A Process for Evaluating the Degree of Susceptibility of a fleet of Power Transformers to Effects of GIC

Ramsis Girgis, Kiran Vedante, and Gary Burden
ABB Power Transformers

Abstract: There has been some misconception in the electric power industry that GIC has caused, and would cause, significant damaging overheating to a large majority of power transformers. A recent study by the first two authors of this paper [1] confirmed that, because of the nature of the GIC currents: (1) Only a finite number of power transformers with certain design features could experience damaging overheating (2) A larger number of transformers would be susceptible to core saturation and some overheating and (3) The rest of the transformers would not be susceptible to either core saturation or damaging overheating. This paper describes a process, where a fleet of power transformers can be properly assessed to determine the type & magnitude of its susceptibility to effects of GIC. As a result, utilities can focus their GIC mitigating efforts on those transformers that are evaluated to be susceptible to damaging effects of GIC. The proposed process has been applied to a fleet of about 1600 power transformers on the ≥ 500 KV part of the US Power Grid. The results of this application are presented in this paper as a Case Study. It was found that 1 in 8 of this group of transformers is evaluated to be susceptible to possible damaging windings overheating; 1 transformer in 4 is found to be susceptible to core saturation but low level of overheating, and 3 transformers in 5 have low level of susceptibility to either effects of GIC.

Keywords: *Power transformers, Power Systems, Geomagnetically Induced Currents, GIC, GMD, DC, Fleet assessment.*

I. INTRODUCTION

The impact of Geomagnetic Disturbances on the power grid is of rising concern. Although severe events are rare, the potential effects cannot be ignored. Also, there has been some misconception that GIC would cause significant damaging overheating to the majority of power transformers (70%) installed on the North America power grid [2]. As a result:

- The industry dictated operating procedures that are too conservative. This caused utilities, in some cases, to unnecessarily take transformers out of service or reduce the load on the transformer significantly.
- Utilities paid more attention to transformers and less on the other effects associated with GIC such as the higher VAR demand and significant current harmonics.

A recent study described in an IEEE paper by authors of this paper [1] confirmed that, because of the nature of GIC:

- Only a finite number of power transformers could experience damaging overheating when subjected to high levels of GIC
- A larger number of transformers would be susceptible to core saturation only; which could result in power system instabilities
- The rest of the transformers would not be susceptible to either core saturation or damaging overheating

As a result, industry leaders from the North American Electric Reliability Corporation (NERC), various North American electric utilities, EPRI, and some power transformer manufacturers, have determined to study this important issue through collaborative research.

This paper describes a process, where a fleet of power transformers can be properly assessed to determine:

1. Which of the Transformers on the fleet would be susceptible to damaging overheating
2. Which transformers would be susceptible to only core saturation & moderate overheating, and
3. Which transformers would have a low level of susceptibility to either effects of GIC.

Utilities can then focus their GIC mitigation effort on transformers in their fleet that are evaluated to be susceptible to core saturation and GIC damaging thermal effects.

First, a summary of the general process of evaluating the Total susceptibility of a power transformer to effects of GIC is described in section-II. This is performed by considering both the transformer design-based susceptibility and its GIC-level susceptibility. The detailed process of evaluating the Design-based susceptibility of a power transformer design is described in Section-III. This is followed, in Section-IV, by describing the process of evaluating the GIC level-based susceptibility. The process of combining both types of susceptibility is described in more detail in section-V. Results of the application of above process to a fleet of about 1600 ≥ 500 KV power transformers on the US Power Grid are presented in Section-VI as a Case Study.

It is to be noted that this process does not apply to specialty power transformers; such as phase-shifting transformers, HVDC transformers, rectifier transformers, etc., nor shunt reactors, and other high voltage power system components.

II. EVALUATION OF TOTAL SUSCEPTIBILITY OF TRANSFORMERS TO EFFECTS OF GIC

The evaluation of the Total susceptibility of a transformer to effects of GIC is done in two steps. The first step is to determine the susceptibility of the transformer to effects of GIC based solely on its design. However, if the transformer is

Dr. Ramsis Girgis is presently the R & D Manager at the ABB Power Transformer plant, Saint Louis, MO.
Mr. Kiran Vedante is presently a Senior R&D Engineer at the ABB Power Transformer plant, Saint Louis, MO.
Mr. Gary Burden is presently a Senior Design Engineer at the ABB Transformer Remanufacturing and Engineering Services Organization at the ABB Power Transformer plant, Saint Louis, MO.

located in an area where the expected levels of GIC are low, the Total susceptibility of the transformer would be much lower than that indicated by only its design. Therefore, the Total susceptibility of a transformer to effects of GIC would not be accurate unless the level of GIC that a transformer would be exposed to is included in the assessment. This process is described in more details in section-V of this paper.

III. DESIGN-BASED SUSCEPTIBILITY

This evaluation uses the electrical parameters and core / winding design of a transformer. Transformers are divided into the following categories:

- Category-I: Transformers not susceptible to effects of GIC
- Category-II: Transformers least susceptible to core saturation
- Category-III: Transformers susceptible to core saturation and some windings & structural parts overheating
- Category-IV Transformers susceptible to both core saturation as well as possible damaging windings and / or Structural parts overheating

Through their thorough investigations and analytical modeling [3], the authors of this paper determined that some combination of electrical and design parameters would determine the degree of susceptibility of power transformers to core saturation and / or windings & structural parts overheating. These are:

1. Voltage Ratings
   - o Higher voltage transformers would be exposed to higher levels of GIC
2. Type of transformer (GSU vs. Auto transformers)
   - o EHV Auto transformers typically have a Delta tertiary, which makes them susceptible to overheating in the Tertiary winding, as will be explained in item 6 below
3. Shell-form
   - o Shell-form transformers, regardless of their core type, are susceptible to core saturation. Also, some of them would be susceptible to damaging winding overheating due to high circulating current when the core saturates, as is explained in item 5 below
4. Single-phase vs. three-phase and Core-type
   - o 3-Phase core form transformers with 3-limb cores are least susceptible to saturation due to GIC
5. Old shell-form GSU designs
   - o GSU shell-form Transformers built before a certain time period had series connections between the two LV windings that were solidly brazed. This allows high circulating currents caused by changed pattern of the leakage flux when the core saturates [4].
6. Winding connections
   - o Transformer designs that have a Delta LV (other than GSU(s)), and those with a Tertiary winding, are susceptible to overheating of this winding. This is caused by the fact that different phases in a bank of 1-phase transformers, or a 3-phase transformer, will experience core saturation at different points on the cycle. This results in a net voltage in the delta winding leading to a circulating current of the same wave-shape. The magnitude of this current is a function of the transformer design and the magnitude of GIC. It is limited by the impedance seen by this winding. Figure 1 below shows an example of calculated wave-shape of the net voltage developing in the Delta winding of a large Auto transformer when subjected to a high level of GIC. Having high-peak pulses, 3 per cycle, causes additional high winding losses that could result in damaging winding overheating. Also, this circulating current will reflect to the primary winding, superimposing on the load current and the high magnetizing current that flow in the primary winding. This could cause additional winding overheating.

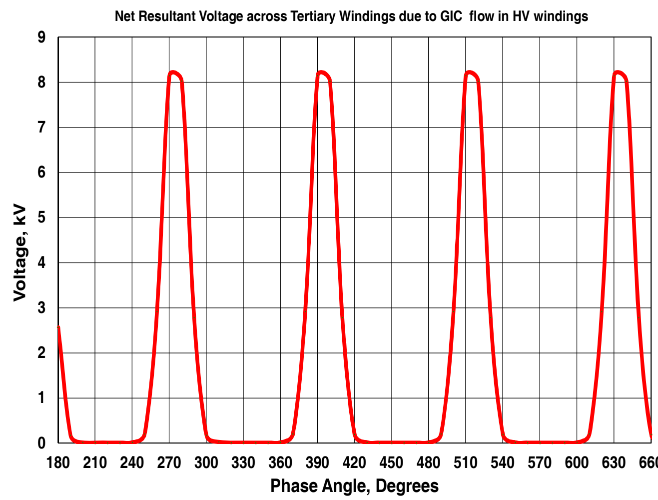

Figure – I: Net Resultant Voltage appearing in the Delta winding due to flow of high GIC in the HV winding

Using above process, power transformers in the fleet can be divided further into the 4 categories introduced in the above as follows;

- If the HV winding of the transformer is connected in Delta, the transformer is not susceptible to GIC => (Category-I)
- If a transformer is a 3-phase Core form, with a 3-limb core, its susceptibility to core saturation is low => (Category-II).
- If a transformer is an old Shell-form with the old LV leads design, its susceptibility to damaging winding overheating is high => (Category-IV).
- Transformers not belonging to the above designs and have a Delta LV (other than GSU(s)), or Tertiary winding. These transformers would be susceptible to windings overheating => (Category-IV).
- Transformers that do not belong to any of the above categories are those which are susceptible to core saturation and some windings and / or structural parts overheating => (Category-III)

IV. GIC LEVEL-BASED SUSCEPTIBILITY

This assessment represents the other part in the process of evaluating the Total susceptibility of a transformer to effects of GIC. As stated before, the Total susceptibility of a transformer can not be correct without considering the level of GIC the transformer is suspected of being exposed to. This level of GIC is determined by a number of factors; such as the region where the transformer is located, the resistance of the soil in that location, etc. The process of evaluating the GIC-Level susceptibility divides transformers into three categories; namely, High, Medium, and Low. These categories are determined using either of the following data:

- Calculated relative levels of GIC that transformers in a certain location would be subjected to for a predetermined reference GMD storm.
- Using published information on relative levels of GIC currents that different geographical regions would be exposed to.

V. TOTAL GIC SUSCEPTIBILITY

The process of assessing the Total susceptibility of a transformer to effects of GIC is basically combining the results of the design-based susceptibility analysis and the GIC level-based susceptibility analysis. This process involves the following procedure:

- Transformers assessed to have a high Total susceptibility to GIC effects are those which are determined to be susceptible to undergo core saturation and possible damaging overheating and are, at the same time, located in high GIC level areas.
- Transformers assessed to have a medium level of Total susceptibility to GIC effects are those which are determined to be either:
    1. Susceptible to undergo core saturation and possible damaging overheating but are located in medium GIC level areas, or
    2. Susceptible to undergo core saturation but no damaging overheating of winding or structural parts and are, at the same time, located in high GIC level areas.
- Transformers assessed to have a low Total susceptibility to effects of GIC are those which are determined to be:
    1. Susceptible to undergo core saturation and possible damaging overheating but are located in low GIC level areas, or
    2. Susceptible to undergo core saturation but no damaging overheating and are located in either medium or low GIC level areas.
- Transformers assessed to have practically no susceptibility to effects of GIC are those which are determined to be either:
    1. Least susceptible to core saturation and at the same time are located in low GIC level areas, or
    2. Not susceptible to GIC based on their winding connections

VI. APPLICATION OF PROCESS – Case Study

As a Case Study, the procedure of evaluating the susceptibility of transformers to effects of GIC as outlined in this paper was applied to a fleet of 1593 large power Transformers in service on the $\geq$ 500 kV part of the US Electric Power grid. This population of transformers consisted of over 1300 single-phase transformers and over 200 three-phase transformers belonging to a total of over 600 different designs. Approximately 700 of these transformers are shell-form transformers and over 800 core-form transformers. These were designed and built on approximately 200 different shell-form designs and nearly 400 different core-form designs. Slightly over 1400 of the transformers are 500 kV transformers and the rest are 765 kV transformers. The power ratings of these transformers ranged mainly from over 100 MVA to as high as 1000 MVA. The group represented over 900 Autotransformers, about 450 Generator Step-Up transformers, and about 200 other Multi-winding transformers.

Results of design-based assessment of GIC susceptibility

First, the electrical performance parameters and the main design data, such as core type, winding connections, year of manufacture, etc. were collected for each of the over 600 transformer designs. Table-I below summarizes the results of this design-based GIC susceptibility assessment of the transformer fleet. The table presents the number of transformers belonging to each of the four Categories.

Table-I: Summary of results of design-based assessment of GIC susceptibility

Number of transformers	Categories of Design-Based Susceptibility				
	Total	IV	III	II	I
Actual Count	1593	1056	464	73	0
% of Total	100 %	66 %	29 %	5 %	0 %

The above table indicates that, based on their electrical parameters and core & windings design alone, 2/3rd of these transformers would be susceptible to core saturation & possible damaging windings / structural parts overheating when subjected to high levels of GIC. Correspondingly, about 30 % of these transformers would be susceptible to core saturation and some overheating, and about 5 % are least susceptible to core saturation. There were no transformers that are not susceptible to effects of GIC. This is because the HV windings of all these studied EHV transformers were Y-connected.

Results of level-based assessment of GIC susceptibility

The transformers used in this Case study are located across all regions of the United States. Using published information on different levels of GIC currents, which these different regions would be exposed to [1], the GIC-level susceptibility of these transformers was determined considering their geographic location. The location of all but 53 of the 1593 transformers in this case study could be identified. A summary of the degree of GIC-level based susceptibility of these transformers is given in Table-II below. The Table shows that only about 1 in 5 transformers is located in a high level GIC area; about 1 in 3 is located in a medium level of GIC area; and half of this transformer population is located in a low level GIC area.

Table-II: Summary of estimated number of transformers susceptible to different levels of GIC

Number of transformers	Susceptibility to Level of GIC Categories			
	Total	High	Medium	Low
Actual Count	1538	290	490	758
% of Total	100 %	19 %	32 %	49 %

Results of assessment of Total Susceptibility to effects of GIC

The Total susceptibility of the transformers in this Case Study has been determined following the procedure explained earlier in Section-V. Table-III below summarizes the results of applying this process to the 1538 transformers identified in this Case Study. In this table, and for easy reference, the High degree of Total susceptibility to effects of GIC is indicated in "**Orange**"; the medium degree in "**Yellow**"; the low degree in "**Green**", and the minimal Total susceptibility in "**Blue**".

The Table shows that only about 1 in 8 transformers are estimated to have a high degree of Total susceptibility to effects of GIC. Correspondingly, about 1 in 4 has a medium level, and 3 in 5 have a low level, or practically no, susceptibility to effects of GIC.

Table-III: Summary of results of assessment of Total GIC susceptibility of transformers in the Case Study

Number of transformers	Total Susceptibility Categories				
	Total	Orange	Yellow	Green	Blue
Actual Count	1538	198	415	899	26
% of Totals	100%	13 %	27 %	58 %	2 %

The summaries presented in Tables-I, -II, and -III are presented again in a bar chart format in Figure-2. The figure demonstrates the whole process of assessing the true Total susceptibility of transformers to effects of GIC. The figure shows the following:

- While 2/3rd of all transformers in this Case Study were determined, based on their designs, to have a high level of susceptibility to possible damaging overheating, this group drops to about 1 in 8 when considering the locations of these transformers.
- Correspondingly, the number of transformers that have a medium level of Total susceptibility is only a little lower than that determined to have that level of susceptibility based on the design alone (27 % versus 29 %)
- The group of transformers determined to have low Total susceptibility to effects of GIC increased from being 1 in 20, when considering the design alone, to about 60 % of all transformers in this study when considering the GIC exposure of these transformers to GIC.

The color code used in Table-III is used in the figure below.

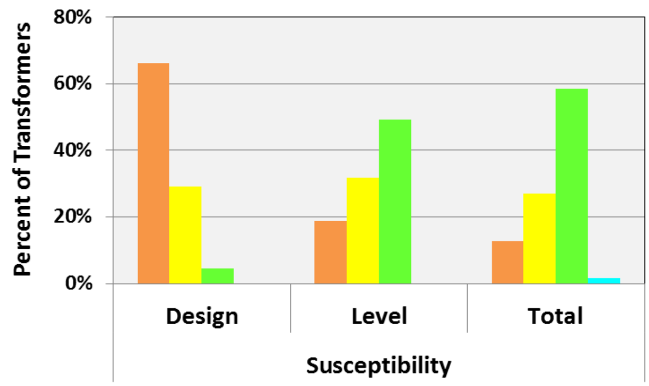

Figure-2: Resultant Total GIC Susceptibility in Case Study

VII. CONCLUDING REMARKS

Providing utilities with information on the degree of the susceptibility of power transformers on their grid to effects of GIC would allow them to focus their mitigation / studies effort. Hence, system blackouts and possible damages to these transformers can be avoided in future GMD events. For example, utilities could request manufacturers of transformers, identified to be susceptible to core saturation, to provide data on the additional VAR consumption and current harmonics as a function of the level of GIC the transformer would be exposed to. Power system analysts would use such data, to perform system simulations for evaluating the response of the power system and its components during a GMD storm. As a result of these studies:

- Proper contingencies can be built in the Power System for such magnitudes of VAR, so Voltage Collapse and possible grid black-outs can be avoided.
- Increasing robustness of the network; including providing additional network protection and adjusting settings of relays and other susceptible equipment.
- Developing special / proper operating procedures during a GMD storm; such as line load-sharing, desensitization of susceptible equipment, and minimizing voltage regulations.
- Installation of appropriate GIC blocking devices, if needed.

Another result of the assessment process described in this paper is that utilities can request manufacturers of the transformers, identified as being highly susceptible to damaging windings and or structural parts overheating, to perform more detailed magnetic and thermal analysis to determine the GIC Capability of these transformers [3] avoiding possible damaging overheating.

VIII. ACKNOWLEDGMENTS

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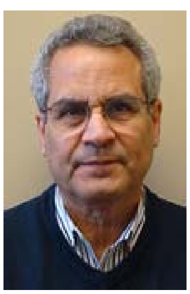

Dr. Ramsis S. Girgis (Life member 2011) is presently the Research & Development manger at the Power Transformer Division of ABB located in St. Louis, Missouri. He is also the leader of the global ABB R&D activities in the area of "Transformer Core Performance" and Co – Leader of the global ABB R&D activities in the "Transformer Noise" area.

Dr. Girgis received his Ph.D. degree from the University of Saskatchewan, Canada, in Electrical Engineering in 1978. He has over 45 years of R&D experience in the area of power, distribution, and high frequency transformers, rotating machines, and pulse power components. He has published and presented over 70 scientific papers in IEEE, IEE, CIGRE, and other international journals and co – authored chapters in two electrical engineering handbooks on "Transformer design" and "Transformer noise". He is presently the chairman of the IEEE Transformers Standards Work Group revising the IEEE Noise measuring Standards C57.12.90, section 13. He is the past Technical Advisor representing the US National Committee in the IEC Technical Committee 14.

Mr. Kiran B. Vedante (SM'2006) is presently a Consulting Research & Development Engineer at the Power Transformer Division of ABB Inc. located in St. Louis, Missouri. He completed his Master of Electrical Engineering degree with specialization in HV Engineering in 1995; from VJ Technological Institute (Mumbai University). Before joining ABB, Kiran worked for various renowned Transformer companies like Siemens, USA, Pennsylvania Transformers, USA, and Crompton Greaves Limited, India. He has a Total work experience of more than 21 years. His present research work is mainly focused in the area of Core performance and Effects of GIC/DC on Power Transformers. He is an active member of a number of Working Groups and Task Forces in IEEE Transformer Standards Committee and a member of IEEE PES. Kiran has co-authored and presented more than 5 Technical Papers in the area of GIC and its effects on power transformers in National and International conferences.

Mr. Gary L. Burden is presently a Principal Design Engineer at the Power Transformer Division of ABB Inc. located in St. Louis, Missouri. He completed his Bachelor of Engineering degree in 1973 from Purdue University. He started work with Westinghouse in 1974 and has designed Large Power transformers utilizing both Shell – form and Core – form transformer technologies. He has Total work experience of nearly 40 years. His present engineering work is mainly focused in the area of Engineering Solutions projects assessing the aging fleet of Power Transformers throughout the US.