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Update on Object-oriented DSE Based Protection

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Abstract

Present numerical relays have enough numerical capability to run tens of protection functions simultaneously within the same relay. In a substation with a few tens of relays, this capability leads to hundreds of protection function within the substation and the need to coordinate all these protection functions. This complexity increases the possibility of human error and mis-coordination. In addition, there is still no 100 percent reliable approach for protection against some system conditions, such as high impedance faults, faults near neutrals, etc. In the modern substation, the numerical relays maybe integrated into an automation system and the ability to share information or transmit the information into a central system for better protection and control decisions. Obviously, the numerical relays have developed much potential compared with traditional relays, but still they can offer more.

In previous work, a new protection approach based on dynamic state estimation (coined setting-less protection by EPRI) was proposed. The approach is a generalization of differential protection. The differential protection monitors Kirchhoff's current law while the proposed method monitors all physical laws that the device under protection should obey. The setting-less protection is based on dynamic state estimation (DSE) which monitors device dynamic models by fitting the real time measurement data to the model. Under normal operation, the device estimated measurement data from DSE should be exactly the same as the real measurement data. The mismatch between real measurements and estimated measurements indicates abnormalities in the device, then diagnose or trip decision should be made.

This paper provides two recent updates for the above concept: (a) an object-oriented approach for the DSE based protection approach, utilizing the State and Control Algebraic Quadratic Companion Form (SCAQCF) mathematical model to describe a protection zone, and (b) a merging unit based implementation of the method allowing full IEC 61850 implementation of the method. Two protection zone examples are provided in this paper, i.e. reactor protection and capacitor bank protection.

I. INTRODUCTION

Digital protective relays with powerful numerical capability are widely installed in present power system. Compared with traditional electromechanical relays which convert voltages and currents into magnetic forces and torques, numerical relays use microprocessor to convert voltages and currents to digital quantities. It is obvious that one traditional electromechanical relay is designed to perform only one protective function while tens of protective functions can be integrated into one numerical relay. In a modern substation each numerical relay has an average of 12 protective functions [1]. The coordination of these protective functions and tens of numerical relays in one substation becomes quite complicated. This complexity increases the possibility of human error and mis-coordination. Although lots of research has been done on the topic of coordinating different relays to make them provide more reliable protection, there is still no satisfactory solution. According to NERC's data, the number one root cause of system disturbances is protection relaying while most of relay issues are caused by wrong protection settings. In addition, some system fault conditions are hard to be detected by present protective functions such as high impedance fault, fault near neutrals, etc. Much effort has been made to solve this kind of protection gaps. Mathematical Morphology is used to detect the high impedance fault in [2] and a Morlet wavelet transform high impedance fault detection approach is utilized in [3]. Unfortunately, neither of these methods has perfect detection when the fault current difference caused by the high impedance fault is really small.

To solve these protection gaps, a novel protection method called Dynamic State Estimation (DSE) based protection is introduced in [4]. Since this DSE based protection approach requires no specific settings or very few settings for the numerical relay, EPRI names it setting-less protection. It utilizes the dynamic device model as the input and monitors the device (protection zone) health status by fitting the real time measurement data to the device model. The details of the DSE based protection will be reviewed in this paper. To generalize the proposed approach, an object-oriented manner should be introduced so that it can be applicable to all apparatus in the power system. In this paper, a State and Control Algebraic Quadratic Companion Form (SCAQCF) mathematical model standard is utilized to describe the protection zone in the same syntax, which enables the DSE-based protection approach to be object-oriented. Meanwhile a merging unit based implementation of the proposed method by using IEC 61850 GOOSE message is introduced in this paper as well.

II. DSE-Based Protection Method

This section introduces the overall protection framework at first. Then the State and Control Algebraic Quadratic Companion Form (SCAQCF) model, dynamic state estimation algorithm and the protection logic will be addressed respectively.

A. Overall Protection Framework

The proposed object-oriented DSE-based protection approach reads the object (protection zone) mathematical model at the initialization step. This mathematical model is in the SCAQCF form so that the proposed method is generic to all the protection zones. With the help of the data acquisition system, a SCAQCF dynamic measurement model containing actual measurement model, virtual measurement model, derived measurement model and pseudo measurement model is created [5]-[8]. As the real-time streaming measurements keep coming, the proposed protection scheme monitors the protection zone by fitting the real time measurement data to the dynamic model. Under normal operation, the device estimated measurement data from DSE should be exactly the same as the real measurement data. The mismatch between real measurements and estimated measurements indicates abnormalities in the device, then diagnose or trip decision should be made. The entire framework is illustrated in Figure 1.

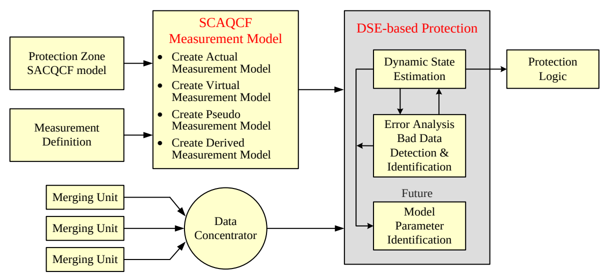

Figure 1. DSE-based Protection Method Framework

B. State and Control Algebraic Quadratic Companion Form (SCAQCF) Model

Most of the devices in power system are nonlinear and it is easy to write the device model in a nonlinear expression which may contain some differential terms. After applying quadratization and quadratic integration mathematical algorithms [9]-[12], the state and control algebraic quadratic companion form model is obtained. It has the following standard form:

$$\begin{Bmatrix} I(\mathbf{x},\mathbf{u}) \\ \vdots \\ 0 \\ \vdots \end{Bmatrix} = Y_{eqx}\mathbf{x} + \begin{Bmatrix} \vdots \\ \mathbf{x}^T F_{eqx}^i \mathbf{x} \\ \vdots \end{Bmatrix} + Y_{equ}\mathbf{u} + \begin{Bmatrix} \vdots \\ \mathbf{u}^T F_{equ}^i \mathbf{u} \\ \vdots \end{Bmatrix} + \begin{Bmatrix} \vdots \\ \mathbf{x}^T F_{eqxu}^i \mathbf{u} \\ \vdots \end{Bmatrix} - B_{eq} \tag{1}$$

where:

$I(\mathbf{x},\mathbf{u})$: Currents that flow into the device at two adjacent time step t and time t_m, $I=\left[I(t),I(t_m)\right]$

$\mathbf{x}$: external and internal state variables of the device model at both time t and time t_m, $\mathbf{x}=\left[\mathbf{x}(t),\mathbf{x}(t_m)\right]$

$\mathbf{u}$: control variables of the device model at both time t and time t_m, $\mathbf{u}=\left[\mathbf{u}(t),\mathbf{u}(t_m)\right]$

Y_{eqx}: constant state matrix for model linear part

F_{eqx}: constant state matrices for model quadratic part

Y_{equ}: constant control matrix for model linear part

F_{equ}: constant control matrices for model quadratic part

F_{eqxu}: constant state and control matrices for model quadratic part

B_{eq}: constant vector of the device model (past history).

The states in the SCAQCF are usually terminal voltages of the device and some auxiliary internal states. The control variables are device variables which obtain the values from control signals like transformer tap, converter control command, etc.

C. Dynamic State Estimation

Any measurement of a device in power system can be expressed in the described SCAQCF form:

$$\begin{aligned} z_k(t)=h_k\left(x,u\right)+\eta_k &= \sum_i a^k_{i,t,x}\cdot x_i(t)+\sum_i a^k_{i,tm,x}\cdot x_i(t_m) \\ &+\sum_{i,j} b^k_{i,j,t,x}\cdot x_i(t)\cdot x_j(t)+\sum_{i,j} b^k_{i,j,tm,x}\cdot x_i(t_m)\cdot x_j(t_m) \\ &+\sum_i a^k_{i,t,u}\cdot u_i(t)+\sum_i a^k_{i,tm,u}\cdot u_i(t_m) \\ &+\sum_{i,j} b^k_{i,j,t,u}\cdot u_i(t)\cdot u_j(t)+\sum_{i,j} b^k_{i,j,tm,u}\cdot u_i(t_m)\cdot u_j(t_m) \\ &+c_k(t)+\eta_k \end{aligned} \tag{2}$$

where z is the measurement, t is the present time, t_m is the midpoint between the present and previous time, x is the state variables, u is the control variables, a is the coefficients of linear terms, b is the coefficients of nonlinear terms, c is the constant term, and η is the measurement error.

The weighted least squares approach is used for the dynamic state estimation algorithm. The algorithm is defined as follows.

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

where $s_i=\dfrac{\eta_i}{\sigma_i}$, $W=diag\left\{\dots,\dfrac{1}{\sigma_i^2},\dots\right\}$

σ_i is the standard deviation of the meter by which the corresponding measurement z is measured; W is the diagonal matrix whose non-zero entries are the inverse of the variance of the measurement error.

The solution is given with Newton's iterative algorithm:

$$\mathbf{x}^{v+1}=\mathbf{x}^{v}-(H^TWH)^{-1}H^TW(h(\mathbf{x}^{v})-\mathbf{z}) \tag{4}$$

where H is the Jacobean matrix: $H=\dfrac{\partial h(\mathbf{x},\mathbf{u})}{\partial \mathbf{x}}$

$$H=\frac{\partial h(\mathbf{x},\mathbf{u})}{\partial \mathbf{x}}=Y_{m,x}+\left\{\begin{matrix}\vdots\\ \mathbf{x}^TF^i_{m,x}+F^i_{m,x}\mathbf{x}\\ \vdots\end{matrix}\right\}+\left\{\begin{matrix}\vdots\\ F^i_{m,xu}\mathbf{u}\\ \vdots\end{matrix}\right\} \tag{5}$$

The fact that the number of measurements of a component exceeds the number of state guarantees the system to be observable. More details about all types of measurements in SCAQCF model could be found in [5]-[8].

D. DSE-based Protection Logic

Once the solution is calculated by equation (4), the chi-square test [14] is applied to all measurements. The 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 protection zone. The chi-square is calculated as follows:

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

Based on the chi-square, the confidence level (or probability) that the measurements and the model fit together within the accuracy of the meters is computed by:

$$Pr[\chi^2\geq\xi]=1-Pr[\chi^2\leq\xi]=1-Pr(\xi,v) \tag{7}$$

where v is the degree of freedom and it is the difference between the number of measurements and states.

It is obvious that confidence level around 100% (small chi-square value) infers the measurements are highly consistent with the dynamic model of the protection zone, which means there is no internal abnormality. On the other side, confidence level around 0% (big chi-square value) infers the measurements do not fit with the dynamic model estimated values, which means the dynamic model cannot represent the present actual device. It is clear some internal abnormalities have changed the structure of the model, so the protective relay should take action (trip or diagnose) and protect the protection zone from further damage. The decision to trip or to diagnose depends on whether the internal abnormality is permanent and the severity of it, which can be represented by the value of chi-square.

III. IMPLEMENTATION OF DSE-BASED PROTECTION METHOD

A merging unit based implementation which allows full IEC 61850 communications is described in this section.

A. Merging Unit

A merging unit is acted as a bridge between primary equipment and protection devices to capture and transmit signals. It can convert the analog signals from electronic CT/VT to digital signals for the process bus. The GPS pulse per second (PPS) signals in the merging unit can adjust the sampling interval to realize the synchronous sampling automatically. The data synchronization is quite important for the proposed DSE-based protection method because only measurements in the same time stamp could fit the dynamic model. Otherwise it would detect abnormality in the protection zone. If the GPS signal is lost, the merging unit can still use angle adjustment interpolation to guarantee the data synchronization. These two methods are used in combination to achieve better accuracy and reliability.

B. IEC 61850 GOOSE Message

IEC 61850 is a standard for the design of electrical substation automation. The abstract data models defined in IEC 61850 can be mapped into a number of protocols [13]. The protocol we use in our implementation is Generic Object Oriented Substation Events (GOOSE) message. It is a control model mechanism in which any format of data (status, value) is grouped into a data set and transmitted within a time period of 4 milliseconds.

C. Lab Implementation

The implementation is illustrated in Figure 2. Since it is impractical to achieve real measurements from electronic CT/VT in the lab, computer simulation based signals are utilized alternatively.

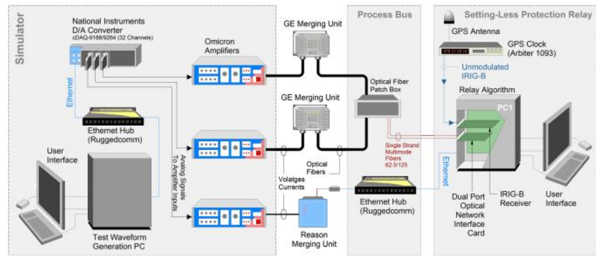

Figure 2. Lab Implementation Illustration

WinXFM generates digital streaming waveforms to the NI 32 channel DC/AC converter. Omicron amplifiers receive the analog signals from the converter and amplify these signals to a range which is very similar to real output of CT/VT. Then, two merging units from Reason and GE are utilized to collect the analog signals and convert them to digital signals. These digital signals are transmitted to relays by using the standard protocol IEC 61850 GOOSE Message. At the relay stage, our proposed DSE-based protection scheme performs dynamic state estimation and provides the protection results. The sampling rate of the waveform generated by WinXFM is 5000 samples/sec (similar to the present top merging unit data transmission speed), which means the proposed DSE-based protection approach should determine the protection decision in 400 μs to avoid coming data overlap.

IV. NUMERICAL CASES

Two demonstration examples are given in this section: reactor protection and capacitor bank protection.

A. Protection Example 1: Reactor

In reality, the cores of reactors are saturable and inrush currents are generated when the reactors are suddenly connected to the generating sources. Since the inrush currents are very large, it might trip the breaker if the relay has good settings to block it.

In this example, the protection of three phase saturable-core reactors is present and the configuration in the simulation is shown in Figure 3.

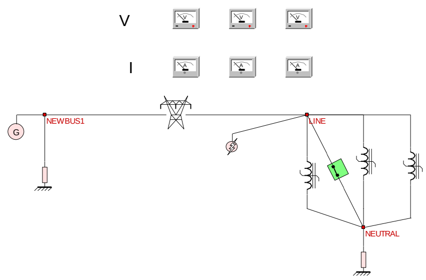

Figure 3. Saturable Core Reactors Configuration

The SCAQCF model for three phase saturable-core Reactors is not listed here because it contains many equations and the space for this paper is not enough. It can be found in [15]. The result of the DSE-based protection is shown in Figure 4.

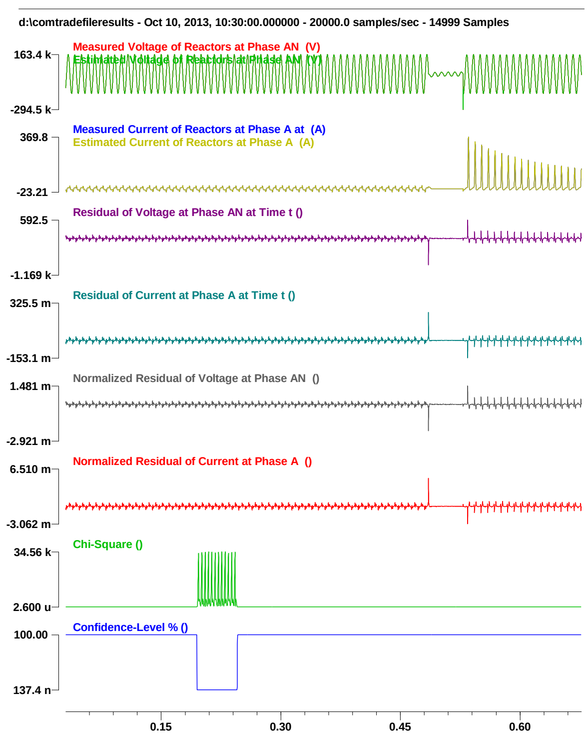

Figure 4. Saturable Core Reactors DSE-based Protection Result

From the above figure, it can be seen that an internal fault happens at 0.20s and clears at 0.25s. Because of the fault, the residual becomes large and the confidence level drops to zero very quickly, which means the relays should send a trip signal to the breakers to prevent the damage of reactors. Meanwhile an external single line to ground fault occurs at 0.48s and clears at 0.53s. The terminal voltage drops to very low and restores to nominal value after the fault, thus a large inrush current is generated. The residual is small or just an impulse and the confidence level remains 100% since the fault is outside. Therefore, the relay will not trip the reactors (Since the fault is on the transmission line, the line will be trip by its own protective relay using DSE-based protection).

B. *Protection Example 2: Capacitor Bank*

The three phase capacitor bank consists of 48 identical capacitor elements with 4 capacitors per leg and 4 legs per phase. Each capacitor element is 4.8 μF which yields 14.4 μF for the entire capacitor bank. The configuration of the three phase capacitor bank used in the simulation is shown in Fig 5.

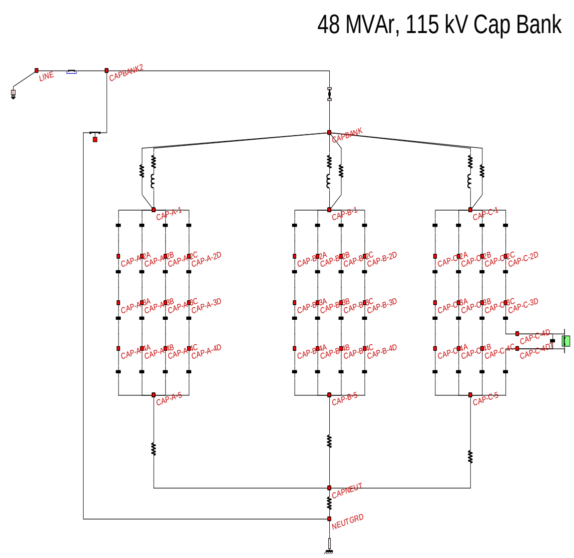

Figure 5. Capacitor Bank Configuration

The SCAQCF model for three phase capacitor bank is not listed here because it contains many equations and the space for this paper is not enough. It can be found in [15]. The result of the DSE-based protection is shown in Fig 6.

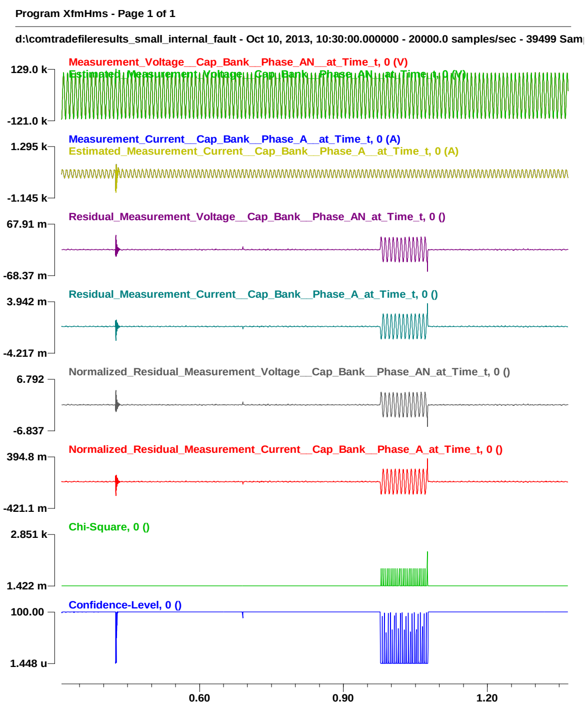

Figure 6. Capacitor Bank DSE-based Protection Result

From the above figure, it can be seen that the internal fault happens at 0.97s and clears at 1.08s. Because of the fault, the residual becomes large and the confidence level drops to zero very quickly. Since this internal fault is quite small, the confidence level is oscillating during the internal fault period. An integral function could be applied to this confidence level to make it low all the time during the internal fault. It is also obvious that different from the internal faults, the external faults at 0.43s only cause an impulse on the confidence level.

The execution time for the reactor and capacitor bank protection from the lab implementation is around 100 µs, which is much shorter than the required 400µs. Thus the speed of the proposed DSE-based protection meets the qualification of real-time protection.

V. Conclusion

This paper has presented two updates for the DSE-based protection method. An object-oriented manner utilizing State and Control Algebraic Quadratic Companion Form is introduced to generalize the mathematical model of power apparatus, thus the DSE-based protection algorithm can be applied to all protection zones automatically. Also a merging unit based lab implementation is performed to verify the effectiveness and dependability of the proposed approach. The merging units read the real-time streaming data from WinXFM which is used to generate real-time waveforms. Meanwhile the merging units transmit digital GPS synchronized data to relays and computers by IEC 61850 GOOSE message. The demonstration shows that the confidence level accurately presents the health status of the protection zone even if the internal fault is quite small.

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VII. BIOGRAPHIES

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