Paper accepted for presentation at 2003 IEEE Bologna Power Tech Conference, June 23th-26th, Bologna, Italy

Modeling GIC Effects on Power Systems: The Need to Model Magnetic Status of Transformers

W. Chandrasena, P. G. McLaren, *Fellow, IEEE*, U. D. Annakkage, *Member, IEEE*, and R. P. Jayasinghe, *Member, IEEE*

***Abstract*— This paper describes the simulation of the effects of GIC (Geomagnetically Induced Currents) in a power system using a new transformer model. The simulation studies demonstrate that it is important to accuratly model the remanence effects in the core of the power transformer.**

***Index Terms*— eddy currents, hysteresis, losses, power transformers, simulation**

I. Introduction

During a GIC event (Geomagnetically Induced Current) the current that enters the grounded-wye transformers appears as quasi-dc in comparison to the normal power system frequencies. If the zero sequence reluctance of the transformer is low, GIC biases the operating point of the magnetization characteristics to one side. Since peak ac flux in the power transformer is designed to be close to the knee of the magnetization characteristics, this bias causes the transformer to enter the saturation region in the half cycle in which the ac causes a flux in the same direction as the bias. This effect is known as half-cycle saturation, and it is the source of nearly all of the operating and equipment problems experienced during a GIC event. Because of the half-cycle saturation, the transformer draws a large asymmetrical exciting current and it results in increased reactive power consumption as well as the generation of significant levels of harmonic currents. There have been many reported cases of undesirable effects on power systems during GIC events that include the Hydro-Quebec outage in 1989 [1]- [4].

During a GIC event, the extent of saturation experienced by the core of a power transformer depends on the magnitude of the quasi dc current and the history of the state of the magnetic core. In addition, the severity of half cycle saturation determines the nature of the waveform of the asymmetrical magnetizing current, and hence the generation of harmonic currents and the increased reactive power consumption. Therefore an electromagnetic transient simulation carried out to analyze the effects of GIC on a power system requires an accurate representation of non-linearities in the iron core of the power transformer. Thus, the correct representation of the hysteresis loop is important so that it handles long term remanence and recoil loops.

This paper presents simulation results to show the effects of GIC on a power system. These simulations were carried out using an improved low frequency transformer model developed for use in GIC studies. This new transformer model is based on the Jiles Atherton (JA) phenomenological model of a ferromagnetic material [5]. The JA theory has been used in [6] in the simulation of current transformers, and it has been shown that the hysteresis model based on the JA theory accurately represents the long term remanence recoil loops in the transformer cores.

Simulation results presented in this paper show effects of GIC on the waveform of currents in a transmission line of a power system. In addition these studies also show that an electromagnetic transient simulation carried out to model such an event requires not only the magnitude of the quasi-dc neutral current, but also its history with respect to any particular point of interest. This is due to the fact that the extent of the saturation of the transformer core depends on its past status, and hence the present status of the core cannot be modeled accurately without taking the history into consideration. Therefore, these results highlight the importance of modeling the remanence effects of the magnetic core.

A brief review of the new transformer model developed is presented in the following section [7]. Simulation results obtained with this new model during a GIC study are presented in section III.

II. Review of Transformer Core Models

During the past decade a considerable effort has been devoted to the development of simulation models of power transformers [8]- [12]. These models contain a wide range of modelling details of the iron core of the transformer with varying degree of complexities.

There have been numerous approaches to modelling ferromagnetic hysteresis loops. A bibliographic review of the hysteresis models presented during the past three decades is given in [13]. Many of these attempts are curve fits, which ignore the underlying physics of the material behavior. At the other extreme, micromagnetic methods consider all known energies on a very small scale and find the domain configuration that gives the minimum energy. In general intermediate solutions models, which can relate micro-structural parameters to the macroscopic responses of the material to outside fields are more suitable for time domain simulations [14]. The new

The Authors are grateful to Manitoba Hydro and the Office of Naval Research (USA) for the financial and technological support to carry out the research described in this paper.

W. Chandrasena and U. D. Annakkage are with the Department of Electrical and Computer Engineering, University of Manitoba, Winnipeg, MB, Canada.

P. G. McLaren is with the Center for Advanced Power Systems, Florida State University, Tallahassee, FL, USA.

R. P. Jayasinghe is with Manitoba HVDC Research Centre, Winnipeg, MB, Canada.

0-7803-7967-5/03/$17.00 ©2003 IEEE

transformer model is based on the Jiles Atherton (JA) theory of ferromagnetic material [5], which is one of the core models considered as classical.

A. The new model : Incorporating the JA Theory

The new model was implemented with the electromagnetic transient simulation program EMTDC. The existing transformer model uses a piece-wise linearly interpolated curve to represent saturation [15]. The piece-wise linear representation does not properly represent the long term remanence, and the increased levels of harmonic currents when the transformer undergoes half cycle saturation. Therefore instead of using this representation to model the B-H characteristics, we have incorporated the differential equations described in the JA theory to model the hysteresis characteristics of the transformer core.

There exists a wide variety of representations for losses in transformer models used for power system transient studies. The most commonly used method to represent losses is to add a shunt resistance across one winding as in [10]. A frequency dependent resistance matrix is used in [16] to model the effects produced by eddy currents. A different approach is used in [17], where the relationship between an equivalent eddy current field and the rate of change of flux density has been experimentally obtained to represent losses in current transformers. In the new model, we have extended the hysteresis model based on the JA theory to incorporate the effects of classical eddy current loss and excess or anomalous loss [18]-[20].

In the present study, the winding capacitance is neglected, because the GIC phenomena studied are of low frequency. Thus, the transformer core model presented in [12] was used as the basis of the new model.

B. Comparison of Simulation and Test Results

1) Open Circuit Tests: A series of tests were carried out to validate the new transformer model using a 3 kVA, 115 V / 2300 V, 60 Hz single phase distribution transformer. Figure 1 shows the comparison of the simulated waveform and the recorded waveform at the rated voltage and frequency. A close comparison is seen between the simulation and the recorded waveform. The percentage error in the rms value of the magnetizing current is -1%, and the percentage error for the simulated power loss is 2%. Figure 2 shows the comparison of the simulated B-H loops produced by the new model at different excitation frequencies. It shows that the width of the B-H loop increases as the frequency is increased as expected.

2) Remanence: During short time simulations, piecewise linear solutions of saturation can give the impression that they handle remanence because the system time constants maintain the magnetization over several hundreds of milliseconds. However, over time scales of seconds the flux decays to zero. In the new model, hysteresis is represented using the JA theory, and hence it accurately represents the long term remanence and recoil loops in the transformer cores. Simulations were carried out to demonstrate this effect using an existing transformer model in EMTDC that uses a piecewise linear saturation characteristic [15] and the new model.

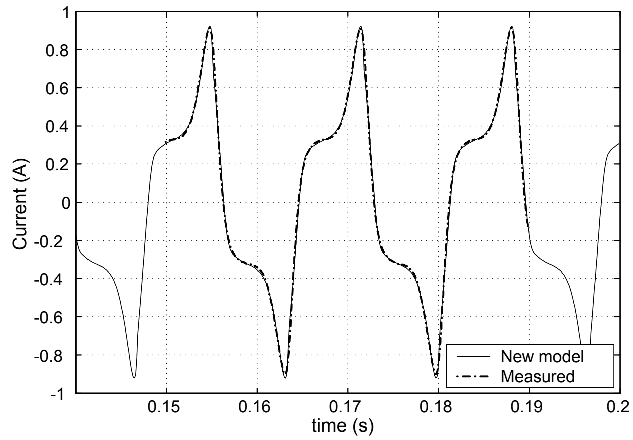

Fig. 1. Magnetizing current at the rated conditions

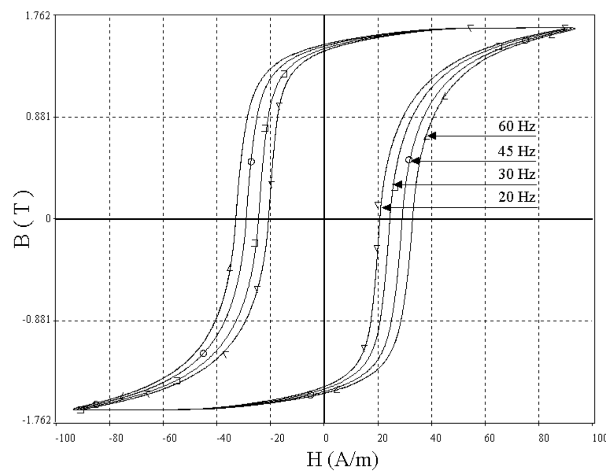

Fig. 2. B-H loops at different frequencies

Simulations were carried out with the existing model where; (a) a resistive load of 0.01 pu, (b) a resistive load of 1.0 pu were connected at the secondary terminals. The simulated system consists of a single phase source connected to the transformer through a single phase breaker. Fig.3 shows the simulated waveform of flux obtained when the breaker was opened. In the existing model the output waveform of flux has been normalized to obtain a peak flux density of 1.0 pu, whereas the output of the new model plots the flux density in Tesla. During these simulations, a resistive load was connected to the transformer so that it leaves maximum remanent flux in the core at the time of opening the breaker. The comparison shows that the flux in the core decays to zero after a small time duration with the existing model. This duration is dependent on the system time constant as shown in Fig.3 (a) and (b).

The same simulation was carried out with the new model. When the breaker was opened, flux in the core gradually decays and then remains at the remanent flux level as in Fig.4 (around -1.0 T even beyond 60 seconds). Therefore this comparison shows that a hysteresis model based on the

JA theory properly represents the long term remanence in the core, whereas a piece-wise linear representation would fail to maintain the remanent flux beyond several hundred milliseconds.

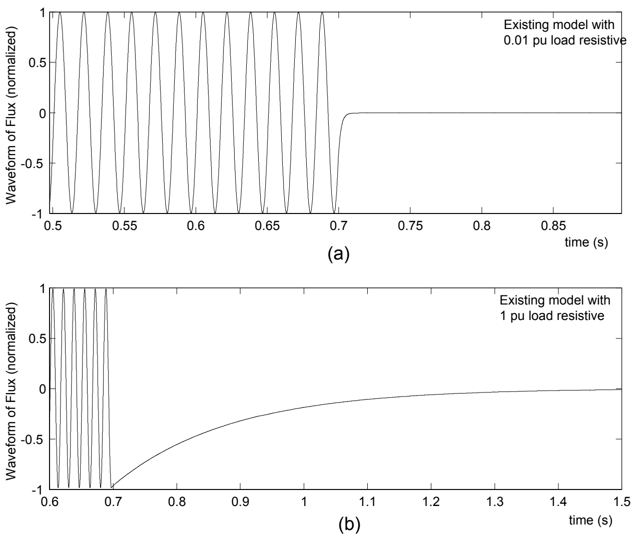

Fig. 3. Waveform of flux density (normalized) obtained with the existing model in EMTDC, when the breaker was opened.

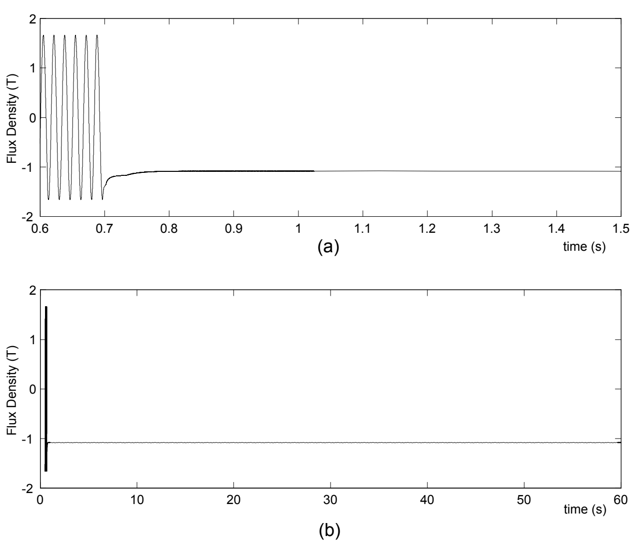

Fig. 4. Waveform of flux density obtained with the new model when the breaker was opened.

III. GIC STUDIES

The simulation studies carried out to analyze the effects of GIC on a power system involve dc superimposed on ac excitation. These studies are usually based on the injection of measured quasi dc current into the neutral of the simulation model of the power transformer to represent a GIC event. The resulting simulated currents have been compared with the recorded waveforms or measurements [21]-[24].

The simulation results obtained during a GIC study that was carried out using the new transformer model are presented in the following section. The simulation studies described in [22] were used as the basis of this analysis.

A. Description of the system

The 500 kV transmission line from Dorsey, Manitoba to Forbes and Chisago in Minnesota connects three substations. The northern section of the system is 528 km long and it connects Dorsey HVDC Converter station to Forbes substation. The southern section of the system is 220 km long and it connects Forbes substation to Chisago substation. The Dorsey-Forbes section is transposed at 4 locations and Forbes-Chisago section is transposed at 3 locations.

The autotransformer at Dorsey consists of three single phase units and each separate unit is a two winding transformer. The windings are connected to form a 230/500/46 kV three phase unit with the 230 kV and 500 kV windings connected as an autotransformer. The 230 kV and 500 kV windings are star connected and grounded whereas the 46 kV winding is connected as a delta winding. The transformer is rated for 720 MVA without cooling and 1200 MVA with cooling. The autotransformer at Forbes is a similar one with the exception that the tertiary winding is rated for only 13.8 kV. At the Dorsey Substation, filters are connected on the 230 kV side to minimize the harmonics introduced by the HVDC converter station.

The 230/500/46 kV, 240 MVA transformers at Dorsey and Forbes substations were represented with the new model. Fig.5 shows the measured V-I characteristics of the transformers at Dorsey compared with the simulated V-I curve. In addition, the winding resistances of transformers were represented with external resistors. The transmission lines were represented using the frequency dependent phase model in EMTDC [25].

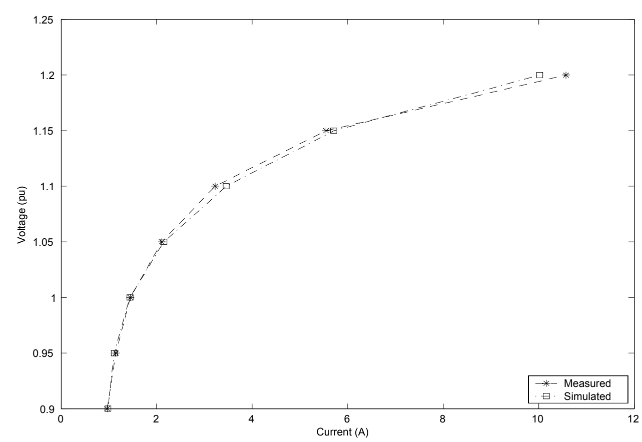

Fig. 5. V - I characteristics of the transformer

In order to model a specific event, the power flow along the lines, the bus voltages at each substation, and the equivalent network impedances at each node are required to initialize a simulation case. Once the simulation is initialized, the magnitude of the quasi-dc current can be injected into the system through the neutrals of the grounded wye connected transformers, if it is assumed that GIC is produced by a uniform electric field. Meanwhile, voltage sources in the transmission lines can be used to represent GIC produced by a realistic electric field [26].

B. Simulation results

GIC are quasi dc currents that have a very slow variation in frequency. Severe GIC events can persist for periods of several hours and can occur for several days in succession. However, a high magnitude of GIC with one polarity usually lasts for a few minutes before changing polarity. If the history of the waveform of quasi dc neutral current and the state of the transformer core are not known, a demagnetized core is usually assumed as the initial conditions. In addition, if variation of the magnitude of quasi-dc current is not known, the injected neutral current is modeled with a constant magnitude.

Initial comparisons were carried out assuming that the history of the waveform of quasi dc neutral current is not known. Therefore a constant dc neutral current of 30 A was considered for the analysis. During the simulation, transformers reach a fully saturated state for the given bias, provided that the simulation was run long enough to reach that state. The harmonic content of the simulated waveform of phase A current in the 500 kV line is given in Fig.6. The presence of odd and even harmonics can be seen, which is due to the half cycle saturation of the transformers. The magnitude of the fundamental component was 167 A.

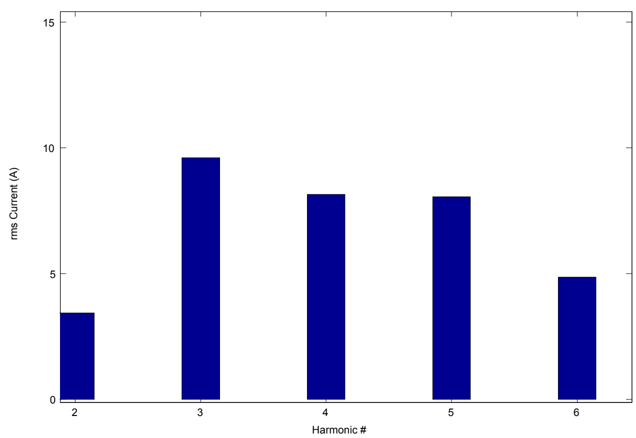

Fig. 6. Harmonic content of the phase A current in the 500 kV line with a constant dc neutral current of 30A

The second simulation case was carried out assuming that the past variation of the dc neutral current is known. The same power system was subjected to the dc neutral current variation given in Fig.7, that has a peak magnitude of 90 A. Simulated waveforms are compared considering two snaps taken when the dc neutral current is 30 A (points **1** and **2** in Fig.7). This allows us to make direct comparisons with the previous simulation case as all the comparisons were carried out at the same dc neutral current. The harmonic content of the phase A current in the 500 kV transmission line is compared in Fig.8 when the dc neutral current is 30 A (i.e. points **1** and **2** in Fig.7). This figure shows that the harmonic components and hence the waveform of current have a strong dependency on the history of the magnetic core. Even though both points of interest record the same dc neutral current, the core has experienced the peak dc bias before reaching the point **2** in Fig.7, and hence has affected the extent of saturation in the core. Therefore, the extent of saturation in the core at the point **2** is significantly greater than it is for the point **1**. The same trend can be seen with the increased reactive power consumption in the transformer at points **1** and **2** respectively.

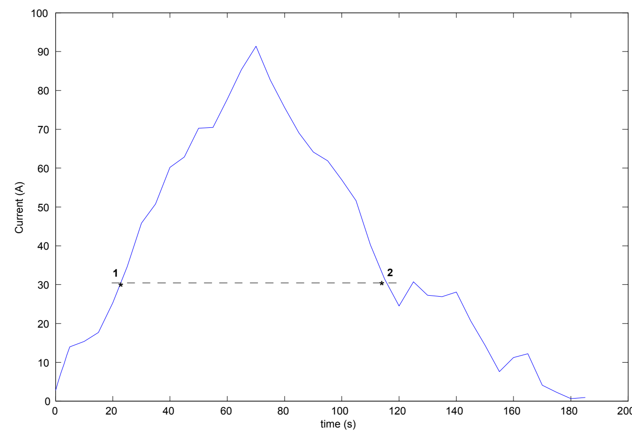

Fig. 7. Variation of the dc neutral current

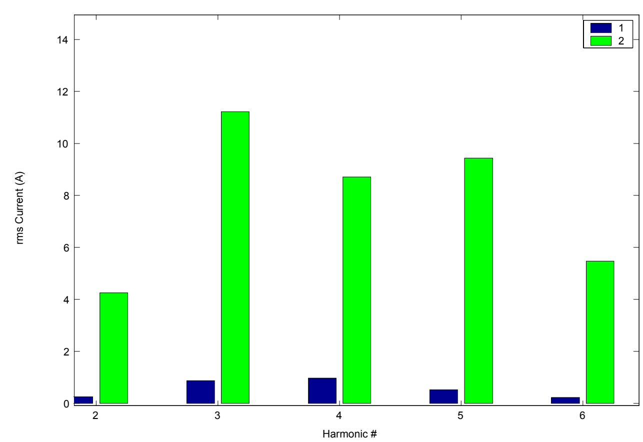

Fig. 8. Harmonic content of the current when the neutral current is **1** and **2** in Fig.5 respectively

Similarly, the comparison of the harmonic contents of line currents obtained with a constant dc neutral current of 30 A, and with the dc neutral current at **2** in Fig.7 shows that the application of a constant neutral current during the simulation may not represent the worst case scenario of that point of interest (Fig.8). The extent of saturation in the core at **2** depends on the history of the neutral current, i.e. the peak value, the rate of change, and the total duration on one polarity.

Simulation cases presented so far have assumed a demagnetized core as the initial conditions. However, the transformer core could have had remanent flux prior to undergoing half cycle saturation due to the dc neutral current considered in Fig.7. As a result of this remanent flux, the extent of half cycle saturation in the core can be either increased or decreased, which is mainly dependent on the level of the remanent flux and the polarity of the quasi dc current. Therefore, if remanence is considered in the simulation, the harmonic content at **1** in Fig.7 can be either increased or decreased from the values given in Fig.8. However, the harmonic content at **2** in Fig.7 may not be affected significantly, unless the level of remanent flux is high enough to affect the overall extent of saturation in the core.

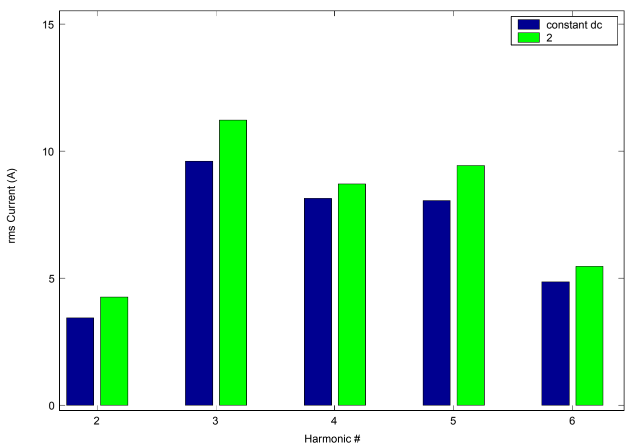

Fig. 9. Harmonic content of the current when the dc neutral current is **2** in Fig.5 and a constant magnitude of 30 A

IV. Discussion

Simulation results presented in the previous section have shown that the simulated waveform of current is dependent on the history of the quasi dc neutral current. Field measurements carried out during GIC events have shown that there could be large scale differences in the magnetic and electric fields measured at different recording sites spread over a large area [27]. These differences can be attributed to the distance between the sites and the electrojet, and differences in the local geology. In addition, if the simultaneity of measured samples are considered, it is likely that the maximum recorded GIC may not have occurred simultaneously across all the sites. Therefore, a simulation carried out to validate a GIC event requires the actual variation of quasi dc current to be considered to properly represent conditions that may have prevailed at the time of the recording. This becomes more important as the simulated waveforms of current are dependent on the variation of the quasi dc current in the neutral.

In addition, the core of the transformer can have remanent flux as a result of the status of the magnetic core prior to this event under consideration. If the core of the transformer has remanent flux, it also affects the extent of saturation experienced. In general, any particular change in the status of the magnetic core, which can be due to remanent flux in the core, or history of the quasi dc current, could directly affect the harmonic content of the waveform of current and the increase in reactive power consumption in the transformer.

Simulation studies carried out to analyze the effects of GIC on a power system may involve validation of a GIC event using measured data as well the prediction of the worst case scenario using the estimated values of electric fields and GIC. Meanwhile, the foregoing discussion has shown that the history of the state of the magnetic core of the transformer and the history of the quasi dc neutral current have a direct effect on the simulation results. Thus, initialization of a simulation model could significantly affect the outcome of a simulation case. The initial values of the network equivalents, especially the bus voltages, have an effect on the flux in the transformers. However, the initialization of the transformer model itself becomes more important during a GIC study, as the state of the magnetic core directly depends on its initial conditions. It is usually possible to initialize remanence in a typical transformer model, however it requires outside intervention whereas the new transformer model used in this paper will do it automatically. Therefore, the availability of a recorded variation or the estimated values of the quasi dc neutral current becomes useful in this endeavour.

Usually GIC events can last for several hours. A simulation study, however, may focus on the maximum reported dc current in the neutral or focus on a specific event that may have happened. If an analysis considers the instant where the maximum dc current was reported, it is likely that the initialization of the transformer assuming a demagnetized core would have negligible effects on the simulation results, provided that the duration of the dc current is long enough to reach the fully saturated state, and the level of remanent flux (if any) is fairly small so that it does not affect the overall extent of the saturation. Similarly, if the network under consideration experiences the maximum dc current simultaneously across the network, a constant dc current may be used in the simulation due to the same reasons.

However, if different points in a network do not experience the peak dc current simultaneously, it requires proper consideration of the recorded variation or the predicted values of quasi dc current. Similar consideration is required if a simulation study is carried out to analyze a specific recorded event. In such situations, the remanent flux in the transformer core can be initialized by considering a portion of the variation of dc current prior to the point of interest. Meanwhile, it is likely that different points in a network may not experience the peak dc current simultaneously as discussed above. In such situations, if a constant dc current is used to represent GIC, instead of using the measured data or a predicted variation, the simulation may not represent the worst case scenario of that point of interest as shown in the simulation results.

V. Conclusions

Simulations carried out to analyze the effects of GIC on a power system show that the waveform of line current depends on the history of the quasi dc current. Therefore highlights the importance of modelling the remanence in the core of the transformer as it affects the harmonic content of the waveform of current and the increase in reactive power consumption in the transformer. The simulations also show that depending on the variation of the quasi dc current in a network, the modeling of GIC with a constant dc current may not produce the worst case scenario of that event.

REFERENCES

[1] W.F. Davidson, "The magnetic storm of march 24, 1940 - effects in the power system", The Edison Electric Bulletin, July 1940, pp. 365 –366.

[2] G. Blais and P. Metsa, "Operating the Hydro-Quebec grid under magnetic storm conditions since the storm of 13 March 1989", *Proceedings of Solar- Terrestrial Predictions Workshop*, Ottawa, 1993, vol.1, pp. 108 – 130.

[3] V.D. Albertson et al., "Geomagnetic disturbance effects on power systems", *IEEE Transactions on Power Delivery*, vol. 8, pp. 1206–1216, July 1993.

[4] B.Bozoki et al., "The effects of GIC on protective relaying", *IEEE Transactions on Power Delivery*, vol. 11, pp. 725–739, April 1996.

[5] D.C. Jiles and D.L. Atherton, "Theory of ferromagnetic hysteresis", *Journal of Magnetism and Magnetic Materials*, vol. 61, pp.48–60, 1986.

[6] U.D. Annakkage, P.G. McLaren, E.Dirks, R.P. Jayasinghe, and A.D. Parker, "A current transformer model based on the Jiles-Atherton theory of ferromagnetic hysteresis", *IEEE Transactions on Power Delivery*, vol. 15, pp. 57–61, January 2000.

[7] W.Chandrasena, P.G. McLaren, U.D. Annakkage, and R.P. Jayasinghe, "An improved low frequency transformer model for use in GIC studies", paper TPWRD-00354-2002.R.1.

[8] F.de Leon and A.Semlyen, "Complete transformer model for electromagnetic transients", *IEEE Transactions on Power Delivery*, vol. 9, pp. 231–239,1994

[9] B.A. Mork, "Five legged wound core transformer model: Derivation, parameters, implementation, and evaluation", *IEEE Transactions on Power Delivery*, vol. 14, pp. 1519–1526, October 1999.

[10] X.Chen, "A three phase multi-legged transformer model in ATP using the directly formed inverse inductance matrix", *IEEE Transactions on Power Delivery*, vol. 11, pp. 1554–1562, July 1996.

[11] C.M. Arturi, "Transient simulation of a three phase five limb step up transformer following an out of phase synchronization", *IEEE Transactions on Power Delivery*, vol. 6, pp. 196–207, January 1991.

[12] J.Arrillaga, W.Enright, N.R. Watson, and A.R. Woods, "Improved simulation of HVDC converter transformers in electromagnetic transient programs", *IEE Proc.-Gener. Transm. Distrib.*, vol. 144, pp. 100–106, March 1997.

[13] F.de Leon and A.Semlyen, "A simple representation of dynamic hysteresis losses in power transformers", *IEEE Transactions on Power Delivery*, vol. 10, pp. 315–321, January 1995

[14] F.Liorzou, B.Phelps, and D.L. Atherton, "Macroscopic models of magnetization", *IEEE Transactions on Magnetics*, vol. 36, pp. 418–428, March 2000.

[15] W.Enright, O.B. Nayak, G.D. Irwin, and J.Arrillaga, "An electromagnetic transient model of multi-limb transformers using normalized core concept", *Proc. International conference on Power Systems Transients (IPST)*, June 1997, pp. 93–98.

[16] F.de Leon and A.Semlyen, "Detailed modeling of eddy current effects for transformer transients", *IEEE Transactions on Power Delivery*, vol. 9, pp. 1143–1150, April 1994.

[17] T.Fujiwara and R.Tahara, "Eddy current modeling of silicon steel for use on spice", *IEEE Transactions on Magnetics*, vol. 31, pp. 4059–4061, November 1995.

[18] C.D.Graham Jr., "Physical origin of losses in conducting ferromagnetic materials", *J. Appl. Phys.*, vol. 53, no. 11, pp. 8276–8280, November 1982.

[19] G.Bertotti, "General properties of power losses in soft ferromagnetic materials", *IEEE Transactions on Magnetics*, vol. 24, no. 1, pp. 621–630, January 1988.

[20] D.C. Jiles,"Modelling the effects of eddy current losses on frequency dependent hysteresis in electrically conducting media", *IEEE Transactions on Magnetics*, vol. 30, pp. 4326–4328, 1994.

[21] R.P. Jayasinghe, P.G. McLaren, and T.Gouldsborough, "Effect of GIC on overcurrent protection for filter banks", *Proc. WESCANEX'93*, 1993, pp. 36–42.

[22] R.P. Jayasinghe, Investigation of Protection Problems Due to Geomagnetically Induced Currents, *PhD thesis*, University of Manitoba, 1997.

[23] F.S. Prabhakara, L.N. Hannett, R.J. Ringlee, and J.Z. Ponder, "Geomagnetic effects modelling part II - geomagnetically induced current study results", *IEEE Transactions on Power Systems*, vol. 7, no. 2, pp. 565–571, may 1992.

[24] D.H. Boteler, R.M. Shier, T.Watanabe, and R.E. Horita, "Effects of geomagnetically induced currents in the BC hydro 500 kV system", *IEEE Transactions on Power Delivery*, vol. 4, no. 1, pp. 818 – 823, Jan 1989.

[25] B.Gustavsen, G.Irwin, R.Mangelord, D.Brandt, and K.Kent, "Transmission line models for the simulation of interaction phenomena between parallel ac and dc overhead lines", *International Conference on Power System Transients, IPST'99*, Budapest - Hungary, pp. 61 – 67, June 1999.

[26] D.H. Boteler and R.J. Pirjola, "Modelling geomagnetically induced currents produced by realistic and uniform electric fields", *IEEE Transactions on Power Delivery*, vol. 13, no. 4, pp. 1303–1308, October 1998.

[27] L.Bolduc, P.Langlois, D.Boteler, and R.Pirjola, "A study of geomagnetic disturbances in Quebec, 1. general results", *IEEE Transactions on Power Delivery*, vol. 13, no. 4, pp. 1251 – 1256, Oct 1998.