The Impact of Solar Storms on Protective Relays for Saturable-Core Transformers

Rui Fan[1], *Student Member, IEEE,* Yu Liu[1], *Student Member, IEEE,* Aniemi Umana[1], *Member, IEEE,*
Zhenyu Tan[1], *Student Member, IEEE,* Liangyi Sun[1], *Student Member, IEEE,* and Yiran An[2]
[1]School of Electrical and Computer Engineering, Georgia Institute of Technology, USA
[2]State Grid Shanghai Pudong Electric Power Supply Company, China
Email: rfan7@gatech.edu

***Abstract*- Solar storms often cause transient variations in the Earth's magnetic field. These storms are called geomagnetic disturbances (GMDs). GMDs can generate quasi-direct geomagnetically induced currents (GICs) through the neutral connections of transformers and transmission lines at the affected regions. GICs are quite detrimental to transformers because they can saturate transformer cores and generate harmonics in the windings. Power Transformers are typically protected by the commercial relays in which several protective functions are implemented. When GICs flow through a transformer, the protective relays for the transformer may be affected. Studies have shown the impact of solar storm includes reactive power loss, voltage fluctuation, and transformer heating. In this paper, numerical simulations are conducted to study the impact of solar storms on the protective relays for saturable-core transformer. Also, the commonly applied transformer protection functions in commercial relays are investigated in relation to GICs. The results indicate that the protective relays may not provide adequate protection for the transformers in the presence of solar storms.**

***Index Terms*- Solar Storms, geomagnetically induced currents (GICs), transformer saturation, protective relays**

I. INTRODUCTION

Geomagnetic disturbances (GMDs) are the transient variations in the Earth's magnetic field that are caused by the solar storms or coronal mass ejections [1]-[2]. Solar storms release large amount of charged particles, which travel about 1 to 3 days until they get to the Earth [3]. The charged particles cause short-term variations in the Earth's magnetic field and induce earth surface potentials (ESPs) with values up to 10 volts/km or higher [4]. The ESPs in turn produce geomagnetically induced currents (GICs) through the neutral connections of transformers and transmission lines in the vicinity of the affected regions. The frequency of GICs are typically below 1 Hz, therefore GICs are considered quasi-direct or direct currents for the purposes of electric grid analysis. The quasi-direct GICs can saturate transformer cores and generate harmonics in the windings, causing detrimental effects such as reactive power losses, voltage fluctuations, and transformer heating [5]-[6].

The magnitude of GICs recorded on the neutrals of transformers, and the frequency of occurrence are considerably larger than anticipated [7]. Researchers had pointed out that solar storms may be the major cause of transformer problems from 1980 to 1994. There were also records indicating that the transformer failures at the Eskom network of South Africa were caused by solar storms in late October and early November of 2003 [8].

High-voltage transformers are especially vulnerable to the geomagnetic disturbances caused by solar storms. The low resistivity of high-voltage transformer makes it easier for GICs to find an electric path. Moreover, the quasi-direct GICs draw increases magnetizing current, which can lead to core saturation and the generation of harmonics in the windings. The core saturation and harmonics in the windings make protecting the transformer with traditional relays challenging. Transformer heating is another problem caused by the GICs. The increased magnetizing currents result in increased copper losses (i^2R) in the transformer windings. Excessive eddy-current losses are also experienced in the transformer cores due to the harmonics. The increased temperature in the transformer could cause thermal protection relays to trip.

The detrimental impact of solar storms on transformer protective relays is twofold. First, severe GICs may saturate the transformers, generating an unbalanced differential current. If the differential current is higher than the setting, the percentage-differential relays would tend to mis-operate (which is not necessary) during normal operations [9]-[10]. Second, many transformer protective relays are implemented with harmonic-restrained differential protective functions. The purpose of these functions is to prevent unnecessary, false-tripping during transformer energization. However, since the harmonics caused by GICs depend on the severity of the GMDs, strong GMDs may significantly increase the second or fourth harmonic levels in the harmonic-restrained differential relays. If the levels are higher than the relay settings, correct trip signals could be blocked during transformer internal faults.

To analyze the impact of solar storms on saturable-core transformer relays, appropriate model of transformers are necessary to study the cores saturation caused by GICs [11]. In this paper, the transformer cores are modelled with highly non-linear equations to represent the non-linear magnetization characteristics. If GICs flow into a transformer, its core will saturate in a manner consistent with its non-linear models. Studies of the solar storm impact are conducted based on the presented non-linear transformer model. Specifically, numerical simulations are performed to study the impact of a solar storm on 500kV three-phase transformers. Several commonly used protective strategies have been summarized in this paper to show the effects of solar storms on transformers relaying system.

This paper is organized as follows. In Section II, the non-linear models of saturable-core transformers are introduced. In Section III, the transformer relay functions are discussed. The numerical simulations on three-phase high-voltage transformers are presented in Section IV and in Section V the conclusion is discussed.

II. Non-linear Model of Saturable-Core Transformers

Transformers are commonly treated as linear models. However, to study the impact of GICs, the non-linear model is presented in this section to mimic actual core saturation conditions. For simplicity, the non-linear model is introduced using a single-phase, two winding transformer, as is shown in Figure 1. Obviously, this single-phase, non-linear model can be easily generalized to three-phase multi-winding transformers.

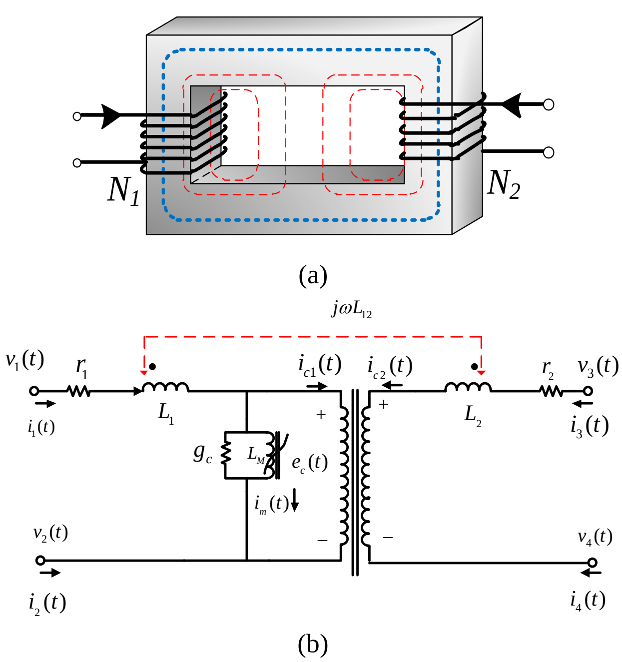

Figure 1. Single-phase transformer model: (a) two-winding transformer, (b) equivalent circuit.

The model of the single-phase saturable-core transformer is represented with following differential algebraic equations:

$$i_1(t) = i_{c1}(t) + i_m(t) + g_c e_c(t) \tag{1}$$

$$i_2(t) = -i_{c1}(t) - i_m(t) - g_c e_c(t) \tag{2}$$

$$i_3(t) = i_{c2}(t) \tag{3}$$

$$i_4(t) = -i_{c2}(t) \tag{4}$$

$$0 = v_1(t) - v_2(t) - r_1 i_1(t) - L_1 \frac{di_1(t)}{dt} - L_{12}\frac{di_3(t)}{dt} - e_c(t) \tag{5}$$

$$0 = v_3(t) - v_4(t) - r_2 i_2(t) - L_2 \frac{di_2(t)}{dt} - L_{12}\frac{di_1(t)}{dt} - \frac{N_2}{N_1} e_c(t) \tag{6}$$

$$0 = e_c(t) - \frac{d\lambda(t)}{dt} \tag{7}$$

$$0 = N_1 i_{c1}(t) + N_2 i_{c2}(t) \tag{8}$$

$$0 = i_m(t) - i_0 \left| \frac{\lambda(t)}{\lambda_0} \right|^n sign\left(\lambda(t)\right) \tag{9}$$

where $v_{1\sim4}(t)$ and $i_{1\sim4}(t)$ are the terminal voltages and currents respectively. The terms: $r_1, r_2, L_1, L_2, L_{12}$ are the corresponding resistances, inductances and mutual inductance. N_1 and N_2 are the number of turns at the primary and secondary sides, g_c is the excitation conductance, $i_m(t)$ is the magnetizing current and $\lambda(t)$ is the flux linkage through the iron core. Lastly, i_0 and λ_0 are the equation constants, n is the exponent, and $sign$ is the sign of function.

The transformer core model is represented by equation (9), which is highly non-linear. For typical materials used for transformer cores, the exponent n can be in the order of 11 to 13, resulting in a profound non-linearity [12]. By adopting this non-linear model of the core, non-linear magnetization characteristics when the GICs go through the transformer is accurately represented.

III. Protective Functions of Transformers Relays

Transformer are critical components of the power system network. Therefore, these transformers, depending on the size, are often protected with advanced protective relays. These transformer relays, especially the microprocessor-based relays, are equipped with multiple protection functions [13]. The most commonly used protective functions include percentage-differential function, harmonic-restrained differential function, negative-sequence differential function, overcurrent function, thermal protective function and Gas-and-pressure protective function. This protective functions of the transformer relays are summarized next.

The percentage-differential protection scheme is one of the most popular legacy transformer protection schemes, as shown in Figure 2. It monitors the currents coming to the transformer and calculates the operating current $I_{op} = \left|\vec{I}_{s1} + \vec{I}_{s2}\right|$ and restraining current $I_{res} = \frac{1}{2}\left|\vec{I}_{s1} - \vec{I}_{s2}\right|$, where I_{s1} and I_{s2} are the secondary currents of CTs on the terminals of the single phase transformer, respectively. Ideally, the operating current I_{op} remains zero unless an internal fault occurs. However, the existence of variable-tap transformers and instrumentation errors make this simple criterion inappropriate for practical applications. To overcome this problem, a minimum pickup current $I_{\min}$ and differential ratio $K = I_{op} / I_{res}$ are introduced. The transformer is only tripped if (1) $I_{op} > I_{\min}$; and (2) the ratio $K = I_{op} / I_{res}$ exceeds a certain threshold.

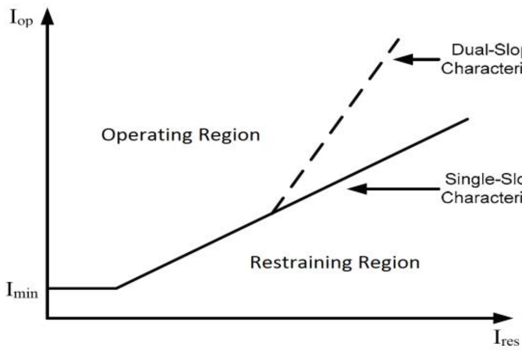

Figure 2. Percentage-differential protection method

Harmonic-restrained differential protection monitors the 2nd or 4th harmonic level in the operating current, in addition to all the quantities that percentage differential protection function monitored. It blocks any trip signal if the harmonic levels are higher than the settings to avoid relay mis-operation during transformer normal energization.

Negative-sequence differential protection is based on the fact that internal faults create disturbances of the symmetry of transformer terminal currents [14]. Similar to the percentage-differential protection, this method uses the negative-sequence operating current $I_{op(Q)}$ and negative-sequence restraining current $I_{res(Q)}$ of transformer to make trip decisions. The negative-sequence differential protection only trips the transformer if (1) $I_{op(Q)} > I_{\min(Q)}$; and (2) the ratio $K_{(Q)} = I_{op(Q)} / I_{res(Q)}$ exceeds a preset threshold.

The overcurrent protection is also widely used for transformer protection. It is set to trip the transformer if the values of the terminal currents exceed the pickup current for a duration determined by the inverse/definite time curve.

Thermal protection is used to protect the transformer from excessive heat, which would be detrimental to the transformer windings. This heat could be due to overload conditions, over-excitation or a malfunctioning transformer cooling system. If the temperature heat exceeds the setting, this function will trip the transformer.

Gas-and-pressure relays monitor the accumulation of gas and sudden change in pressure inside the transformer tank to detect the internal faults. A combined gas-accumulator and pressure relay, called the "Buchholz" relay, has been in successful service for over 70 years.

IV. Numerical Simulations and Results

Numerical simulations have been performed to study the impact of solar storms on high-voltage saturable-core transformers protective relays, as shown in Figure 3. The 500/115 kV three-phase transformers, connected with a 300 km transmission line are presented with the aforementioned non-linear model. Solar storms generate the induced earth surface potential (ESP) with a value of 2 volts/km. It should also be noted that 2 volts/km is far from the extreme levels of induced ESPs, which could have values as high as 10 volts/km.

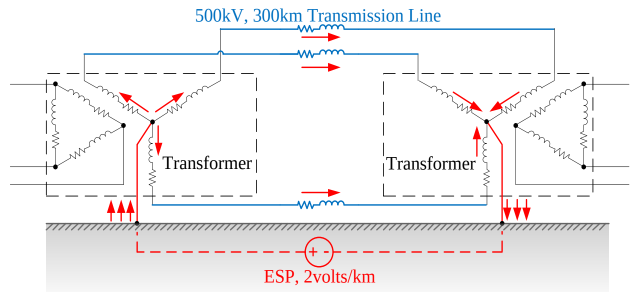

Figure 3. Test system for numerical simulations

The currents that flow in the network depends on both the induced voltage between the neutral grounding points of the two 500 kV transformers, and the resistances of transmission lines, transformers and their groundings. The parameters of transformers and transmission lines are listed on Table I and Table II.

Table I. Transformer parameters

Power Rating (MVA)	400
Voltage (kV)	115/500
Leakage Reactance (p.u.)	0.10
Resistance (p.u.)	0.02

Table II. Transmission lines parameters

Power Voltage (kV)	500
Length (km)	300
Resistance per Phase (Ohms/km)	0.059
Inductance per Phase (mH/km)	1.67

Several commonly used protective strategies have been selected to protect the transformer. The simple percentage differential function is not applied for transformer protection because of the danger of undesirable tripping on inrush. While the gas-and-pressure model is too complicated that it is not included as well. The corresponding transformer relays have the following settings: (a) harmonic-restrained differential protection: the percent differential threshold setting is 20%, the minimum pickup operating current is 10A (referred to the primary side) and the 2nd harmonic blocking level is 20%; (b) negative-sequence differential protection: the percent differential threshold setting is 20%, the minimum pickup operating current is 1.0A (referred to the primary side); (c) time-overcurrent protection: the pickup current referred to the primary side is 1200 A and the time dial is 0.1 and very inverse; (d) thermal protection: the temperature limit is 105℃. The simulation results are used to analyze the impact of solar storms on the transformer and the associated protective relays as follows.

A. Core saturation and harmonics in the windings

Core saturation: The transformer terminal voltage and current (with and without GICs) are shown in Figure 4. The blue dash lines represent the transformer terminal voltage and current measurements at normal operations; while the red solid lines represent those measurements under the influence of GICs. The voltage and current waveforms are pure sinusoids when the transformer is operating under normal conditions. When the quasi-direct GICs flow through the transformer, obvious distortions occur to the waveforms because of the cores saturation.

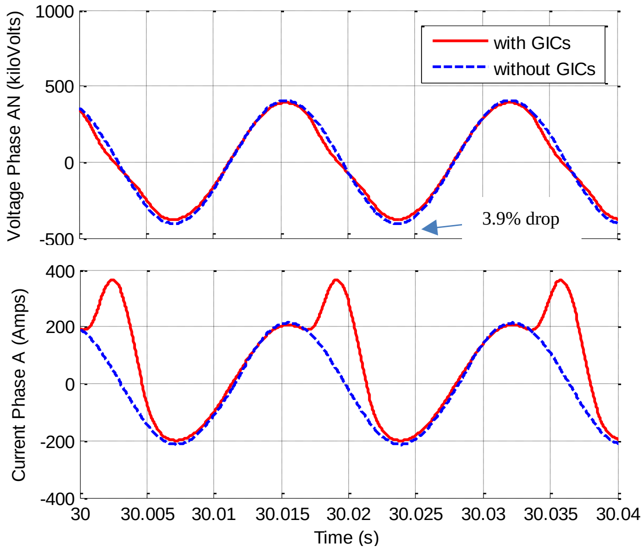

Figure 4. Impact of solar storms on transformer core saturation

Harmonics in the windings: The saturated transformer contains large amounts of even and odd harmonics as a result of the solar storm. The fundamental value and 2^{nd} through 7^{th} order harmonics are shown in Figure 5. These harmonic levels in transformer terminal currents are very high. The 2^{nd} harmonic is about 30% and the 3^{rd} harmonic is about 20%. These harmonics are extremely harmful to the transformer.

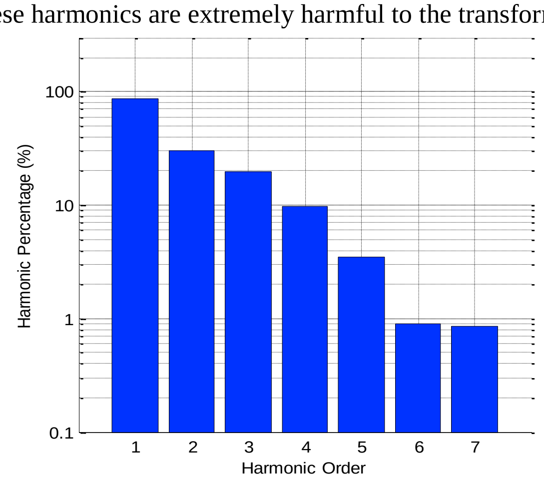

Figure 5. Harmonic in transformer currents

B. Impact on transformer protective relaying functions

In this part, a 10 % winding fault near the neutral terminal occurs on the transformer at 10.03s, during the solar storm period. The performance of the transformer protective functions are presented next.

Harmonic-restrained differential protection: The results of harmonic-restrained differential protection are also shown in Figure 6. The operating current is about 126 A, which is larger than the 10A setting. The restraining current is about 172A. The differential percent is 73%, which is also more than the 20% setting. However, the 2^{nd} harmonic levels in the operating current is higher than the 20% setting, which means this function will block the trip signal. Therefore, the harmonic-restraint differential protection will not falsely trip the transformer before the winding fault occurs. However, when the 10% winding fault actually takes place, the transformer trip command is still be inhibited by this harmonic relay, thereby preventing the transformer from being tripped.

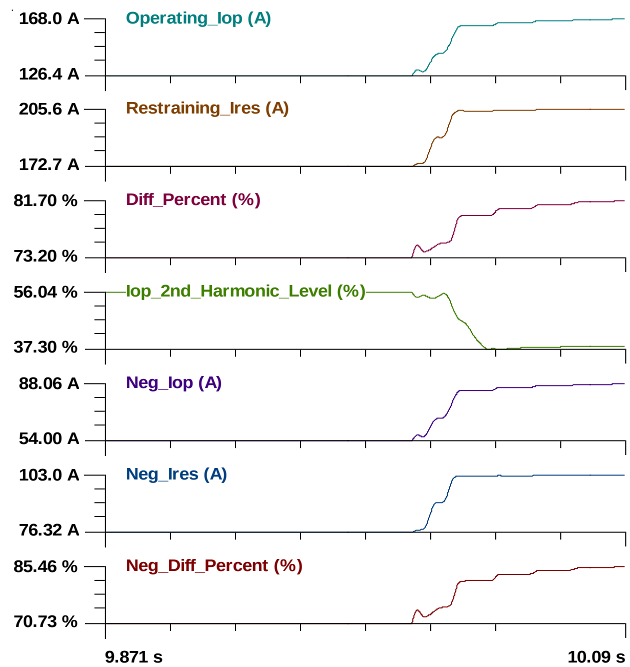

Figure 6. Percentage differential, harmonic-restraint differential and negative-sequence differential protection results

Negative-sequence differential protection: The results of negative-sequence differential protection are also shown in Figure 6. The situation for negative-sequence differential protection in this event is very similar to the percentage differential protection function. As shown in Figure 6, the negative-sequence operating current and differential percent are always higher than the settings. Therefore, this function will falsely trip the transformer before the fault occurs.

Time-overcurrent protection: The result of overcurrent protection is shown in Figure 7. Before the winding fault occurs, the RMS value of transformer primary-side current is about 188 A, which is less than the setting (1200A). When the 10% winding fault occurs, the RMS value goes up to 257A, which is still below the setting. Therefore, this protection function does not offer adequate, sensitive protection for this type of internal fault.

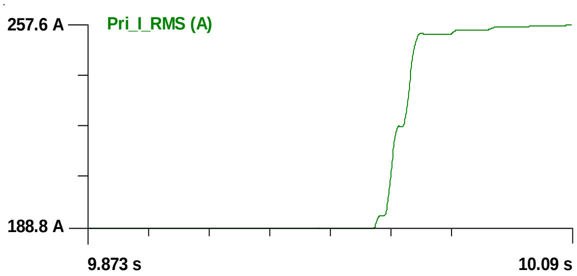

Figure 7. Result of overcurrent protection

Thermal protection: The result of thermal protection is shown in Figure 8. During the entire solar storm period, the temperature of transformer is continually rising. There is only minimal change in temperature when the fault occurs. The temperature is below the 105 °C setting, thus thermal protection function cannot trip the transformer when the fault is initiated.

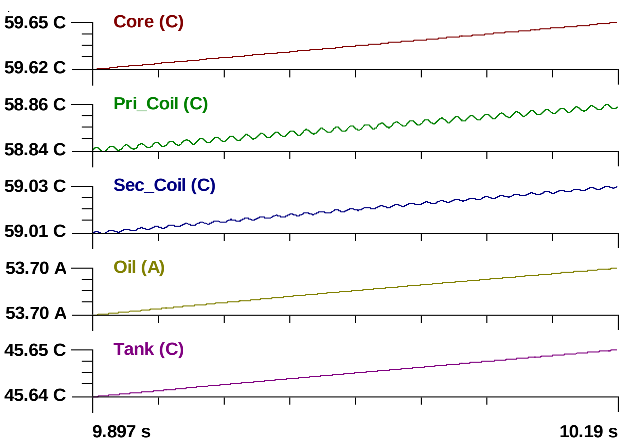

Figure 8. Result of thermal protection

The tripping decision of the transformer protective relay is dependent on the summary of all the above protective functions. Before the fault occurs, some protective functions tend to falsely trip the transformer because of the energization caused by GICs. However, the harmonic-restraint differential function will block any trip signal at this time, thus the transformer will not be falsely tripped by the transformer protective relay. When the fault occurred, some protective functions failed to detect the fault while other functions issued trip signals. However, because of the harmonic-restraint differential function again, the trip signals are blocked. As a consequence, the protective relay will not send a trip signal to protect the transformer because of the influence of solar storm.

V. CONCLUSIONS

This paper studies the impact of solar storms on saturable-core transformer and its protective relays. To simulate the transformer saturation, the transformer core is modeled using high-fidelity, non-linear equations. Simulation results indicate that GICs generated by solar storms can saturate the high-voltage transformer and create large amount of harmonics. The transformer saturation and generated harmonics could cause associated protective relays fail to operate during solar storms.

If the protective relay is implemented with harmonic restrained differential protective functions, it will help prevent mis-operations when the transformers are in normal conditions. However, if an internal fault occurs during solar storms, the affected transformer might not be properly protected by the relays.

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