THERMAL PROBLEMS CAUSED BY HARMONIC FREQUENCY LEAKAGE FLUXES IN 3-PHASE, 3-WINDING CONVERTER TRANSFORMERS

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ABSTRACT

Harmonic frequency leakage flux can be a limiting factor in 3-phase, 3-winding HVDC converter transformers. Investigation of a 3-phase, 3-winding 240 MVA converter transformer failure indicated the failure was caused by harmonic fluxes. Calculations indicated that the magnitudes of these harmonic fluxes to be approximately 45% of the power frequency leakage flux for the transformer, and are little affected by the transformer impedance or the converter firing angle.

A study of the failed transformer loading during its life was made, and a calculation made of the hot spot temperature considering various insulation half-life factors. Based on published information on insulation half-life factors it was estimated that at full load the hot spot temperature of the transformer was about 159^{o}C. From examination of the insulation in the hot spot area, this estimate of hot spot temperature was considered reasonable.

BACKGROUND

The Highgate Converter Station in Vermont is an HVDC back-to-back transmission system with a nominal rating of 200 MW. There is a single 3-phase, 3-winding converter transformer on each side of the station. The ac voltage on the north (Hydro Quebec) side is 120 kV, while that on the south (VELCO) side is 115 kV. The transformers on both sides of the Station, as well as the 'common' spare, are all 240 MVA and are of the same design.

In September 1985 two transformers went into service, one on the north and the other on the south side of the station. From 1985 to 1988 the maximum loading was about 175 MVA, due to transmission system constraints. Then from 1988 until 1995 the maximum loading increased to 240 MVA. Between 1995 and the time when the south side unit failed the transformers were operated generally at up to 240 MVA, but occasionally at overloads of up to 260 MVA. These overloads are within the design capacity of the transformer. In August 1996 the south side converter transformer failed after eleven years in service. The transformer was tripped by the gas detector relay on “fast gas”.

DESCRIPTION OF THE TRANSFORMERS

The transformers are 240 MVA, 120 kV ±15% Gnd Wye/23.3 kV delta/23.3 kV wye, with an impedance of 12.7% on the nominal tap. Each “core type” transformer has a three leg core, with three windings on each leg. On each phase there are two LV windings, each rated for 120 MVA, one connected in delta and the other in wye. There is a wye connected HV winding, rated 240 MVA. Each of the HV windings are in two parts, a main winding and a tapping winding, and these parts are each in two sections, electrically in parallel, one at the top half of the core and the other at the bottom half. A cross section of the winding arrangement on one phase is shown in Figure 1. Next to the core are the two LV windings, both have the same inside and outside diameters, and are arranged one above the other. These LV windings consist of two layer disc-spiral windings. Outside the LV windings is the major insulation, followed by the main HV winding, and outside the main HV winding is the tapping winding.

EXAMINATION OF THE TRANSFORMERS

After the cover of a particular transformer had been removed, the core and winding assembly was removed for repair. The top yoke of the core was removed, and the windings taken off the core leg. Then the LV windings were removed for disassembly.

The First Transformer (South Bus)

This was the transformer that had failed in service. The failure had occurred at the bottom of the top LV (or delta) winding in the inside layer of one phase. It would be expected in the case of the failure in a large transformer, that most of the evidence, in this case of overheating, would be destroyed or masked by the short circuit itself. However, in this transformer there was ample evidence of damage to the insulation as a result of overheating. Damage had occurred not only on the other end of the faulted winding, but also on the other LV winding on that phase, and on all the LV windings on the phases.

240 MVA, 3-Phase Transformer
Winding Arrangement.

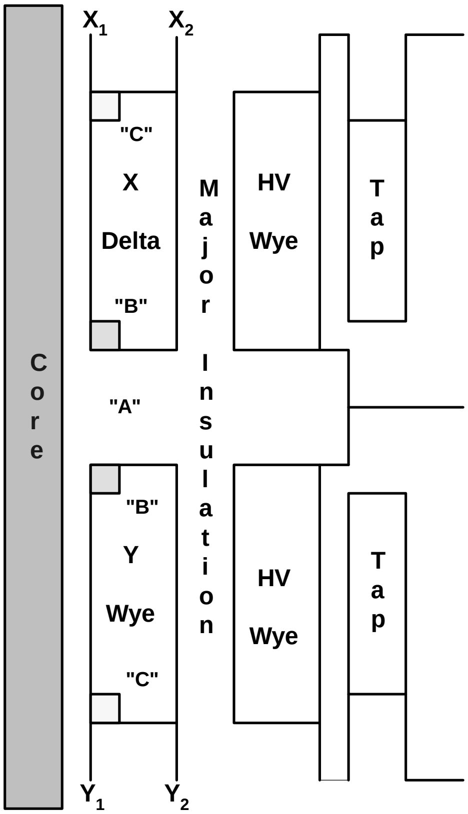


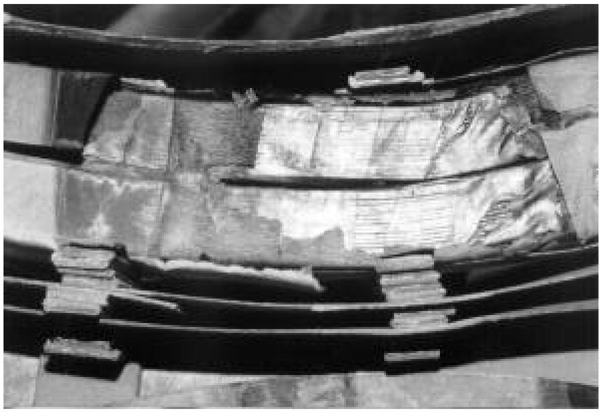
Figure 1

The three end turns at the top and bottom of both LV windings had been provided with extra insulation. The examination showed that these end turns had been subject to damage as a result of overheating, and that the damage had been greatest at the centre of the leg where the two LV windings are adjacent, close to point “A” in Figure 1. The damage was most extensive on the end turns on the inside layer, and was worse on the top or delta winding than on the bottom or wye connected winding point “B” in Figure 1.

At the other, or outer end of the LV windings there were also signs of damage due to overheating but to a much lesser extent (point “C” in Figure 1).

<u>The Second Transformer (North Bus)</u>

The second transformer also carried the same LV currents as the first unit for the first eleven years. In addition it had been in service for eight months longer. As expected the degree of overheating damage was greater. This unit did not fail in service but was repaired based on the findings of the investigation into the failure of the first transformer. Other than the faulted area in the first transformer the pattern of damage in the two transformers was the same. For example the continuously transposed conductor enamel at the bottom of the top winding in the second unit had become completely carbonized and in effect had fused with the remains of the overall paper insulation “outside” it. A photograph of the damage to the bottom of the delta LV winding on phase 2 is shown in Figure 2.



Damage at the bottom of Delta LV winding

Figure 2

<u>The "Spare" Transformer</u>

This transformer was only in service for 18 months, and for over 15 months of this period the converter loading was limited to 180 MW. In 1997 the repaired “north” unit replaced this transformer. The “spare” transformer was sent to the factory for examination.

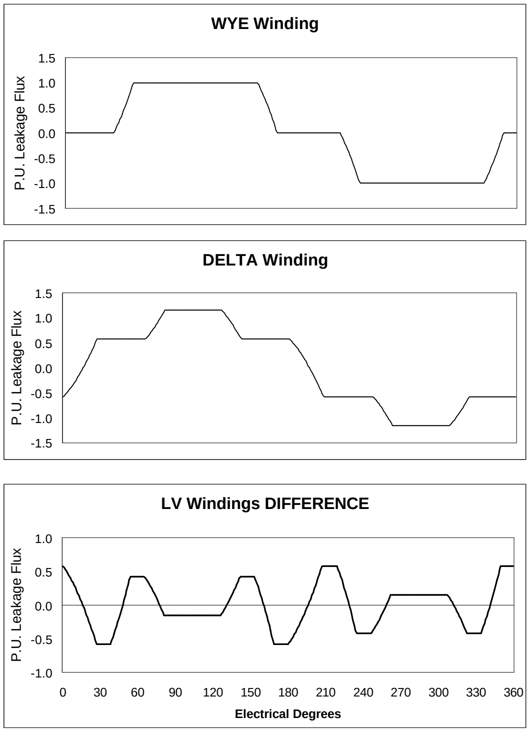
This transformer did not fail in service, but because of the experience on the first and second transformers, and because this unit produced significant amounts of gas-in-oil, particularly carbon monoxide, it was sent to the factory for examination.

As expected, a considerable amount of damage was found to the top of the Y windings and rather more damage to the X windings.

DISCUSSION

The most extensive damage was found on the end turns of the inner layer of the LV windings, particularly at the 'centre' of each phase where the LV windings are adjacent.

In a conventional ac power transformer with two LV windings and an HV winding on one leg, the currents in the two LV windings are usually in phase or close to it. Normally this would be the case even if the two LV’s were of different vector groups, although for generator transformers for example they would both be connected in delta. In a converter transformer, one LV is connected in wye and the other in delta, and because the converter valves in the two groups fire 30° electrical apart, the leakage flux in the two windings will be different. The difference in leakage flux between the two windings with the normal operating firing angle of 20° and overlap angle of approximately 16°, is shown in Figure 3. The waveforms and magnitudes of the valve winding phase fluxes are shown at the top and centre of Figure 3. In the case of the delta while the current is reduced by a factor of 1/3, the number of turns is $\sqrt{3}$ larger and hence the flux Φ becomes as shown. The difference between these fluxes is shown at the bottom of Figure 3. Note the wye winding leakage flux is taken as 1.00 and the 60 Hz fundamental frequency component of this flux is $\pi/\sqrt{6} = 1.28$ p.u. This calculation shows that there will be a difference in the RMS leakage flux amounting to some 44.8% of the normal 60 Hz transformer leakage flux. The waveform of this flux has 300 Hz and 420 Hz components of 37.1% and 23.2% respectively, plus some higher harmonics. Due to the difference in the phase angle of the harmonic currents of the two LV windings, this flux difference is prevented from linking both LV windings. Due to the low reluctance of the core the flux passes between the two LV windings and enters the core steel. This flux can affect particularly the end turn of each winding in the “gap” between the windings, and because of the high harmonic content it may cause localized heating of the winding conductors due to induced eddy currents.



Electrical Degrees
Valve Windings Leakage Flutes
Figure 3

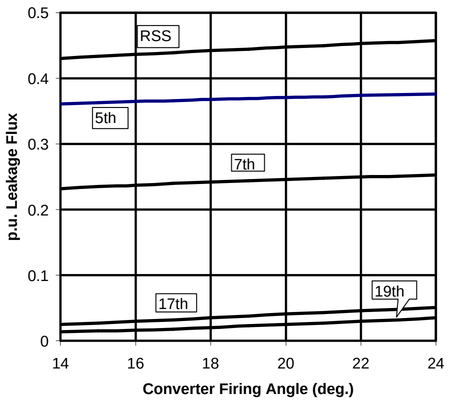
The radial component of flux in the vicinity of the end of the LV windings will cause eddy currents in the local conductors. As the LV windings were wound spirally the half turn at both ends of a layer tended to “stick out” beyond the level of the turn in the other layer. The axial height of the original delta winding conductors was over 18% larger than those on the wye winding conductors. Larger conductors will have higher eddy losses and hence the delta winding conductors would be expected to get hotter than the wye winding. This is probably the reason why the delta winding failed on the first transformer.

To make matters worse, the three end turns on each layer of the LV windings had more insulation on them in the original design. This insulation was provided to increase the impulse strength of the winding. Thus the end-turns had to withstand greater internal loss due to eddy current losses from the harmonic leakage flux, while at the same time, because of the additional insulation, had less effective cooling.

The magnitude of the leakage fluxes for the various conditions discussed below were calculated using a computer program which uses classic formulae as given in the references 1 and 2. The results of the calculations for a given firing angle are the same whether considering a rectifier or an inverter. All the calculations apply to the conditions at full load current. The only harmonics that need to be considered are the 5th, 7th, 17th and 19th frequencies.

The 11th, 13th, 23rd and 25th harmonic fluxes are in phase and will link both windings. Harmonics above the 30th are small and can be neglected.

The Highgate converter transformers have a 12.7% reactance and the normal firing angle of the converter is about 20°. For these parameters the RMS value of leakage flux difference in the LV's at full load is 44.8%. The difference in the leakage fluxes will exist in all converter transformers regardless of the design. On large single-phase transformers, the LV windings are usually on separate core legs, and the individual LV winding leakage fluxes will return to the core and not create a problem. But on converter transformers with two same diameter LV windings on one core leg, the difference in the two leakage fluxes has to exit between the two LV windings. Calculations were made for range of operating firing angles of 14° to 24° and the difference in leakage flux in the LV's varied from 46.5% to 43.3%. The RSS value of the leakage flux and the chief constituent harmonic components as a function of firing angle are shown in Figure 4.



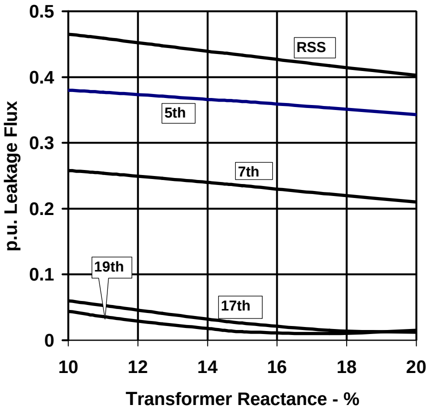
Converter Firing Angle (deg.)
Harmonics as a function of Firing Angle
Figure 4

Calculations were also carried out for transformer reactance between 10% and 20%, and over the range of firing angles from 14° to 24°. The results of these calculations are shown in Table 1. The difference in RSS leakage flux between the LV's varied only between 38.1 and 47.3% over the wide range of firing angles and transformer reactances considered. The highlighted line in Table 1 represents the Highgate transformers, with 12.7 % impedance and a firing angle of 20°. The component of 5th to 19th harmonics in the difference leakage flux as well as the RSS of the resultant is shown in Figure 5.

TABLE 1

Variation of LV Leakage Flux Differences with Transformer Reactance, for firing angles from 14° to 24°

Converter Firing Angle (°)	**Transformer Reactance (%)**	**HarmonIc**				
		5 th (pu)	**7th** (pu)	**17 th** (pu)	**19 th** (pu)	**RRS** (pu)
14	10	0.372	0.247	0.043	0.027	0.449
	12	0.364	0.236	0.029	0.016	0.435
	14	0.355	0.225	0.019	0.013	0.421
	16	0.346	0.214	0.015	0.016	0.408
	18	0.338	0.203	0.016	0.019	0.394
	20	0.329	0.192	0.020	0.022	0.381
16	10	0.375	0.251	0.049	0.033	0.455
	12	0.367	0.241	0.034	0.020	0.441
	14	0.359	0.230	0.022	0.012	0.428
	16	0.351	0.220	0.015	0.013	0.414
	18	0.342	0.209	0.014	0.017	0.402
	20	0.334	0.198	0.017	0.020	0.389
18	10	0.378	0.255	0.055	0.039	0.461
	12	0.371	0.245	0.040	0.024	0.447
	14	0.363	0.235	0.027	0.014	0.434
	16	0.355	0.225	0.017	0.011	0.421
	18	0.347	0.215	0.013	0.014	0.408
	20	0.339	0.204	0.014	0.018	0.396
20	10	0.380	0.258	0.060	0.044	0.465
	12	0.373	0.249	0.045	0.029	0.452
	12.7	**0.371**	**0.246**	**0.041**	**0.025**	**0.448**
	14	0.366	0.240	0.032	0.018	0.439
	16	0.359	0.230	0.021	0.010	0.427
	18	0.351	0.220	0.013	0.011	0.415
	20	0.343	0.210	0.012	0.015	0.403
22	10	0.382	0.261	0.065	0.049	0.470
	12	0.376	0.253	0.051	0.034	0.457
	14	0.369	0.244	0.037	0.022	0.445
	16	0.362	0.234	0.025	0.012	0.432
	18	0.355	0.225	0.016	0.009	0.421
	20	0.347	0.215	0.011	0.013	0.409
24	10	0.384	0.263	0.069	0.053	0.474
	12	0.378	0.256	0.055	0.039	0.461
	14	0.372	0.247	0.042	0.026	0.449
	16	0.365	0.238	0.030	0.016	0.438
	18	0.358	0.229	0.019	0.009	0.426
	20	0.351	0.220	0.012	0.010	0.415



Harmonics as a function of Reactance
Figure 5

The results indicate that, within the range of practical transformer reactances and the normal operating firing angles of HVDC converters, the difference in leakage flux in the LV's only varies by some 15% and for general converter transformer design use may be taken as 45% for practical purposes. The 5th and 7th harmonic components may be taken as 37% and 25% respectively.

REMEDIAL ACTION

The dimensions of the replacement LV windings were constrained by the size of the original LV windings. The LV windings were re-designed with much smaller conductors and a larger number of conductor strands. All of the additional insulation on the end turns except for a single pressboard angle ring were dispensed with. The temperature rise test on the first repaired transformer was satisfactory, the average winding rise on the delta connected LV winding was reduced by 5.5°C compared with the original design. This was achieved in spite of an increase in the I^2R loss still using CTC conductors. These conductors have a larger number of parallel strands, occupy the same space, with each strand being smaller than the original. This results in a slightly higher average current density. However, there was an overall reduction in stray loss, both the normal "60 Hz" stray loss plus the harmonic loss, that more than compensated for the increased I^2R loss. As well as redistributing the losses and decreasing the total load loss in the LV windings, the cooling was also improved by eliminating the additional insulation on the end turns of the LV windings.

In turn, all three transformers were repaired and factory tested. The tests on the LV windings were performed at the full design test levels, while the original HV windings, which were reused, were tested at reduced levels. The first repaired unit was subjected to a temperature rise test with allowance for harmonic currents. After testing, each transformer was returned to site. The first unit was in service from April 1997. The second transformer was in service from October 1997 until September 1998, when it was taken out of service so that the third unit could be installed in order for it to be in service during its warranty period. There have been no performance problems on the repaired transformers.

When the third, "Spare", unit was repaired, it had a fibre optic winding temperature measurement system installed. When in service, the temperature as measured by the sensors in the previously "hottest spots", as observed by the examinations described above, the temperature did not exceed 80°C, and were close to the calculated values.

CONCLUSIONS

a) Because of the special characteristics of converter operation, with three phase three winding converter transformers with two same diameter LV windings on each core leg, there is a significant component of leakage flux that passes between the two LV windings.

b) For practical design purposes the magnitude of the component of leakage flux between the LV windings may be taken as 45% of the power frequency transformer phase leakage flux. This flux includes 5th and 7th harmonic components of 37% and 25% respectively.

c) As far as converter operation is concerned, variation of firing angle has little effect on the magnitude of the harmonic leakage fluxes.

d) Converter transformers with both valve side windings on the same leg need to be designed to cope with these fluxes. This requires the use of small enough conductors to reduce the eddy current heating to acceptable levels and/or providing adequate cooling at the ends of the windings.

e) From an analysis of the converter loading discussed in the Appendix, it has been estimated that the local hot spot of the winding reached almost 160°C when the converter was operating continuously at full load.

APPENDIX

LIFE CONSUMED OVER DIFFERENT PERIODS

Four different insurance companies carried the insurance coverage during the service life of the first transformer. As a result it was necessary to estimate the amount of damage sustained to the transformer over the various periods of coverage.

Ageing is primarily determined by winding hot spot temperatures. The hot spot is a function of the transformer loading and ambient temperatures.

The total life for this transformer was from 1985 until 1996 when failure occurred, a period of about 96,200 hours. The loading for the transformer was obtained from three sources, from chart recorder sheets up to the end of 1989, from operator’s logs, and after the beginning of 1990 from a computer log of hourly converter loading. The forced coolers had been set up with the fans operating when the winding temperature reached about 80°C. As a result the transformer would have operated at a fairly constant oil temperature throughout the year. To a close approximation, the winding gradient will vary in proportion to the square of the converter current.

The effective hours were calculated, with respect to a converter load of 200 MW, using:

$$H_e = 2^{\left(\frac{T_{200} - Le\ x\ T_{200}}{Fh}\right)}$$

where:

H_e = the effective time (hours/hour)

L_e = effective heating at the load in that hour

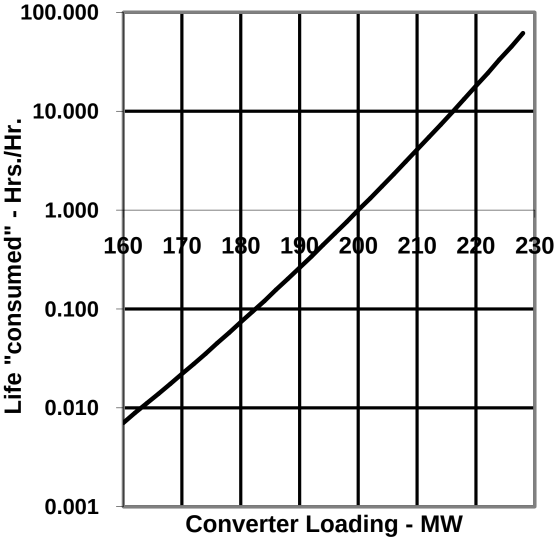
F_h = half life factor

T_{200} = hot spot temperature at a converter load of 200 MW

Using these calculations, for each hour of converter operation the effective time was determined. For different converter loadings the value of H_e was:

Load (MW)	**Effective Time H_e (hours/hour)**
160	0.007 (25.5 seconds)
180	0.07 (4 min 40 sec.)
200	1.00 (60 min.)
220	18 (18 hours)

Taking the nominal converter loading of 200 MW as the reference, 160 MVA for one hour would produce the same amount of insulation deterioration as 200 MW for 36 seconds, while 120 MVA for one hour would produce the same amount of insulation change as 200 MW for 15 hours. The cause of life "consumed" against MW loading shown in Figure 6.



Life “Consumed” during operation
Figure 6

As the total life of the failed transformer was known, using various values of F_h, it was possible to calculate what hot spot was required in order to achieve the actual total life. For each of these calculations the amount of life "used up" in any given period was exactly the same, all that changed was the value of T_{200}.

The "straight line" plot of T_{200} against F_h is shown in Figure 6. The values of F_h from 7 to 10 covers the range generally referred to in the literature. In Reference 3 for insulation temperatures above 120°C, the value of F_h is 8°C. From our calculations this gave one "chosen value" of T_{200} of 159°C. This appeared to be consistent with the damage that was found in the transformers.

Because the life of the original south transformer was known, changing the insulation half life factor did not affect the amount of damage for any particular period. What did change was the hot spot temperature. Plotting Hot Spot Temperature against insulation half-life temperature "rise" gave the curve shown in Figure 7.

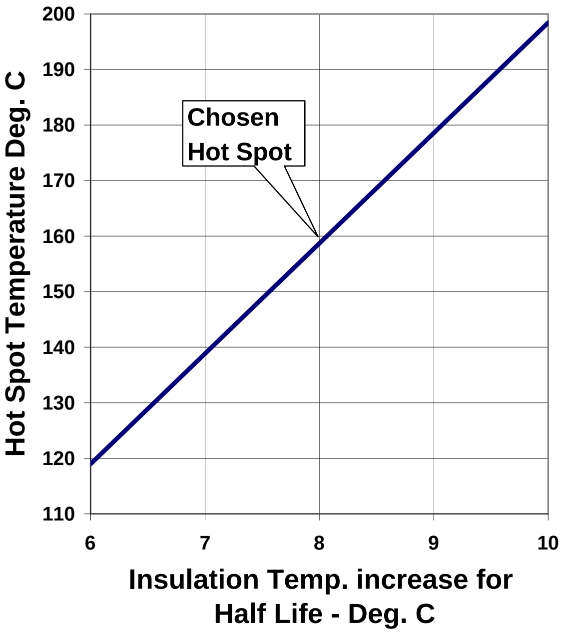


Figure 7

According to McNutt, [Reference 3] for insulation temperatures over 120°C, an 8^oC-temperature increase halves the insulation life. For this half-life, Figure 7 gives a hot spot of 159°C. It is felt that this corresponds reasonably to the temperature required to produce the winding insulation deterioration that was observed.

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