactance when you need it. It is wrong to put in an iron-clad reactive coil, which gives four per cent reactance at full load current, and when you get 25 times full load current, the reactance disappears by magnetic saturation, and wave shape distortion comes in. This has not been mentioned, because it is obvious. If you put reactance in to limit the short circuit current, the reactance must be there under short circuit, and this excludes the use of iron. In a transformer the maximum flux on short circuit is only full voltage flux, and magnetic saturation at short circuit thus cannot occur in a transformer, but in an additional reactance, it may, if iron is used, and that mistake has been made more than once, to use iron in power limiting reactances, with the obvious result, that the reactance was not there when you wanted it, and so did not serve the purpose for which it was designed.

J. M. Weed: Mr. Alexanderson's equation for cooling with forced circulation of air is represented by a straight line curve between watts and air velocity, cutting the axis for watts at one watt per sq. in. This line, no doubt, approximates the actual physical conditions for the high air velocities occurring in machines. For low velocities such as we find in the air which cools the self-cooled transformer the actual curve will be found to droop from the straight line and to cut the axis not far from the zero point. A similar condition exists with reference to the action of the oil in cooling transformer coils. This does not indicate that the largest temperature drop is in the insulation, as was suggested by Mr. Alexanderson, but rather that a very large temperature drop exists from the surface of the coil to the oil or from the surface of the tank to the air with the slow velocities occurring with natural circulation. This temperature drop at the surface is very much reduced by means of increased velocities obtained by artificial circulation. Some consideration was given to this matter in my paper and some also to the question of heat conductivity of insulating materials.

I would say that there must be something wrong with the transformer tests which showed a temperature rise increasing more rapidly than the watts per sq. in. producing this rise, since I have found from a large number of tests that there is a distinct

tendency in the other direction. I have not found any definite variation in the thermal resistance of solid insulating materials, but do find a reduction of the equivalent thermal resistance at the surface of the coil, or the tank, as the watts increase, which I have attributed to the increased velocity which is automatically produced in the cooling fluid.

Mr. Mershon's questions about corrugations, and relative areas of surfaces exposed to oil and air, are partially answered in the last few paragraphs of my paper. To be more explicit, without being too exact, I would say that the space on the air side of the corrugations may, to advantage, be made from two or three times as great as that on the oil side. The width of the oil space may be reduced to from one inch to one-half inch, depending upon the height of the tank, without causing a serious drop in the oil temperature while passing downward from the top to the bottom of the tank. The width of the air space should vary from one to two and one-half inches, depending upon the height of the tank and the depth of the corrugations. If this space is too large the heat does not sufficiently penetrate the enclosed air, and part of the space is wasted, while if it is too small the friction to the passage of the air is too great, and its acceleration is not sufficient to draw in enough new air to keep its temperature down to a point which is properly effective in absorbing heat from the surface of the tank.

Within limits the higher the tank the wider the corrugations should be, both inside and outside, and the deeper the corrugations the wider they should be.

It is instructive, when considering the size of the corrugations, to reflect that with a given ratio of pitch to depth of corrugation, and given perimeter, the area of the tank surface will be the same whatever the size of the corrugation. The volumes of air and oil brought within the corrugations, and thus brought within effective range of the surface, will depend however upon the size of the corrugations. If the reduction in size is carried to the limit, the conditions of cooling approach those of a plain surface, which gives the minimum cooling for the given perimeter, although we have not reduced the area of our corrugated surface. Thus, within limits, the larger the corrugations, the more effective the surface.

As to the relative amounts of surface which should be exposed to air and oil respectively, if there were just so much total surface which could be distributed at will between the oil and the air this question would be more logical. With the cast iron tank with ribs we can make either surface what we wish, regardless of the other. Though the ribs may be said to be less important on the side toward the oil than on the side toward the air, since the temperature drop from the tank to air is normally greater than that from the oil to the tank, yet they are valuable on both sides. Because we have ribs on the outside surface is no reason why we should not also have ribs on the inside surface.

With the corrugated surfaces, keeping the perimeter of the tank the same, the external surface will be increased somewhat by closing or collapsing the spaces on the oil side, keeping the width of external spaces the same, on account of the increased number of corrugations.

By closing all the internal spaces we might obtain an increase of about 50 per cent in external surface but this would be accompanied by a decrease of about 75 per cent in the internal surface. Assuming that the drop from the oil to the tank, before the corrugations are closed, is six deg., and that the drop from the tank to air is 30 deg., if each of these drops is proportional to the watts per sq. in. on the respective surfaces (which is not strictly correct) the respective drops after closing the corrugations will be 20 deg. external and 24 deg. internal. The sum of the two drops is now 44 deg. as compared with 36 deg. before the corrugations were closed. This calculation is rough and probably gives results somewhat exaggerated but it correctly illustrates the tendency.

Mr. Mershon may object that he did not contemplate closing all of the corrugations, but each corrugation must be considered to a certain extent independently, since the heat which would be conducted through the thin sheet steel tank from the corrugation which is not closed to the one which is closed would be much smaller than at first imagined. Moreover, the reduction in the temperature drop from the tank to the air will be less than would be expected from the amount of increase in the surface, since, not being adjacent to the hot oil, the tank temperature will be somewhat reduced toward the tips of the closed corrugation.

In addition to the above I should like also to offer some remarks on Mr. Pickler's discussion of Mr. Green's paper as follows:

Mr. Pickler's statements regarding mechanical forces and regulation in his discussion of Mr. Green's paper seemed to give a wrong impression. It is the natural tendency of the resistance element of regulation to be reduced with increased capacity, but not of the reactance element. Certainly the reactance in ohms would decrease but the per cent reactance, or reactance volts, tends to increase to the extent that for a given per cent reactance it becomes necessary to break the windings of a large transformer up into a larger number of groups than those of a small one. It is certainly true moreover, that the mechanical forces under short circuit conditions in any given transformer will be reduced by increasing its reactance. It is true, in fact, that if all dimensions and parts of the transformer including the coil supports are increased in equal proportion, all sizes of transformer will be equally safe, except for the affect of the variation in the space factor of the windings which is unfavorable for the larger sizes.

In order to be equally safe, therefore, the larger sizes must be protected by a greater than normal increase, either in the strength of the coil supports or else in the per cent reactance.

R. W. Atkinson (by letter): While the writer wishes to confirm certain of the points brought up by the author, he wishes to take exception to certain of the others. He is glad to see presented before the Institute, the formulae for the calculation of regulation and particularly those regarding the effect of magnetizing current, and would refer to the work done by the Bureau of Standards. The question was taken up very carefully by them, both theoretically and experimentally. They arrived at the same conclusions given by the author. Their results are published in their Bulletin No. 2, Vol. 6. However, the writer does not agree that the cost to the central station of regulation is ordinarily dependent upon the selling price of the power. He also wishes to comment slightly upon the curves in Figs. 4, 5 and 6. It is intended only to mention the above points with a very brief analysis of the reasons for the conclusions.

It is merely desired to call closer attention to the Figs. 4, 5 and 6. The casual reader might draw somewhat erroneous conclusions. In Fig. 5 it is desired to point out that with a purely lighting load where the effect of regulation is most marked, the influence of reactance upon regulation is least noticeable. It is suggested that the various transformers represented in Fig. 6 by curves 1 to 7, could scarcely be considered as having the same general dimensions. No. 7 would have $\frac{1}{4}$ the copper loss of No. 1. Obviously, this would require a very much larger and more expensive transformer unless, of course, some characteristics not mentioned are sacrificed. In case the reduction of the copper loss is at the expense of increased iron loss, the reactance would be reduced in approximately the same ratio as the copper loss. The same comment would apply to Fig. 4 but in a much less degree.

It has been frequently asserted that, on a lamp load, due to a reduction of voltage at the customer's outlet, regulation reduces the power sold to the customer and that therefore the cost to the central station is the difference between the selling price and cost price of this amount of power. Suppose this is true. We ask then why does it not pay to raise the voltage of the system and sell more power, why not do this indefinitely? It is unnecessary to analyze the reasons for not so doing. However, we know that it will pay to make the average voltage of the system approximately that which we would maintain all the time if it were not for regulation. If there is a certain voltage which it would be desirable to maintain uniformly, if possible, it would seem to scarcely require argument that if it is impossible to maintain a uniform voltage, the next best thing is to make the voltage vary *above* and *below* this desirable voltage, and as close to it as possible. The cost of regulation then lies in the effect of this variation of voltage, and regulation is costly just to the extent of the uncertainty and the variation of receiver voltage due to it.

An important effect of the irregularity of voltage is the re-

sultant variation of candle-power of the lamps of the system. In the case of carbon lamps, there is as well a variation of the color of the light. The problem then becomes quite largely one of the psychology of the customer. It is quite certain that if the variation of candle-power becomes serious enough to be offensive, it is very expensive to the lighting company, and is negligible only when not noticeable to the ordinary customer.

The most important effect of regulation is upon the life of the lamps. A lamp burning one-half the time at 109 volts and the other half of the time at 111 volts, has a shorter life than one burning steadily at 110 volts. It is possible to calculate this loss of life due to regulation very accurately from the performance curves furnished by the lamp companies. One thing of interest is that the loss of life varies approximately as the square of the regulation.

The average candle-power and efficiency are not so greatly affected. As a matter of fact, both are slightly increased under the above specific conditions of 109 volts half the time and 111 half the time, as compared with a uniform voltage of 110.

The copper loss of the transformer is so closely related to its regulation on a lighting load, that we may be pardoned for a brief reference to the cost of this copper loss. It needs merely to be mentioned that the cost of power occurring almost entirely at or near the peak, is much greater than the cost per kilowatt hour of an all day load. If this cost is the one cent per kw. hr., mentioned then perhaps the copper loss costs two cents. It is not intended here to show the amount of the difference but merely to call attention to its existence.

There are a great many factors which may influence this problem including those mentioned by the author. Some others are: regulation of the secondary circuit between the transformer and the customer's outlet; the possibility of the voltage of the primary being raised at times of general heavy load on the feeder. The first may be of considerable importance and complicate the problem accordingly. It is sometimes practicable to reduce materially the effects of bad regulation by consideration of the latter.

The writer has attempted to show in a general way that the cost to the central station of regulation is affected not by the selling price of the power, but by the effect upon the life and the candle-power of the lamp and upon the resulting satisfaction of the customer. Where regulation is important, that part due to reactance can always be kept low with less expense than that part due to resistance. The problem of the cost of regulation is an important part of the larger one, that of the cost of the transformer losses, and is a subject which is of great interest to both the designing engineer and to the operating engineer.

C. E. Allen: In regard to Mr. Walden's question regarding the increase in cross section of the cores, it is not clear as to just which figure is referred to, but at any rate the cross section of the core would vary, depending upon its construction. This

would be also true of the weight. As to the increase in cost of the transformer I have no figures at hand that are sufficiently accurate to answer this question, but I might add that the weight of copper would increase directly as the increase in the mean length of turn due to the larger cross section, and there would be also an increase in the weight of the copper due to the increase of $\frac{A}{L}$, which represents the leakage path of the flux, in determining the regulation. It would not be an economical design to improve the regulation by increasing the cross section and allowing the number of turns to remain the same.

In replying to Mr. R. W. Atkinson's discussion, the writer appreciates that there is nothing original brought out in the paper, as all the formulæ brought in have been worked out by Dr. Bedell of Cornell University, Mr. Fortesque and various others. The writer has simply made a summation of correlated facts, with a view of showing certain points, which he hoped would be sufficient to justify the Institute adopting a standard method for determining the regulation.

As to the conclusions that might be drawn from Figs. 4, 5 and 6, this depends altogether upon the experience of the reader. The paper is only intended for those familiar with the subject. As to the variation in the power delivered due to changes in regulation, I have been over this subject with various central station engineers, whom I believe represent the leading men in their respective lines, and in all cases they have figured the loss due to poor regulation at the selling price less the cost of delivering the energy to the transformers. Mr. Atkinson asks why it would not pay to increase the voltage indefinitely. While this is no doubt obvious to many, I will answer by stating that there is the question of satisfactory service, which must be considered. Mr. Atkinson has based his statements entirely upon the assumption that only an incandescent lamp load was used. As a matter of fact the importance of the paper at this time is due to the increased day load made up of heating apparatus, etc., the nature of which is similar to that of an incandescent lamp, but where the question of renewals does not enter. On account of this increasing day load, the regulation and copper loss have both become of more importance than previously. At one time the iron loss of a transformer was considered to have a relative value six times that of the copper. This was assuming that full load existed only four hours of the day. To-day the same difference does not exist and, therefore, the value of the regulation and copper loss have been increased.

In taking up this subject the author has not dealt with its influence on induction motors; which is quite as important as the other loads. This is appreciated by central stations serving industrial districts and is brought out in Mr. A. E. Walden's discussion.