

IMPROVING TRANSFORMER PROTECTION



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Abstract - Power transformers play a critical role in the power system. These transformers are subject to internal short circuits, external short circuits and abnormal operating conditions. The following protection challenges to power transformers will be explored, and methods to improve the protection provided:

- Remanence in a current transformer (CT) may cause misoperation of phase differential protection due to compromised CT performance. Heavy through-faults, sympathetic inrush and recovery inrush all cause high current. This combined with high remanent flux, can create a security issue. IEEE CT performance calculations will be used to support the use of dual slope differential characteristics to promote secure differential protection operation when challenged with unequal CT performance.
- On transformer energizing, 2nd harmonic current has been traditionally used as a means to prevent phase differential misoperation. Certain transformers may not exhibit high enough 2nd harmonic, causing a dependability issue if the restraint is set too low. The use of 2nd and 4th harmonics for inrush detection will be shown to enhance reliability during energizing inrush situations.
- Overexcitation can occur from abnormal operation of the utility system or the plant's excitation control. Causes of overexcitation will be outlined and use of volts per hertz protection explored. With overexcitation occurring from system voltage rise, the phase differential protection has been traditionally blocked using 5th harmonic restraint. This may cause an undesired non-operation of the phase differential protection if an internal fault occurs while the transformer is overexcited, causing a delay in tripping and severe damage to the transformer. A technique using adaptive phase differential pick-up value will be illustrated to overcome this challenge.
- On resistance-grounded power transformers, phase differential protection sensitivity for ground faults near the neutral is decreased. The use of ground differential protection will be explored and the increased sensitivity gained will be demonstrated.

I. CT REMANENCE AND PERFORMANCE

Remanence is magnetization left behind in a ferromagnetic material (such as iron) after an external magnetic field is removed. In CTs, remanence due to high currents being interrupted in the presence of DC offset will cause CTs to saturate below secondary voltage rating. As an example, a 1000A:5A C400 CT could saturate with 200V in the secondary circuit below the Class C definition of accuracy, +/-10% at 20X rated current.

The tendency for a CT to saturate is increased by other factors working alone or in combination:

- High system X/R ratio which increases time constant of the CT saturation period
- CT secondary circuit burden which causes high CT secondary voltage
- High primary fault or through-fault current which causes high secondary CT voltage

There are many technical papers on the subject of modeling the behavior of iron-cored current transformers used for protective relaying purposes. One of the difficulties in using an elaborate model is obtaining the parameters for a particular case in order to implement that model. For example, the excitation current in the region below the knee-point is a complex combination of magnetizing, hysteresis and eddy-current components, the parameters of which are usually not known in a particular case. The IEEE Power System Relaying Committee (PSRC) developed a simplified model for CT saturation that includes the major parameters that should be considered. The simplified model makes use of the fact that if the excitation current waveform reaches into the saturated region, the part of the waveform in the below-knee-point region has negligible effect. This simplifies the solution greatly and makes this a great tool for practicing engineers to aid in dimensioning CTs. The model is explained in Appendix 1.

The following analysis explores the effects of CT saturation two-node differential protection application where we assume one CT replicated perfectly and the other CT replicates per the model. From here, we can analyze the differential current developed for both internal faults and external through-faults, as shown in Figs. 1a and 1b.

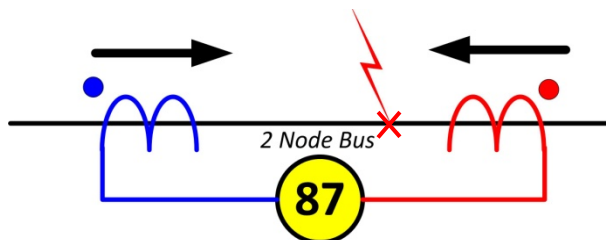


Fig. 1a Two Node Differential, Internal Fault

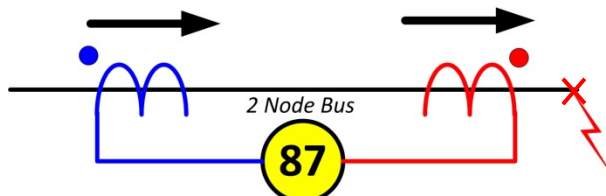


Fig. 1b Two Node Differential, Through-Fault

Key to proper operation of the differential element is the development of restraint and operating slopes and breakpoints. The following series of graphs shows the ideal CT secondary current and the current produced from the model. In these examples, assumptions are:

- Inverse of saturation curve slope = 22
- RMS voltage at 10A excitation current = 400V
- Turns ratio = 80 (400:5)
- Winding resistance = 0.3Ω
- Burden resistance = 0.5Ω
- Burden reactance = 0.5Ω

- System X/R ratio = 12

Increasing values of remanence (R), DC offset and primary current (A) are then applied, with resultant ideal and replicated currents displayed. In addition to the AC waveforms, RMS values are provided and these become the basis for the differential quantity developed in a relay.

Figure 2 shows using the CT Saturation Calculator with a C400 400:5 ratio CT having a remanent flux value of 0.5, offset of 0.5 with 2000A applied. The ideal and replicated secondary currents are exactly the same.

Figure 3 shows using the CT Saturation Calculator with a C400 400:5 ratio CT having a remanent flux value of 0.5, offset of 0.5 with 4000A applied, an increase of 2000A. The replicated secondary current is slightly less than the ideal current from cycles 3 through 7. The maximum RMS difference is quite small at approximately 5%, with a corresponding maximum resulting differential quantity of approximately 5%.

Figure 4 shows using the CT Saturation Calculator with a C400 400:5 ratio CT having a remanent flux value of 0.5, offset of 0.5 with 8000A applied, and increase of 4000A. The replicated secondary current is less than the ideal current from cycles 2 through 7. The maximum RMS difference occurs on the 2nd cycle at approximately 25%, with a corresponding maximum resulting differential quantity of approximately 25%.

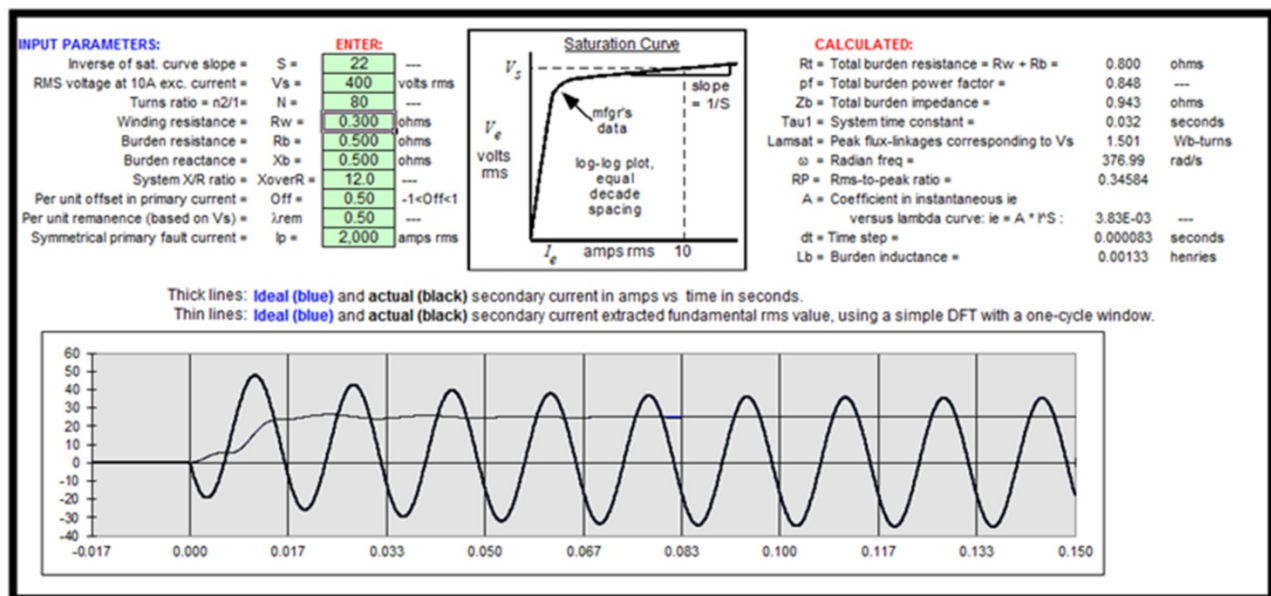


Fig. 2 400:5, C400, R=0.5, Offset = 0.5, 2000A

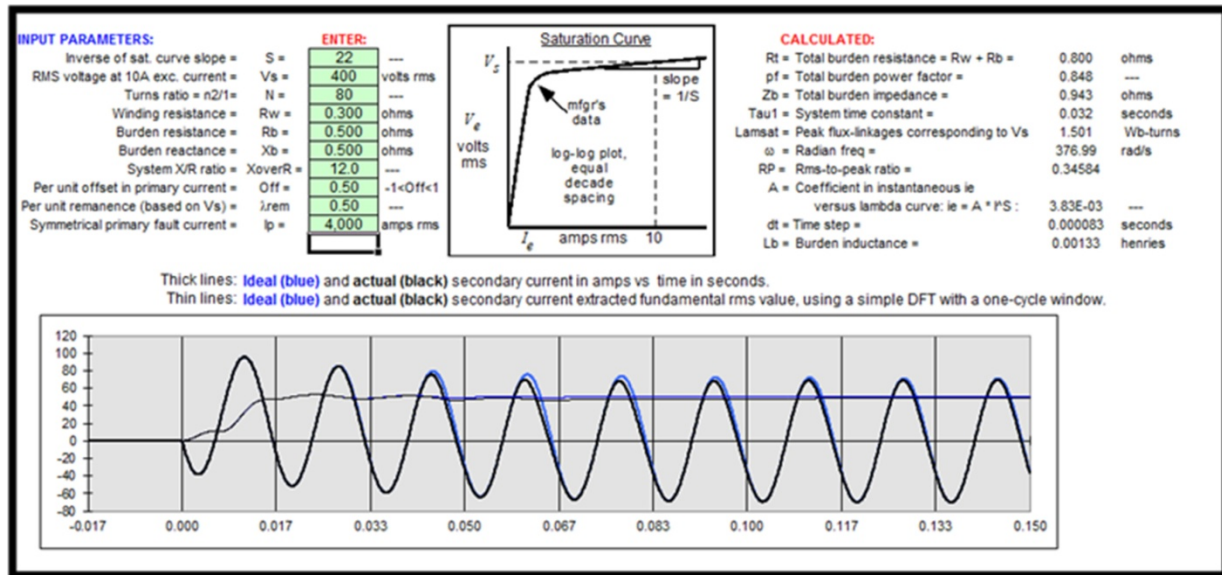


Fig. 3 400:5, C400, R=0.5, Offset = 0.5, 4000A

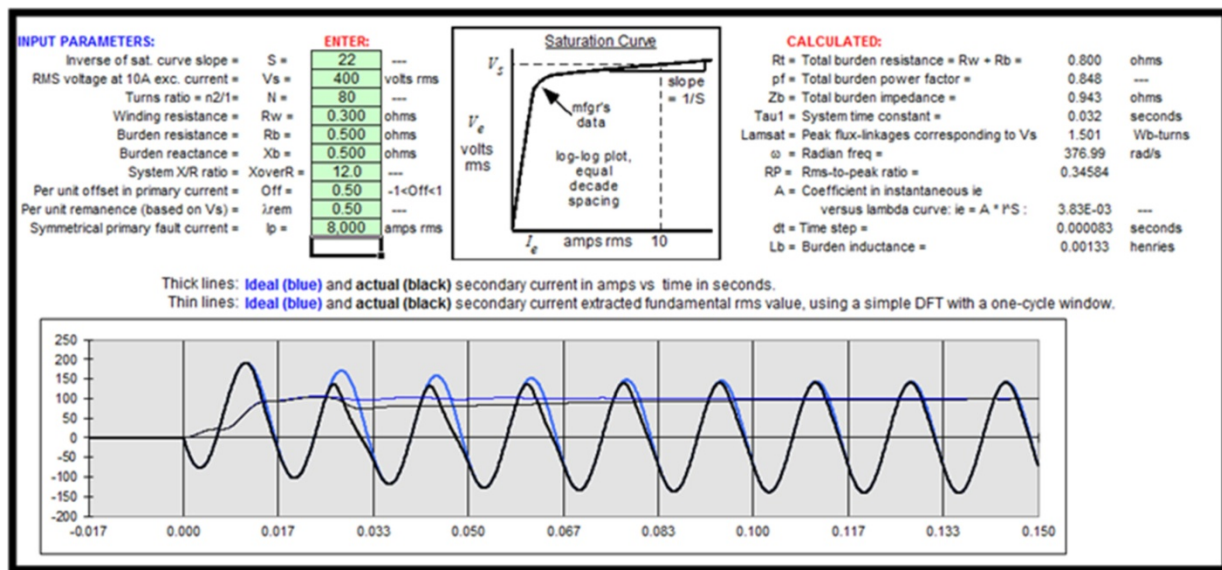


Fig. 4 400:5, C400, R=0.5, Offset = 0.5, 8000A

Figure 5 shows using the CT Saturation Calculator with a C400 400:5 ratio CT having a remanent flux value of 0.5, offset of 0.75 (increase of 25%) with 8000A applied. The replicated secondary current is less than the ideal current from cycles 1 through 7. The maximum RMS difference occurs on the 2nd cycle at approximately 45%, with a corresponding maximum resulting differential quantity of approximately 45%.

Figure 6 shows using the CT Saturation Calculator with a C400 400:5 ratio CT having a remanent flux value

of 0.75 (increase of 25%), offset of 0.75 with 8000A applied. The replicated secondary current is less than the ideal current from cycles 1 through 7. The maximum RMS difference occurs on the 2nd cycle at approximately 50%, with a corresponding maximum resulting differential quantity of approximately 50%.

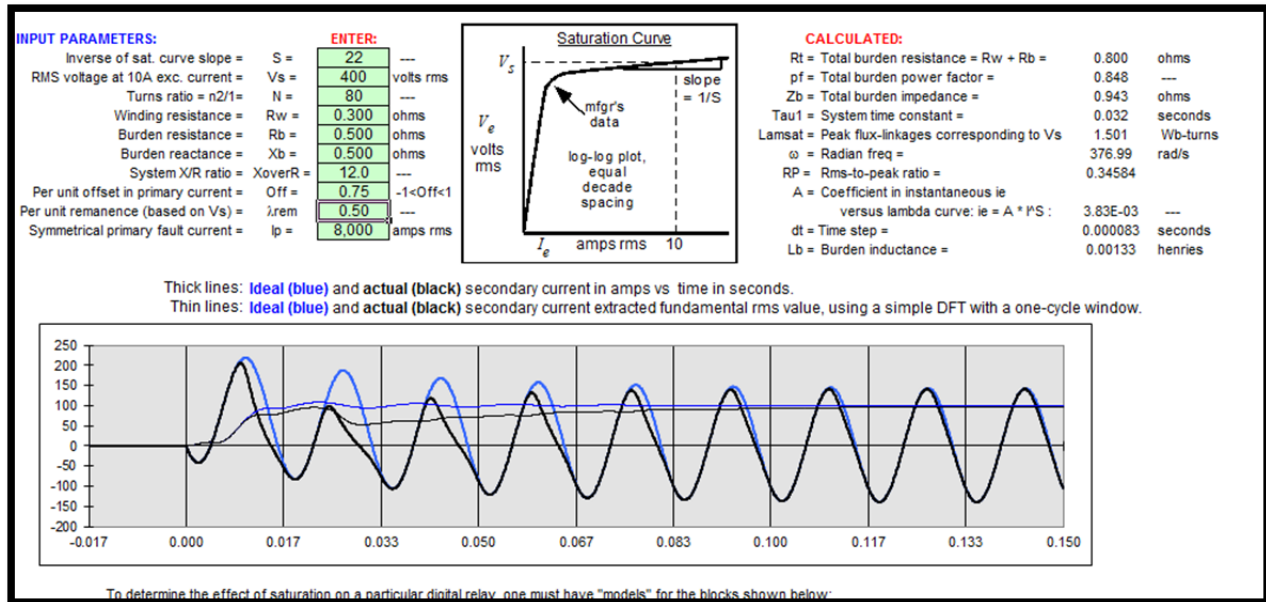


Fig. 5 400:5, C400, R=0.5, Offset = 0.75, 8000A

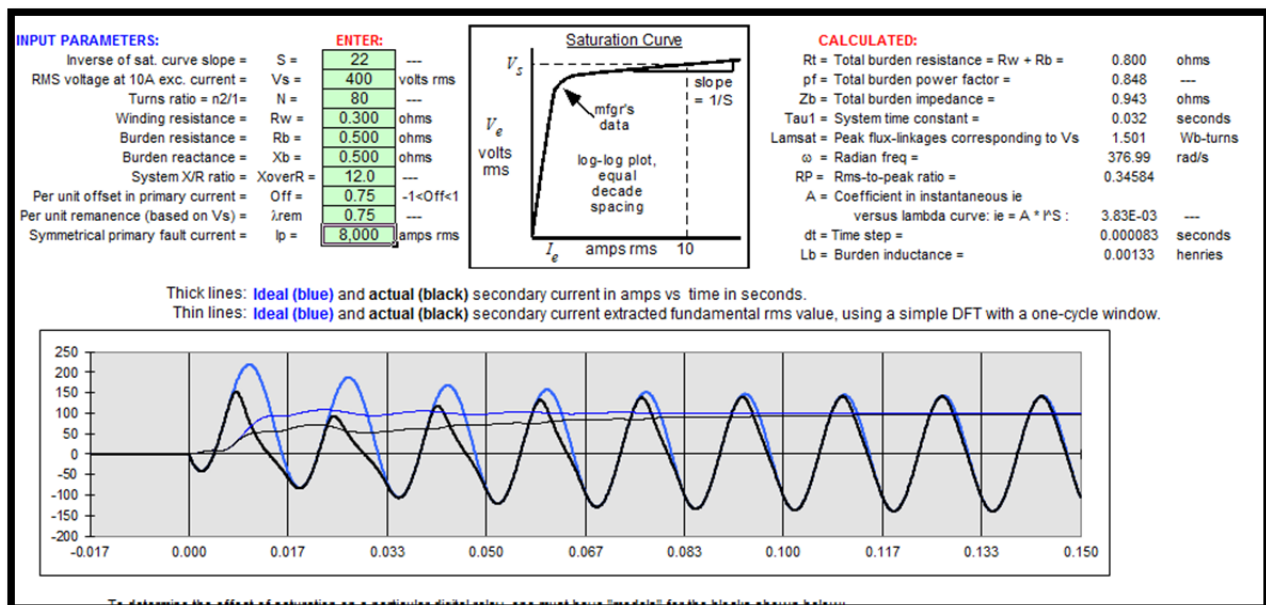


Fig. 6 400:5, C400, R=0.75, Offset = 0.75, 8000A

Armed with such an analysis, the protection engineer can now examine the particular relay's differential element characteristic and develop settings for pickup, slopes and slope change breakpoint to maximize security for external through-faults and maintain dependability for internal faults.

The differential element of the relay under consideration uses the sum of the scalar values for the operating quantity and the sum of the absolute values divided by for the restraining quantity.

$$I_{OP} = \overrightarrow{I_{W1}} + \overrightarrow{I_{W2}}$$

$$I_{RES} = \frac{\sum |I_{W1}| + |I_{W2}|}{2}$$

Table 1 provides a summary of the modeled CT performance and provides quantities for internal faults and external faults.

Assumptions:

- Rated current (full load): 400A = 1 pu
- Maximum through or internal fault current = 20X rated = 20pu

TABLE 1
OPERATING AND RESTRAINT DATA

| Fig | Rated I | Test I | Rated/Test (pu) | % Diff (max) | EXT Op | EXT Res | INT Op | INT Res |
|-----|---------|--------|-----------------|--------------|--------|---------|--------|---------|
| 2 | 400 | 2000 | 5 | 0 | 0 | 5 | 11 | 5 |
| 3 | 400 | 4000 | 10 | 5 | 0.5 | 9.75 | 20.5 | 9.75 |
| 4 | 400 | 8000 | 20 | 25 | 5 | 17.5 | 36 | 17.5 |
| 5 | 400 | 8000 | 20 | 45 | 9 | 15.5 | 32 | 15.5 |
| 6 | 400 | 8000 | 20 | 50 | 10 | 15 | 31 | 15 |

Taking the data in table and plotting for the various modeled simulations, the scatter graph in Fig. 7 displays the following results.

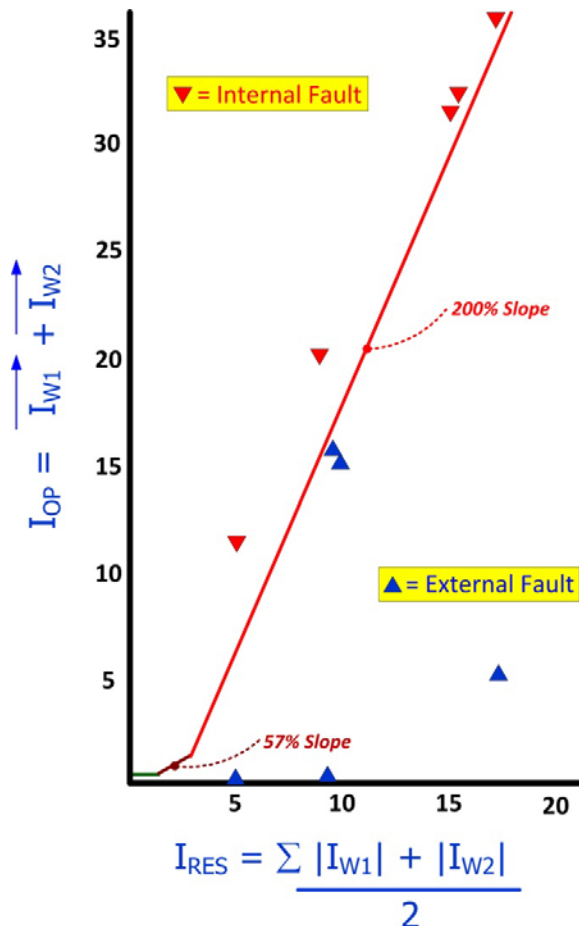


Fig. 7 Modeled Test Plots

From examining the plots for internal and external faults, the following settings result:

Pick up: 0.35pu

This is based on Class "C" CT accuracy of +/-10% at 20X rated current (2 CTs = 20%), plus LTC (load tap changing transformer) error of +/- 10%, plus magnetizing current of 2%, plus 3% margin

Breakpoint for Slope 1: 1.5pu

This is based on an expectation that as current increases in the CTs, the possibility for error increases.

Slope 1: 57%

This was visually curve-fit between the pickup value and slope 2.

This acts to dynamically desensitize the element as the current in the CTs increases

Slope 2 Breakpoint: 3.0pu

This is based on an expectation that as current increases in the CTs, the possibility for error increases.

Slope 2: 200%

This was visually fit with a straight line between the trip and restrain points. Taking two points in the line and using $\Delta \text{rise} / \Delta \text{run} * (100) = \% \text{ slope}$ yields $[20-10] / [10-5] * 100 = 200\%$.

This is based on an expectation that as current increases in the CTs, the possibility for error increases.

For determining the setting of a differential element, the performance of the element should be evaluated at various degrees of saturation for internal and external faults. Relay elements from different manufacturers use different restraining and operating calculations to arrive at restrain and operate decisions, and careful evaluation is recommended.

II. COPING WITH TRANSFORMER INRUSH

Transformers undergo magnetizing inrush for various reasons:

- *Initial energizing inrush* that occurs when the transformer is energized from the completely deenergized state.
- *Sympathetic inrush* that occurs when an energized transformer undergoes inrush after a neighboring transformer energizes. When the neighboring transformer energizes, it rapidly pulls down the system voltage, and as the energizing transformer goes through its inrush period, the voltage rise results in an inrush on the already energized transformer.
- *Recovery inrush* that occurs when an energized transformer undergoes inrush after a fault occurs and is cleared. The fault will cause a step change in the system voltage, and the fault clearing provides a step change in the voltage rise.

Inrush can cause undesirable trips and delay putting a transformer into service as current flowing into a transformer is greater than the current flowing out of it. Magnetizing inrush current is distinguishable from fault current by harmonic components. Traditionally, 2nd harmonic restraint has been applied to prevent undesired tripping of differential elements when challenged by inrush. The amount of 2nd harmonics present in the transformer inrush currents depends upon the magnetizing characteristics of the transformer core and residual magnetism present in the core. Modern transformers tend to have low core losses and very steep magnetizing characteristics, and corresponding lower values of 2nd harmonic are generated. Fortunately, even order harmonics are generated during inrush, not only 2nd harmonic.

Figs. 8a, b, c and d show an inrush waveform in different views. Figure 8a, "Actual," shows the inrush waveform as non-perfect sinusoidal as various harmonics are contained within. Figure 8b, "f," shows the fundamental (60Hz) value). Figure 8c "2nd," shows the second harmonic component of the inrush waveform. Figure 8d "4th," shows the fourth harmonic component of the inrush waveform. Both the 2nd and 4th inrush harmonics are approximately 1/5 the value of the fundamental value.

A security strategy that uses 2nd and 4th harmonic restraint can provide improved security against undesired tripping during inrush periods without sacrificing dependability.

$$I_{RES:2-4} = \sqrt{(I_{RES:2}^2 + I_{RES:4}^2)}$$

The setting of the even harmonic restraint should be set to a low enough value to provide security against misoperation during transformer magnetizing inrush current; it should not be lower than the amount of even harmonics generated during internal fault conditions with CT saturation so as not to compromise reliability for heavy internal fault detection.

Modern transformers tend to have low core losses and very steep magnetizing characteristics. When the relay is applied to this type of transformer, the even harmonic setting should be set around 10% (in some cases, the setting may be lower than 10%).

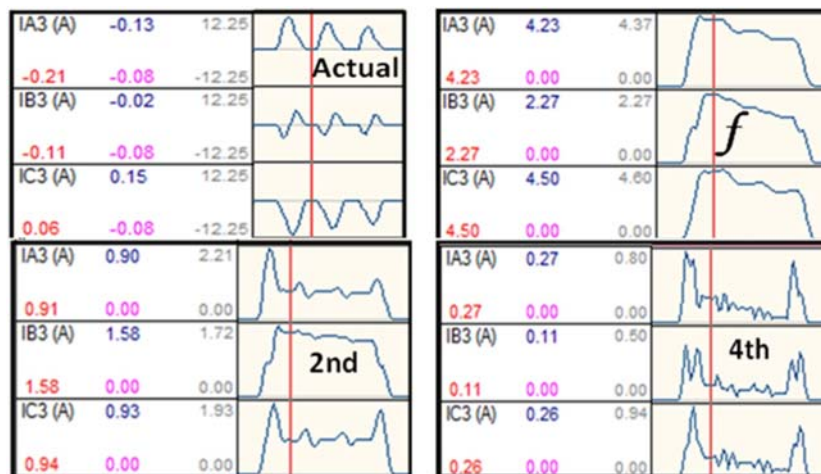
Older transformer designs tend to have higher amounts of even harmonics, where a setting of 15% or greater can provide security against misoperation during magnetizing inrush conditions.

III. COPING WITH TRANSFORMER OVEREXCITATION

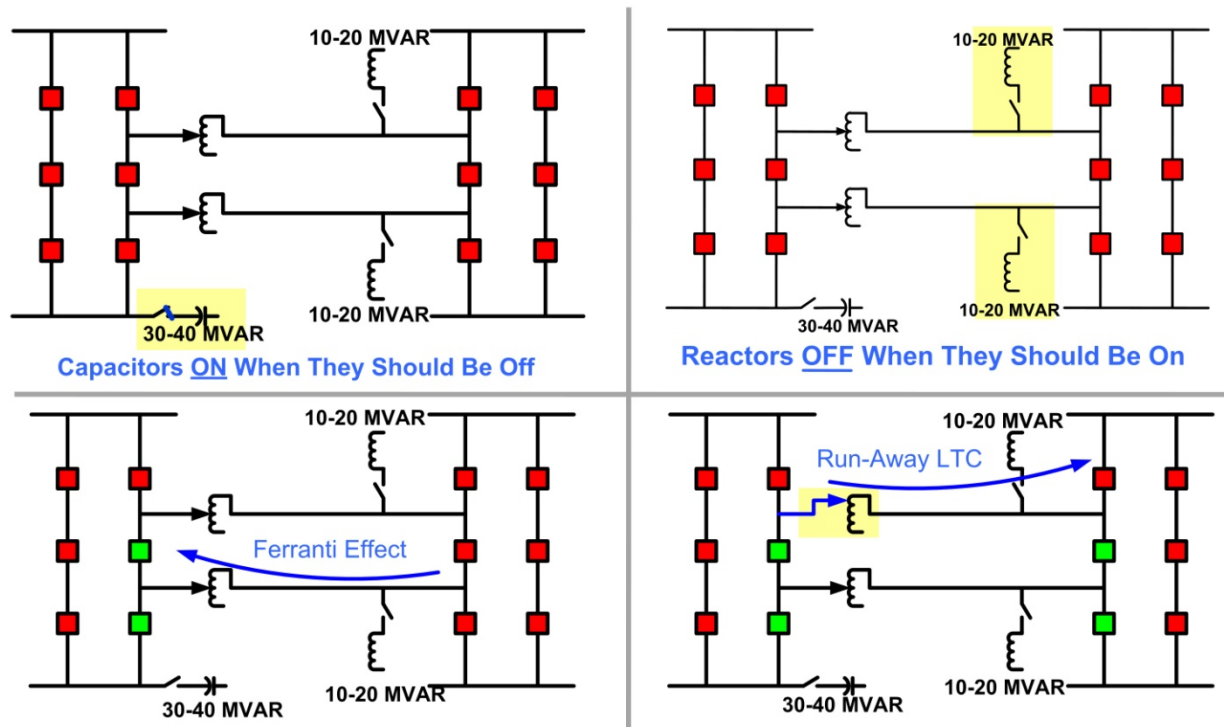
Overexcitation of a transformer can occur whenever the ratio of the per unit voltage to per unit frequency (V/Hz) at the secondary terminals of a transformer exceeds its rating of 1.05 per unit (PU) on transformer base at full load, 0.8 power factor, or 1.1 PU at no load. Overexcitation causes excessive flux to spill over into areas of the transformer. Non-laminated components at the ends of the cores, which were not designed to carry these higher levels of flux, begin to heat up because of the higher losses induced in them. This can cause severe localized overheating in the unit transformer and generator and eventual breakdown in the core assembly or winding insulation.

Overexcitation events are typically associated with generation plants, but can and do occur in transmission and distribution systems. Several possible causes of overexcitation are explored in the Figs. 9a, b, c, and d.

- Fig. 9a: Capacitors switched on when reactive support is not required may cause system overvoltage
- Fig. 9b: Reactors switched off when there is an excess amount of VAR that may cause system overvoltage
- Fig 9c: Breaker failure of one end on a long transmission line creates VAR (Ferranti effect) may cause system overvoltage
- Fig. 9d: A runaway load tap changer (LTC) may cause system overvoltage



Figs. 8a, b, c, d Inrush Currents:
Actual, Fundamental, 2nd Harmonic and 4th Harmonic Levels



Figs. 9a, b, c, d Causes of Transformer Overexcitation

These events can occur without any warning from a failure in the control system or final control elements. Concentrating on differential protection, during a transformer overexcitation event, the excessive flux that spills out of the core appears as a differential quantity. More current enters the transformer input winding than leaves the output(s) winding.

Fig. 10 shows overexcitation events on a transformer where the source breaker was closed, and the load breaker was open. At the left side of the oscillograph, the only current into the transformer is magnetizing current. As voltage increases, current is drawn into the transformers, and none of it leaves on the load winding.

When examining this current, it can be seen to be rich in 5th harmonic content (see Fig. 11).

For differential protection, 5th harmonic restraint has been used to prevent undesired tripping by blocking the

differential element when 5th harmonic is present. An issue with blocking the differential element during overexcitation is if a single-phase fault or two-phase fault occurs in the transformer, and one phase remains unfaulted, the differential element remains blocked.

As overexcitation in transmission and distribution systems is typically caused by the voltage component of the V/Hz value, a transformer is actually more inclined to fault during an overexcitation event as the voltage is higher than rated. It is at this moment that the differential element should not be blocked.

An improved strategy is to raise the pickup of the differential element during an overexcitation event to keep the element secure against undesired tripping, yet allow the element to release if an internal fault occurs during the overexcitation event. See Fig. 12.

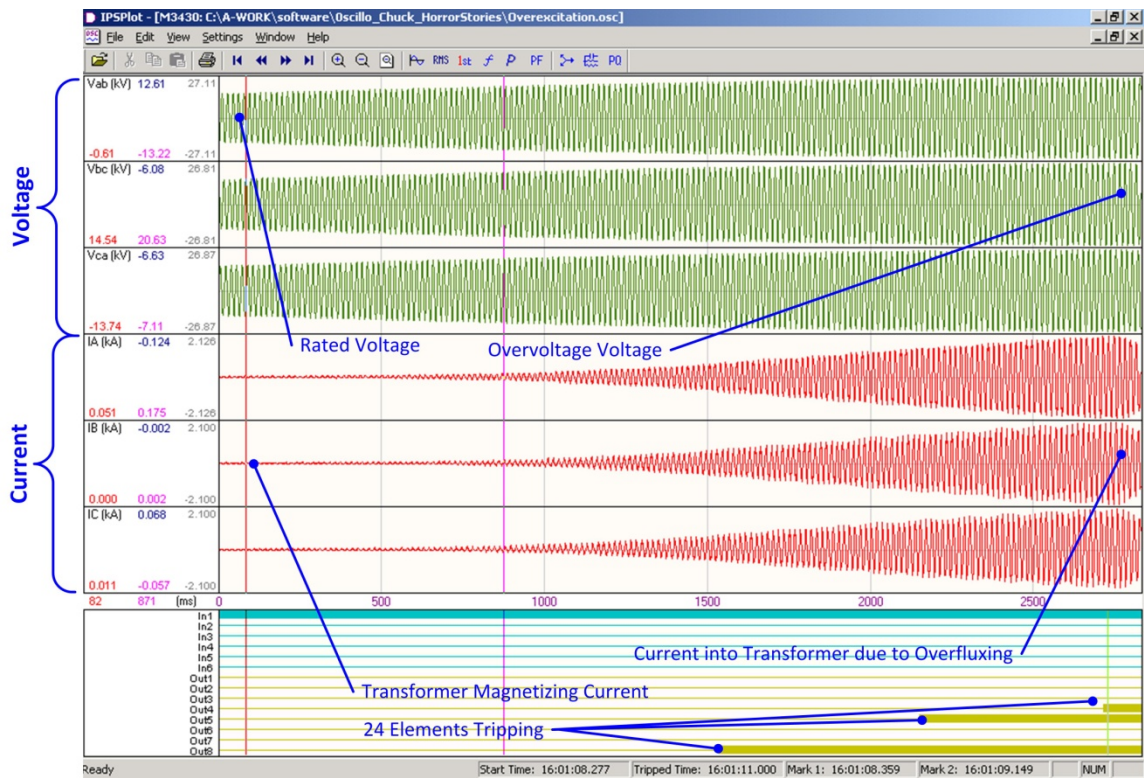


Fig. 10 Overexcitation Event, Current into Transformer

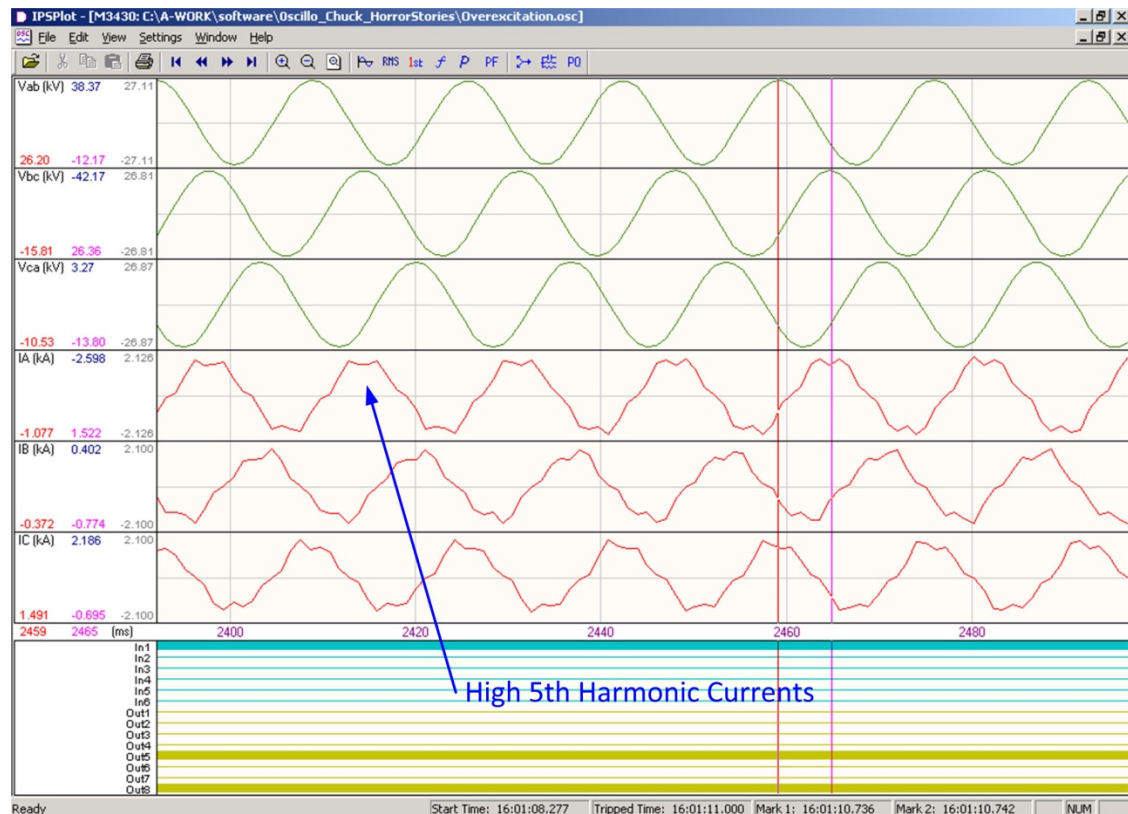


Fig. 11 5th Harmonic Exhibited in Overexcited Transformer Inflow Current

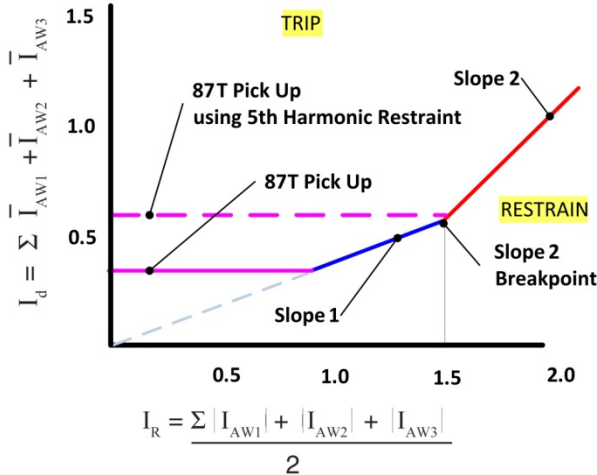


Fig. 12 Adaptive Characteristic for Raising Pickup during Overexcitation

IV. DIFFERENTIAL SENSITIVITY ON RESISTANCE GROUNDED TRANSFORMERS

Resistance grounded transformers are used to limit ground fault current and associated damage. A consequence of using a resistance in the ground of a power transformer is the decreased sensitivity exhibited by the phase differential element to detect ground faults near the transformer neutral. Consider the transformer in Fig. 13.

The multifunction differential relay provides phase differential (87) and ground differential (87G) elements (other elements omitted for simplicity). At 25MVA, the 13.8kV secondary has a nominal rated current of 1047A. With a 1200:5 CT applied and a 400A limited ground, a ground fault involving the full winding would yield $400/1047 = 0.38\text{pu}$. This is at the fringe of the 0.35pu

minimum pickup that would typically be applied to the phase differential element. The phase differential element is essentially blinded to any ground fault using the 0.35pu minimum pickup setting.

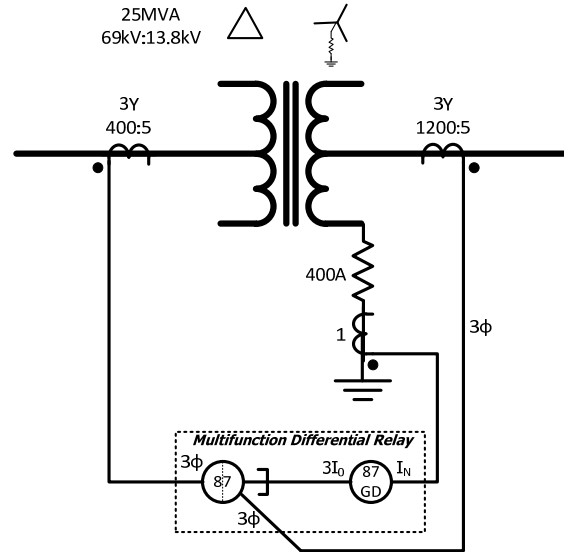


Fig. 13 Example Transformer Application

Fortunately, the ground differential element provides much greater sensitivity, and remains secure against saturation. The ground fault element uses the ground current from the transformer ground CT and compares it to the $3I_0$ from the phases associated with the grounded neutral winding. Figs. 14, 15 and 16 illustrate the principle of operation under various protection challenges.

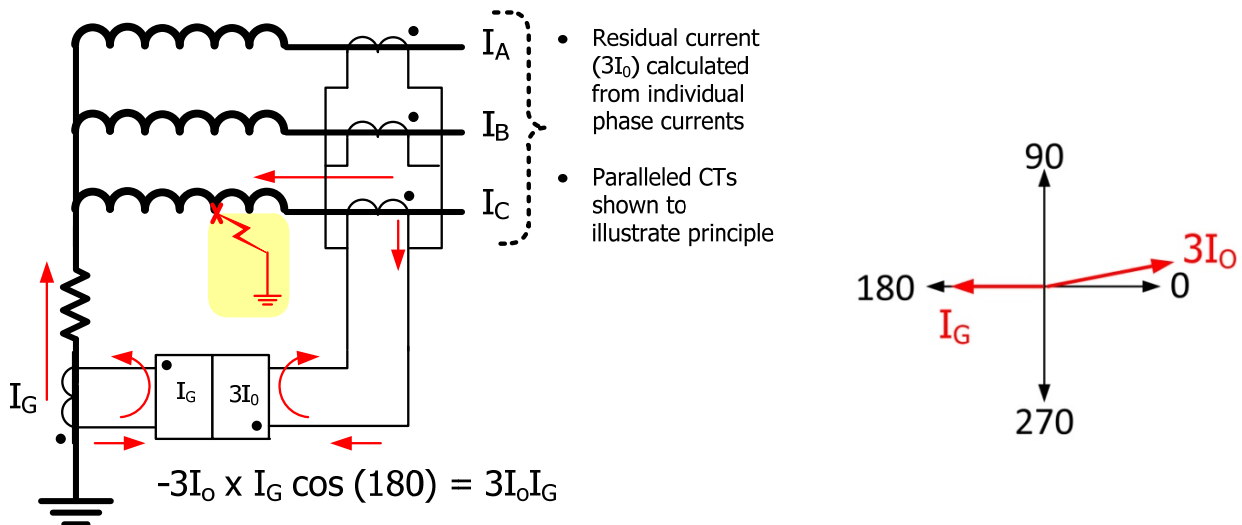


Fig. 14 87GD with Internal Fault, Double Fed

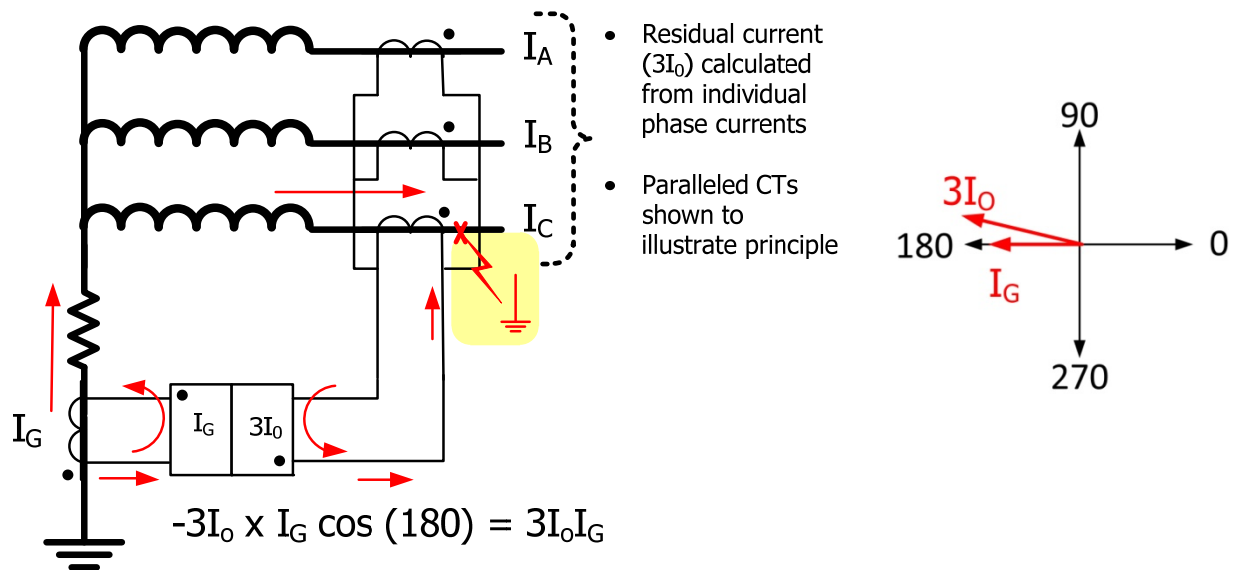


Fig. 15 87GD with External Through Fault

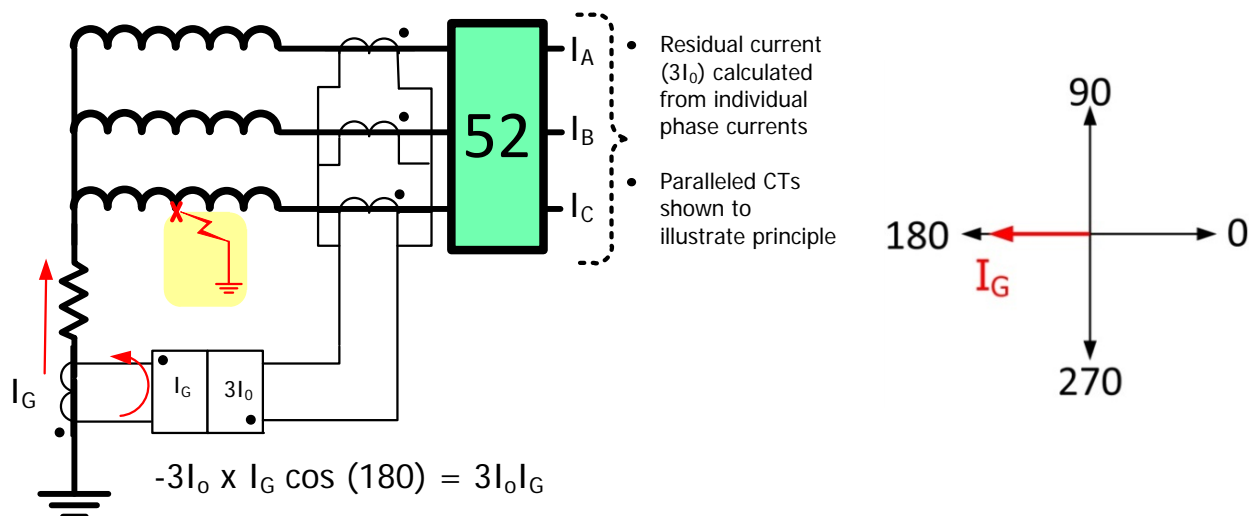


Fig. 16 87GD with Internal Fault, Single Feed

V. SUMMARY AND CONCLUSIONS

Transformer differential protection incurs challenges not found in other differential applications (ex., generator and bus). With proper element design and setting, application challenges regarding security and dependability can be overcome.

1. The operating principle and quantities for restraint and operation should be understood, and an analysis of internal and external faults with various fault current levels, offset and remanent flux levels using an IEEE CT secondary circuit performance model can help determine settings.

2. The use of 2nd and 4th harmonics restraint can provide improved security for all types of inrush phenomena versus use of 2nd harmonic alone.
3. The use of 5th harmonic restraint can be improved by raising the pickup when 5th harmonic from overexcitation is encountered. This enhances dependability from the typical employment of 5th harmonic restraint that blocks the differential element.
4. The use of ground differential to supplement phase differential provides improved sensitivity and dependability to detect ground faults in transformers.

VI. AUTHOR BIOGRAPHY

Wayne Hartmann is a Protection and Smart Grid Solution Manager for Beckwith Electric. He provides customer and industry linkage to Beckwith Electric's solutions, as well as contributing expertise for application engineering, training and product development.

Before joining Beckwith Electric, Wayne performed in application, sales and marketing management capacities with PowerSecure, General Electric, Siemens Power T&D and Alstom T&D. During the course of Wayne's participation in the industry, his focus has been on the application of protection and control systems for electrical generation, transmission, distribution, and distributed energy resources.

Wayne is very active in IEEE as a Senior Member serving as a Main Committee Member of the IEEE Power System Relaying Committee (PSRC) for 25 years. His IEEE tenure includes having chaired the Rotating Machinery Protection Subcommittee ('07-'10), contributing to numerous standards, guides, transactions, reports and tutorials, and teaching at the T&D Conference and various local PES and IAS chapters. He is presently Chair of the PSRC Working Group "Investigation of the Criteria for the Transfer of Motor Buses." He has authored and presented numerous technical papers and contributed to McGraw-Hill's "Standard Handbook of Power Plant Engineering, 2nd Ed."

VII. REFERENCES

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- [2] *Protective Relaying for Power Generation Systems*; Donald Reimert; CRC Press; 2006, ISBN 0-8247-0700-2
- [3] *M-3311A Instruction Book*; Beckwith Electric; 2007
- [4] C37.91-2008 - *IEEE Guide for Protecting Power Transformers*; IEEE Power System Relaying Committee

APPENDIX 1

IEEE CT Saturation Calculator is available at:

http://www.pes-psrc.org/Reports/CT_SAT%2010-01-03.zip

The calculator has explanations of use embedded in the Excel file.

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