Dynamic State Estimation-based Protection of Power Transformers

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***Abstract*- Power transformers are expensive and critical power system components. Reliable and secure protection schemes for transformers are extremely important. While transformer protection has evolved to a high degree of sophistication they cannot ensure 100% reliable and secure protection. A new transformer protection scheme based on dynamic state estimation is proposed. The dynamic transformer state is continuously estimated from measurements and the protective decision is based on the transformer state only (operating condition or health status). This scheme requires very few and simple settings, such as maximum permissible hot spot temperature. The protection algorithm is object-oriented. Specifically, the transformer model is expressed in a standard format, named the algebraic quadratic companion form (AQCF) and the dynamic state estimation operates directly on this object model. The method has been demonstrated in the laboratory. The paper describes the laboratory hardware. An example transformer protection is presented for a 115/25 kV three-phase transformer. Results verify the advantages of this scheme over traditional methods.**

***Index Terms*- Dynamic state estimation, transformer protection, object-oriented, inrush current, internal fault**

I. Introduction

Transformers are expensive and critical power system components. Main objective of transformer protection is to detect transformer internal faults or transformer overheating and trip the transformer for these events and to avoid tripping for external system faults [1]. Transformer internal faults are so dangerous that they can destroy the transformer and sometimes may cause an explosion. To limit the damage and the repair cost, modern transformer protective relays use high-end microprocessors to implement multiple transformer protective functions. This approach increases the complexity of protection settings. According to NERC's data, the industry experiences 10% mis-operations with most of them are caused by wrong protection settings [2]. To increase the relay reliability, many transformer protection functions have been developed with simple settings. The most popular and effective protection scheme for transformer is the differential protection, and it has served well for many years. However, differential protection cannot detect all faulted conditions. For example, when an inter-turn or high impedance turn-ground fault near neutral happens in transformer, the induced three-phase unbalanced currents are too small to be noticed. Moreover, when transformer energization occurs, inrush current flow resembles the condition of an internal fault [3]. As a consequence, differential transformer relays tend to fail for certain internal faults or energization events. Remedies are typically applied but they do have limitations.

Harmonic-restrained differential relays were introduced to address the issues arising from transformer energization [4]-[5]. These relays are based on studies indicating that the second-harmonic component of the inrush current is typically above 15% of the fundamental current, while it is very low for internal faults. Unfortunately, the level of second-harmonic component in inrush currents is substantially lower in transformers with improved core steel [6]. Other transformer protection schemes using artificial neural network (ANN) or fuzzy logic have been proposed [7]-[9]. These methods claim to detect internal faults that cannot be detected by traditional relays. The main drawback of ANN or fuzzy logic methods is the requirement of a large training set and the possibility that the training set is not inclusive of all the events that may occur in the real world. Wavelet-based differential protection schemes have also been used for power transformer protection [10]-[11]. The performance of wavelet-based methods is dependent upon mother wavelet selections and in general these methods require much more development to understand their performance in transformer protection. All above transformer protection schemes are unable to detect high impedance or faults near the neutral of a transformer.

This paper describes a new protection scheme based on dynamic state estimation (DSE). This method has been inspired from differential protection, and it does not require coordination with other protection functions. Specifically, the proposed scheme continuously monitors transformer terminal voltages and currents and other measurable quantities such as tap settings, temperatures, etc. The measurement data are

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utilized in a dynamic state estimator of the transformer protection zone. The dynamic state estimation simply determines how well the measured data fit the dynamic model of the transformer. When the fit is within the accuracy of the meters by which the measurements are taking, the dynamic state estimate provides the true operating condition of the transformer. Discrepancies indicate an internal abnormality. The relay takes decisions based on the operating condition of the transformer. This scheme does not require any coordination with other protection functions. The only setting in this case is the maximum permissible hot spot temperature (typically 105 Celsius).

The computational process requires the dynamic model of the transformer, the measurements and the dynamic state algorithm. The analytics have been implemented in an object-oriented manner. Specifically, the dynamic model of the transformer is expressed in an object with specific syntax referred to as the algebraic quadratic companion form (AQCF). The measurements, obtained with traditional relaying instrumentation or via merging units, is also expressed in an object with similar syntax as the AQCF. The dynamic state estimation algorithm operates directly with the model and measurements expressed in above objects.

This paper is organized as follows. In Section II, the proposed DSE-based approach is introduced. In Section III, hardware implementation is discussed. In Section IV, two numerical cases of a three-phase transformer are tested with the proposed method and compared to traditional transformer protection. Section V presents conclusions.

II. Dynamic State Estimation-Based Protection

A. *Overall Structure of Proposed Scheme*

An overview of the proposed DSE-based transformer protection scheme is shown in Figure 1.

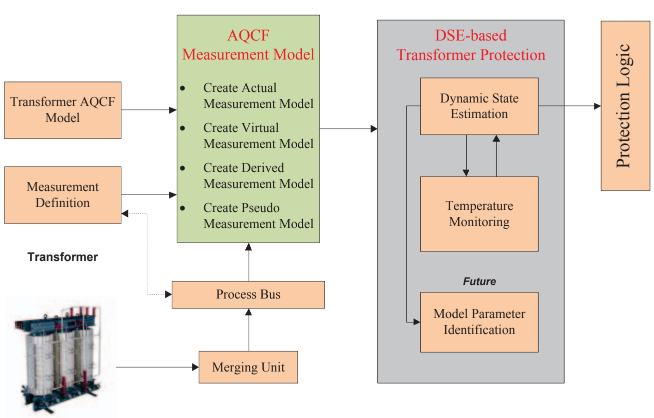

Figure 1. Overview of DSE-based transformer protection scheme

The algorithm for the DSE-based protection is object oriented and the state estimation algorithm has been streamlined for the purpose of increasing efficiency. Transformer device model is written in AQCF format and proposed algorithm automatically formulates the measurement model in AQCF syntax, as illustrated in the Figure. Details of the AQCF model will be addressed in the next sections. To set the relay, we only need to know the maximum permissible operating conditions such as maximum permissible temperature. The DSE-based protection approach has two kinds of input data. One is the measurement model in AQCF syntax, the other one is the real-time measurements data coming from merging units (process bus). The dynamic state estimation is based on weighted least squares (WLS) method, performs bad data detection and identification and, if needed, parameter estimation. In addition, a Chi-square test is applied to determine the probability that the transformer operating condition is consistent with the transformer dynamic model. This probability is an indication that there are no internal abnormalities in the transformer, such as a ground fault, a coil to coil fault, etc. The protection logic is based on the following criteria: if the real-time measurements fit the transformer device measurement model well, then the transformer is in a healthy status; otherwise, some abnormalities occur inside the transformer and protection action should be taken.

B. *Algebraic Quadratic Companion Form (AQCF)*

Algebraic quadratic companion form (AQCF) is the result of quadratic integration of physical mathematical model of transformers [2]. It has the following standard form:

$$\begin{Bmatrix} i(t) \\ 0 \\ 0 \\ i(t_m) \\ 0 \\ 0 \end{Bmatrix} = Y_{eqx}\mathbf{x}(t,t_m) + \begin{Bmatrix} \vdots \\ \mathbf{x}(t,t_m)^T \left\langle F_{eqx}^{i} \right\rangle \mathbf{x}(t,t_m) \\ \vdots \end{Bmatrix} - B_{eq} \qquad (1)$$

where:

$[i(t),\ i(t_m)]$: currents that flow into the device at two adjacent time step t and time t_m;
$[x(t),\ x(t_m)]$: external and internal state variables of the device model at both time t and time t_m;
Y_{eqx}: constant state matrix for model linear part
F_{eqx} : constant state matrices for model quadratic part
B_{eq}: constant past history vector of the device model.

The states in the AQCF are terminal voltages of transformer and other internal states such as transformer flux in each core leg, magnetizing current, etc.

C. *Dynamic State Estimation and Protection Logic*

Dynamic state estimation uses redundant measurements to compute the best estimate of the operating states of transformers. The measurements are transformer terminal voltages and currents, temperatures, as well as some virtual measurements representing the internal mathematical relationships of the transformer. Details of the AQCF measurements model are described in [13]. Any measurement can be expressed in terms of the state of the transformer with the aid of the transformer model in AQCF form, Equation (1). Specifically it can be written as follows:

$$\begin{aligned} z_k(t) = h_k\left(x\right) + \eta_k &= \sum_i a_{i,t,x}^k \cdot x_i(t) + \sum_i a_{i,tm,x}^k \cdot x_i(t_m) \\ &+ \sum_{i,j} b_{i,j,t,x}^k \cdot x_i(t) \cdot x_j(t) + \sum_{i,j} b_{i,j,tm,x}^k \cdot x_i(t_m) \cdot x_j(t_m) + c_k(t) + \eta_k \end{aligned} \quad (2)$$

where $\boldsymbol{z}$ is the measurement, $\boldsymbol{t}$ is the present time, $\boldsymbol{t_m}$ is the midpoint between the present and previous time, $\boldsymbol{x}$ is the state variables, $\boldsymbol{a}$ is the coefficient of linear terms, $\boldsymbol{b}$ is the coefficients of nonlinear terms, $\boldsymbol{c}$ is the constant term, and $\boldsymbol{\eta}$ is the measurement error [13].

The WLS method, which minimizes the sum of the weighted squares of the components of the residual vector $\boldsymbol{r}$, is used in this algorithm. Mathematically:

$$Minimize \quad J = \sum_{i=1}^{n} \left(\frac{h_i(x) - z_i}{\sigma_i} \right)^2 = \sum_{i=1}^{n} s_i^2 = \eta^T W \eta \quad (3)$$

where $\boldsymbol{s_i} = \frac{\eta_i}{\sigma_i}$, $\boldsymbol{W} = diag\left\{\cdots, \frac{1}{\sigma_i^2}, \cdots\right\}$ and $\boldsymbol{\sigma_i}$ is the standard deviation of the meter by which the corresponding measurement $\boldsymbol{z}$ is measured; $\boldsymbol{W}$ is the diagonal matrix whose non-zero entries are the inverse of the variance of the measurement errors. The solution is given with Newton's iterative algorithm:

$$\mathbf{x}^{\nu+1} = \mathbf{x}^{\nu} - (H^T W H)^{-1} H^T W (h(\mathbf{x}^{\nu}) - \mathbf{z}) \quad (4)$$

where $\boldsymbol{H}$ is the Jacobean matrix:

$$H = \frac{\partial h(\mathbf{x})}{\partial \mathbf{x}} \quad (5)$$

Once the solution is calculated by equation (4), chi-square test is applied. Chi-square test quantifies the goodness of fit between the model and measurements by providing the probability that the measurements are consistent with the dynamic model of the power transformer. Chi-square test is applied as follows [13]. First the quantity ξ is computed:

$$\xi = \sum_i \left(\frac{h_i(x) - z_i}{\sigma_i}\right)^2 \quad (6)$$

The probability (confidence level) that the measurements and the model fit together within the accuracy of the meters is computed from:

$$Pr[\chi^2 \geq \xi] = 1 - Pr[\chi^2 \leq \xi] = 1 - Pr(\xi, \nu) \quad (7)$$

where $\boldsymbol{\nu}$ is the degree of freedom and it is the difference between the number of measurements and states.

A confidence level around 100% (small chi-square value) infers the measurements are highly consistent with the dynamic model of transformer, while a confidence level around 0% (large chi-square value) means that measurements do not match the dynamic model of the transformer [2]. Protective decision is made on the basis of the chi-square test. To avoid false tripping from transients, the result of the chi-square test is integrated over a user selected interval (one or two cycles) before a trip command is issued.

III. Laboratory Hardware Implementation

Laboratory testing is the most effective way to test any new methodology. The proposed DSE-based protection scheme is tested in the laboratory with implementation of merging unit, GPS signals and IEC 61850 communications. The structure of laboratory hardware implementation is shown in Figure 2.

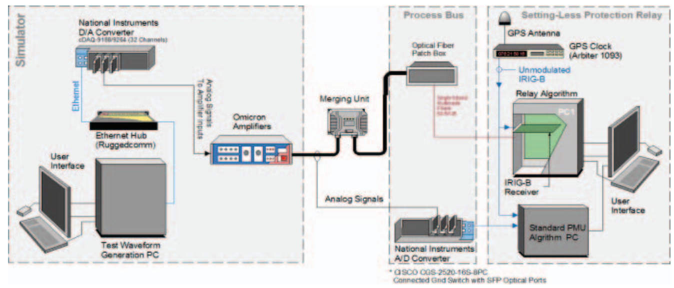

Figure 2. Laboratory hardware implementation

A merging unit acts as a bridge between primary equipment and protection devices to capture and transmit signals [2]. It converts the analog signals from analog CT/VT signals to digital signals, which are then transmitted to the process bus. Data are synchronized by the used of an Arbiter 1093 GPS. In the laboratory, the signals are generated in a simulation platform (program WinXFM) that generates and streams digital waveforms of transformer events to a National Instrument D/A converter. The national Instrument D/A converter send the analog signals to a bank of OMICRON amplifiers which amplify them to standard relay instrumentation voltages and currents. These signals are in the range of typical outputs from CT/VTs. These signals are fed to the merging units. The merging units convert the signals to digital form and the digital signals are transmitted to the process bus via standard protocol (IEC 61850). A personal computer is connected to the process bus and acts as a data concentrator that feeds the collected data to dynamic state estimator. The merging unit sampling rate is 5000 samples/sec, which means the proposed DSE-based protection approach should perform each dynamic state estimation in less than 400 µs to avoid overlap of incoming data. The dynamic state estimation algorithm has been optimized and it is performed in fraction of the available time of 400 µs.

IV. Numerical Results

We present two examples for the purpose of comparing the performance of the DSE based protection method with legacy protection functions. The first case involves an event that generates inrush currents in the transformer – no internal fault. The second event involves an internal ground fault near the neutral of the transformer. These cases are presented here and compared to the traditional protection functions. The test system used for numerical test is shown in Figure 3. A 30 MVA, 115/25kV three-phase delta-wye saturable-core transformer is the protection zone of interest. It is designated as T1 in the figure.

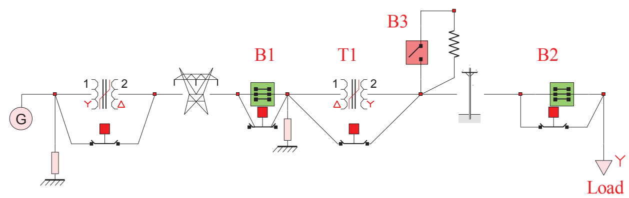

Figure 3. Test System for Numerical Experiments

A. Case One: Transformer Inrush Current

In this case, the breaker B3 is open while the load at the end of distribution line is connected with the breaker B2 closed. The transformer is energized at time t=6.21s by closing the breaker B1. At first, the traditional differential scheme is applied. There are two settings for the differential scheme. One is the differential proportional index K, which is the ratio of operating current $I_o = |N_1\widetilde{I_1} - kN_2\widetilde{I_2}|$ over restraining current $I_R = |N_1\widetilde{I_1} + kN_2\widetilde{I_2}|/2$. The other setting is the minimum operating current I_{min}, which is 2.0 Amps in this case. The differential relay trips if (1) $I_o > I_{min}$ and (2) index **K** is larger than 20%, giving enough margin for introduced errors caused by the tap changers and non-matching of CT. The results of differential protection scheme are shown in Figure 4.

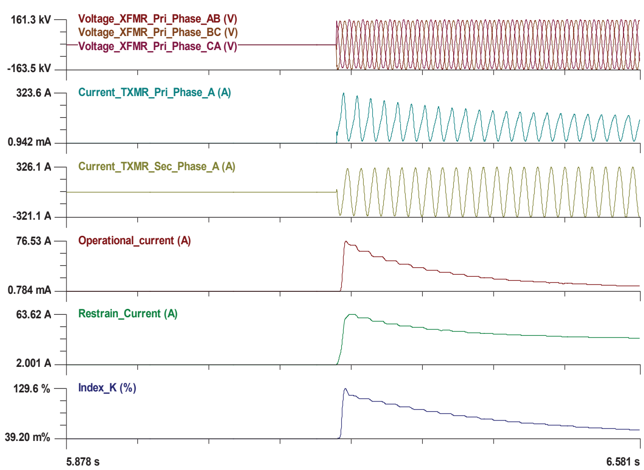

Figure 4. Differential protection scheme for inrush current

In Figure 4, the differential protection scheme detects almost zero operating current and at the beginning. However, at time t = 6.21s, an inrush current that is almost twice the value of steady-state operational current occurs after suddenly closing the breaker B1. A very large operating current is detected and the index **K** jumps to 129.6%, which could cause a false tripping of the differential relay. In practical situations, differential relays have additional functions (such as harmonic restraints) to detect the inrush current. However, these functions cannot ensure 100% reliability. Differential relays still tend to falsely trip the transformer if it experiences severe inrush currents.

The results of proposed DSE-based protection scheme are shown in Figure 5. The dynamic state estimator monitors the residual of states and the health condition of transformer in real time. The confidence level stays 100% at the beginning. It drops suddenly when the energization happens, but then it returns again to 100% immediately (less than a small fraction of a cycle). This means the DSE-based protection scheme detects the existence of the inrush current and notices nothing wrong inside the transformer. Therefore, it won't trip the transformer. In fact, the proposed DSE-based scheme can guarantee 100% reliability for inrush situations because the model of transformer does not change and the measurements still fit the model under transformer energization. The execution time is around 13μs, thus it meets the requirement of less than (400 μs).

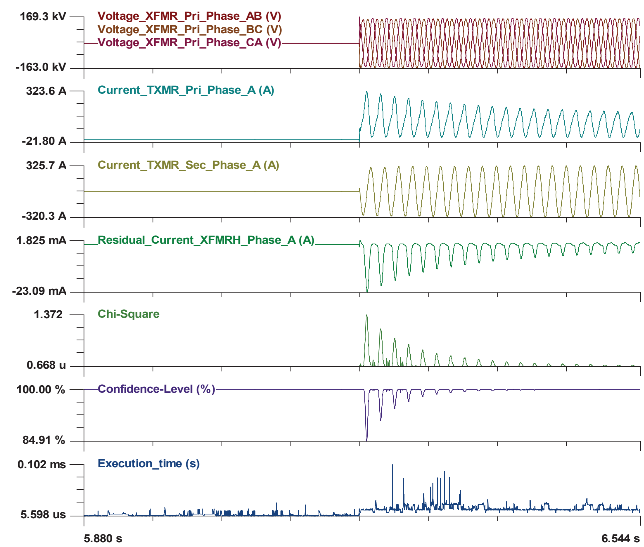

Figure 5. Proposed DSE-based protection scheme for inrush current of transformer

B. Case Two: Turn-ground Fault Near Neutral Terminal of Transformer

In this case, the breakers B1 and B2 stay closed. A 5% turn-ground fault near neutral terminal of the transformer happens at time t=8.1s by closing the breaker B3. The results of differential protection scheme are shown in Figure 6.

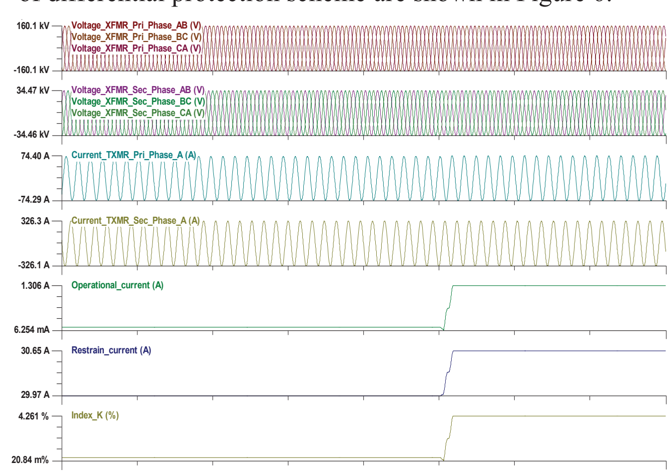

Figure 6. Differential protection for turn-ground fault near neutral terminal of transformer

At the beginning, the transformer operates normally and the differential protection scheme detects zero operating current. When the 5% turn-ground fault near neutral terminal of transformer happens at time t=8.1s, no obvious changes happen at either primary or secondary side currents of the transformer. The differential scheme detects only a very small operating current and the largest value of index K is about 4.26%. This value is too small thus the differential scheme fails to alert the relay about this internal fault. As a consequence, the transformer is not tripped and the damages are inevitable.

The results of proposed DSE-based protection scheme are shown in Figure 7. The residual and chi-square values are very small during normal operation, which indicates that transformer is in a good health condition. When the 5% turn-ground internal fault happens at time t=8.1s, they increase rapidly while the confidence level drops from 100% to zero immediately. The proposed scheme detects the fault and it would trip the transformer. It is noticed that confidence level is oscillating during this fault period because the internal fault is too small. An integral function is applied to smooth the waveform. The execution time is around $15\mu s$, thus it also meets the requirement of less than (400 μs) in this case.

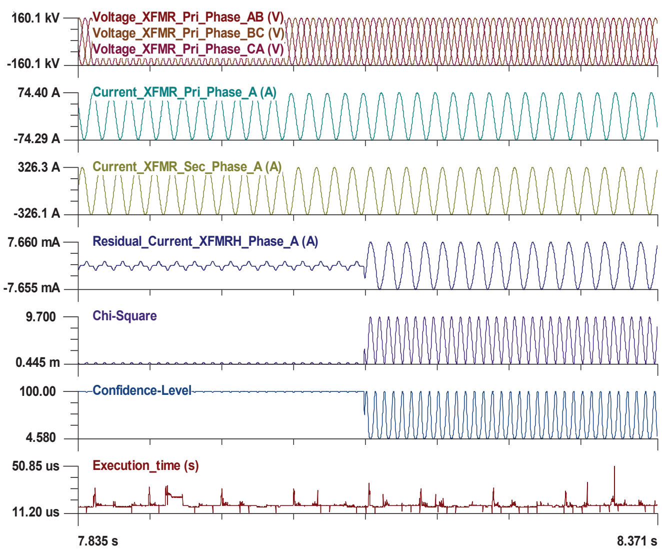

Figure 7. Proposed DSE-based protection for turn-ground fault near neutral terminal of transformer

V. Conclusions

This paper proposes a dynamic state estimation based protection method for power transformers. The proposed method and traditional differential method are compared with two numerical cases. In the first case with inrush current, traditional differential method tend to falsely trip the transformer under severe energization. In contrast, proposed DSE-based method guarantees 100% reliability no matter how severe the energization is. Regarding the minor turn-ground fault near the neutral terminal as shown in second case, traditional differential method fails to detect it while proposed method successfully and reliably detects the fault. The proposed scheme provides dependable and secure protection for transformer with additional benefits, such as simple settings and fast computing speed.

The proposed DSE-based scheme will be field tested on actual transformers in the near future.

Acknowledgment

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