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A Faster FEM Based Approach for Obtaining Steady State Transformer Winding Currents Under GIC

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SUMMARY

When GIC currents flow through the transformer they produce an offset to the normal magnetization of core, resulting in part cycle saturation. During the saturated interval, the small magnetizing current rises to a larger value resulting in effects not anticipated during design. With such GIC effects in transformers getting more attention in recent years, a number of tools have been developed for analyzing the same.

Circuit coupled Finite Element Method is one such tool which is used when detailed modeling is necessary. Tank and Delta windings, material non-linearity, 3D geometry details and complex connections can be accurately represented by this method. It also offers a unified approach for arriving at current waveforms, main and leakage field distribution in space & time, winding flux linkage and inductances, losses and their distribution, temperature rise and hot spots etc. However it becomes a challenge to solve for steady state winding currents through this approach because of associated RL circuit transients. Since FEM uses a time stepping approach, where solution for each time step by itself can take much longer, this tool becomes practically not useful for circuits with huge time constant as is the case with GIC.

This paper develops a "smart start" like technique which skips the initial transients and solve directly for steady state when transformers are fed by DC shifted AC voltage source. In this regards a steady state which can take as long as 15 seconds could be reached in 5 milli-second, 3K times faster. Thus the technique described in this paper can be used to solve for GIC currents in transformer which were not previously possible using FEM. The present paper describes the development and application of the technique together with present challenges and future work.

KEYWORDS

GIC, Transformers, Circuit Coupled FEM, RL Transients, Magnetising current, Faster steady state, Smart start

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1. Introduction

Geomagnetically Induced Currents (GIC) are quasi-DC currents typically 0.01 Hz – 0.5 Hz, which are caused when Coronal Mass Ejection (CME) from sun interacts with earth magnetosphere. The flow of such GIC currents through power transformer causes part-cycle saturation [2] which can result in

- Increased reactive power absorption & System Voltage instability
- Current harmonics generation & Transformer heating
- Vibration & Noise

A number of tools have been developed to study the effects of GIC in transformers. Circuit coupled Finite Element Method is one such tool which is used when detailed modeling and both circuit and field results are necessary. However it becomes a challenge to solve for steady state winding currents through this approach because of transients associated with RL circuit behavior resulting in long solution time.

The present scope of the paper is to address the challenge by developing a smart start approach which significantly reduces the simulation time by appropriately modifying the excitation voltages so that steady state conditions are directly solved for without the transients involved. Thus the technique described in this paper can be used to solve for GIC currents in transformer which were not previously possible using FEM.

2. Smart start for AC voltages without DC shift

When any winding (RL circuit) is subjected to an AC voltage without DC shift, the current and flux linking the winding has DC components which eventually decays to zero when steady state is reached. If the winding inductances are very large compared to resistance as is the case of any iron cored transformer under no load conditions, the time to reach steady state will be relatively longer.

Hence if any numerical tools like time stepping FEM are used to simulate them, reaching steady state within reasonable time may not be possible. In addition, if other complexities like non linearity, saturation and 3D geometry are added, a steady state cannot be reached with available computational resources. Hence alternative approaches for quick simulation of steady state are needed.

Smart start energization is one such technique whose idea is to increase or decrease currents, voltages and fluxes from zero until the linkage flux in each phase reaches the value of the flux in the steady state condition corresponding to the start point of the applied voltage. The smart start process takes less than quarter of cycle and after that the real voltages are applied. Four different smart start techniques were studied in the present work and subsequently discussed.

2.1 Linear Ramp Smart Start

In this method, initial flux is established as the integral of linear ramping up/down applied voltage. [7] The Ramp smart start equation is

$$V = kt \qquad (1)$$

Where $k = \frac{2}{T_{start}^2}\left[\frac{\beta V_{max}}{\omega} - 0.5 * t_s * V_{start}\right]$

T_{start} = Duration of the smart start period, can be made as small as quarter of a cycle
β = +1 or -1 based on the angle of induced voltage at first moment
V_{max} = Peak value of sinusoidal voltage
ω = Angular frequency
t_s = Time step of simulation
V_{start} = Applied phase voltage at the first moment

2.2 Cosine Smart Start

The principle is same as linear Ramp smart start, but rather than establishing the initial flux by Ramp voltage, a sinusoidal voltage is used for the smart start period, say a quarter of cycle. Accordingly the smart start voltage equations can be deduced as [10]

$$V_a = V_m * \sin(2\pi f t) + if(t < \frac{0.25}{60}, -V_m * \cos(0) * \cos(2\pi f t), 0) \qquad (2)$$

V_a = Instantaneous applied voltage
V_m = Peak value of applied voltage

The smart start voltages of other phases are similar but phase shifted by 120 & 240 degrees respectively.

2.3 Exponentially Rising Sinusoid

An exponentially increasing (in several cycles) sinusoidal voltage excitation can be used to achieve smart start, so that steady state is reached quickly. The corresponding smart start equation is

$$V = V_{peak} * \left(1 - e^{-\frac{t}{\tau}}\right) * \cos(2 * \pi * f * t) \qquad (2)$$

V = Instantaneous applied voltage
V_{peak} = Peak value of applied voltage
τ = Time constant

2.4 Steady State Speed up

The steps used in the method are summarized as follows:

- The Initial phase current I0 is set to zero & the problem is solved for one electrical cycle.
- The maximum, minimum and the DC offset values are calculated for the 3Ø currents.
- DC offset/2 is subtracted from the previous I0 to determine the new value of I0
- Solve the transient problem for one cycle & continue looping until the relative error is less than Target %
- Using the last value of I0 as starting current, solve for the desired number of electrical cycles.

Table I Smart Start techniques speed comparison summary

S.No	**Smart Start Method**	**No. of 60 Hz AC cycles required to reach steady state**
1.	No Smart Start	120 Cycles
2.	Linear Ramp Smart Start	¼ Cycle
3.	Cosine Smart Start	¼ Cycle
4.	Exp. Rising Sinusoid	50 Cycles
5.	Steady state speed-up	12 Cycles

3 New Modified Smart start for GIC

All the smart start techniques discussed above works for AC voltages without a DC shift. But under GIC conditions where windings are excited by DC shifted AC voltage; DC transients are still present which offsets the benefits of the otherwise useful smart start. Hence in this paper a modified smart start approach is developed which is equally applicable for GIC conditions. This approach for the sake of the paper will henceforth be called as ACDC smart start approach.

This takes on the same principles of AC smart start approach and extends it for DC shifted AC. The idea is to get the flux linkage same as steady state when DC shifted AC voltages are applied. For this we need to know the steady state DC flux. This can be approximately determined by a quick Magnetostatic FEM run to determine the inductance of the excited winding, other geometry being the same. The approximate steady state DC flux linkage can then be obtained as a product of Inductance and the DC amps required in the circuit. The DC flux linkage is set during the smart start energization period by adding an additional DC voltage excitation whose value equals the ratio of DC flux and Smart start time period.

The accuracy of the approach can be increased by improving the DC Amps value used to obtain Steady state DC flux linkage so that the average amps at the steady state equals GIC amps needed. In fact this is used as the condition to check if steady state is reached in any kind of simulation. The corresponding average flux will then be the steady state flux. It is this value of steady state average flux which is important to assess if the transformer saturates under GIC and the corresponding harmonics and the MVAR increase. The corresponding smart start equations are

$$V_a = V_m * \sin(2\pi f t) + if\left(t < \frac{0.25}{60}, -V_m * \cos(0) * \cos(2\pi f t) + V_{sA}, V_{dc}\right)$$

$$V_b = V_m * \sin\left(2\pi f t + \frac{2\pi}{3}\right) + if\left(t < \frac{0.25}{60}, -V_m * \cos(0) * \cos(2\pi f t) + V_{sA}, V_{dc}\right) \tag{4}$$

$$V_c = V_m * \sin\left(2\pi f t + \frac{4\pi}{3}\right) + if\left(t < \frac{0.25}{60}, -V_m * \cos(0) * \cos(2\pi f t) + V_{sA}, V_{dc}\right)$$

Where

$$V_{sA} = \frac{k_{DCA}}{T_s}, V_{sB} = \frac{k_{DCB}}{T_s}, V_{sC} = \frac{k_{DCC}}{T_s}$$

$$k_{DCA} = L_{ac} * DC_{ErrA}, k_{DCB} = L_{ac} * DC_{ErrB}, k_{DCC} = L_{ac} * DC_{ErrC}$$

Where

$$L_{ac} = Aircore\ inductance\ with\ tank\ from\ FEM\ Magnetostatic\ Analysis \tag{5}$$

$$DC_{ErrA} = Desired\ A\ phase\ GIC\ Amps + (GIC - I_{A\,(ave)})$$
$$DC_{ErrB} = Desired\ B\ phase\ GIC\ Amps + (GIC - I_{B\,(ave)})$$
$$DC_{ErrB} = Desired\ C\ phase\ GIC\ Amps + (GIC - I_{C\,(ave)})$$

$$k_{DCA}, k_{DCB}, k_{DCC} = Steady\ state\ DC\ flux\ linkage\ of\ A, B\ \&\ C\ phase\ respectively$$

$$V_{sA}, V_{sB}, V_{sC} = DC\ smart\ start\ voltage\ for\ A, B\ \&\ C\ phase\ respectively$$

4 Analysis

A 2D planar FEM model comprising of 3 phase core, windings and tank was used as a template model to compare the accuracy of the ACDC smart start technique developed. LV winding was excited with DC shifted AC voltage source and HV winding was open circuited to simulate GIC under no load conditions. The model parameters used are shown below in Table II

Table II Model Parameters

Name	Value
LV wdg Resistance	1mOhm
AC Voltage applied (peak)	11268V
HV turns	1000
LV turns	76
DC voltage applied	5V

The model geometry and BH curve of core material used are shown in Figure 1. Tank is modelled as linear with permeability of 200.

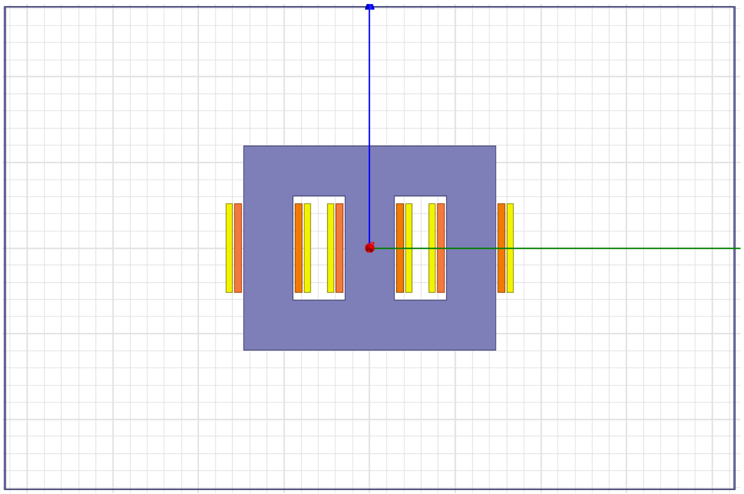


Figure 1 Model Geometry

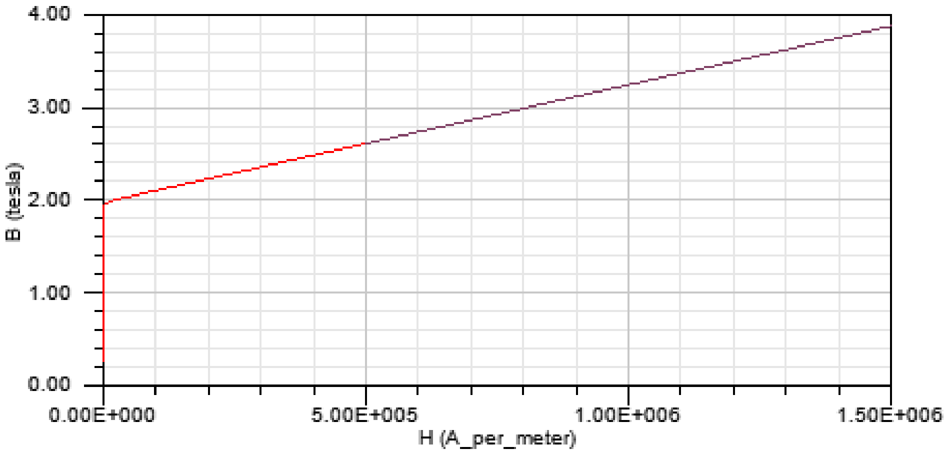


Figure 2 Core BH curve

5 Results & Validation

LV winding magnetising current, flux linkage and their harmonic contents were obtained from analysis and compared with the corresponding full transient study for validation. The ACDC smart start model was solved for 3 cycles (50 ms) whereas the full transient model was solved for 900 cycles (15 s). 5V of DC voltage applied, resulted in 5000A of DC as calculated from winding resistance. A very high DC current of 5000 A was purposefully chosen so as to ensure saturation of the three limb core construction considered for study. The problem was solved until the average of magnetising current in all phase reached nearly 5000 A which is the steady state criterion.

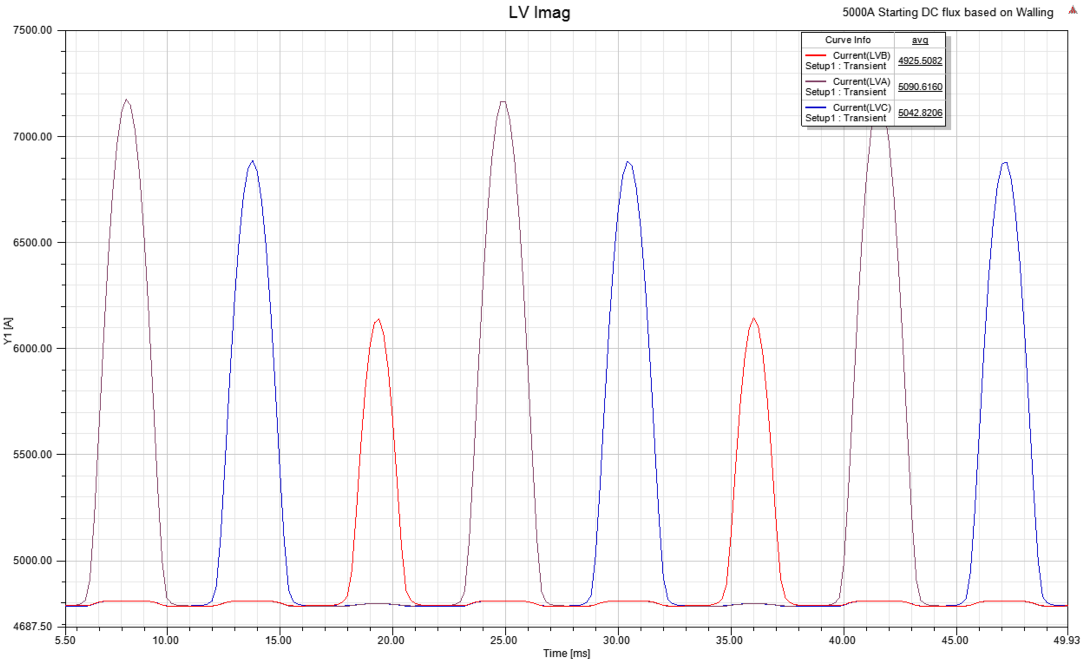


Figure 3 LV Magnetising current with ACDC Smart Start

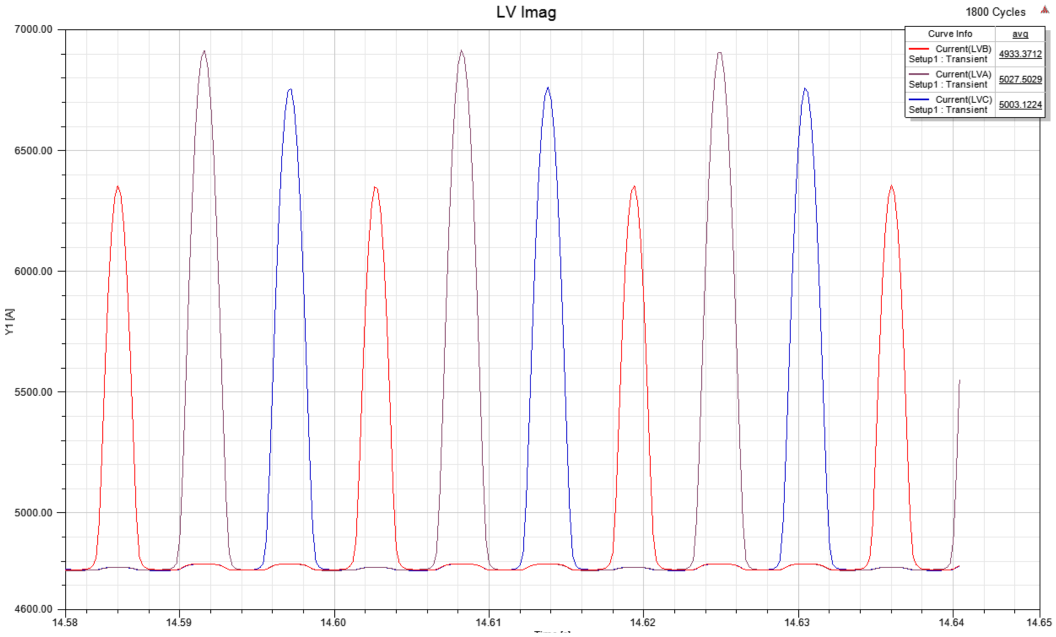
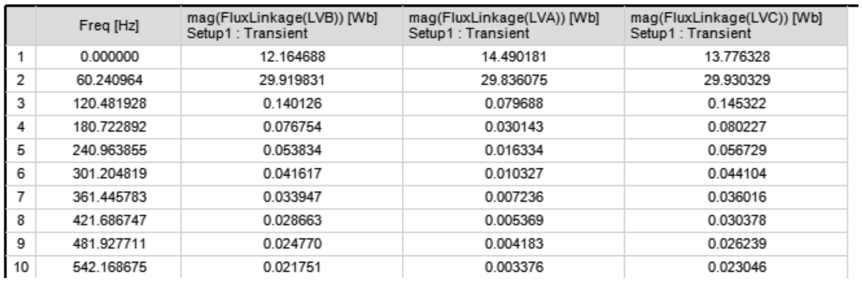


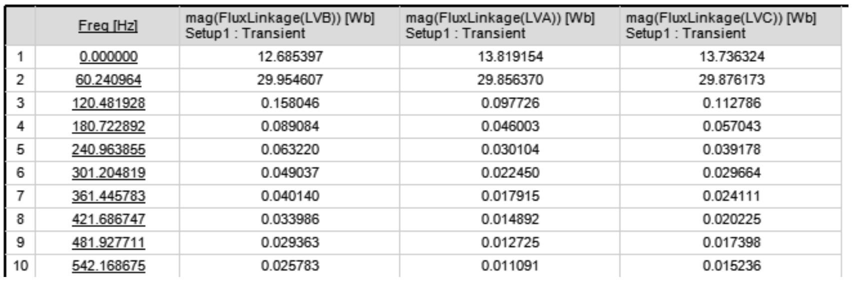
Figure 4 LV Magnetising current under Full Transient

Table III LV flux linkage harmonics with ACDC Smart Start



	Freq [Hz]	mag(FluxLinkage(LVB)) [Wb] Setup1 : Transient	mag(FluxLinkage(LVA)) [Wb] Setup1 : Transient	mag(FluxLinkage(LVC)) [Wb] Setup1 : Transient
1	0.000000	12.164688	14.490181	13.776328
2	60.240964	29.919831	29.836075	29.930329
3	120.481928	0.140126	0.079688	0.145322
4	180.722892	0.076754	0.030143	0.080227
5	240.963855	0.053834	0.016334	0.056729
6	301.204819	0.041617	0.010327	0.044104
7	361.445783	0.033947	0.007236	0.036016
8	421.686747	0.028663	0.005369	0.030378
9	481.927711	0.024770	0.004183	0.026239
10	542.168675	0.021751	0.003376	0.023046

Table IV LV flux linkage harmonics under Full Transient



	Freq [Hz]	mag(FluxLinkage(LVB)) [Wb] Setup1 : Transient	mag(FluxLinkage(LVA)) [Wb] Setup1 : Transient	mag(FluxLinkage(LVC)) [Wb] Setup1 : Transient
1	0.000000	12.685397	13.819154	13.736324
2	60.240964	29.954607	29.856370	29.876173
3	120.481928	0.158046	0.097726	0.112786
4	180.722892	0.089084	0.046003	0.057043
5	240.963855	0.063220	0.030104	0.039178
6	301.204819	0.049037	0.022450	0.029664
7	361.445783	0.040140	0.017915	0.024111
8	421.686747	0.033986	0.014892	0.020225
9	481.927711	0.029363	0.012725	0.017398
10	542.168675	0.025783	0.011091	0.015236

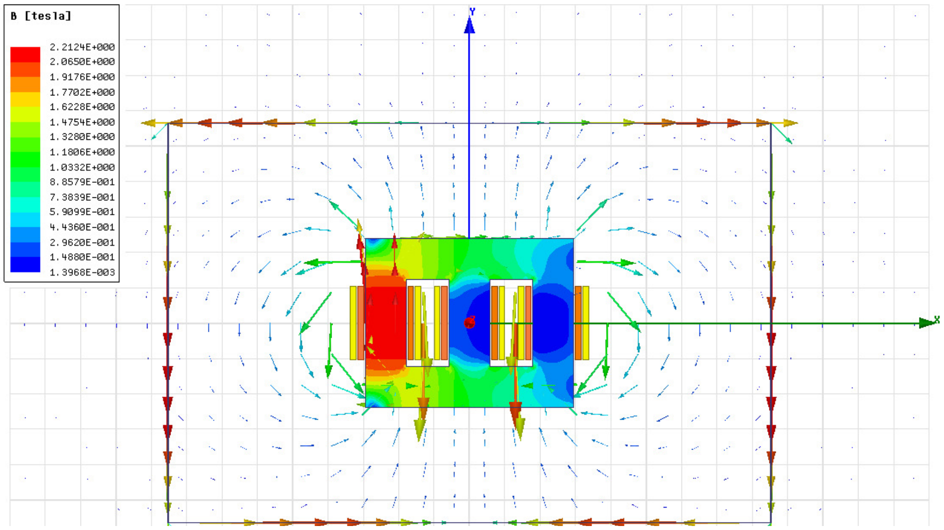


Figure 5 Flux density distribution

As seen from figures, the average magnetising currents from both methods were close to 5000 A, but the ACDC smart start was 3k times faster than the full transient method. FFT of flux linkage as shown in Table III & Table IV indicate that the average or DC flux in all phases were also in close agreement. The results are compared in Table V

Table V Comparison of Full Transient and ACDC Smart start results

	Full Transient	**AC DC soft start**
DC flux A phase (Wb)	13.82	14.49
DC flux B phase (Wb)	12.69	12.16
DC flux C phase (Wb)	13.73	13.77
AC flux density (T)	1.74	1.74
AC+DC core flux density (T)	2.21	2.23

6 Challenges & Future work

This technique presently works for transformers without delta windings. Under smart start period the ramping DC voltages induce currents in Delta winding which interferes with smart start. Work is in progress to resolve this issue. The technique is also being improved to match the current and flux harmonic spectrum from both full transient and ACDC smart start methods.

7 Conclusion

The present study aims at using Circuit field coupled FEM as a single complete analysis tool for analyzing GIC phenomena in transformers. In this regard a new smart start method is proposed to reduce the solution time when transformer windings are excited with DC shifted AC voltage source. The proposed smart start technique was 3k times faster than the corresponding full transient solutions. Winding currents, flux linkage and average flux density were compared from both methods and the results matched with reasonable accuracy. This technique is being improved so that it can be used for transformers with delta windings. With this tool in place, any complex transformer geometry and circuit connections could be modeled and analyzed for coupled multiphysics solutions.

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