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Dynamic State Estimation Based Protection: Laboratory Validation

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SUMMARY

The significant changes occurring on the power grid today with the increases in renewable resources at the transmission and distribution level along with their associated variability, new loads such as electric vehicles and other electronic loads the impact on traditional protection and control approaches is considerable. This added complexity imposes new challenges for the protection and control engineer in applying traditional approaches, many of these approaches date back to the early electromechanical relays. The time has come to investigate new methods that capitalize on the technological capability the industry has available today. The numerical relay increased its domination to the point that today it has almost completely displaced electromechanical and solid state relays. However, the capabilities of numerical relays are not fully utilized today; specifically, they simply mimic the logics that are developed for the electromechanical relays but with much more flexibility. Recent developments towards substation automation are utilizing the numerical relays for SCADA, communications and in general an integrated system for protection and control. These approaches indicate the recognition that numerical relays offer much more than simply mimicking protection functions of the past.

We present a new protection scheme that is a generalization of differential protection. The approach is based on dynamic state estimation. Specifically, the protection scheme is based on continuously monitoring terminal voltages and currents of the component and other possible quantities such as tap setting, temperature, etc. as appropriate for the component under protection. The monitored data are utilized in a localized dynamic state estimation that continuously provides the dynamic state of the component. The dynamic state is then used to determine the health of the component. Tripping or no tripping is decided on the basis of the health of the component. The basic approach is described in the text of the paper. The feasibility has been tested in the laboratory. The experimental setup is described in the body of the paper. The laboratory tests have verified that present day microprocessors can perform the analytics required within the time interval of two successive data samples and therefore the setting-less protective device can operate continuously as any other numerical relay. The setting-less protection will be demonstrated in the field. A pilot project has been approved. In

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this project we will implement the setting-less protection on a 765/345/13.8 kV autobank and a 765 kV, 150 mile long line. A brief description of the project is described in the body of the paper.

KEYWORDS

Dynamic State Estimation, Differential Protection, Merging Units, Confidence Level

1. Introduction

The changing face of the electric power system due to new power apparatus and the proliferation of customer owned resources and smart devices calls for new approaches for protection, control and operation of the emerging electric power system. The emerging system requires better protection, more integration and more automation [1-2]. Better protection is required as we deal with systems with power electronic interfaces that limit fault currents to levels comparable to load currents; a fact that makes the traditional protection approaches obsolete. The integrated and automated system can take advantage of the combination of utility and customer resources to make the operation efficient (loss minimization, load levelization, etc.) and to improve the reliability of the system by responding in cases of need.

This paper proposes an infrastructure of data acquisition systems that provide the necessary information for an automated system that enables autonomous protection, model validation, a distributed state estimation and an integrated system of applications. The details of this system are given below.

2. Proposed Zone Protection Approach

The numerical relay with present day high performance microprocessors has replaced the electromechanical and solid state relays. Such numerical relays can perform multiple protection functions. The multifunctional capability can cause complex coordination problems. The complexity can cause inconsistencies and the incorrect operation of relay, thus degrading security and/or dependability. These limitations of numerical relays are mainly due to the fact that the traditional numerical relays are monitoring a specific small number of quantities (e.g., three currents and three voltages) and trip circuit breakers when a quantity or quantities enter a certain area (relay characteristic area). However, it is possible that the specific quantity or quantities do not always indicate the health of the component under protection, i.e. the condition may be a tolerable condition for which tripping is not warranted. There are other examples that present relaying approaches may not properly detect an intolerable condition.

For more secure protection of power components such as transmission lines, transformers, capacitor banks, motors, generators, etc., a new method has been developed that continuously monitor the dynamic model of the component under protection via dynamic state estimation. Specifically, the proposed method extracts the dynamic model of the component under protection via dynamic state estimation [3-7]. The dynamic model of the component accurately reflects the condition of the component and the decision to trip or not to trip the component is based on the condition of the component irrespectively of the parameter of condition of other system components. Figure 1 illustrates this concept. The proposed method requires a monitoring system of the component under protection that continuously measures terminal data (such as the terminal voltage magnitude and angle, the frequency, and the rate of frequency change) and component status data (such as the tap setting and the temperature). The dynamic state estimation processes these measurement data and extracts the real time dynamic model of the component and its operating conditions. It is clarified that the rate of frequency change is computed by using data from at least two consecutive cycles. Specifically, at each cycle the frequency of the system is computed by processing all the captured waveforms at that cycle. By comparing this value to the frequency value of the previous cycle the rate of frequency change is computed.

After estimating the operating conditions, the well-known chi-square test calculates the probability that the measurement data are consistent with the component model (see Figure 1). In other words, this probability, which indicates the confidence level of the goodness of fit of the component model to the measurements, can be used to assess the health of the transformer. The high confidence level indicates a good fit between the measurements and the model, which indicates that the operating condition of the component is normal. However, if the component has internal faults, the confidence level would be almost zero (i.e., the very poor fit between the measurement and the transformer model).

In general, the proposed method can identify any internal abnormality of the component within a cycle and trip the circuit breaker immediately. It is emphasized that the proposed dynamic state estimation based protection scheme is a generalization of differential protection. For this reason any internal fault in the protected zone will immediately detected by the proposed scheme - the same fast way as an internal fault is detected by a differential protection scheme. Furthermore, it does not degrade the security because a relay does not trip in the event of normal behaviour of the component, for example

inrush currents or over excitation currents in case of transformers, since in these cases the method produces a high confidence level that the normal behaviour of the component is consistent with the model of the component. Note also that the method does not require any settings or any coordination with other relays.

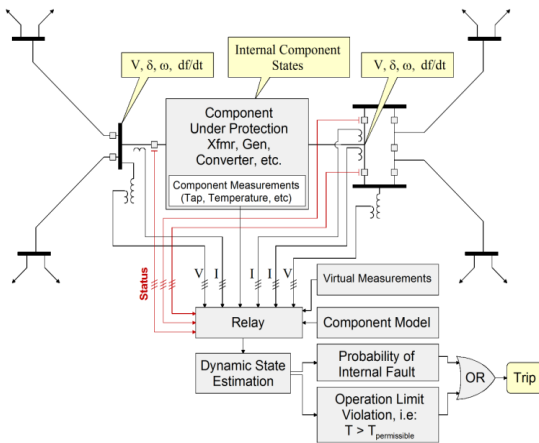


Figure 1: Illustration of Setting-less Component Protection Scheme

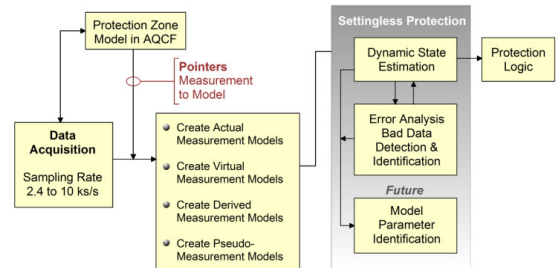


Figure 2: Setting-Less Protection Relay Organization

While the proposed scheme can be viewed as a generalization of differential protection, its reliability is much better than differential protection. As an example while line to line internal faults cannot be detected by differential schemes, the proposed dynamic state estimation protection does detect line to line internal faults immediately.

3. Implementation of Setting-less Protection

The implementation of the setting-less protection [9] has been approached from an object orientation point of view. For this purpose the constituent parts of the approach have been evaluated and have been abstracted into a number of objects. Specifically, the setting-less approach requires the following objects:

- mathematical model of the protection zone
- physical measurements of analogue and digital data
- mathematical model of the physical measurements
- mathematical model of the virtual measurements
- mathematical model of the derived measurements
- mathematical model of the pseudo measurements
- dynamic state estimation algorithms
- bad data detection and identification algorithm
- protection logic and trip signals
- online parameter identification method

Each device mathematical model is expressed in the generalized State and Control Algebraic Quadratic Companion Form (SCAQCF) so that each model is an object. This object represents the algebraic and differential equations of the protection zone in a standard syntax. This object model has been presented in previous publications [9] and it will not be repeated here. The dynamic state estimation uses this model and standard least squares method to determine the real time status of the protection zone. The overall process of the setting-less protection is illustrated in Figure 2.

Note that the overall approach shows that when necessary the method performs parameter identification for fine tuning the model of the protection zone. The method is conceptually simple. When a disturbance occurs the dynamic state estimation process is modified by treating selected parameters of the model as unknowns in the estimation process. The resulting solution of the dynamic state estimation provides better estimates of the parameters of the zone.

4. Zone Protection Illustrative Examples

Two illustrative examples are provided, one for a capacitor bank and another for the saturable core reactor. A test system was constructed that includes among other components, a capacitor bank and a saturable core inductor at different locations of the system. The capacitor bank model is illustrated in

Figure 3. The setting-less relay monitors four voltages at the terminals of the cap bank and neutral, three currents at the terminals of the cap bank (top current) and three current at the neutral connection of the capacitor bank. Several events were simulated: 1) external faults, 2) switching inrush conditions, and 3) internal faults. The simulated values of voltages and currents at the terminals of capacitor bank are recorded in COMTRADE format, and then the data is "played back" into the setting-less protection relay. The results for two cases are described next.

External Fault: A single-phase-to-ground fault is simulated on phase A of a nearby bus. The fault is cleared at 0.1 seconds. Figure 4 depicts the measured voltages and currents (left part of Figure 4) and a small sample of the results in the following form (see right side of Figure 4): the measured and estimated values of phase A voltage (top trace), the measured and estimated values of phase B voltage (second trace), the measured and estimated values of phase C voltage (third trace), the residuals of phase A voltage and the confidence level that the protection zone is in healthy condition (bottom trace). Note that the health of the capacitor bank is high with 100% confidence level during the normal operation condition. During the external fault condition, transient voltage and current values resulting in 0% confidence level for a short period of time which rapidly returns to 100% confidence level. Therefore, it can be concluded that the proposed setting-less scheme successfully determines that the fault is not an internal fault and avoids nuisance trips.

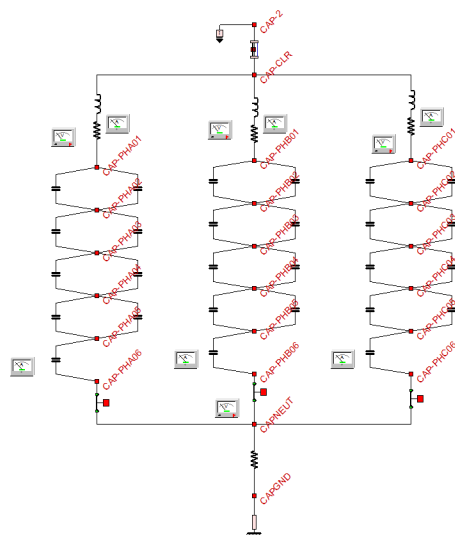


Figure 3: Grounded wye-connected capacitor bank.

Internal Fault: A fault occurs inside the capacitor bank. The fault is a short circuit between two cap elements on phase A. The internal fault initiated at 0.1 sec and then cleared at 0.15 sec. Figure 5 depicts the measured voltages and currents (left part of Figure 5) and a small sample of the results in the following form (see right side of Figure 5): the measured and estimated values of phase A voltage (top trace), the measured and estimated values of phase B voltage (second trace), the measured and estimated values of phase C voltage (third trace), the residuals of phase A voltage and the confidence level that the protection zone is in healthy condition (bottom trace). Note that the health of the capacitor bank is high with 100% confidence level during the normal operation condition. During the internal fault condition the confidence level is 0% indicating a fault zone condition. Therefore, it can be concluded that

the proposed setting-less scheme successfully determines the internal fault condition and generates a trip signal to isolate the fault condition.

The inductor model is represented with a high order model that captures the nonlinear characteristics of the saturable core reactor. The setting-less relay monitors three voltages at the terminals of reactor and three currents at the terminals of the reactor. Two events have been studied: (a) reactor energization and (b) source switching. These events have been selected to illustrate the ability of the dynamic state estimator to track the highly nonlinear behaviour of the saturable reactor and its ability to recognize these events as "normal".

Reactor energization: At a certain time the reactor is energized. Inrush current transients are triggered. Figure 6 (left side) shows the following: (a) Measured voltage waveform at reactor phase A, (b) Estimated voltage waveform, (c) Residual, (d) Normalized residual, (e) Chi-square, and (f) Confidence level. Note that the estimated values of the inrush current are pretty much identical to measurements. This is verified from the low value of the residual as well. This example illustrates the ability of the dynamic state estimator to track these transients very closely, even if these transients are highly nonlinear.

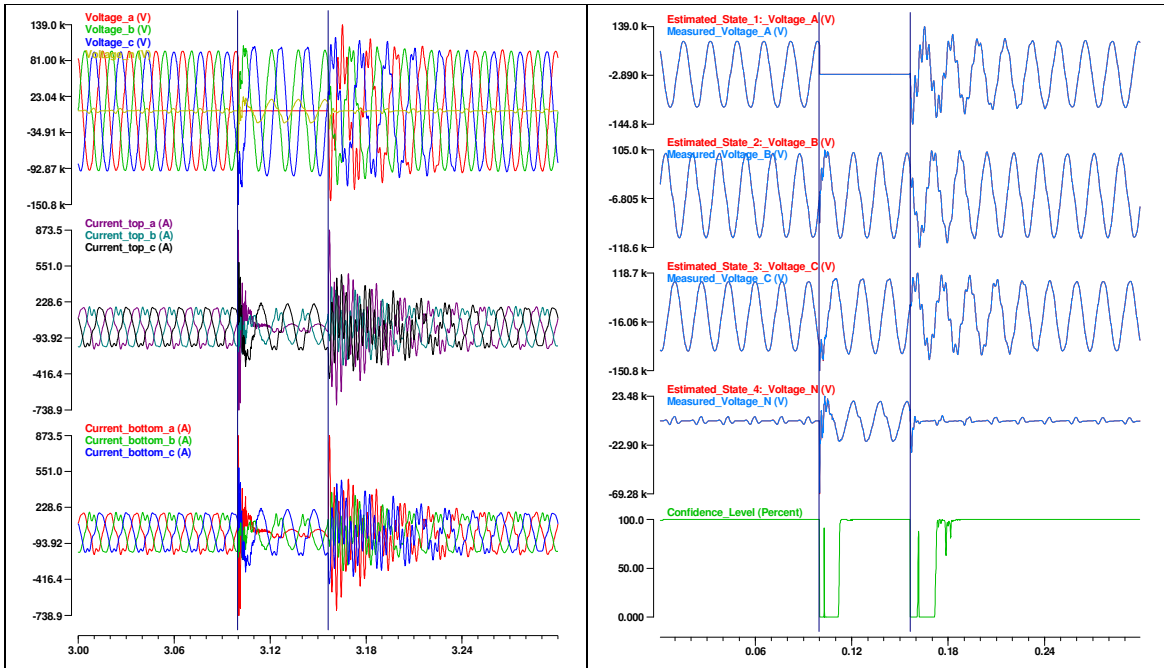


Figure 4: External fault condition: Measurement signals of capacitor bank

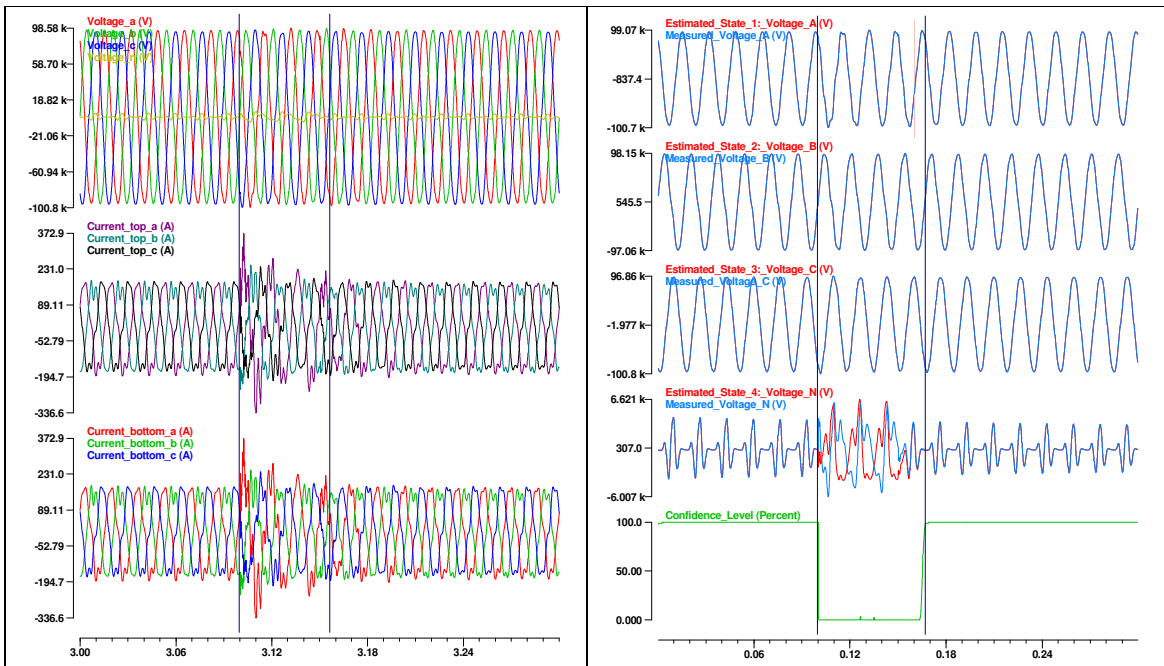


Figure 5: Internal Fault Event: Measurement signals of capacitor bank

Reactor Source Switching: At a certain time the reactor is switched from one source to another. The two sources are not synchronized. There is a phase difference between the two sources. A transient is generated in the saturable core reactor. These transients are “inrush” type transients and they are illustrated on the right side of Figure 6. Note again the ability of the dynamic state estimator to track these transients very closely.

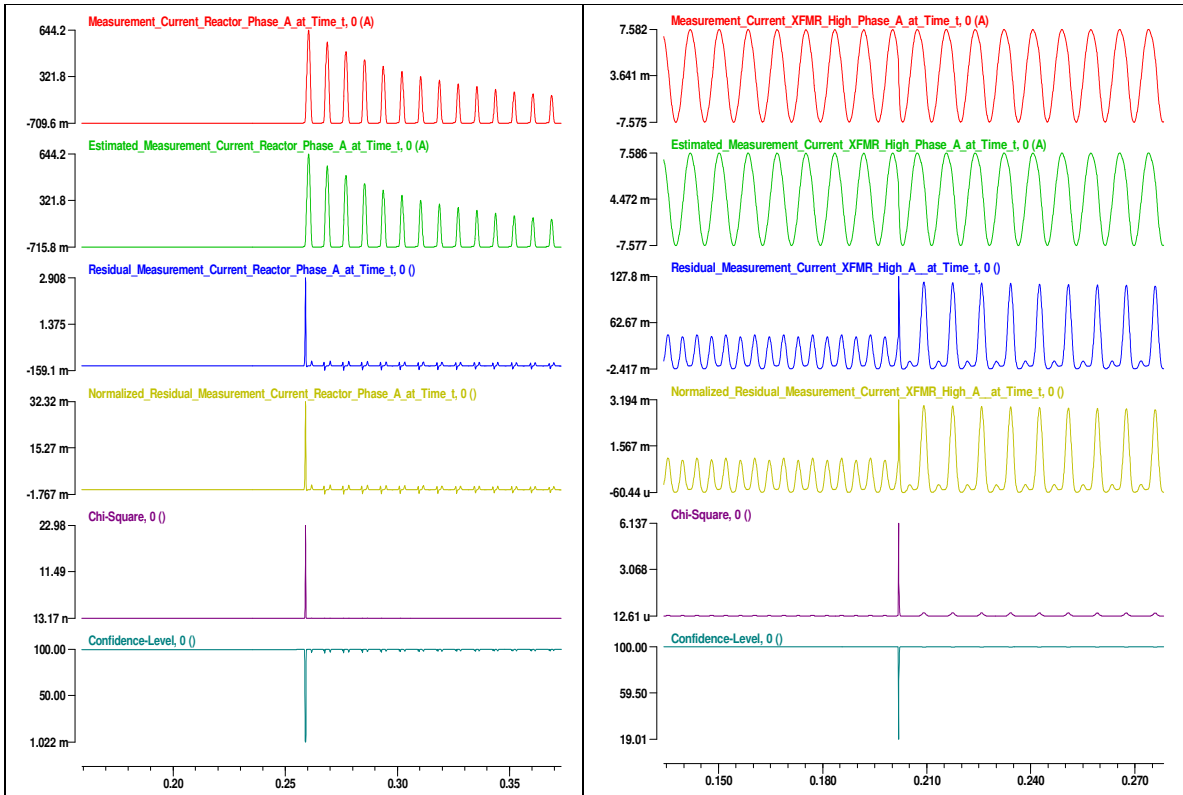


Figure 6: Dynamic State Estimation Results for a Saturable Core Reactor
(a) Left Side: Energization event, (b) Right Side: Switching source event

5. Laboratory Testing

The feasibility of the approach is presently tested in the laboratory. The laboratory setup for testing the dynamic state estimation based protection scheme for any protection zone is shown in Figure 7. The operation of the protection zone is represented with a digital simulator. The results of the digital simulation are fed into a multichannel digital to analogue converter and the analogue outputs are fed into a set of amplifiers. The amplifiers generate signals at relay instrumentation levels (69V and 1A/5A) which are connected to IEC 61850 merging units. The IEC 61850 merging units are connected to a process bus. A personal computer is connected to the process bus via an optical input/output board. The personal computer serves as the relay. The figure also shows relays for illustrative purposes but presently is not used.

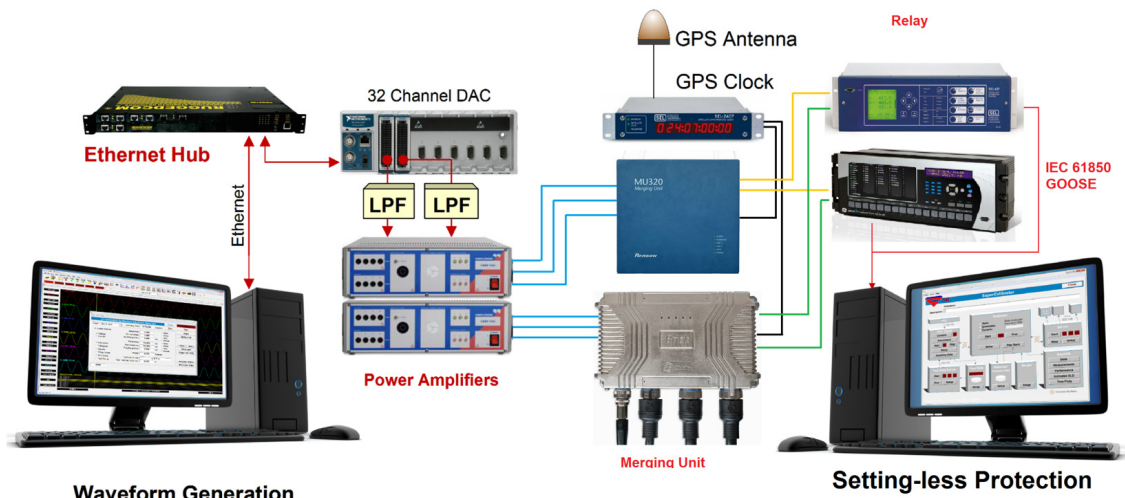


Figure 7: Laboratory Equipment and Interconnections for Setting-less Protection Testing

Figure 8 shows the circuit diagram for a test on a three phase transformer. The amplifiers are not shown. Note that the three phase transformer is simulated with the digital simulator. Past the transformer everything else is physical devices that are interconnected as they would have been in the substation. Finally Figure 9 shows a photograph of the laboratory.

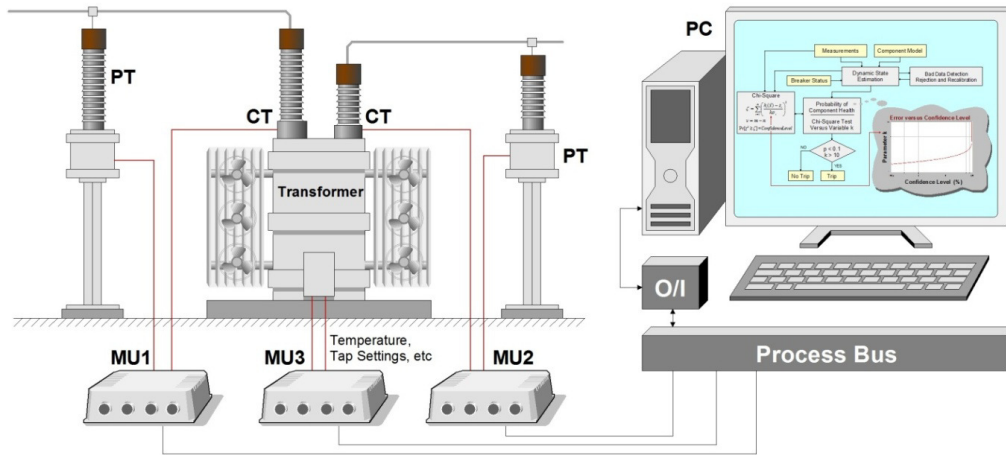


Figure 8: Circuit Diagram of the Testing Experiment (Transformer Operation is Simulated - All Other Represent Physical Equipment

The laboratory tests have achieved the following: (a) the physical devices (in this case the merging units, process bus and computer) work together, and (b) the computations of the setting-less protection are performed within the time interval between consecutive sampled data and we do not have a problem with data coming faster than they can be processed.

A number of visualizations have been also developed. Once such visualization is shown in Figure 10. The visualization shows the operating condition of a three phase transformer (actual currents and voltages at the two three-phase terminals of the transformer) as well as the performance of the setting-less relay and the decisions/or no decisions of the relay.

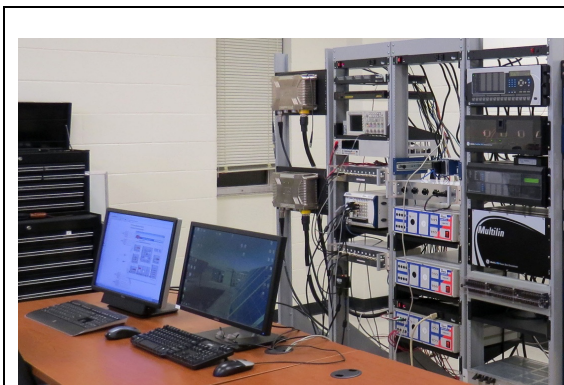


Figure 9: Photograph of the Laboratory

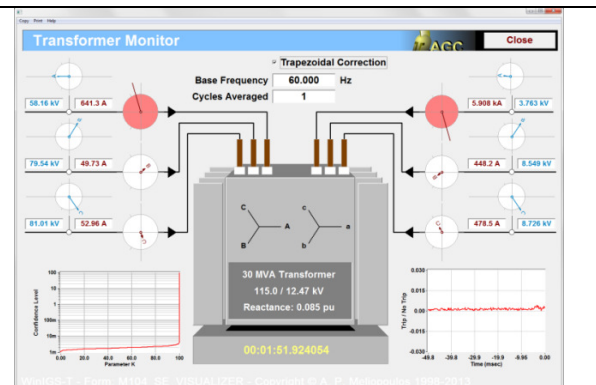


Figure 10: Visualisation of Transformer Setting-Less Protection

6. Conclusions

The basic concept and objectives of the smart grid and grid modernization is to utilize existing and future technologies for the purpose of increasing the level of automation and autonomy of the power system of the future. Towards this goal it is important to remove human intervention or needs for human input as much as possible to avoid possibilities of human error as the operation of the system becomes more complex and the number of players is increasing. We have proposed a new protection scheme that can adaptively diagnose the health condition of the component under protection. The approach leads to protection schemes that do not require settings or the settings are simplified. The proposed method can differentiate internally faulted components from unfaulted conditions; for

example, in case of transformer protection, the method can identify the high inrush current and/or over excitation currents as normal operation, while it can identify a fault near the neutral of the transformer. The proposed method is based on dynamic state estimation using real-time measurement data and the dynamic model of the component; the real-time measurement data are continuously provided by online monitoring system. From these measurements and the dynamic model, the dynamic state estimation produces the real-time dynamic states of the component as well as the confidence level that indicates the goodness of fit of the component model to the measurements. This confidence level can be used to assess the health of the component; if the confidence level is almost zero, then we can conclude that any internal fault has occurred inside the component.

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