Transformer failures in regions incorrectly considered to have low GIC-risk

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***Abstract*— *A close association has been identified between the theoretical calculation of geomagnetically induced currents (GICs) in a large network, practical measurements of GICs, the results of dissolved gas analysis (DGA) records, and damage in recently failed transformers in Southern Africa. Together these indicate that GICs may contribute significantly to transformer failures on large transmission systems in mid-latitude regions, where GICs are generally thought not to be significant.*

***Index Terms*— *Power transformers, Failure analysis, Geomagnetically induced currents.*

I. INTRODUCTION

POWER systems in mid- and low-latitude countries, such as Southern Africa, South America and Australia, are generally not considered to be susceptible to damage by geomagnetically induced currents (GICs), but recent research in Southern Africa indicates a possibility that GICs might contribute significantly to the failure of transformers.

Transformer failures incur high direct costs, disrupt utility operations and increase the risk of major power system outages. Improved understanding of the causes and mechanisms of failures is needed to reduce the incidence of failures and their effects on power systems. Many studies have identified apparently significant causes of transformer failure, and usually lead to proposals to reduce a particular problem.

This paper describes evidence indicating that the role of GICs in failures may be underestimated in regions remote from the auroral zones most commonly associated with GICs, and discusses some of the implications.

II. BACKGROUND

Insulation failure was shown to be the most common cause of failure in the early service life of large power transformers in an analysis of transformer failures in South Africa [1]. The report confirmed, to some extent, an international study of transformer failures [2]. Neither report includes GICs as a possible cause of failure.

On the other hand, several authors have reported power system disturbances and equipment damage ascribed to GICs induced by geomagnetic storms. A severe storm in March 1989 initiated tripping of 735 kV lines and complete collapse of Hydro-Quebec’s power system [3], and gas generation and damage to the Salem 1 generator step up transformer (GSU) [4]. Effects of GICs on power systems include “changes in system var requirements, increases in harmonic current magnitudes, increased transformer stray and eddy losses, and problems with system voltage control” [5]. Repeated exposures to GICs “lead to cumulative damage that can ultimately lead to transformer failure” and units at base load power stations are more vulnerable because they are relatively heavily loaded and have less margin for heat stress [6].

Clearly, if GICs contribute to transformer failure, the apparent symptoms of failure are diverse and might be attributed to other factors instead of GICs, such as insulation failure. Network transformers, for example, are exposed to through-faults and overvoltages that could provoke final failure, even if initial damage is by GICs. Therefore, before examining the evidence of several transformer failures, it is useful to consider the processes by which GICs could weaken the condition of a transformer and the symptoms that would indicate the contribution of GICs to failure.

III CHARACTERISTICS OF GEOMAGNETIC STORMS AND GICS

A geomagnetic disturbance is the result of charged particles from the sun, starting as a coronal mass ejection, reaching the earth’s magnetic field and distorting it. Research continues into the processes, but the effects are geomagnetic storms (lasting hours), sub-storms (minutes) and short impulses. The distortion is apparent as changes in the earth’s magnetic field, measured in terms of the magnitude (in nT/min) and direction (in degrees/min) of the field.

The changing magnetic field induces currents in the large loops of conductor made up of transmission lines connected through the earthed neutrals of transformers and substation grounding to “true earth”, and the current flowing through the earth between those transformers, as illustrated in Fig 1.

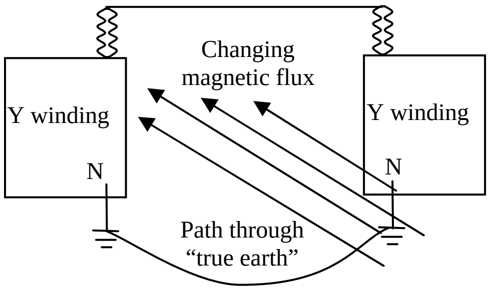

Fig 1: Conducting loop in which GIC is induced by variation of magnetic field coupling

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Koen [7] applied the approach developed by Lahtinen and Pirjola [8] to calculate the induced currents in the Southern African main transmission system (MTS), using the magnetic field changes measured at the Hermanus Magnetic Observatory (HMO). The calculations were based on a model that assumes a plane magnetospheric current and a homogeneous earth. Further, it assumed that the changes over large regions distant from the magnetic poles, such as over most of Southern Africa, are almost the same because the field change is dominated by the planar current [9]. The calculated results compared well with transformer currents measured in two MTS substations when geomagnetic storms occurred, as illustrated in Fig 2 [7]. In May 2005 a current of 13 A was measured at the Hydra substation.

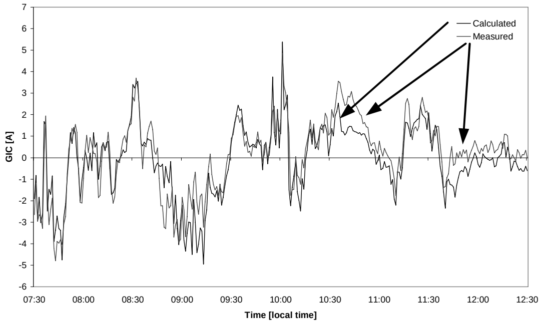

Fig 2: 10 sec average values of calculated and measured GIC (in A) in the neutral of the 500 MVA autotransformer at Grassridge substation over five hours of storm on 31 Mar 2001 [7].

Recent analysis shows that field changes over large areas are not the same, as had been assumed. Interpolating magnetic field measurements from three observatories, as illustrated in Fig 3, improves the agreement between calculated and measured values of GICs [10].

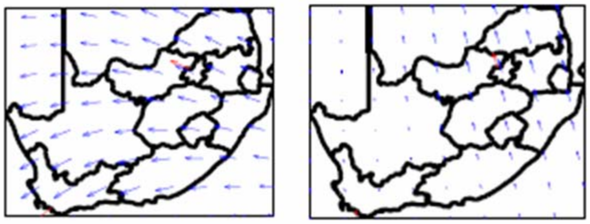

Fig 3: Variation of magnetic field across Southern Africa, at 2 min interval, at 11:03 and 11:05 on August 2005, showing difference across region [10]

IV RESPONSE OF TRANSFORMERS TO GICS

The GIC reflects the variation of the magnetic field, so it is characterised by slow changes. This quasi-direct current GIC flowing through a transformer off-sets the power frequency magnetisation curve so that the magnetic circuit operates asymmetrically on the B-H curve. Transformers are designed to operate in the linear portion of the curve with only a small magnetising current, without approaching the non-linear regions of core saturation. Even small GICs can produce sufficient off-set for the transformer to reach saturation in the half cycle of the ac current that is in the same direction as the GIC. As the core saturates, the permeability tends to 1 and the flux fills the whole space of the winding, so is very different from the flux distribution under normal conditions.

Normal leakage flux is controlled by non-magnetic (stainless steel or aluminium) shields, shunts or cheek plates, the dimensions of which are critical for controlling eddy current losses and heating [11]. Under normal conditions, with most flux in the magnetic core, the non-magnetic plates carry little flux and generate only small losses. Under half-wave core saturation, the losses in some parts of the leakage flux shields may increase significantly, causing localised heating.

Half-wave saturation also increases the magnetising current and distorts the magnetisation current waveform [12]. The distorted magnetising current has harmonics that correlate well with the GIC, as shown in Fig 4, and indicate saturation.

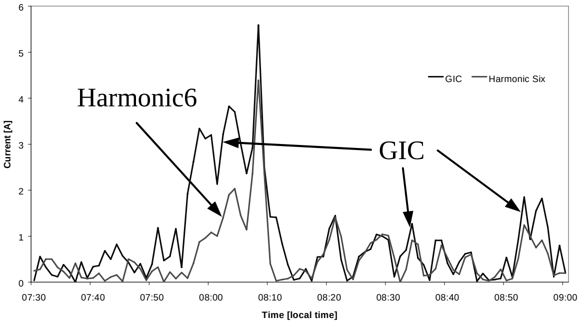

Fig 4: GIC and 6th harmonic measured in the autotransformer at Grassridge substation on 6 November 2001 [7]

The measured GICs at Grassridge substation are interesting in two respects. The currents are similar in magnitude to those calculated for transformers on the NGC network in UK, where GICs were reported as the cause of failure of two 400 kV 240 MVA transformers [13]. Secondly, several researchers have indicated that three-limb transformers, like the one at Grassridge substation, are less susceptible to GICs than single-phase or five-limb three-phase transformers [5, 14]. The measurements of GICs and harmonics indicate that saturation occurred more than once in a three-limb three-phase transformer with GICs as low as 2 A/phase.

Price [15] analysed the effects of GICs on single-, three- and five-limb transformers, including the shunt effect of the tank and other components, and verified the analysis by physical tests. He concluded that “tank shunting effects for three- and five-limb core-type transformers are important”, and local heating is affected by the construction details.

Without adequate control of the flux under saturation conditions, local heating in parts of the transformer may not be cooled effectively, leading to rapid temperature increase. The intensity of overheating depends on the saturation flux paths, cooling flow and the thermal condition or loading of the transformer. Overheating causes the breakdown of oil and paper insulation, leading to gassing that can be detected and analysed by dissolved gas analysis (DGA).

Shunt reactors are similar in many respects to power transformers, except that they generally have gapped cores. Laboratory tests at University of Cape Town show that direct current can flow in model three-limb three-phase reactors with small gaps. The response of a reactor to GICs could be similar to the response of a three-limb transformer, with the core gap of a reactor having a similar effect to the core-tank gap of the transformer. Despite the relatively high reluctance of the magnetic path compared with a closed-core, some quasi-dc GIC will flow through a reactor and, as for a transformer, the response will be determined by the construction details. Koen and Gaunt [16] reported reactor failures and elevated levels of dissolved gas closely associated with exposure to geomagnetic storms, although “the failure of reactors due to GICs appears not to have been reported and is generally unknown”.

While the practical measurements on the MTS demonstrated saturation of transformers that were previously expected to be unaffected by GICs, there has been no practical demonstration of a direct association between GICs and the initiation of gassing in transformers. However, in November 2003 this changed, with elevated levels of dissolved gas in several transformers being closely associated with a major storm.

V THERMAL DAMAGE BY GICS DURING NOV 2003

The condition of twelve 400 kV GSU transformers, each rated 700 MVA, at the Tutuka and Matimba power stations and six 275 kV GSU transformers at Lethabo power station is checked regularly, with some units equipped with on-line DGA instruments. After the severe geomagnetic storm at the beginning of November 2003, often referred to as the “Halloween storm”, the levels of some dissolved gasses in the transformers increased rapidly. A transformer at Lethabo power station tripped on protection on 17 November. There was a further severe storm on 20 November. On 23 November the Matimba #3 transformer tripped on protection and on 19 January 2004 one of the transformers at Tutuka was taken out of service. Two more transformers at Matimba power station (#5 and #6) had to be removed from service with high levels of DGA in June 2004. A second transformer at Lethabo power station tripped on Buchholz protection in November 2004.

The DGA records are not the same for all the transformers, but all of them show a sharp change at the end of October 2003, when the first storm occurred. Based on the DGA records, most of the transformers at these power stations appear to have been damaged by the effects of the geomagnetic storms. The DGA record for one of the Matimba transformers, shown in Fig 5, is fairly typical. Gas levels fell when the transformer loading was reduced following the sharp increase after 31 October. By August 2004, about 10 months after the storm, this transformer had not yet failed, although damage was evident from the generation of gases.

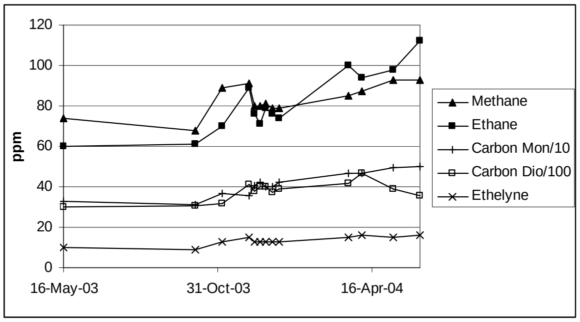

Fig 5: DGA results Matimba #1: May 2003 to June 2004

Although absolute levels of gas are low, the DGA results of the Tutuka and Matimba transformers produce ratios that are consistent with low temperature thermal degradation as described by Mollmann and Pahlavanpour [17] and Saha [18]. Typically, on four apparently damaged transformers:

Ethylene:methane C2H4 / CH4 = 0,2 - 0,9
Ethane:methane C2H6 / CH4 = 0,2 - 1
Methane:hydrogen CH4 / H2 = 2 - 5
Ethylene:ethane C2H4 / C2H6 = 0.4 - 4.6
Acetylene C2H2 negligible

In the transformer depicted in Fig 6 the level of CO2, a product of low temperature degradation of cellulose, was approximately 10 times higher than the level of CO. Relatively higher CO or ethylene content would indicate higher temperature degradation.

Inspections of all the failed transformers identified heat damage, mostly to paper insulation, in various parts of the transformers, as illustrated in Figs 6 to 8. The damage is consistent with the DGA results. In all cases, the extent of the damage appears to be small, and discoloration of paper insulation beyond the immediate vicinity of the fault is superficial, which explains why the absolute levels of dissolved gas are low - even below the threshold considered significant for most DGA assessment.

Fig 6: Failure in HV winding of Lethabo #6

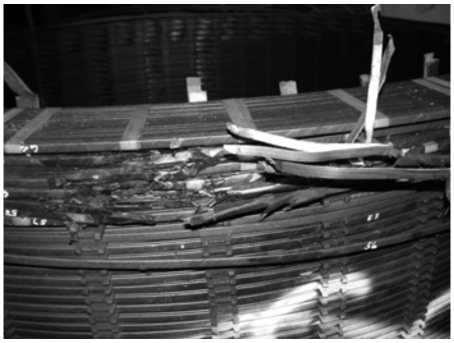

Fig 7: Failure in HV winding of Matimba #4

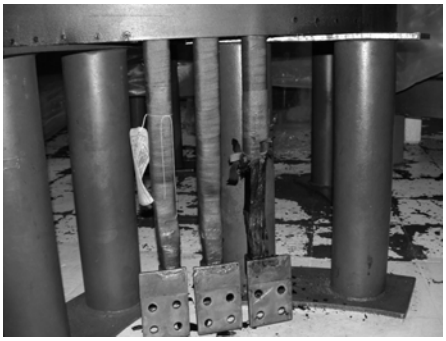

Fig 8: Overheating of LV terminals of Tutuka #1

VI OTHER POSSIBLE CAUSES OF DAMAGE

The possibility that the damage evident in these transformers was initiated by GICs is supported by Koen's identification of the Matimba and Tutuka power stations as among the installations most exposed to GICs in the Eskom MTS [7] and the sudden onset of gassing in several transformers, coincident with each other and a significant geomagnetic storm.

The DGA records of the transformers at these two locations indicate that deterioration continues after the initial damage, affected by transformer loading and possibly other stresses. A transformer might fail only months after the initial damage and, unless frequent DGA samples have been taken, could appear to fail for "unknown causes" or a subsequent stress incident. This aspect raises the possibility that the damage in November 2003 could have been caused by stresses other than the GICs estimated to have flowed through the transformers.

Failure of transformers is often ascribed to damage of internal insulation by external overvoltages or network faults. No major system faults were reported at the time of onset of the gas generation. While overvoltage events or system faults could affect all the transformers at one power station, they would be unlikely to affect simultaneously most of the transformers at three power stations where damage occurred, especially as the power stations are far apart with other substations between them.

Other significant causes of transformer failures are settling in and aging. The damaged transformers are about 10-15 years old, not the oldest or newest in the fleet. Two or three transformers simultaneously showing evidence of aging might be described as coincidence, but the change in so many transformers suggests a common response to a specific event. Therefore the damage is most unlikely to be a result of settling in, aging, or defective design or manufacturing defects.

Copper sulphide formation in transformers or reactors with corrosive oils has recently become a concern. The mechanism of formation is not yet well understood, but the rate depends on various factors, including the oxygen content, and appears to increase significantly with temperature [19]. It is extremely unlikely that copper sulphide formation simultaneously and alone initiated the failure of the transformers, although it is possible that simultaneous localised heating caused by GICs could contribute to copper sulphide formation.

A further event reduces the possibility of a common failure cause other than GICs. On 11 December 2003 the protection tripped a two-year old 90 MVA 330 kV GSU at NamPower's Ruacana power station in northern Namibia. The damage within part of one HV winding, shown in Fig 9, was similar to that of the transformers shown in Figs 6 and 7. Ruacana is on the same synchronous network as the other stations where transformer damage occurred during the same period, but is separated physically by 1400 km and electrically by over 2000 km of circuit. All these stations were found to be among the most "GIC exposed" installations in Southern Africa [7].

Fig 9: Damaged HV winding of Ruacana GSU transformer

VII IMPLICATIONS

The coincident onset of gas generation in widely separated transformers of different ages, the relative "exposure" of the transformers to GICs, and the similarities between the nature of damage and its timing all indicate that the system-wide effect of GICs is likely to be a more significant initiator of the failures than overloading, overvoltages, system faults, copper sulphide formation or manufacturing defects. Some of these other factors may contribute to failure by weakening transformers and explain why some failed and others did not.

The damage in all the transformers inspected appears to be initiated by local overheating. The DGA results are consistent with low temperature degradation of insulation. The levels of dissolved gases are below levels generally considered to be significant, and this is consistent with localised overheating.

The nature of faults caused by low temperature local overheating in windings is such that much of the evidence at the site of a fault would be obscured by subsequent disruptive failure. It is unlikely, therefore, that inspections after a disruptive fault will identify evidence of low temperature local overheating at the fault position. Unless overheating caused by leakage flux established by GICs is specifically considered, which is unlikely based on current knowledge of the problem, GICs will not be reported as a cause of faults.

Does damage caused by low temperature local overheating always leads to failure and, if so, how quickly? Once core saturation by the GIC is removed, thermally damaged paper insulation will be less robust than before the event. Another mechanism of further damage must be considered, such as by leakage currents, partial discharge or reduced heat transfer through the damaged paper, causing further local heating to an extent that degradation continues. Such mechanisms could explain why gas generation and DGA levels decrease when the transformer loading is reduced. Eventually, depending on the extent of the initial damage, the presence of air and water in the transformer [20], and operating stresses, the damaged insulation in a small area will fail, even if the DGA levels are significantly below those usually indicating incipient failure. However, since the initial damage and the subsequent operating conditions are variable, the breakdown level or the likelihood of failure is difficult to determine. In the cases reported here, the DGA indicated the onset or increase of damage coincident with a severe storm. Thereafter, some transformers failed quite quickly, others took months, and some might survive until gradual deterioration, a severe system fault, overvoltage or another GIC event causes the damage to be extended to the point of failure. Accordingly, any transformer exhibiting an increase in levels of dissolved gasses that indicate paper degradation after a geomagnetic event should be considered as distressed.

The nature or location of GIC initiated damage is not the same for all the transformers. Designs differ and transformers made to the same design are not always manufactured identically. Similar GICs through similar transformers might cause slightly different patterns of leakage flux, and the weakest part of one transformer's insulation might differ from another's. The most likely failure point will be where leakage flux creates a condition that exceeds the local cooling capacity. In extreme cases, part of the tank or core might melt, but in most cases damage might only be observed in a winding or a lead, as in the cases reported here. The GIC should not be thought of as a single cause of a fault, but as a stress that exposes relative weaknesses, which become localised hot spots and eventually lead to failure.

Extreme GIC events do not occur only at the peak of or late in a solar cycle [21] and final failure may not easily be linked to the solar cycle or a specific storm. However, based on these responses to GICs, it would be expected that transformer failures should increase during periods following geomagnetic storms. Such a trend is evident from an analysis of failures of large transformers, all over 230 kV, on the Eskom MTS during the past 20 years. The failure for winding, core or lead damage of 143 large transformers appears to increase after storm events, as shown in Fig 10. The storm severity indicator is based on the geomagnetic storm periods during the year, with K7 and K8 occurrences weighted as 0,25 and 0,5 respectively compared with a K9 occurrence. It is recognised that K values measured at the HMO are a crude indication of the severity of storms in respect of producing GICs, but in the absence of a better index, this composite value has been used. The higher incidence of transformer failures during the years after geomagnetic storms is similar to that reported for transformers in North America relative to the solar cycle [22].

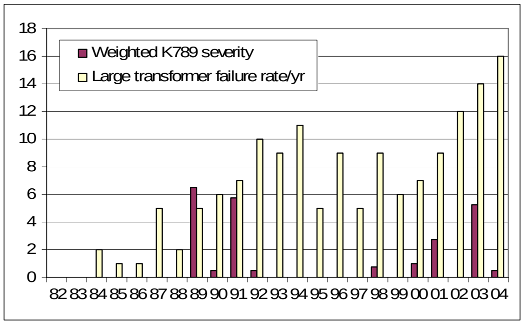

Fig 10: Annual failures of large transformers with winding, core or lead damage, relative to the severity of geomagnetic storms. (2004: based on half year result.)

These failures must be considered in the context of the approximately 400 failure records from which only those of higher voltage transformers with particular types of damage were extracted. The increase of these particular types of transformer failures after severe geomagnetic storms does not imply that all failures in those periods are initiated by GICs, but does support the other evidence presented in this paper associating some transformer failures with damage initiated by GICs. Better knowledge of the damage mechanisms, the vulnerability of different transformers and the storm severity in respect of potential damage would allow better correlation between them. However, even if only the excess failures above a base frequency of (say) six per year of this type of failure are attributed to initial damage caused by GICs, the resultant loss of life in this system is significant.

VIII RESPONSIBILITY OF DESIGNERS AND UTILITIES

There are some interesting implications for the analysis and reporting of failures. Excluding GICs from consideration results in all faults being ascribed to other causes. Subsequent analysis of fault data would show that GICs are not reported as a cause of faults, further obscuring the possible underlying processes of damage initiation. If utility engineers do not recognise that transformer failures are due to GICs, based on evidence available from storm occurrences, network analysis, incident reports and damage inspections, then little or no liability can be attached to transformer suppliers with less access to the relevant data. A manufacturer that could show that failures might be associated with GICs, but that GICs were not considered or identified in specifications or incident reports by the utility engineers, could avoid or reduce any liability for damage.

Avoiding damage by GICs requires that transformers be designed and built so that leakage flux resulting from saturation will not cause local overheating. Mitigation can be implemented by suitable flux shunts, adequate clearances between the tank and core, aligning conductors so that leakage flux does not produce significant eddy currents, improving the cooling where local heating might be expected, and other techniques already used by manufacturers. Transformers have been designed, built and tested to survive saturation by very high GICs [23]. Some utilities already specify that transformers must withstand the effects of large GICs, with compliance demonstrated by finite element modelling of the flux produced. Design reviews for transformers in less exposed situations could similarly take into account the effects of GICs at levels appropriate to the network.

Temporary network reconfiguration can be used to reduce the magnitudes of GICs [7], and might be a suitable way to reduce transformer stress in networks that are only infrequently exposed to severe geomagnetic storms, such as outside the auroral zones. Where many transformers are already installed without specified GIC capability, temporary network reconfiguration during storms may be the most effective short-term mitigation procedure. Factors to be considered include the reliability of the reconfigured network, the costs of modified power despatch, the transformer risk associated with the redistributed GICs, and the conditions under which reconfiguration will be implemented. Long-term mitigation can be achieved by installing series capacitors in long transmission lines to block the quasi-DC GICs, with possible benefits for power flow capacity.

IX CONCLUSION

The close association between GIC analysis, the results of DGA monitoring, the inspections of recently failed transformers, and the cyclical variation of transformer failures indicates that GICs may be a significant cause of transformer failures on a large transmission system even in this region lying between 18 and 30^{o}S and generally considered to have low GIC risk. It appears that small GICs may cause damage in transformers that are not designed to withstand the effects of flux distortion. Similar conditions may apply in many other networks where GICs are not recognized as a significant risk.

Further research is required to confirm the implications of the findings reported here. An improved understanding of the response of magnetic circuits and windings to GICs appears needed. There is scope to investigate further the processes that contribute to the degradation of the transformer insulation. Suitable approaches are needed for DGA interpretation for low levels of gas generated in conjunction with severe geomagnetic storms. Finally, appropriate mitigation techniques, including improved specifications for new transformers and operational network modification procedures that take into account the variability according to network topology of GIC flow, risk of damage to transformers and system reliability, must be developed to protect equipment from similar damage when the next severe geomagnetic storm arrives.

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