ABNORMAL STRAINS IN TRANSFORMERS

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The subject treated in this paper is one of the greatest intricacy but is presented here in the simplest possible manner. Abnormal strains in transformers are analysed under the headings of over-voltage, over-current, and over-frequency strains. Effective arresters, choke coils, and heavy end-turn insulation take care of the first; heavy current conditions may be handled by a stout mechanical design and the provision of high reactances, internal and sometimes external; while in guarding the transformer against high frequency strains, resort may be made to a combination of inductances with energy-absorbing devices, the former to guard against excessive intensity of travelling waves, the latter against the formation of standing waves from whatever travelling waves may appear in the system. Dr. Steinmetz is better fitted than any other man for handling this very intricate subject; and his ability to reduce this theory to simple terms for the benefit of designers, operators and salesmen, represents a very great feat of literary exposition.—Editor.

An electric circuit has voltage, current and frequency, and abnormal strains in transformers thus may be due to excessive voltage, excessive current or excessive frequency. Excessive voltage leads to puncture and destruction of the insulation, and, if by the puncture of the insulation a short-circuit is produced, may result in excessive current strains. Excessive current strains as occurring in short-circuits, etc., give mechanical stresses due to magnetic forces, which may result in deformation or tearing to pieces of the structure. Excessive frequencies lead to locally high voltages where the frequency exists, voltages which may be less than the line voltage, but, by appearing across a coil or part of the transformer only, may be higher than the insulation of this part can stand.

Excessive Voltage Strains

Such strains are produced by lightning, switching operation, as connecting and disconnecting the transformer from the generating system, or connecting and disconnecting apparatus from the transformer, etc. They may be between winding and the ground, or between turns or parts of the winding, or both. If for instance lightning suddenly raises the voltage of the line above ground, the insulation of the transformer to ground has to stand this voltage. All insulation is designed for, and tested for one minute (A.I.E.E. Standardization Rules) with a safety factor of 4. That is, while in normal operation the line voltage comes across two insulations—from terminal to ground and from ground back to the other terminal—double line voltage is applied across a single insulation, from coil to ground.

The maximum voltage rise which can occur under normal switching operation is limited to double voltage, at the end of the line, where the switching impulse adds itself to the line voltage, or the switching wave reflects, as it is usually expressed. It therefore still has a safety factor 2, so that over-voltage break down to ground as result of switching is not liable to occur; but where switching causes damage it is usually due to high frequency produced by it.

The voltage of lightning is unlimited, and the voltage which lightning can produce on the line thus is limited by the weakest part of the insulation to ground. This, with proper lightning protection is the lightning arrester; and by the lightning arrester the excess voltage which may be produced on the line and thereby on the transformer is limited by the discharge of the arrester, 50 to 100 per cent above line voltage, and therefore still well within the safety factor of the transformer insulation. Breakdown to ground by excess voltage due to lightning, with lightning arresters in the station, can therefore occur only if the energy of the lightning stroke at the station is very far beyond the discharge capacity of the arrester; that is, by a direct lightning stroke at or very near to the station. This is of such rare occurrence that it need hardly be considered.

Without lightning arrester, the weakest part of the system breaks down to ground. Before the introduction of the suspension insulator this usually was the line; since the introduction of the suspension insulator it usually is the transformer, and the necessity of installing lightning arresters at transformer stations thus has been very greatly increased by the introduction of the suspension insulator.

To conclude, then: with proper lightning protection at the transformer stations, the danger of breakdown to ground as the result of excess voltage is practically absent.

Excess voltages also appear between turns, especially the end turns of the transformer. Suppose a dead transformer of ***negligible*** *electrostatic capacity*, T in Fig. 1, is switched into a circuit of voltage e, by closing the switch S. Before the switch S is closed, all the transformer turns are at zero voltage. At the moment of closing the switch S, the voltage e is put on the first turn 1, but the second turn, 2, is still at zero voltage. The full voltage e thus comes across the insulation of the first turn. A moment—a ten-millionth or hundred-millionth of a second later—the voltage has passed around the first turn and reached the second turn, but the third turn is still at zero voltage. Then full voltage e comes across the first two turns, and each turn gets approximately half voltage, $e/2$. Thus the maximum voltage to which the insulation of the second turn is exposed, is $e/2$. Still a moment later the voltage has reached the third turn, while the fourth turn is still at zero voltage, and the first three turns thus divide the line voltage, each receiving $e/3$. In this manner in successive moments the voltage spreads over more and more turns, and each turn gets correspondingly less voltage, until the voltage has traversed all the transformer turns, and each turn gets e/n voltage—if n = number of transformer turns.

The voltages to which successive transformer turns are exposed in switching the transformer into a circuit of voltage e, thus are:

	1st Turn	2nd Turn	3rd Turn	4th Turn	5th Turn	6th Turn	nth Turn
Before switching . .	0	0	0	0	0	0	0
In the moment of switching	e	0	0	0	0	0	0
Next moment	$e/2$	$e/2$	0	0	0	0	0
3rd moment	$e/3$	$e/3$	$e/3$	0	0	0	0
4th moment	$e/4$	$e/4$	$e/4$	$e/4$	0	0	0
5th moment	$e/5$	$e/5$	$e/5$	$e/5$	$e/5$	0	0
nth moment	e/n	e/n	e/n	e/n	e/n	e/n	e/n

As seen, the voltage strain between the turns, resulting from switching, rapidly decreases and becomes negligible towards the interior of the transformer, but is excessive at the end turns.

Therefore end turns of the transformer are provided with extra heavy insulation.

Obviously, no extra heavy insulation, which could be put on the end turn, would stand for any length of time the full line voltage, to which the end turn is exposed in the first moment. However, the disruptive effect of voltage depends upon the time of voltage application, and full voltage is on the end turn only an extremely short time, less than a millionth of a second, while the voltage passes around this turn. Then the voltage drops to half, one-third, etc. Nevertheless, even for such short time, the extra heavy insulation can not give safety against the excessive voltages appearing on the first turns.

Assuming now we take the first 9 turns of the transformer, and put them outside, where we can specially insulate them, and where momentary discharge can not harm them; and call them a "choke coil" or "lightning protective inductance." The first remaining transformer turn then is what before was the 10th turn, and receives as maximum only one-tenth of the line voltage, and, as this voltage exists momentarily only, it is easy then to insulate for it. The installation of a very small choke coil—equal to 9 transformer turns only—thus has reduced the switching strains at the transformer end turns to one-tenth and brought them well within safe insulation.

In momentarily short-circuiting the transformer, the same strains are produced by momentarily withdrawing the voltage e, first from the end turn, then the first two turns, etc. This occurs when switching a transmission line, cable or other device of high capacity onto the transformer. The capacity, as a reservoir, acts as a momentary short-circuit and drops the terminal voltage to zero, until it is charged and the voltage comes back to normal again—in a thousandth of a second, more or less.

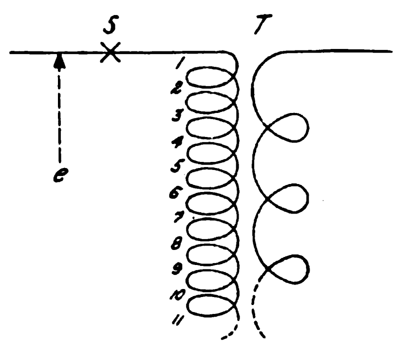

Fig. 1

If lightning raises the line voltage momentarily 50 per cent, up to the discharge voltage of the lightning arrester, this momentary

50 per cent increase of voltage, suddenly put on the transformer, enters the transformer with the same voltage strains between the end turns, and sudden excess voltage to ground, this is accompanied by sudden excess voltage between the end turns.

Since, as seen, a very small choke coil, equal to a few transformer turns only, reduces the end turn strains so much as to be safely taken care of by extra heavy insulation, it follows that:

The combination of effective lightning arresters (the aluminum arrester), with a small choke coil (the hour-glass coil) and extra heavy insulation of the transformer end turns, affords practically complete protection against *excessive voltage strains* between transformer and ground, or between the end turns of the transformer, as may result from lightning, switching operation, etc.

Insulation breakdowns in transformers, aside from accidental faulty construction or mechanical damage, are therefore practically always due to high frequency.

Excessive Current Strains

In a loaded transformer a mechanical force, —a repulsion—exists between primary and secondary coil, or rather, between the primary and secondary coils and the magnetic stray field between the coils. This repulsive force is used in constant current transformers, to move primary and secondary coils with regard to each other and so give the constant current regulation. It equally exists in the ordinary transformers, and the coils therefore have to be supported mechanically against these forces. At full load, this mechanical magnetic force is small. It varies, however, with the square of the current (being proportional to the current *times* the stray field, and as the latter is proportional to the current it becomes proportional to the current square). The mechanical force thus rapidly increases with increasing current, and may become formidable and destructive at excessive currents, as those of short-circuit.

If the system to which the transformer is connected is of such large power as to keep up the impressed voltage on the transformer even if the secondary is short-circuited, then the only limit of current in the transformer is the transformer impedance, which practically is equal to the transformer reactance. In a transformer of 4 per cent reactance, that is, a transformer in which at full load the reactance voltage equals 4 per cent of full voltage, the short-circuit current at full impressed voltage would be 25 times full load current, and the mechanical forces thus $25^2 = 625$ times as large as at full load. In large transformers, of thousands of kilowatt capacity, these forces then amount to hundreds of tons. That is, the coils have to be supported mechanically so as to stand, in case of short-circuit, vibratory mechanical stresses of hundreds of tons.

As there necessarily is an economic limit to the mechanical strength which can be given to a structure, it follows that the lower the mechanical forces at short-circuit can be kept, the safer will be the structure. This means as low short-circuit current (hence as high reactance) as permissible. Therefore, in larger transformers it is not safe to permit less than 4 per cent internal reactance, and from 4 to 8 per cent will in general be the most satisfactory value of transformer reactance.

Since, even with the highest permissible internal reactance, in large transformers on high power systems which can keep up the voltage, a short-circuit puts tremendous stresses on the mechanical structure of the transformer, short-circuits necessarily involve a certain danger; and while transformers must be built, and are built to stand occasional short-circuits, very frequent short-circuits finally lead to mechanical damage, and therefore should be avoided as much as possible; and all apparatus and devices, which produce or may cause short-circuits, should as far as possible be eliminated from the neighborhood of the transformers.

At lower voltage, the short-circuit forces are decreased proportionally to the square of the voltage. Thus, if at short-circuit the voltage drops to half value, the short-circuit current also drops to half value, and the short-circuit strain to one quarter the value which it would have at full voltage. Therefore transformers which mechanically could not safely stand short-circuits at full voltage, as low reactance transformers, may in a system of limited power, as at the end of a transmission line, safely stand frequent short-circuits. But if finally the system is increased in power, and becomes more able to keep up the voltage at the transformer, the same transformer which before stood numerous short-circuits may be torn to pieces. That low reactance transformers have safely stood numerous short-circuits in one system is, therefore, no evidence that they would not be torn to pieces in another system of larger power; or in the same system at a place where the power is less limited, as near the generators; or in the same place, when by installing more generators the available power is increased.

External reactances in the phase leads are more effective in reducing the short-circuit stresses, than increased internal reactance, since the external reactance not only reduces the short-circuit current, but also the voltage at the transformer terminals. They are, however, more complicated and more expensive than the design of the transformer for higher reactance.

Excessive currents also may appear locally in a transformer, in short-circuited turns, coils or sections. Thus if some turns of a large transformer are short-circuited, as by high frequency discharge or mechanical deformation, in those turns a current flows, which is limited only by the impedance of these turns, and therefore may be very many times full load current. The mechanical repulsive force between the current in the short-circuited turns and the adjacent turns then may blow the adjacent turns away, and give the appearance as if something had exploded inside of the coil. The same phenomenon has been observed in generator coils, etc., but is not very frequent; and short-circuited turns, if not very numerous, usually lead to destruction of the insulation by heat, by charring, and thereby the short-circuit gradually spreads, until it becomes general. This is more frequent in smaller transformers.

To guard against the stresses of excessive currents, extremely strong mechanical construction of the transformer, a design for high internal reactance, and where needed additional reactances in the phase leads are available, together with all those precautions in the operation of the system, which avoid the occurrence of bad short-circuits as much as possible.

Excessive Frequency Strains

High frequency strains can as a rule only occur in transformers which have appreciable distributed capacity, that is, in high voltage transformers, above 50,000 volts. The low and medium voltage transformer usually contains only resistance and inductance, but no appreciable electrostatic capacity, and high frequency can not enter such a transformer and can not originate in it, but is limited to the end turns, and these are protected by extra heavy insulation, and a small choke coil in the lines. Therefore, high frequency troubles have become serious only with the development of the transformers for very high voltage transmissions. In these, the high potential winding, due to the many turns and the high voltage, gives appreciable capacity effects, that is, the winding is a circuit of distributed capacity, inductance and resistance, like a transmission line, and as in the latter, waves and impulses can enter into and traverse the transformer winding, and originate in it.

High frequency disturbances may be due to traveling waves, and to standing waves, and originate from lightning disturbances, switching operation, arcing grounds, etc.

Assuming for instance that the transformer winding in Fig. 1 contains appreciable electrostatic capacity. That is, every turn or coil of it can act as a reservoir, absorbing appreciable current. Before the switch S is closed, all the transformer coils are at zero voltage. In the moment when the switch is closed and voltage e impressed upon the transformer, the voltage does not instantly appear even on the first coil 1, but a big current rushes into this coil, gradually, within a hundred thousandth of a second or so—charging it, as a reservoir, up to voltage e. In the next moment, current rushes from the first into the second coil, charging this up to voltage, then in the third one and so on, and so successively—in an extremely short time the transformer coils are energized. When the first transformer coil has been charged up to voltage e, current is still rushing into it. This current can not instantly stop, and therefore, continuing to flow, raises the voltage of the first coil still higher, until finally the rising voltage stops the flow of current into coil 1, leaving this charged to a voltage nearly equal to $2e$. As this voltage is higher than the supply voltage e, current begins to rush out of the coil 1 again, back to the switch S and forward to coil 2, and the voltage of the first coil drops down to normal, e. When normal voltage is reached, the current still flows out of coil 1, and continues to flow, as it can not suddenly stop, and lowers coil 1 below the supply voltage, down to near zero, until the outrushing current is stopped by the decreasing voltage. Then current begins to flow in again, as the coil is below supply voltage, and so on alternately, with gradually decreasing amplitude, current rushes in and out of coil 1, and the voltage rises above and falls below supply voltage. The same play occurs in coil 2, 3, etc. Coil 2 however, receives the in-rushing current and the voltage after coil 1, and thus reaches maximum voltage a little later than 1, and a somewhat lower maximum voltage; coil 3 reaches maximum voltage again a little later than 2, and so on. That is, oscillations of voltage and current occur successively in the coils; or in other words, an electric wave travels into and through the transformer, starting at maximum intensity at the switching point, and progressing, with decreasing intensity, through the transformer, until it either dies out, or reaches the end of the winding and is there reflected back. In the latter case, the reflected returning wave combines with the incoming wave to form a standing wave, as will be shown later.

If the traveling wave is due to a single impulse, as closing the switch and putting the voltage on the transformer, or taking the voltage off, it usually dies out rapidly. If however, successive impulses follow each other, the successive trains of waves may build up to higher and higher intensities, and thereby reach destructive values. This for instance is the case with an arcing ground on the line, as the flash over or puncture of an insulator. Such an arcing ground gives a continuous succession of impulses by withdrawing and again applying the voltage: the arc puts the line on ground and thereby withdraws the voltage from the transformer, and at the same time, by the disappearance of the voltage, the arc goes out. This, however, lets the line build up again in voltage, again starting the arc; this arc discharges the line and goes out, the line again charges and starts the arc, and so on.

The formation of a traveling wave, and its transformation by reflection into a standing wave, may be illustrated by Fig. 2. Assuming we have a rope AB, (1) in Fig. 2, fastened rigidly at B, and give it an impulse by periodically moving it up and down at A. Then a wave forms and runs along the rope, as seen in (1) to (11) of Fig. 2. If the rope were not fastened at B, but continued, the wave would continue beyond B, as shown in dotted lines on the right-hand side of B in (12) to (21) of Fig. 2. However, in this case, in (12) (13) (14) the rope would have to move upwards at B; in (16) (17) (18) downwards, etc. As it is held fixed at B, this is the same as if in (12) (13) (14) a downward impulse were given to the rope at B, in (16) (17) (18) an upward impulse, to keep it in place. This virtual impulse at B, however, starts another traveling wave, running from B backwards towards A, and being the reverse of the continuation of the original wave beyond B, also shown dotted in Fig. 2. It is called the reflected wave or return wave. This return wave, which issues from B

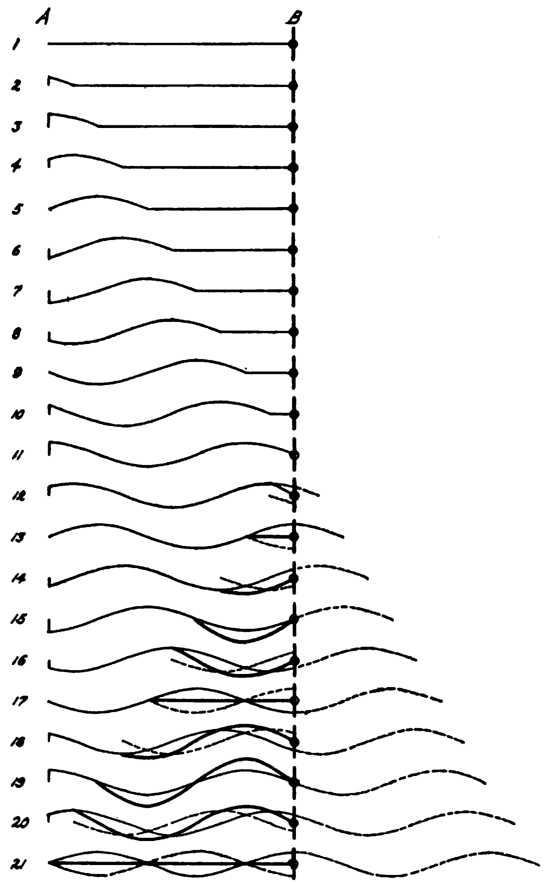

Fig. 2

towards A, superimposes on the original wave coming from A to B, and both combined are shown in curves (12) to (21) in heavy drawn lines. As seen, this resultant wave does not travel, but its maxima and its zeros are always at the same points; and it therefore is a stationary or standing wave, which spreads from B towards A, and is formed by the combination of the traveling wave and its reflected wave.

Just as the wave in the rope, Fig. 2, can not go beyond the rigid support B, so an electric current wave can not travel beyond the open end of the circuit—as this open end must always be zero current—and an electric voltage wave can not travel beyond the point of the transformer, which is held at ground potential. There it reflects and forms a standing wave. Fig. 2 also shows that the final standing wave is of twice the intensity of the traveling wave.

Assume now, that we do not fasten the rope at B in Fig. 2 but have it continued beyond B, and fasten to the rope at B a weight which is so heavy that the impulse of the rope can not appreciably move it. Then the traveling wave, when it reaches B, in (11) of Fig. 2, can not continue beyond it, but is reflected, and the part of the rope beyond B remains at rest. A weight thus stops the traveling wave and reflects it back. Inductance in an electric wave is the analogy of the weight on the rope, and an inductance interposed in the path of an electric traveling wave thus offers a barrier to this wave, and reflects it back on its path, the more completely, the higher the inductance is; just as the weight at B reflects the traveling wave on the rope back the more completely, the heavier the weight is, i.e., the less it can be set in motion by the wave.

In Fig. 2, if at B the rope is not fastened rigidly, but continues beyond B, and is loaded by a weight at B, the traveling wave coming from A is stopped and turned back by the weight at B. However, as the weight is not infinite, the wave impulse will give it some motion, however small it may be, and a part, even if only a very small part, of the traveling wave reaches beyond B into the rope on the right-hand side of B. If then, this part of the rope can oscillate, it will gradually be set in motion, and oscillate with increasing intensity, but in such a manner, that the weight B, which can not move much, is a zero point of the oscillation. That is, gradually a standing wave forms beyond B, transmitted from the standing wave on the left side of B, and this standing wave increases in amplitude, until it has reached the same intensity as the standing wave on the left side of B.

That is, the weight on the rope, while practically stopping the traveling wave, does not stop the standing wave, but merely retards its transfer across B. In the same manner an inductance in an electric circuit, no matter how large, while it more or less completely stops a traveling wave, does not stop a standing wave.

In other words, inductance, such as a choke coil offers no protection against standing waves, but merely forces these standing waves to form so as to make a zero point of current, or anode, at the inductance.

As the standing wave is the cumulative effect of traveling waves, it usually is of greater intensity, that is, higher voltage and destructiveness, than the traveling wave. Inductance offers no material protection against standing waves; but the necessary protection may be secured by preventing the formation of standing waves by the use of energy-absorbing devices, i.e., by consuming the energy of the traveling waves so rapidly that they cannot develop into standing waves: the analogy of anti-hunting devices in synchronous machines.

It seems to follow herefrom, that in the protection of transformers from abnormal frequency strains we have to rely on the combination of inductances with energy absorbing devices, the former to guard against excessive intensity of traveling waves, the latter to guard against the formation of standing waves from whatever traveling waves appear in the system.