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Accurate Calculation of VAR Demand for a Fleet of Power Transformers under the 1-in-100 years Benchmark GMD Scenario

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SUMMARY

This paper presents results of a comprehensive study performed by the authors on a large fleet of Power transformers to demonstrate the significant impact that accurate values of transformer winding resistances, correct Core Types, and correct method of calculation of VAR Demand on the magnitudes of VAR Demand of transformers on the fleet in response to a GMD (**G**eo-**M**agnetic **D**isturbance) event.

The study demonstrates the following:

1. Significant impact of values of Transformer Winding Resistances on calculated GIC (**G**eomagnetically **I**nduced **C**urrent) flow
2. Significant impact of Core Types on calculated values of VAR (Reactive Power) Demand
3. Significant differences in the method of calculation of the VAR Demand commonly used by the Industry and that used by Hitachi Energy
4. Calculated values of the VAR Demand, using the "Hitachi Energy" method of calculation, are significantly lower than those calculated by the method commonly used in the industry

The most significant finding of this study is that the actual magnitudes of the Total VAR Demand on the system in response to the 1 – 100 years Benchmark GMD event is a fraction of what was originally calculated. This is of a significant impact on results of studies of Power System Vulnerability to GMD storms and Corrective Actions to be taken as a result of these studies.

KEYWORDS

GIC, Power Transformers, VAR Demand, Power Systems

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1. INTRODUCTION

A proper study of the vulnerability of a power system to a GMD event requires accurate information of the GIC flow in the system as well as accurate calculation of the resulting additional VAR Demand by the transformers caused by this GIC. Also, accurate calculation of the GIC flow in a power system requires correct values of winding resistances of the transformers. Finally, accurate calculation of the resulting additional VAR Demand by the transformers requires both a correct method of calculation and correct information on the core type that each of the transformers on the system has.

FirstEnergy requested the Hitachi Energy team to perform the following tasks, with the objective of providing accurate values of VAR Demand that would be used for proper evaluation of the vulnerability of their power system to the Benchmark GMD [1]:

Task – I: Validation of values of winding resistances of transformers on the fleet

Task – II: Validation of core types of transformers on the fleet

Task – III: Accurate calculation of the VAR Demand corresponding to the revised GIC flow data

This paper presents results of these 3 studies. First, Section 2 presents the evaluation of the impact of values of winding resistances on calculated GIC flow. This is followed by Section 3 that presents results of the Validation of the Core Types. Section 4 then describes the method used by the Authors to calculate Additional VAR Demand for transformers of different Types when subjected to GIC and with a comparison to methods commonly used presently by the Industry for that purpose. Section 5 presents comparisons of values of Additional VAR Demand calculated by both methods for the three service regions of this Utility. Finally, Section 6 presents a comparison between the total highest VAR Demand for each of the three Regions as well as the total for the whole System, again as calculated by the authors and as calculated by methods presently used by the Industry.

2. VALIDATION OF VALUES OF WINDING RESISTANCES AND IMPACT ON CALCULATED GIC FLOW

As stated earlier, the Hitachi Energy team first performed validation of values of winding resistances of the power transformers on the fleet with HV Winding ≥ 230 kV. Values of most of these resistances were the same as, or close to, those originally reported, but some were different, or very different. Also, for some transformers, values of winding resistances were not originally provided because they were not available, or the values were illegible.

Note that discrepancies of reported winding resistances are mainly caused by the fact that different manufacturers measure winding resistances of 3-Phase transformers differently. For example, some manufacturers measure winding resistance of Y-connected windings line-to-line while others measure it line-to-ground (neutral). This causes a factor of 2 difference. Also, measuring winding resistance of a delta connected winding provides a value that is 2/3 of the winding resistance / phase value.

The revised values of winding resistances were used to calculate the revised GIC flow in the Utility's System. Table 1 below presents a sample of some of the largest deviations in the reported values of GIC calculated using the original values of winding resistances versus those calculated using the revised values. The table demonstrates the significant impact of values of winding resistances on the calculated GIC flow.

Table 1: Values of GIC flow levels calculated using Original vs. Revised values of Winding Resistances

Transformer	Voltage, kV		GIC Level, Amps / Phase	
	HV	LV	with Original, Ω	with Revised, Ω
A	230	34.5	7.4	17.1
B	345	230	24.3	34.0
C	500	138	14.6	18.8
D	345	138	16.8	11.2
E	345	138	9.0	2.2
F	230	34.5	17.9	6.6

3. VALIDATION OF CORE CONSTRUCTION TYPES

Knowing whether the transformer is a Core form or a Shell form, and what core type the transformer has, is paramount to accurate calculation of the Additional VAR Demand. Also, as will be explained in Section 4 below, not only the core type impacts the method of calculation but also the value of the "K" Factor used in the calculation. With the above background, the Utility requested the Hitachi Energy team to confirm the type of transformer (Core form or Shell form) and core type, for their fleet of Power Transformers with High Voltage winding ≥ 230 kV. Table 2 below presents examples of differences between core types originally reported and the correct ones.

Table 2: Originally reported Core Types vs. Actual Core Types

Transformer	Voltage, kV		Core Type	
	Bus 1	Bus 2	Originally reported	Actual
1	115	230	3-Phase, Shell form	3-Phase, Core form, 3-limb
2	138	500	3-Phase, Shell form	3-Phase, Shell form, 7-limb
3	230	34.5	None Reported	3-Phase, Core form, 3-limb
4	115	345	3-Phase, Core form, Generic	3-Phase, Shell form, D-Type
5	500	26	3-Phase, Core form, Generic	3-Phase, Core form, 5-limb
6	230	34.5	3-Phase, Core form, Generic	1-Phase, Core form, 2-limb
7	500	765	1-Phase	1-Phase, Core form, 2-limb
8	500	765	1-Phase	1-Phase, Core form, 4-limb

4. CALCULATION OF VAR DEMAND CAUSED BY GIC

4.1 Calculation Method Presently used by the Industry

The method used by the Industry for calculating Additional VAR Demand caused by GIC uses:

1) One method of calculation for all transformers including the 3-Phase Core form transformer with the 3-limb core type.
2) One fixed value of the "K" factor for all 1-Phase transformers (1.18)
3) The same value of the "K" factor for 5-limb Core form & 7-limb Shell form (0.66)
4) One low value for all 3-Phase Shell form with the D core type (0.33)
5) One low value for all 3-Phase Core form transformers with the 3-limb core type (0.29)
6) For transformers with unknown core types, it uses:
   a. One value of 0.6 for transformers with rated HV windings ≤ 400 kV
   b. Another very different value of 1.68 for all transformers with rated HV winding > 400 kV

4.2 Calculation according to Hitachi Energy

Several factors determine the VAR demand of a transformer on a Power System corresponding to a specific level of GIC flow in the transformer. These are:

1) Core form vs. Shell form
2) Transformer type, such as Generator Step Up transformer, Autotransformer, Step-Up transformer, Step-Down transformer, and two- or multi-winding transformers
3) Transformer core type
4) Value of the "K" Factor used for the calculation of the VAR demand
5) Method used for the calculation of the VAR demand.

The calculation of the additional VAR Demand for a transformer subjected to GIC, for all transformers other than 3-Phase Core form Transformers with the 3-limb core type is as follows:

Additional VAR Demand / Phase = K x GIC x Phase Voltage

An example of this linear relationship for a 1-Phase Core form transformer between Additional VAR Demand and magnitude of GIC is plotted in Figure 1 below.

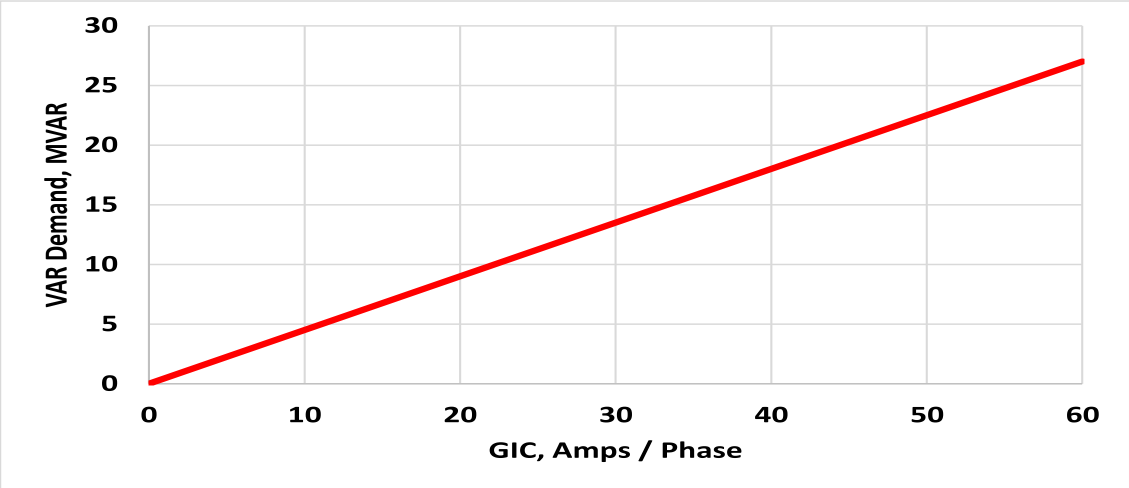


Figure 1: Example of Additional VAR Demand Calculation

This is significantly different compared with a 3-Phase Core form transformer with the 3-limb core type, which requires a certain level of GIC before its core is saturated. This Core Saturation current is referred to as "I_{CS}". Accordingly, the Calculation of the Additional VAR Demand for these transformers is as follows.

For GIC ≤ I_{CS}, Additional VAR Demand = 0 MVAR

For GIC > I_{CS}, Additional VAR Demand / Phase = K x (GIC – I_{CS}) x Phase Voltage

Figure 2 below presents an example of the calculated VAR demand versus GIC for a 3-Phase Core form transformer with the 3-limb core type with a value of I_{CS} = 18 Amps / Phase and a "K" factor value of 0.54.

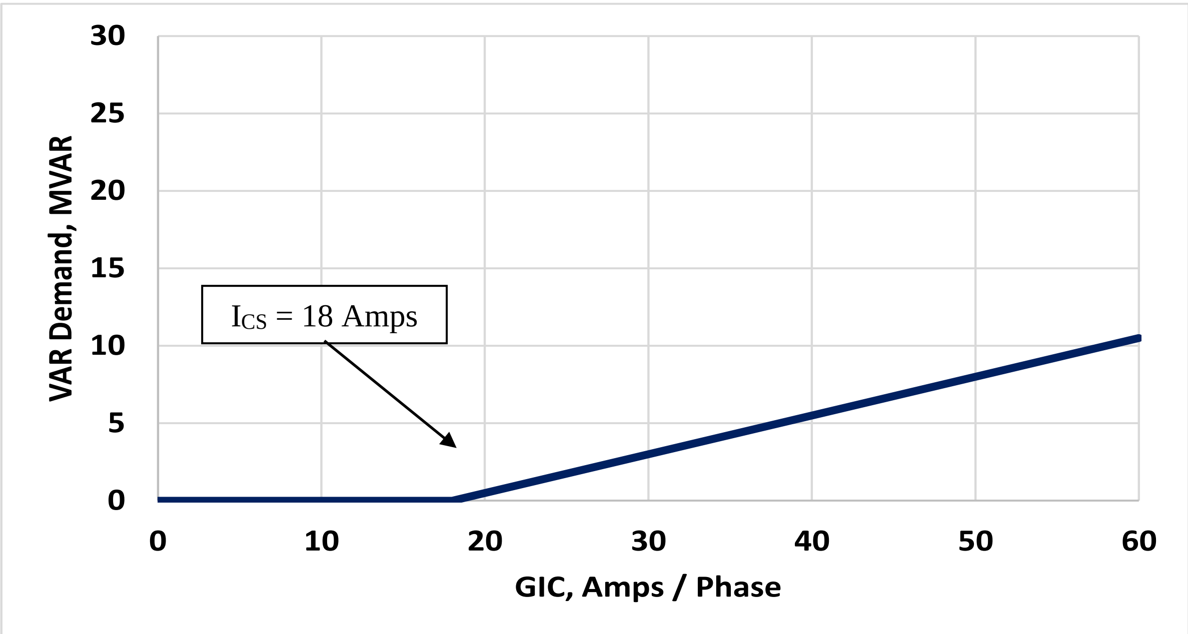


Figure 2: Example of Additional VAR Demand calculation for a 3-Phase Core Form Transformer with the 3-Limb Core Type

Table 3 below presents a summary of the Lowest and Highest values of the "K" Factor used by the Hitachi Energy team for the calculation of the VAR Demand in this study. The table demonstrates the significant difference between the commonly used values stated above, and the values of the “K” factors used by the Hitachi Energy team.

Table 3: Values of the “K” factor used in the VAR Demand Calculations

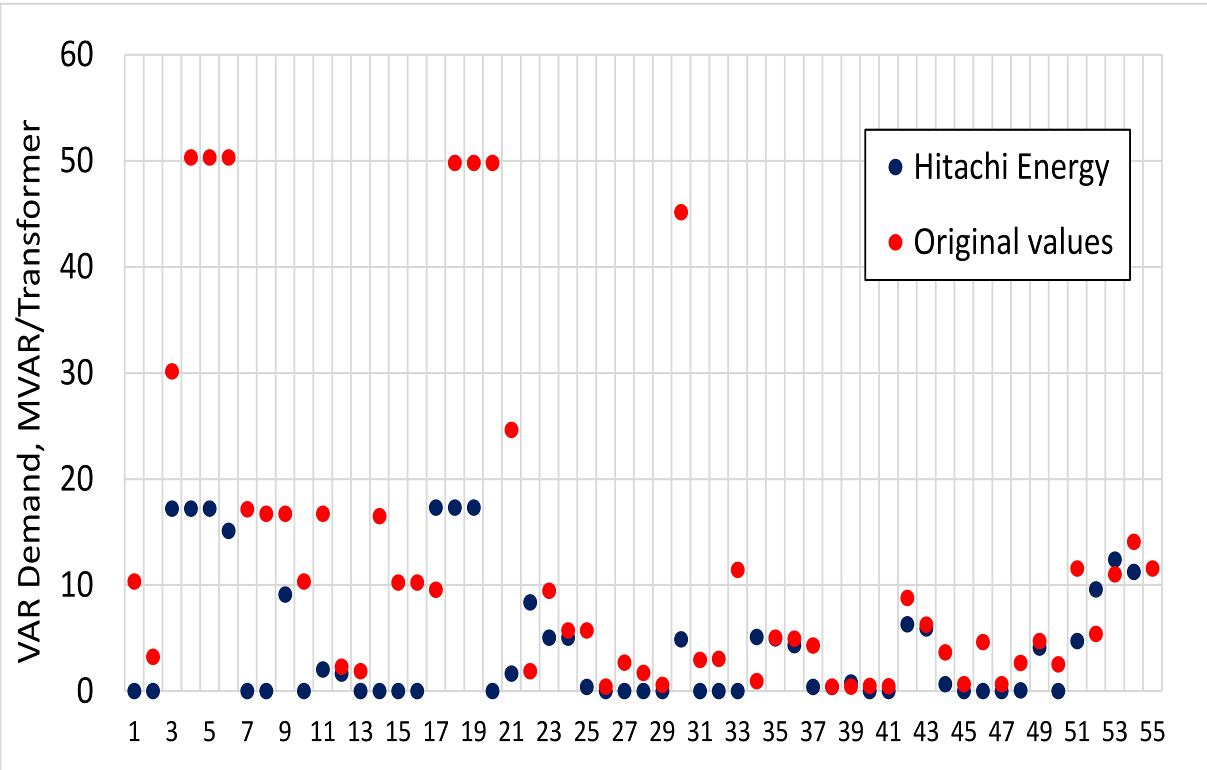
Phase(s)	Type	Core Limbs	Hitachi Energy Lowest	Hitachi Energy Highest
1	Core	2	1.272	1.304
		4	1.325**	
	Shell	D Type	1.380**	
3	Core	3	0.230	0.719
		5	1.170	1.290
	Shell	D Type	1.019	1.130
		7-leg	1.275	1.280

*** 4 Single-Phase transformers of the same design*

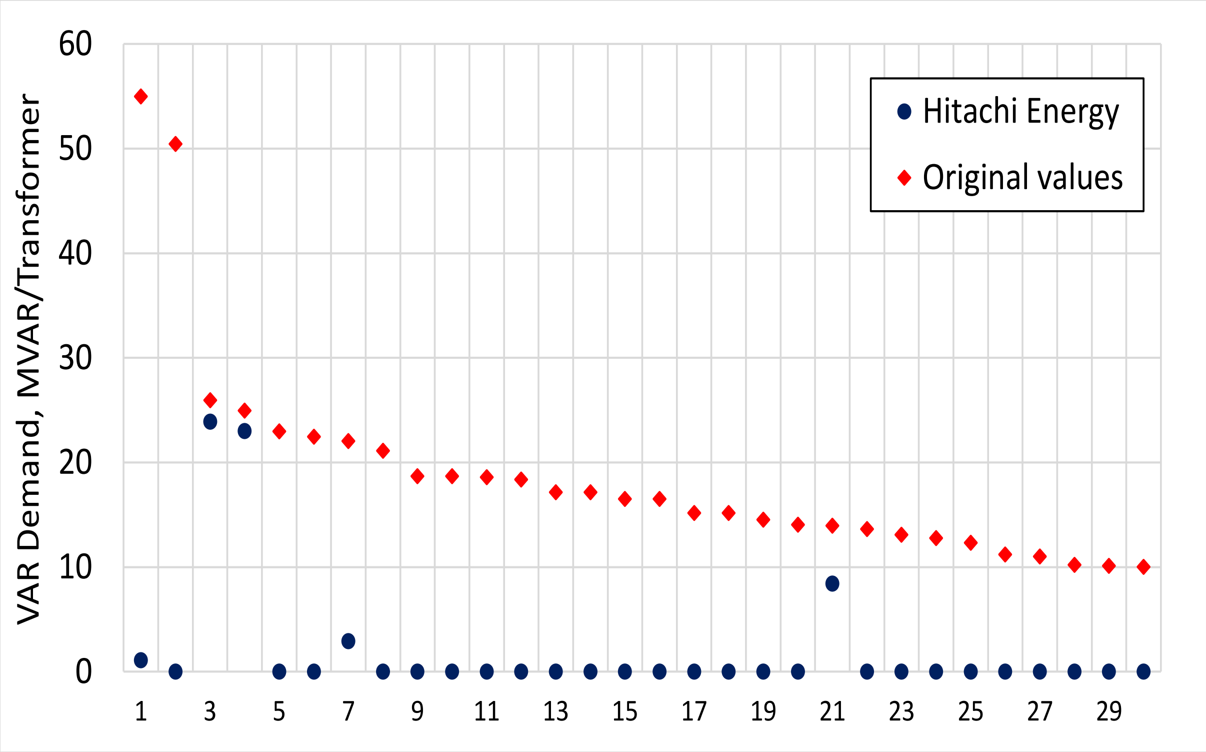
5. CALCULATED ADDITIONAL REACTIVE POWER DEMAND

Additional Reactive Power Demand, corresponding to the revised values of the maximum effective GIC level that each transformer on the fleet is expected to be subjected to under the reference Benchmark GMD Scenario, was calculated by the Hitachi Energy team. These are compared below with values calculated using the method commonly used by the industry, corresponding to the original GIC flow levels (referred to as “Original” values).

Figure 3 below presents two comparisons of the calculated VAR Demand for samples of two different regions of this Utility’s Power System. Figure 3 (a) shows that the original values are mostly overestimated. while Figure 3 (b) shows that the majority of the transformers have zero VAR Demand as they are 3-Phase Core Form transformers with the 3-limb Core Type and hence, at GIC levels < I_{CS}, VAR Demand = 0 MVAR.



(a) Sample from Region 1



(b) Sample from Region 2

Figure 3: Calculated Additional VAR Demand

6. HIGHEST TOTAL ADDITIONAL SYSTEM VAR DEMAND

For Regional Transmission Organizations performing GIC System Vulnerability Analyses, the highest levels of the VAR demand in the (whole) System are calculated. The software, commonly used by the industry for this purpose, determines the angle at which the highest total VAR demand occurs from a Total System perspective, not from a transformer-by-transformer perspective. "Original" values of this Total VAR Demand, corresponding to the 1-in-a-100-year Benchmark event, were reported at two different angles of the GIC electric field; namely 157 degrees using the originally calculated GIC Flow levels (based on originally reported values of winding resistances), and at 158 degrees using the revised GIC Flow levels (based on revised values of the winding resistances).

Table 3 below presents a summary of the "Original" calculated values of the total VAR Demand as well as the corresponding values calculated using the "Hitachi Energy" method for the two sets of GIC flow data corresponding to the two sets of winding resistances, respectively.

Table 3: Total VAR Demand Values using "Hitachi Energy" method vs. "Original Values"

Region	**Calculation**		**Ratio**
	Original	**Hitachi Energy**	
1	417	159	0.38
2	486	71	0.15
3	693	226	0.33
Total	1596	456	0.29

The table above shows that the Total VAR Demand for whole Power System of this utility, calculated by the "Hitachi Energy" method, is less than 1/3rd of the "original" values (29 %). The Figure also shows that, because of the large number of 3-phase Core form transformers with the 3-limb core type in Region – 2, the "Original" values of the VAR demand for that Region are higher than that calculated by Hitachi Energy by almost a factor of 7. These two major findings represent a significant impact on results of System Vulnerability studies and hence on resulting Corrective Actions needed.

7. SUMMARY

This paper presents results of a comprehensive study performed by the Authors on a large fleet of Power transformers. The study demonstrates the following:

1. A Significant impact of values of winding resistances on the calculated GIC flow
2. Significant differences in the method of calculation of VAR Demand commonly used by the industry and that used by Hitachi Energy
3. Calculated values of the VAR Demand using the "Hitachi Energy" method are much lower than those calculated by the method commonly used in the industry

The most important finding from this study is that the actual magnitudes of the Total VAR Demand on this system is a fraction of what was originally calculated using original values of winding resistances, core types, and original levels of GIC. This is of a critical impact on studies of System Vulnerabilities to GMDs and is expected to be true for other Utility Power Systems in North America.

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