A faster FEM based approach for obtaining steady state Transformer winding currents under GIC

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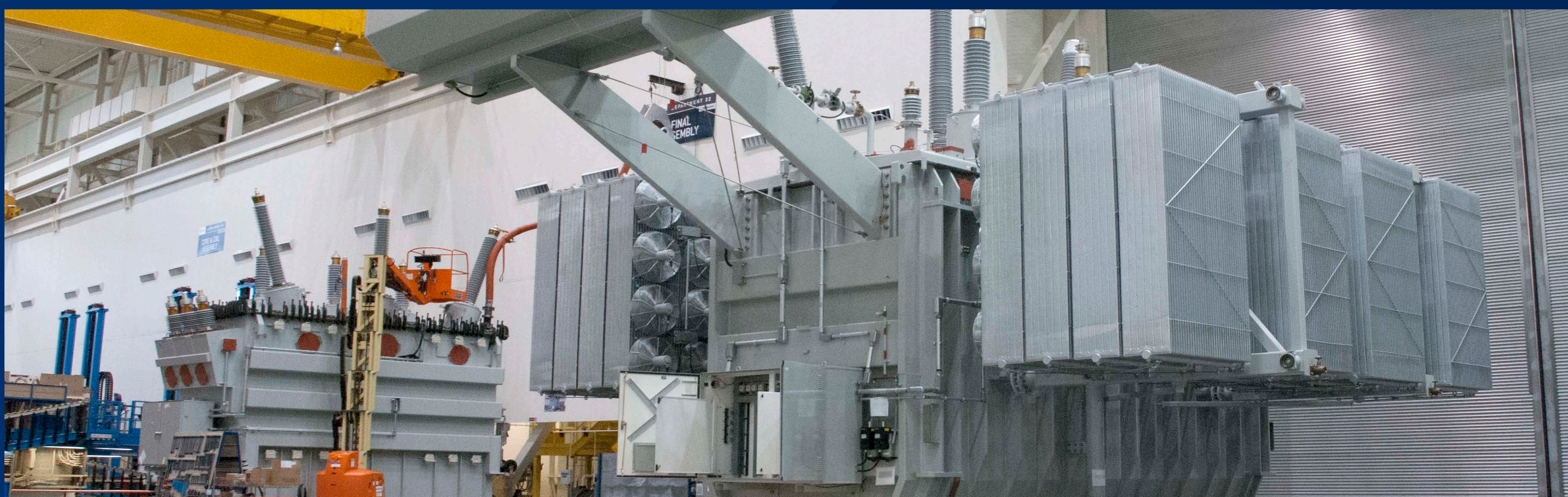
2018 Grid of the Future Symposium



November 13, 2018

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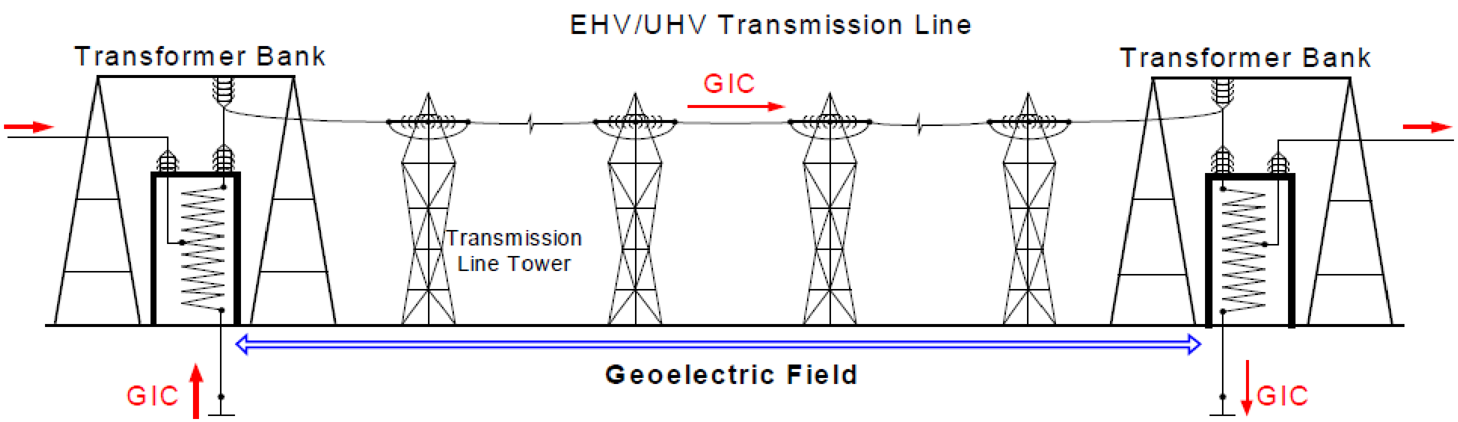
What is GIC & Why it is important?

GIC stands for Geomagnetically Induced Currents

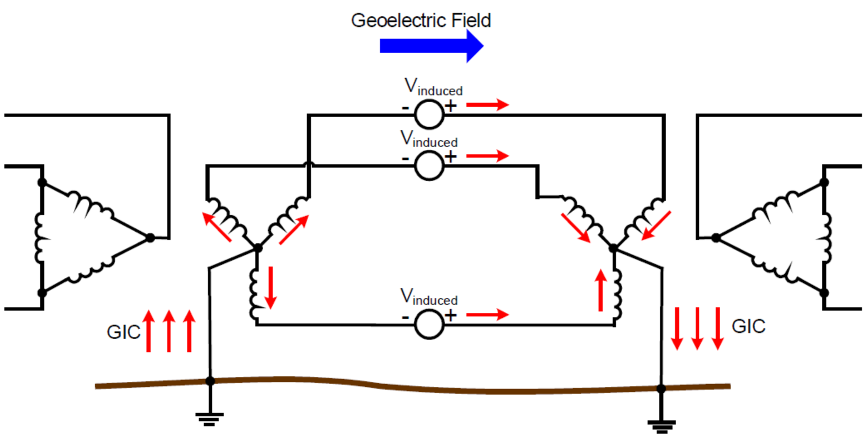
- GIC is a low frequency (0.01 Hz to 0.5 Hz) quasi-dc current.
- These currents are caused when a solar storm results in the movement of earth's magnetic field relative to conducting ionosphere resulting in huge current flowing 100 km – 150 km above the earth's surface.
- These currents called electrojets induce quasi dc potential in series with transmission lines which in turn drives the flow of GIC wherever there is a path for them to flow.
- It is the GIC that flows in transmission lines which affects the power grid as shown below. (IEEE C57.163-2015)

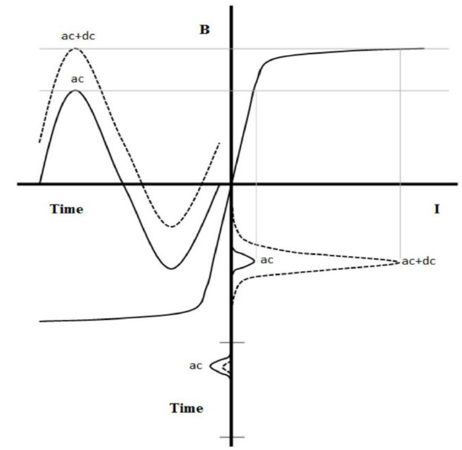


GIC is a Grid Reliability Problem

GIC effects in Transformers

GIC may or may not cause partial saturation of transformers depending on steady state DC flux density shift which in turn depends upon GIC AmpTurns and Reluctance of the path of this DC flux (Magnetic circuit construction).





Provided the transformer undergoes partial saturation, the following effects are possible

- High magnetizing current & associated reactive power absorbed
- Inject significant amount of odd & even harmonics into the power system to which the transformer is connected
- Asymmetrical 3 phase voltage condition & Circulating current in delta windings (Both 3rd harmonic & Zero sequence)
- Thermal effects – Stray flux rich in harmonics and Main flux straying into tie plates , tank & windings causing higher losses & temperature. Increase in core loss but not significant core hot spot due to large thermal time constant of core.
- Higher core sound level, tank vibrations and load sound level causing loosening of terminal leads

Increase in Reactive power demand & Harmonic injection are the major concerns

GIC Modeling Tools & Requirements

Any GIC analysis tool is expected to provide the following outputs

- Magnetic modeling of the transformer core under GIC to calculate the resulting flux density shift and associated magnetizing current pulse and its harmonics, considering the effect of delta winding and loading conditions.
- Magnetic modeling of the transformer under saturated core conditions to determine the magnitude and pattern of leakage flux due to both load current and magnetizing current as well as main core flux in core ,those spilling out from core due to saturation, and those completing its path outside the core.
- Calculation of the resulting total losses and localized loss densities in windings and different structural parts of the transformers like tie plates, yoke clamps and tank
- Calculation of the total temperature rise of the windings and structural parts and hotspots due to the above effects for the exact GIC profile.
- GIC Capability curves showing calculated permissible GIC magnitude as a function of percent transformer rating based on permissible limits of temperature.

Existing GIC Analysis Tools

- Classic Steinmetz equivalent circuit modified for DC
- EMTP/EMTDC based Magnetic Equivalent Circuit methods with saturation models / Topological duals circuits
- Hybrid Methods - EMTP/FEM, System-FEM Co-simulation
- Reluctance Network Methods (RNM)
- DC+AC Superposition approach
- Circuit-Field-Thermal coupled FEM methods

GIC Modeling with FEM

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Benefits

- 3D Transient Nonlinear Circuit coupled FEM tools could be used to directly determine winding currents under GIC conditions as well as their effects on windings and structural parts. It can model the finest geometry and material details as against other equivalent circuit approaches.
- Also any complex connections, multiple independent / interconnected magnetic circuits, complex load / terminal conditions including power electronic components can be accounted easily.
- The exact waveforms of current, voltage & flux could be obtained at any given point in space so that zero sequence and third harmonic effects could be studied and design solutions can be worked out effectively.
- Such an approach may appear computationally expensive but can be still attractive because it offers a unified approach for arriving at current waveforms, main and leakage field distribution in space & time, losses and their distribution, temperature rise and hot spots.
- It can also account for currents in delta windings which has homopolar current components at fundamental and harmonic frequencies circulating inside the delta. Also the delta winding helping effect under saturation can be modeled.

Implementation

- The model is implemented using Ansys Maxwell, 3D Transient solver which supports non-linearity and circuit coupling.
- The complete 3D model with core, windings and tank is created by user developed macro using the design data. The background region was considered oil
- The primary windings are excited by the rated DC shifted AC voltage source with a novel smart start technique and secondary windings are open circuited.

RL circuit transients & the Smart Start technique

- 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.
- 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.
- In this regards a steady state which can take as long as 15 seconds could be reached in 5 milli-second, 3K times faster.
- **The smart start technique described in the present work can be used to solve for GIC currents in transformer which were not previously possible using FEM**.

RL circuit with large time constant excited by voltage source needs smart start technique when analyzed using FEM

AC Smart start methods

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Linear Ramp Smart Start

In this method, initial flux is established as the integral of linear ramping up/down applied voltage

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.

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.

Steady State Speed up

By iterating the initial phase current of windings using DC offset error

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

ACDC Smart start – New Modified Smart start for GIC

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- All the smart start techniques discussed above works for AC voltages without a DC shift
- DC transients are still present which offsets the benefits of the otherwise useful smart start.
- In this paper a modified smart start approach called ACDC Smart start is developed which is equally applicable for GIC conditions.
- 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 Steady state DC flux first.**
- 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.**

ACDC Smart start (Contd…)

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The corresponding smart start equations are

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

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

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

Where

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

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

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

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

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

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

Analysis

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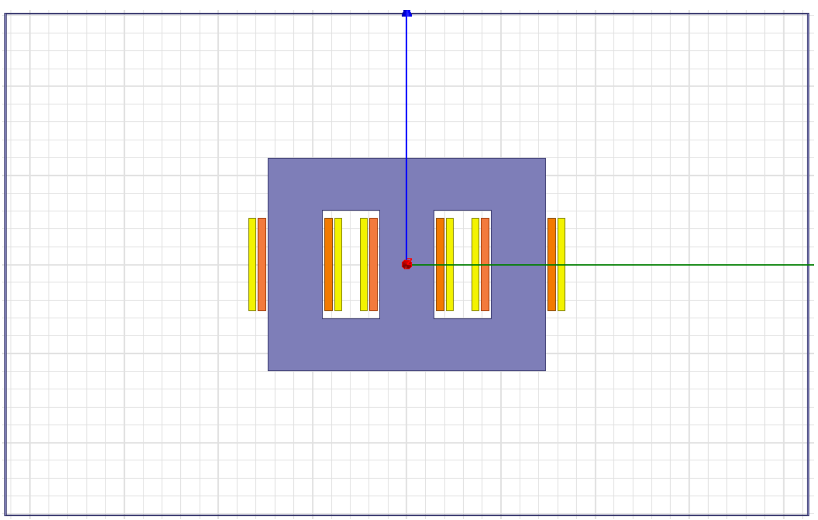
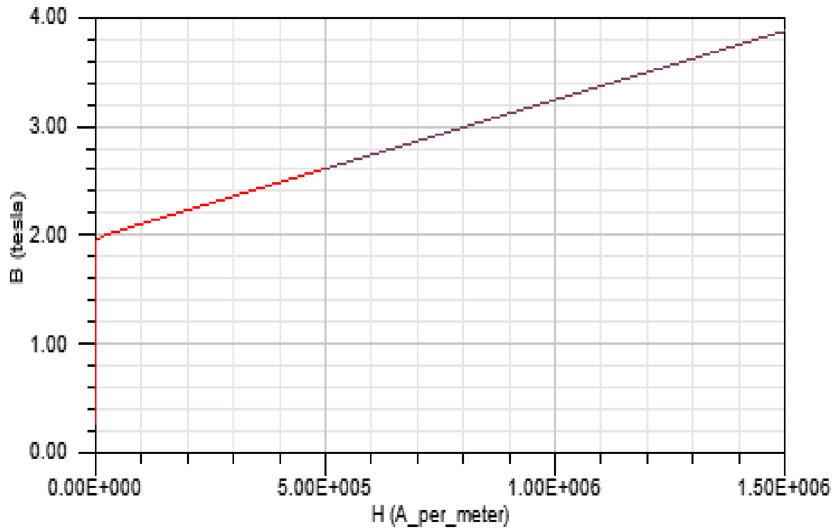
A 2D planar FEM model comprising of 3 phase core, windings and tank was used as a template model to compare the accuracy of the ACDC smart start technique developed. LV winding was excited with DC shifted AC voltage source and HV winding was open circuited to simulate GIC under no load conditions. Tank is modelled as linear with permeability of 200.The model parameters used are shown below in Table

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





Results & Validation

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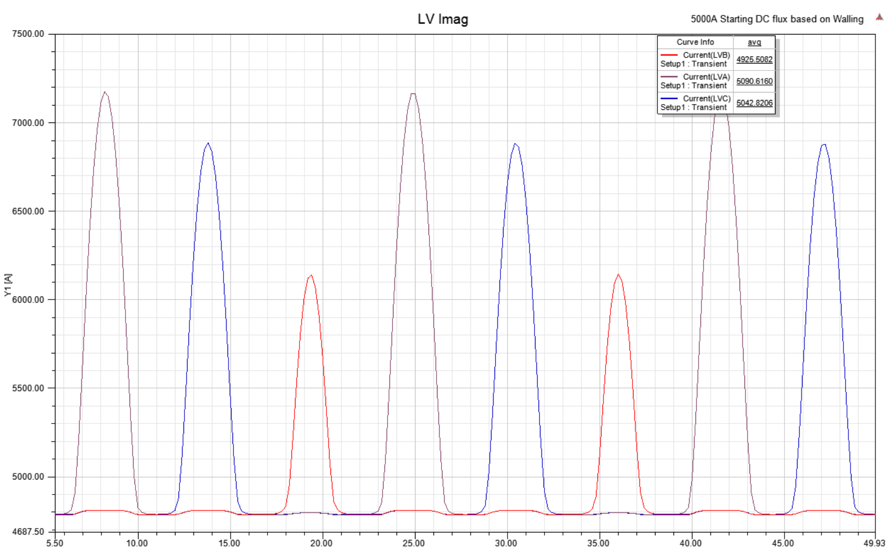
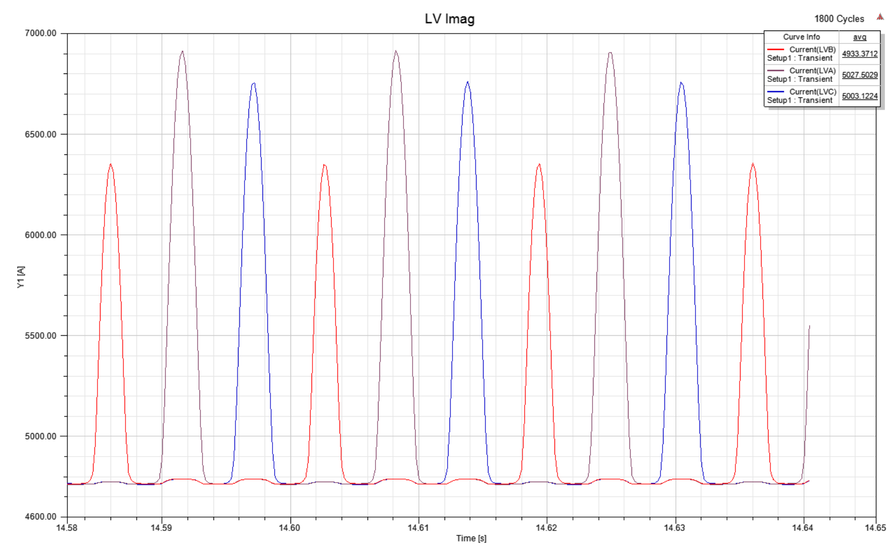
- The ACDC smart start model was solved for 3 cycles (50 ms) whereas the full transient model was solved for 900 cycles (15 s).
- 5V of DC voltage applied, resulted in 5000A of DC as calculated from winding resistance. A very high DC current of 5000 A was purposefully chosen so as to ensure saturation 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.
- LV winding magnetising current, flux linkage and their harmonic contents were obtained from analysis and compared with the corresponding full transient study for validation.



LV Magnetising current with ACDC Smart Start



LV Magnetising current under Full Transient

Results & Validation (Contd…)

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	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

LV flux linkage harmonics under 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	12.685397	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

LV flux linkage harmonics under Full Transient

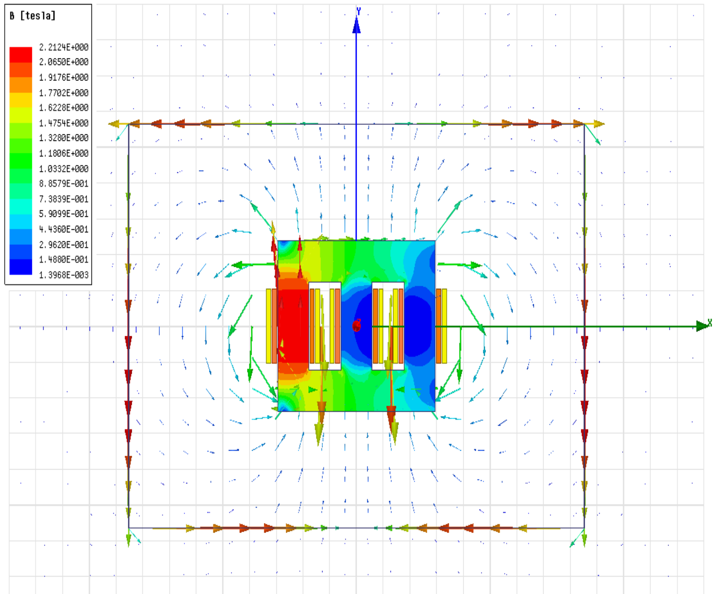

Figure 5 Flux density distribution

Challenges & Future work

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- 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

Summary

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- 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