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Ferroresonance Studies for Protection Relay Replacement on Generator Relays. Lesson Learned and Straightforward Approach for Mitigation Solutions

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SUMMARY

In this paper, ferroresonance occurrence with respect to generator protection relay replacement has been studied based on several recent projects completed by Tetra Tech. As part of their modernization efforts, many utilities are still in the process of upgrading some of their older substations to transition from electromechanical relays to advanced digital relays. Electromechanical relays impose a considerable amount of burden on the Potential Transformer (PT) circuits and contribute to the dampening of the ferroresonance. Digital relays, on the other hand, offer various Protection and Control (P&C) functionality available in a single relay. However, they also reduce the amount of burden imposed on the secondary of PTs and may lead to ferroresonance on the protection circuits of systems such as the secondary side of a generator Main Output Transformer (MOT).

Although ferroresonance phenomena have been studied in detail in various papers and books, little information is available for industrial applications. Furthermore, these ferroresonance studies mainly require detailed Electro-Magnetic Transient (EMT) studies in which the detailed modeling of the system is required. The detailed system modeling for such a system requires extensive on-site measurements as well as increased simulation time. This additional project time can be avoided through an investigation of the system's modes of operation. The aim of this paper is to provide Tetra Tech's most recent experience on ferroresonance evaluation, and its approach based on standard IEEE. C37. 102 "IEEE Guide for AC Generator Protection". This paper will contain the following elements.

- The comparison between the different burdens on the system
- The power system modes of operation and considerations of system Operation Experience (OPEX)
- The existing and updated Protection and Control (P&C) scheme to determine if any additional functionality may lead to ferroresonance
- Summary of Tetra Tech's most recent ferroresonance studies, approach, and conclusions
- Evaluation on whether EMT simulations are required and their added value to the studies
- List of required information for the EMT studies as well as validity of the simulations and their applications

The outcome of this paper will be a straightforward approach for generating facilities operators to determine the risk of ferroresonance in the system and determine the required studies. In addition, this paper will assist the reader in determining the required data for EMT studies, the accuracy of the results, and their applications. Furthermore, this paper provides mitigation solutions for the systems that are susceptible to ferroresonance. These solutions will be presented based on the system modes of operation.

KEYWORDS

Ferroresonance, Generator protection, Relay burden, EMT studies, Transformer MOT

I. Introduction

Conventional Electro-Mechanical (EM) relays with high burden values have been utilized for decades in various parts of the power systems. Recently, these EM relays are being replaced by multifunction digital relay that impose only a fraction of the burden of their electro-mechanical counterparts. This reduced burden has led to issues with ferroresonance in Potential Transformer (PT) circuits. Several studies have been performed to evaluate the ferroresonance phenomena and mitigation methods including [1] and [2]. Although these studies provide a detailed evaluation of the system behaviour during transients in Electromagnetic Transient (EMT) software, there does not seem to be a lot of papers discussing simplified approaches to the ferroresonance problem. The aim of this paper is to provide Tetra Tech's approach for ferroresonance phenomena evaluation for generator relay replacements. The paper is structured as follows:

1. Ferroresonance phenomena due to generator protection replacement
2. Recommended studies (limitation and advantages)
3. Method 1: Review of the existing system operation modes
4. Method 2: Burden resistance calculation based on industry best practices
5. Method 3: Perform detailed EMT studies to determine burden requirements
6. Recommendation and conclusion

II. Ferroresonance phenomena due to generator protection replacement

Ferroresonance is a type of resonance phenomenon which is complex and usually caused by non-linear inductance and capacitance in an electrical circuit. Ferroresonance is characterized by the sudden departure from normal sinusoidal conditions and the emergence of current spikes reaching magnitudes of typically 2 to 5 per unit values. These current spikes arise from the magnetic cores of transformers or reactors going into brief saturation excursions. Such large current spikes give rise to system overvoltages typically reaching values in excess of 1.5 per unit [3].

Based on extensive research and operating experience acquired within the electrical power industry, it is understood that ferroresonance can occur due to the emergence of any of the following scenarios in an electrical power system:

- Presence of a non-linear inductance (ferromagnetic and saturable) such as a power transformer or a potential transformer (PT).
- Presence of capacitors (Cable capacitance, long lines, capacitor bank, etc.).
- Ungrounded system or partially floating and without fixed potential (isolated neutral, single fuse blowing, single phase switching, etc.).
- Lightly loaded circuit. For example, lightly loaded transformer or PT.

Furthermore, the ferroresonance related overcurrents and/or overvoltages could persist for a prolonged period of time within the system, especially in the absence of appropriate damping measures. These overvoltages or overcurrent could be dangerous to electrical equipment and associated protection systems as they could lead to equipment damage and/or nuisance trips.

Various practical measures exist and can be implemented to prevent ferroresonance from occurring within a system. Some of these methods are as follows:

- Avoid switching operations and configurations susceptible to ferroresonance.
- Ensure that system parameter values are not within the range to initiate the ferroresonance (even temporarily)
- Ensure that the energy supplied by the source is insufficient to sustain the ferroresonance phenomenon. This consists of introducing losses which dampen out the ferroresonance when it occurs.

III. Recommended studies (limitation and advantages)

In general, there are three studies that can be considered for generator relay replacement ferroresonance evaluation.

1. Method 1: Review of the existing system operation modes
2. Method 2: Burden resistance calculation based on industry best practices
3. Method 3: Perform detailed EMT studies to determine burden requirements

Table 1 compares the proposed methods based on the complexity of the study, required information, results accuracy, and applicability. As shown in Table 1, the first method is only applicable if there is enough information supporting the fact that the ferroresonance is not a concern while considering relay replacement (this is further explained in section 0). This method requires less information compared to other methods. In Method 2, the required burden for ferroresonance damping can be designed using best industry practices and formulas (this is further explained in section 0). Method 3 is the most detailed study and can provide a more accurate value for the required mitigation method. Although this Method is more accurate than the other two, an extensive amount of information is required as well as additional site measurements (This Method is further explained in Section VI). There is also a possibility that some of the information required for the study is not available. Hence it is expected that typical parameters will be used which consequently provide conservative results. When only typical values are available, method 2 will require less study hours while providing acceptable results.

Table 1 The advantages, disadvantages, and applicability for each approach

	Complexity of the study	Required information	Results accuracy	Applicability
Method 1	Low	Minimum	High	Only when ferroresonance is not expected
Method 2	Medium	Minimum	Medium	When standard information is used. Conservative results
Method 3	High	Extensive	High	When detailed circuit information is available.

IV. Method 1: Review of the existing system operation modes

The first step when performing Ferroresonance studies for relay replacement of a generator unit is to review the existing system operation modes and determine if, during any operation mode, the generator unit will be ungrounded. This practice is required to evaluate if the IEEE C37.102 [4] requirements for ferroresonance are met.

As per IEEE C37.102 section "5.2.2.1. VT ferroresonance and grounding", it is understood that ferroresonance may occur when wye-wye VTs with grounded primaries are connected to an ungrounded system as shown in

Figure 1

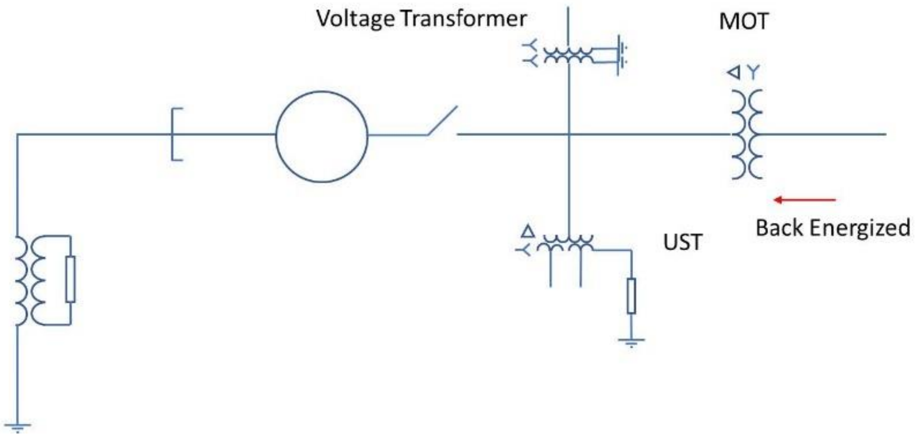

Figure 1 Generator zone configuration that may produce VT Ferroresonance

This condition may occur in the generator zone if either of the following scenarios occur:

- The generator is energized while the generator neutral becomes disconnected and the PTs are left connected to the delta winding of the unit transformer
- The generator is electrically disconnected and the MOT is energized from the grid while the PTs are left connected to the delta winding of the unit transformer

Under any of the above scenarios, if a ground fault or switching operation occurs on the high voltage side of the MOT, the PT may operate in the saturation region which could lead to ferroresonance.

As discussed above, this analysis should be conducted at the early stages of the study to determine the scope of work and avoid any additional studies. The Single Line Diagram (SLD) of the interconnected system and the generating station needs to be reviewed in detail along with the generator operating manual/s. Three scenarios are expected in this study:

- No operation mode satisfies the IEEE C37.102 ferroresonance requirements: The relay replacement should not impose a risk of ferroresonance, and no further studies are required.
- One Operation mode satisfies the IEEE C37.102 ferroresonance requirements: Either remove the mode of operation (if applicable) and update the operation manuals or move to Methods 2 or 3
- Some Operation modes satisfy the IEEE C37.102 ferroresonance requirements: Move to Method 2 or 3

V. Method 2: Burden resistance calculation based on industry best practices

After reviewing the SLD and modes of operation, if presence of ferroresonance is found to be possible, the required additional burden on the new digital relays can be calculated as follows:

a. One method commonly used for sizing damping resistors is taking the calculated burden removed from the system due to the removal of electromechanical relays and subtracting the burden introduced into the system with the addition of the new microprocessor relays. The balance value is the size of the damping resistor required to ensure that the system with the new relays will behave in the same manner as the original.
b. Another method used for the calculation of damping resistor size is the industry recognized damping resistance calculation formula below. The formula is based on the size of the PT [5, 6, 7, 8]:

$$R = \frac{U_S^2}{KP_t - P_m}$$

Where:
R: Resistance
U_s: Rated secondary voltage (V).
k: Factor (0.25 or 1) such that errors and service conditions remain within the limits specified in CAN/CSA-C61869-3:14.
Pt: PT maximum protection accuracy rating (VA).
Pm: Power required for measurement (VA).

The more conservative damping resistor value as calculated from the two methods described above will be applied to each of the Potential Transformers. The more conservative value will be the value with a lower resistance given that the damping resistors are installed in parallel with the new relay. This is due to the lower resistance absorbing more energy under a voltage source and providing a faster dampening response to any potential ferroresonance.

While performing the calculation one should consider the following in the final value selection. Please note that there will be two values achieved for the resistance based on the value of k (25% and 100%). These values can be selected while keeping in mind the following factors:

- Required accuracy rating of the PT: The total added burden power (Watt) should not exceed the PT accuracy
- Thermal Rating of the PT: The total added burden power (Watt) should not exceed the PT thermal rating)
- Percentage error of the PT should not be exceeded (can be obtained from the PT nameplate)

The added burden should be in service when the Main Output Transformer (MOT) circuit is ungrounded and should be removed from the system in normal operating conditions. Figure 2 shows the initial design with electro-mechanical relays while Figure 3 shows the burden connection to the new system with damping resistors added.

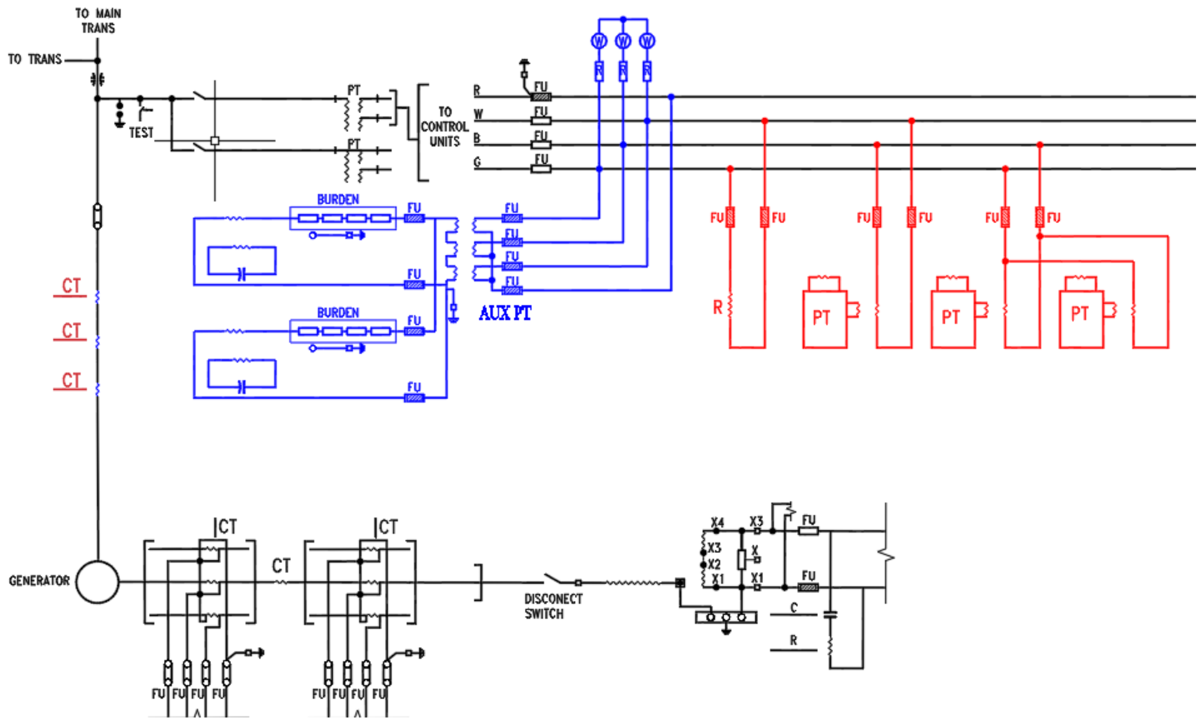

Figure 2 Generator Protection of the Existing System

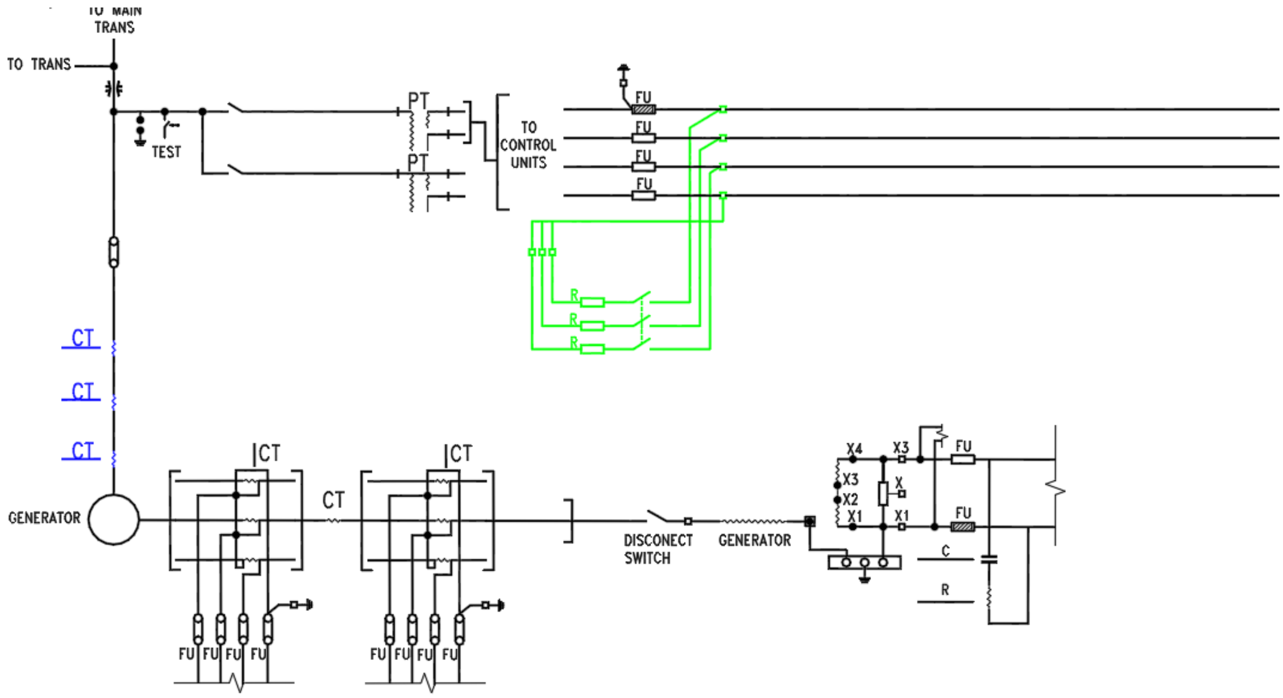

Figure 3 Generator Protection of the New System

VI. Method 3: Perform detailed EMT studies to determine burden requirements

In cases where EMT studies are proposed to calculate the new burden, the following information is required:

- PT saturation curves
- Transformer Capacitances
- Transformer impedances
- Transmission line parameters (conductor, spacing, tower configuration)
- Existing burdens on the system
- MVA short circuit rating at the Point of Interconnection (POI)

Among the above-mentioned information, the transformer capacitances and saturation curves play a vital role in the study and have a greater impact on the results. Based on Tetra Tech's experience on various project, these values are not always available and additional site tests might be required. If the values cannot be determined, conservative values can be achieved by using typical parameters (Found in IEEE C37.011). If typical parameters are used, it is recommended to use method 2 described above. There will not be a significant gain in accuracy when preparing a detailed EMT analysis based on assumed values.

VII. Recommendation and conclusion

Tetra Tech has performed several similar projects and compared each approach in terms of their applicability and accuracy. It has been determined that, in several cases, detailed studies are not required and that the burden reduction may not introduce a ferroresonance risk to the system. The possibility of ferroresonance can be determined by detail evaluation of the existing system operation mode, system grounding, MOT winding configurations, and generator grounding during transients. In addition, although the EMT studies can provide extensive analysis of the system, in many cases, the required information is not available. Hence, typical values will be used to determine a conservative burden value. In cases where values are not available for the detailed study, it is preferable to use the calculations detailed in Method 2.

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