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Setting-less Protection: Laboratory Experiments and Field Trials

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I INTRODUCTION

The numerical relay increased its domination to the point that today has almost completely displaced electromechanical and solid state relays. The capabilities of the numerical relays are not fully utilized today; specifically, by and large, they simply mimic the logics that were developed for the electromechanical relays but with much more flexibility. Recent developments towards the digital substation make the numerical relays logical nodes in an automated system that integrates the functions of protection, SCADA, control, and communications. These approaches indicate the recognition that numerical relays offer much more than simply mimicking protection functions of the past. Yet, the logical nodes use the same protection functions, as presently done by numerical relays.

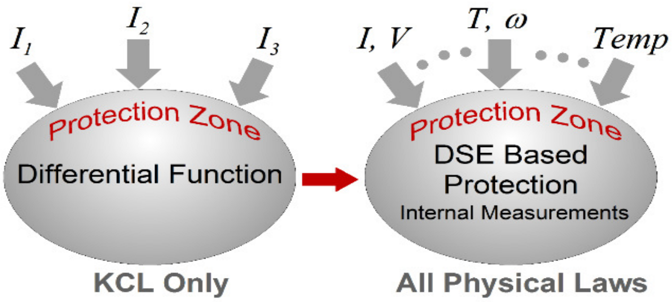

Figure 1: Comparison of Estimation Based Protection to Differential Protection

In the last few years we have proposed, laboratory tested and validated a new protection approach based on dynamic state estimation. The basic idea of the dynamic state estimation based protection (aka setting-less protection) has been inspired from the differential protection function and can be considered as an extension and generalization of differential protection. A conceptual illustration of the DSE based protection is illustrated in Figure 1. In current differential protection the electric currents at all terminals of a protection zone are measured

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and their weighted sum must be equal to zero (generalized Kirchoff's current law). Thus the current differential protection function consists of measuring the sum of the currents and as long as it is zero or near zero no action is taken. The DSE based protection uses as many measurements as available and compares the measurements to the physical laws that the protection zone must obey (not only KCL but KVL, magnetic flux laws, thermodynamic laws, and other as applicable). This comparison is done in a systematic way via dynamic state estimation.

The DSE based protection requires measurements in the protection zone (the more the better), a high fidelity dynamic model of the protected zone, and a dynamic state estimation algorithm. All existing measurements in the protection zone are utilized (currents and voltages at the terminals of the protection zone, as well as voltages and currents inside the protection zone, as in capacitor protection, or speed and torque in case of rotating machinery or other internal measurements including thermal measurements). The dynamic model of the device (physical laws such as KCL, KVL, magnetic flux laws, motion laws, thermodynamic laws, etc.) is used to provide the inter-relationship of all measured quantities to the state of the protected zone. When there is no fault within the protection zone, the measurements should satisfy the dynamic model of the protection zone. A systematic way to verify that the measurements satisfy the mathematical model is a dynamic state estimation procedure. The resulting method is a Dynamic State **E**stimation **B**ased **P**rotection (EBP). When an internal fault occurs, even high impedance faults or faults along a coil, etc., the dynamic state estimation reliably detects the abnormality, by computing the measurements/model discrepancy, and a trip signal can be issued. Because of the ability of the dynamic state estimation to detect even small differences between the measurements and the model, the selectivity and sensitivity of the EBP is very high.

II DESCRIPTION OF EBP

The estimation based protective relay (EBP) requires the following: (a) the dynamic model of the protected component (zone); (b) Dynamic State Estimation process to test the consistency between the measurements and the model; (c) trip logic of the relay. These steps are discussed next.

A. Dynamic Model of the Protected Component

The dynamic model of the protected component consists of a set of differential and algebraic equations. In our EBP method the quadratization process is utilized to reduce all high order nonlinearities of the device model to second order or less by introducing additional variables. By this process we can write the quadratized dynamic model (QDM) of any protection zone (component) in an object-oriented way, which means that all component models have the same syntax. The object-oriented modeling approach leads to standardization of the analytics of the EBP relay for any component. The syntax of the measurement model is (the derivations can be found in [7]):

$$\mathrm{z}(\mathbf{x}) = Y_{mx}\mathbf{x}(t) + \left\{ \begin{matrix} \vdots \\ \mathbf{x}(t)^T \left\langle F_{mx}^{i} \right\rangle \mathbf{x}(t) \\ \vdots \end{matrix} \right\} + D_{mx}\frac{d\mathbf{x}(t)}{dt} + C_m + \eta(t) \qquad (2)$$

where $\mathbf{x}(t)$ is the state variables, $z(t)$ is the measurements, $\eta(t)$ is the measurement errors. The other elements of the model are parameter matrices and vectors of the specific component.

B. Dynamic State Estimation Process

A mathematically rigorous and systematic method to test the consistency between the measurements and the model, is by means of the Dynamic State Estimation. There are several ways to formulate this problem. In this paper we convert the dynamical equations into discrete time equations via the quadratic integration method yielding the Algebraic Quadratic Companion Form (AQCF). Note that the AQCF include variables at both time t and t_m and past history terms at time *t-h*. The syntax of the AQCF for the measurements is:

$$z(\mathbf{x}) = Y_{eqx}\mathbf{x}(t,t_m) + \left\{ \begin{matrix} \vdots \\ \mathbf{x}(t,t_m)^T \left\langle F_{eqx}^i \right\rangle \mathbf{x}(t,t_m) \\ \vdots \end{matrix} \right\} + b_z\left(t-h\right) \tag{4}$$

where $t_m = t - h/2$ is the mid point between time t and $t-h$, and h is the DSE time step. Details of the integration and derivation can be found in [7].

Next, the states of the component are estimated by minimizing the sum of the squared normalized errors, i.e. the weighted least square method is employed. The optimization problem is:

Minimize

$$J(\mathbf{x}) = \eta^T(t)\eta(t) = \left(Y_{eqx}\mathbf{x}(t,t_m) + \left\{ \begin{matrix} \vdots \\ \mathbf{x}(t,t_m)^T \left\langle F_{eqx}^i \right\rangle \mathbf{x}(t,t_m) \\ \vdots \end{matrix} \right\} + b_z\left(t-h\right) - z(\mathbf{x}) \right)^T W \left(Y_{eqx}\mathbf{x}(t,t_m) + \left\{ \begin{matrix} \vdots \\ \mathbf{x}(t,t_m)^T \left\langle F_{eqx}^i \right\rangle \mathbf{x}(t,t_m) \\ \vdots \end{matrix} \right\} + b_z\left(t-h\right) - z(\mathbf{x}) \right) \tag{5}$$

where $\mathbf{W} = \mathrm{diag}\left\{\cdots, 1/\sigma_i^2, \cdots\right\}$ and σ_i is the standard deviation of the measurement error.

The solution of the above optimization problem is given with the following iterative algorithm:

$$\mathbf{x}^{\nu+1} = \mathbf{x}^{\nu} - (H^T W H)^{-1} H^T W \left(Y_{eqx}\mathbf{x}^{\nu}(t,t_m) + \left\{ \begin{matrix} \vdots \\ \mathbf{x}^{\nu}(t,t_m)^T \left\langle F_{eqx}^i \right\rangle \mathbf{x}^{\nu}(t,t_m) \\ \vdots \end{matrix} \right\} + b_z\left(t-h\right) - z(\mathbf{x}^{\nu}) \right) \tag{6}$$

where H is the Jacobean matrix:

$$H = Y_{m,x} + \left\{ \begin{matrix} \vdots \\ \left(\mathbf{x}^{\nu}\right)^T F_{m,x}^i + F_{m,x}^i\left(\mathbf{x}^{\nu}\right) \\ \vdots \end{matrix} \right\} \tag{7}$$

C. Relay Trip Logic

The consistency between the measurements and the model is tested by examing whether the residuals of the Dynamic State Estimation (the differences between the actual and the estimated measurements) is comparable to the measurement errors. If the errors are much larger than the metering errors, we can conclude that the component model has changed and there must be an internal fault. A systematic way to quantify this comparison is to use the chi-square test [13]. The chi-square test provides the probability that there is no internal fault. A zero probability indicates an internal fault. The trip logic uses an integral of the probablity. The parameters of the integral are user selected. For example the parameters can be so selected as to issue a trip command if the probability remains zero for 1.5 cycles.

III EXAMPLE RESULTS

For the purpose of comparing the performance of the DSE based protection method with legacy protection functions, an event involving a ground fault at the coil of a transfomer 5% from the neutral. The selected legacy protection function is the differential function. The settings of differential protection are : pickup current $I_{min} = 0.1 I_N$; and differential ratio threshold $K_{th} = I_{op}/I_{res} = 20\%$. The transformer under protection is a 750kVA 7.98kV/0.277kV single-phase saturable transformer.

The transfomer operates normally when at time t = 3.5s, a 5% turn-ground fault near the neutral terminal of transformer happens on the secondary windings. The performance of the settingless proetction and differential protection are discussed next.

Setting-less Protection *:* The results of proposed setting-less protection are shown in Figure 2. The residual and Chi-square are very small while the confidence level (probability) is 100% during normal operation, indicating that transformer is in a good health condition. When the 5% turn-ground internal fault happens at time t=3.5s, the residual and Chi-square decrease rapidly and the confidence level drops to zero. The zero confidence level indicates abnormalities inside the transformer and protection actions should be taken. It is noticed that confidence level is oscillating during the fault period since the internal fault is too small. An integral function is applied to smooth the waveform and a trip decision is taken to protect the transformer, as shown in the figure.

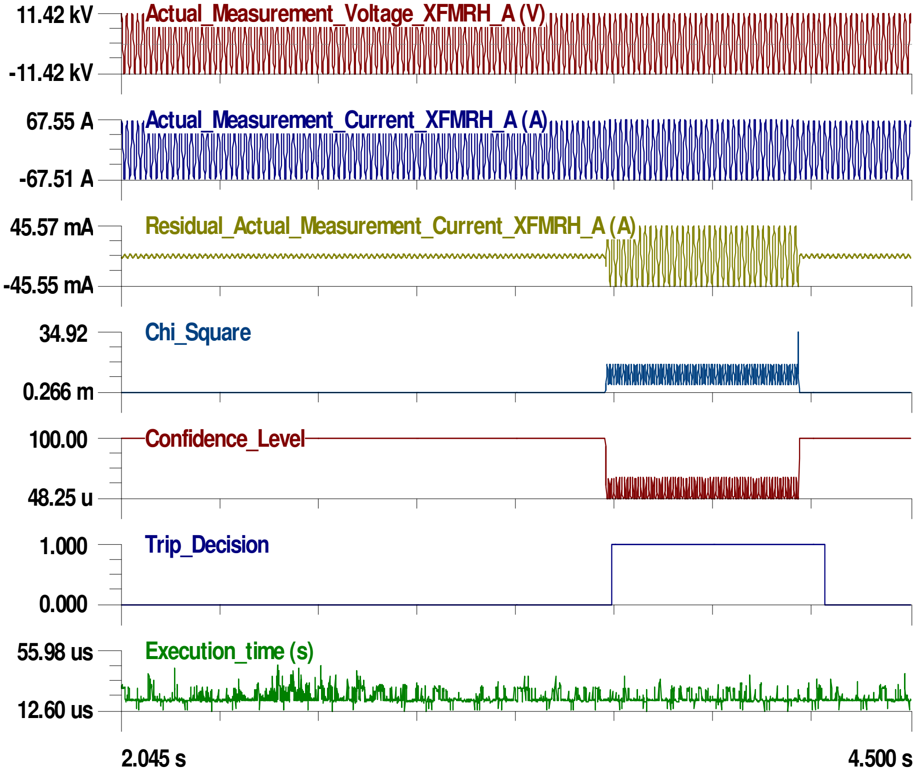

Figure 2: Setting-less Protection for Turn-ground Fault 5% from Neutral

Differential Protection *:* The results for the differential protection are shown in Figure 3. At the beginning the differential protection scheme detects almost zero operating current when the transformer is operating normally. At time t = 3.5s, the breaker B2 is suddenly closed and an operating current occurs at the primary side of the transformer. However, the operating current is very small and the maximum differential index K is about 6.2%. The detected differential index K is smaller than the setting (20%). The differential scheme fails to alert the relay about this internal fault. As a consequence, the transformer is not tripped and the fault continues to damage the transfomer.

In this example, the setting-less protection method provides better protections than traditional methods. The setting-less protection method provides dependable and secure protection for transformer with additional benefits, such as fast computing speed, and simple settings.

The method has been implemented in an object oriented manner where each measurement is an object in a specific syntax. The measurement objects are automatically generated from the dynamical model of the protection zone. The dynamic state estimation is automatically executed using the measurement objects and the dynamic state estimation algorithm. Three algorithms have been tested (Extended Kalman Filter, Constrained Optimization and Unconstrained Optimization).

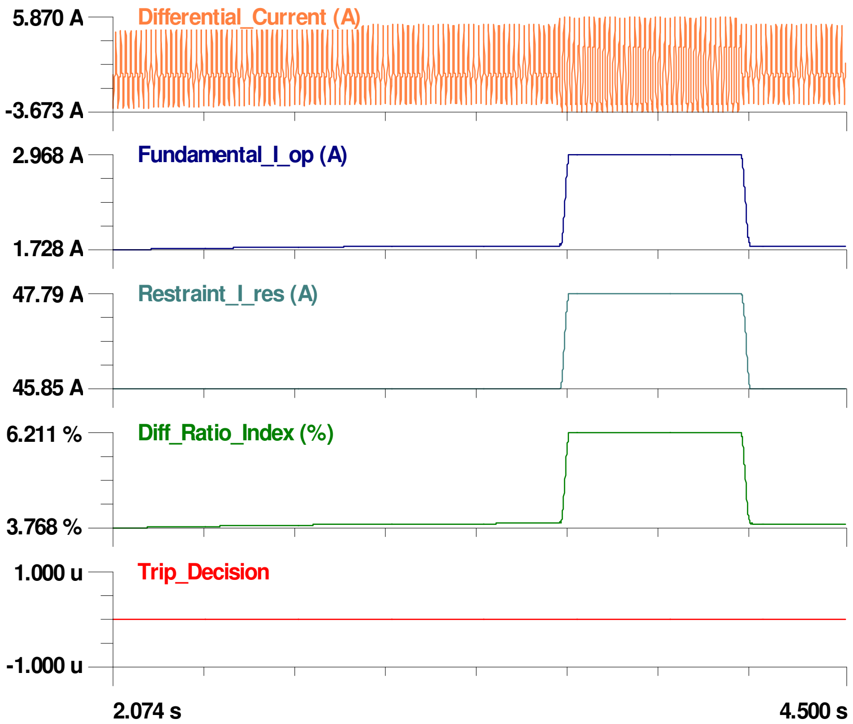

Figure 3: Differential Protection for Turn-ground Fault 5% from Neutral

IV LABORATORY TESTS

The method described in this paper has been extensively tested in the laboratory at Georgia Tech for a variety of protection zones. The laboratory setup is illustrated in Figure 4.

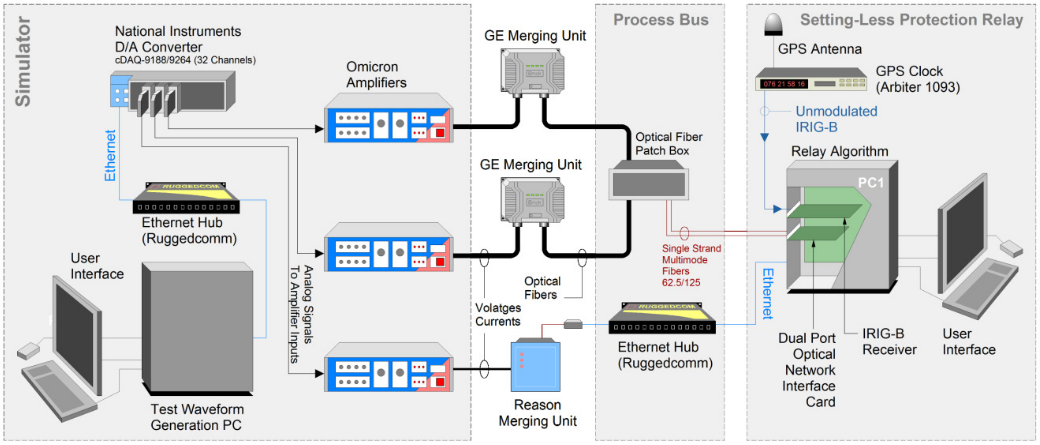

Figure IV: Lab Implementation Illustration

As illustrated in Figure 4, the WinXFM program generates digital streaming waveforms representing the terminal voltages and currents of the protection zone (power system component) to the NI 32 channel DC/AC converter. Omicron amplifiers receive the analog signals from the NI DC/AC converter and amplify these signals to a range comparable to real output of CTs/PTs (for voltages around 50V and for currents around 5A). The electrical output (voltages and currents) of the Omicron amplifiers are fed into merging units from Reason and GE. The setting-less relay is connected to the process bus and receives data from the merging units. The computer communicates with the merging units with IEC 61850-8-1 and IEC 61850-9-2. It performs the dynamic state estimation and the protection logic.

It has been demonstrated that the dynamic state estimation can be performed within the time of consecutive samples. As a matter of fact the algorithms have been streamlined and optimized to the point that the dynamic state estimation is performed in a fraction of the time between samples, even for high sampling rates. We have tested the algorithms with sampling rates of 12 ks/sec.

V FIELD DEMONSTRATIONS

Presently, we have initiated a project, supported by NYSERDA, for field demonstration of the technology on a 765/345/13.8 kV autotransformer and a 765 kV transmission line. The selected architecture is based on merging units with a process bus and the EBP relay will be connected to the process bus. The EBP will be in monitoring mode only and the data will be stored. Field testing results are not available yet since this project just started. Field results and experience will be reported in future papers.

VI ACKNOWLEDGMENT

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