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DEVELOPMENTS IN TRACTION TRANSFORMERS

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Abstract:

Mass transit systems are gaining increased attention and popularity in the country. With this increased activity, more and more lines are getting added under public transit systems in more and more cities. One of the essential elements in the transit system is the traction transformer which powers the trains. With the emphasis on reliability, there is also increased awareness of the energy efficiency required of the traction substation equipments and the transformer in particular.

Traction transformers are not ordinary power or distribution transformers. It has to meet several special requirements, including parameters like voltage regulation, impedance, commutation, short circuit withstand, operation with rectifiers, harmonic losses, wide fluctuation of load currents depending on the cyclic nature, etc. The reliability criteria are stringent and the traction transformers have to be properly designed, manufactured and tested, including short circuit test for validation.
Use of modern design tools like electric and magnetic field mapping and estimation of forces and stresses are helpful in computing them accurately.

With the extensive use of vacuum circuit breakers, the subject of interaction of transformers and breakers have come to fore and new standards (like IEEE C57.142) have come into existence, which recommend methods to mitigate such effects. Author and his team have successfully applied these techniques in real life situations to solve problems.

Work is in the final stages for preparation of a standard for specifically for Traction Power Rectifier Transformers for transit applications (IEEE draft standard 1653.1) under the IEEE Vehicle Standards Committee.

(1) Introduction:

Traction transformers work as the power source for the rectifiers. The traction transformers are different from the usual distribution/ power transformers in many aspects, such as :--

(a) Specific loads, such as trains, trolleys, etc;
(b) Load Cycle;
(c) Temperature rise;

(d) Electrical characteristics (such as short-circuit withstand, commutating reactance, more number of windings, etc);

(e) Longer life expectancy;

(f) Energy efficiency;

(g) more demanding environment.

We shall bring out the different areas of design, construction and application of modern traction transformer.

(2) New Standard IEEE P1653.1

While several aspects of the traction transformers are covered by the IEEE Standard C57.18.10 ("Standard Practices and Requirements for Semiconductor Power Rectifier Transformers"), it was found that there are some specialties of traction transformers which were not adequately covered therein. A new standard IEEE P1653.1 ("Standard Practices and Requirements for Traction Power Rectifier Transformers") has been prepared by the IEEE Vehicles standards committee (waiting for ballot process at the time of writing this article), which addresses those questions. This standard is intended to supplement the IEEE Standard C57.18.10.

(3) Core :

Cores of modern traction transformers are made of high grade grain-oriented silicone steel. Since the cores remain magnetically excited even at no load, the core loss (no-load loss) occurs all the time. Thus higher energy efficiency can be achieved by minimizing the core losses. The cost of energy can be quite high on an annual basis and it is the highest for the no-load losses. The higher the rate of evaluation of energy, the lower should be the no-load losses. One of the methods of achieving this is by using core materials having a low specific loss (watts-per-pound) characteristic.

Another method of lowering the core loss is to use better joints between the leg and the yoke laminations. For the best energy efficiency, modern traction transformers are manufactured with step-lap cut cores, which are more energy efficient than the other conventional cut cores. Use of step-lap cut core also reduces the hotspots within the core, namely at the joints.

(4) Windings :

The high voltage winding has to face the surges arriving through the high-voltage lines. One of the important requirements of a high voltage winding is its ability to withstand transient voltages arising out of switching and also the lightning phenomena. Due to inherent inductances and capacitances of the windings, the surge voltage distribution along the winding (from the line end to the grounded end) is non-linear and depends on the relative magnitudes of the series- and ground-capacitances. The degree of non-linearity (α) depends on the ratio of ground and series capacitances. The performance of the windings can be improved by the use of special techniques such as capacitive shield which result in the decrease of non-linearity of the surge voltage distribution.

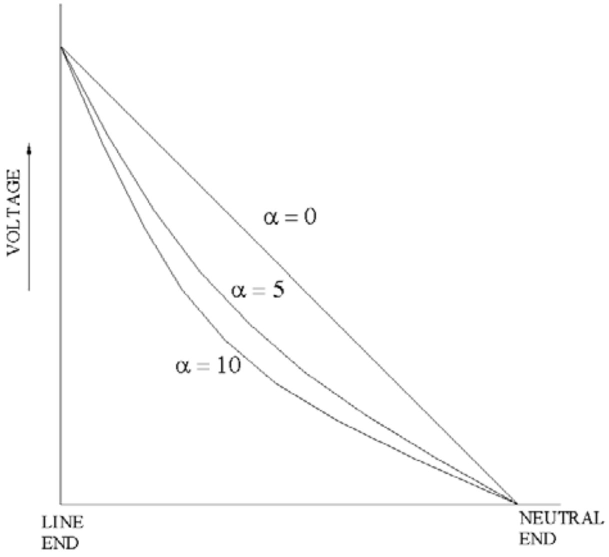


Fig 1. Non-linear distribution of surge voltages along the winding

Another important requirement of the windings is their ability to withstand the short-circuit forces. The ability of the winding to withstand short circuit forces need to be evaluated for the worst condition among the various fault conditions. Modern methods of calculation (by using finite element method) of the short circuit forces are based on computation of the leakage magnetic field and its interaction with the current carrying conductors, such as the windings. These forces need to be contained by the bracing arrangements.

(5) Leakage Magnetic Field and Force Computation :

When the transformer windings are carrying currents, they produce magnetic field, some which "leaks away" from them. This leakage magnetic field interacts with the conductors of the windings and produce electromagnetic forces. In the event of a short-circuit, the magnitude of the current goes up many times and the forces on the conductors go up in the square of that increase. These forces are formidable.

Though there exists some classical formulas for estimation of these forces, a more accurate calculation in possible in modern designs. Using this modern tool, any localized area can be analyzed in greater detail and suitable precautions taken. Fig 2 shows a plot of the leakage magnetic field in a transformer, as seen in a cross-sectional view through the "window" of the transformer.

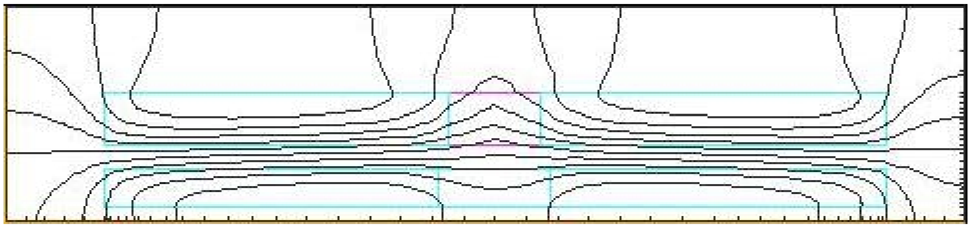
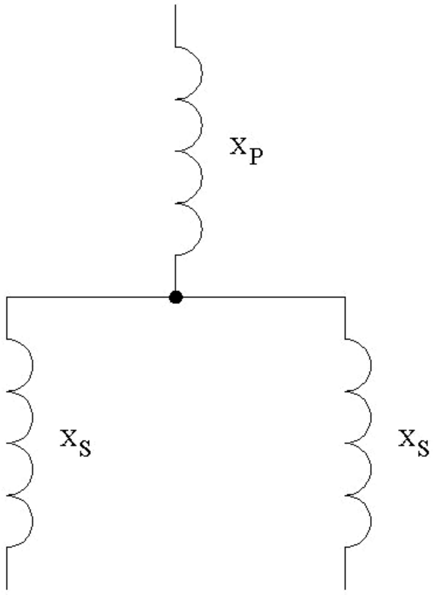


Fig . 2. Plot of Leakage Magnetic Field in a transformer

(6) Circuits :

Traction transformers are often required to feed multiple-pulse rectifiers. The most common rectifier configuration is 12-pulse system. To obtain the 12 pulses, 3-winding transformers having two secondary windings are commonly used; these secondary windings are displaced by 30 electrical degrees between themselves. There are quite a few other circuits for rectifier applications. One of the other possibility is to use two separate 2-winding transformers, one with wye-delta connection and another with delta-delta connection. Such an arrangement provides a total separation between the low voltage windings and thus become a case of zero coupling. If both the LV windings are on the same transformer, there would be some degree of magnetic coupling between these windings. If the magnetic coupling is high, it is known as close-coupled and if the coupling is low, it is known as loose-coupled.

The impedance of the three windings Transformer (HV and two LVs) can be represented by the following circuit (see Fig 3).



where X_P = primary reactance
X_S = secondary reactance
K = coupling factor

Fig. 3 . Equivalent circuit of a 3-winding transformer

The Impedance between HV and LV1 winding is (Xp + Xs) and so is the Impedance between HV and LV2. The coupling factor K between LV 1 and LV2 is expressed as K= Xp / (Xp + Xs). When Xp =0 and therefore K=0, the secondaries are fully uncoupled. When Xs = 0 and therefore K=1 , the secondaries are fully coupled. In most 3-winding transformers the degree of coupling lies somewhere between these two extremes. The degree of the coupling between the secondaries determine the DC voltage regulation characteristics of the transformer-and-rectifier set-up.

(7) DC Voltage Characteristics

Annex –B of (draft) IEEE Std 1653.1 gives the correlation between commutating reactance of the rectifier transformer and the inherent voltage regulation of the transformer-rectifier assembly. Fig 4 shows the typical DC Voltage characteristics required of a traction transformer. The solid line represents the nominal voltage at different load magnitudes, whereas the dotted lines show the tolerance band .

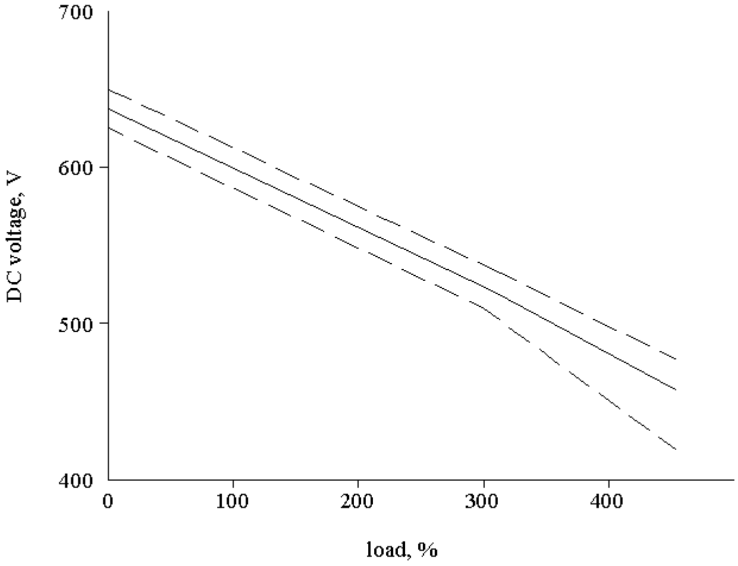


Fig 4. DC Voltage Characteristics

(8) Tolerance on Voltage Difference between Secondary Windings:

Modern traction power rectifier transformers are expected to have closer tolerances than the usual ANSI tolerance of 0.5% on the voltage ratio. The voltage difference between the delta-secondary and the wye-secondary windings should not exceed 0.35%. This can be achieved by either having turns ratios like 11 and 19 turns in the wye- and delta- connected secondary windings. Obtaining the ratios within the above limits with turns lower than 11:19 would call for adding small controllable reactors, or compensating transformers, on each branch of the secondary winding, which will effectively provide the same voltage on-load. A detailed explanation has been provided in IEEE Draft standard 1653.1.

(9) Overload Cycles :

The two primary effects of the load cycles (i.e. overloads) are thermal and mechanical in nature. Proper considerations have to be given for estimation of temperature rises so as to contain it within safe limits to maintain the mechanical strength of the winding conductors and the insulation integrity.

The radial and the axial forces go up in the square proportion of the load. Thus the electromagnetic design of the core and coil must incorporate such features which generate the least amount of forces in the first place, by employing techniques like ampere-turn balancing, using detailed computer programs. Also, the mechanical design of the clamping and bracing arrangements has to be suitable to withstand the forces.

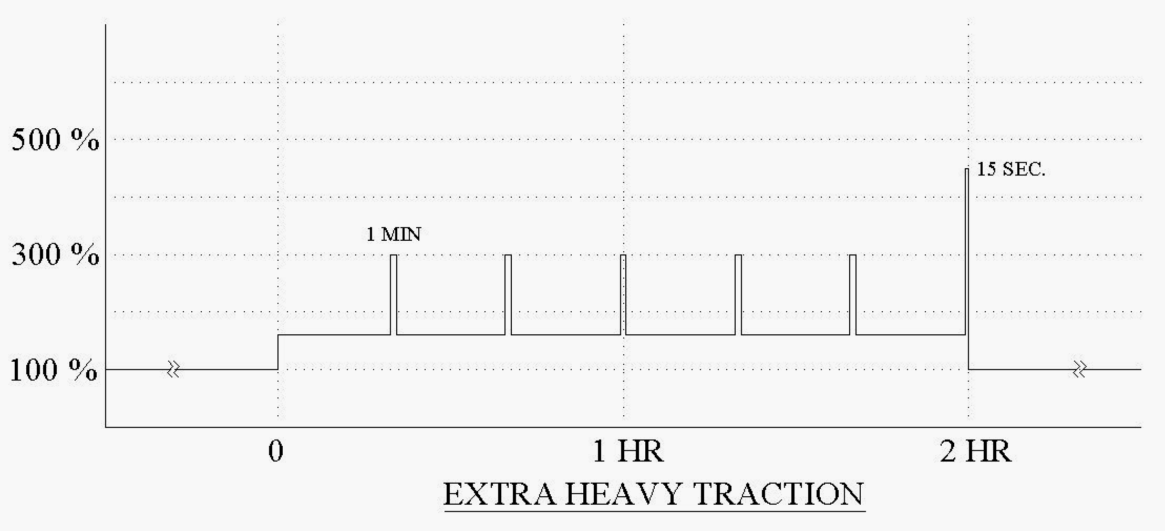


Fig 5 Load cycle of Extra Heavy Duty Traction

The life of the insulating material goes down to half for every 8-10 degree C increase in temperature. On the other hand, the life increases by a factor of 2 for every 8-10 degree C decrease in temperature. Since the temperature of the transformer winding (and hence the insulation) varies according to the loading of the transformer, a weighted impact of the loss of life has to be calculated when the load has a repetitive pattern.

Short-time hottest-spot temperature due to the overload can be allowed to exceed the limits, provided due regard is paid to the loss of life criteria. An RMS value of the overload may be used to simplify the calculation of relative loss of life. For example, for Extra-heavy duty traction service, the load cycle is 100% continuous, followed by 150% for 2 hours, mixed with 5 equally spaced 300% loads of 1 minute duration each and a final 15 second (i.e. 0.25 minute) of 450% load.

The RMS load for the above condition = $[(1.5^2 \text{ x } 120 + 3.0^2 \text{ x } 5 + 4.5^2 \text{ x } 0.25)/125.25]^{0.5}$ = 1.61 PU for the duration of 2 hr, 5.25 minutes and 1.00 PU for 21 hr, 54.75mniutes.

(10) Harmonic Losses :

The load current flowing through a traction transformer is non-sinusoidal due to the rectifier action. Several harmonics are present in the current wave form and these harmonics produce additional eddy and stray losses in the windings as well as the structural parts. Winding eddy currents are known to increase by the square of the current as well as the square of the frequency. Each harmonic component would result in a different amount of eddy loss depending on its frequency and magnitude. If the harmonic spectrum is known, then the per unit magnitudes are expressed as I_h (pu) for each harmonic and the overall harmonic losses are enhanced (by a simplistic formula) :--

$$F_{HL-WE} = \sum_{1}^{n} I_h(pu)^2 h^2$$

Apart from the eddy losses, there are some stray losses which take place in various other parts of the transformer, such as structures, connections, etc. These losses do not go up in the same proportion as the winding eddy losses. Using a simplistic formula, the stray losses can be multiplied by a factor

$$F_{HL-OSL} = \sum_{1}^{n} I_h(pu)^2 h^{0.8}$$

The total losses due the harmonic operations are obtained by adding the above enhanced eddy and other stray losses to the I^2.R losses.

The IEEE standard C57.18.10 gives a good explanation of detailed methods of the above expressions. This method is more rigorous than the simplistic method of using the "K" factor. In fact the multiplier is not necessarily the same for all windings and proper knowledge of the harmonic spectrum would allow optimal design for each winding.

The direct effect of the harmonic losses is additional temperature rise of the windings and structures. These need to be properly evaluated within the design of traction transformer and appropriate measures taken.

(11) TESTING OF TRACTION TRANSFORMERS

While some of the basic tests on a traction transformer are same as for a distribution or power transformer, there are few tests which are special for traction transformers.

(11.1) Temp Rise Test, with effects of Harmonics

The temperature rise tests on traction transformers can be conducted according to the methods described in IEEE standard C57.12.90 for liquid-filled transformers and IEEE C5712.91 for dry type transformers. However, the winding losses for traction transformers shall be calculated for the service condition, namely the enhanced harmonic losses.

(11.2) Short Circuit Tests:

Short-circuit tests are conducted to verify the mechanical and thermal abilities of the transformer resulting from the effects of short-circuit currents flowing through the transformers. The symmetrical value of the short-circuit current is expressed by

$$I_{SC} = \frac{I_R}{Z_T + Z_S}$$

where Z_T = per unit impedance of the transformer and
Z_S = per unit system impedance

. However, the first cycle peak will be of a much higher magnitude than the symmetrical current value. Depending on the X/R ratio of the transformer, the first cycle peak value could be as high as 2.82 times symmetrical current.

The short circuit tests are conducted according to IEEE Standard C57.12.00 and C57.12.90 for liquid filled transformers.

Combined Transformer and Rectifier test : If specified, short circuit test on traction power rectifier transformer can be performed as short circuit test on the entire transformer and rectifier line-up.

(12) Switching Transients due to Breaker – Transformer Interaction

A number of transformers failed dielectrically in field applications, although those units had passed all factory tests and were protected by arresters. These units failed shortly after some switching event. Several dielectric failures within the windings were reported. These unexplained failures had raised industry interest. Initially, these problems were not generally well understood. Studies by groups such as IEEE, consisting of industry experts from transformer, breakers and power systems collaborated to analyze and understand the problem. This IEEE group has brought out a guide (IEEE C57.142-2010) on this subject.

(12.1) A simplified explanation:

Any circuit breaker, SF6 or Vacuum produces over-voltages due to sudden interruption of current (known as “current-chopping”). As a result, it will give rise to transient recovery voltage, and due to re-striking during breaker operation. These transient over-voltages are both aperiodic and oscillatory in nature.

The resonance is a function of the system parameters of the sub-station, the breaker close / open operation and the transformer characteristics. Whenever there is a sudden interruption of the current in a breaker (Vacuum breaker or a SF6 Puffer type breaker), there will be a transient recovery voltage. This transient over voltage build-up breaks down the breaker contact gap, since the breaker contacts are still in motion and are in the process of separating. This re-ignition process continues and repeats itself until the contacts are sufficiently apart and the gap cannot be re-ignited by the recovery voltage. The rate of rise of the recovery voltage transients is a function of the inductance and capacitance of the system.

Transformer windings are a complex network of inductances and capacitances. Such circuits exhibit a complex response characteristic versus frequency and will exhibit several natural frequencies of the transformer windings. When such a network is excited by the re-ignition transients, it can be magnified many times, if the input frequencies coincide with one or more of the natural frequencies of the winding. As a result, large internal voltages can be developed, resulting in a failure of the transformer windings. The lightning arresters connected at the terminals of the transformers are not effective in protecting the transformers against these types of internal over-voltages.

These voltages can be much higher than those produced by standard factory test wave forms. That is the reason why these transformers failed in the field, even though they had passed all the factory tests.

This phenomenon has been observed in both dry-type transformers as well as oil-filled transformers.

Questions have been asked why some transformers failed due to this phenomenon whereas others did not fail. The simple answer to that question is in those cases, the natural frequencies of the transformer coincided with the exciting frequencies of the switching transients.

(12.2) Protection / Mitigation Techniques

In addition to the standard surge arresters, it is strongly recommended to install a SNUBBER circuit at the incoming terminals of the transformer which connect to the breaker (per IEEE C57.142-2010).

A snubber circuit (see Fig 6) typically consists of capacitance and resistance connected to the primary terminals of the transformer and the ground. The values of the resistances and capacitances are determined specific to each installation, where rapid energy dumping is essential to mitigation. These resistors dissipate the energy. A fuse is added in each of the phases, in series with the resistances and capacitances.

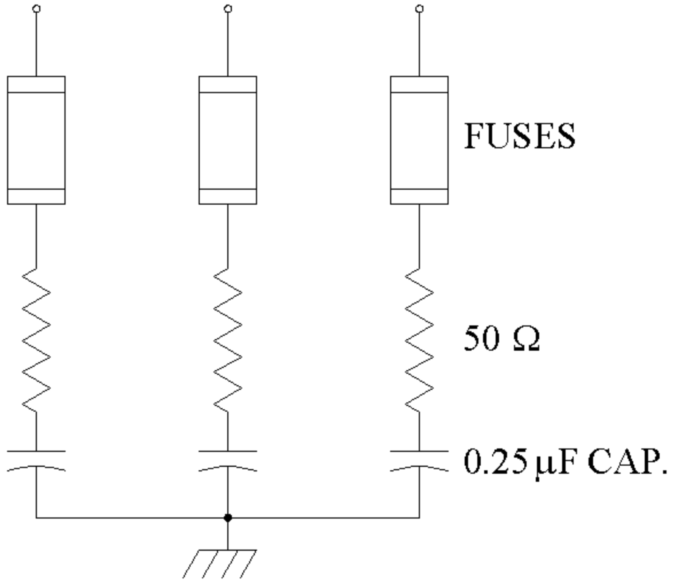


Fig. 6. Snubber Circuit

(13) Conclusion :

Modern Traction transformers are more reliable and are more energy efficient They are more balanced between the secondary windings and when used in a properly designed system would feed less amount of harmonics back into the system. Long Life can be expected from well-designed and -manufactured traction transformers. Use of snubber circuits in cases where required would prevent possible failures from the transients generated due to breaker-transformer interactions.

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