Integrated Automation System Based on Protection Zone Dynamic State Estimation

A. P. Sakis Meliopoulos, *Fellow, IEEE*, George J. Cokkinides, *Senior Member, IEEE*, Paul Myrda, *Member, IEEE*

***Abstract*--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 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.**

In previous work, we presented 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 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 present paper takes the above concept one step further. Using the dynamic state estimation of a protection zone as the basic technology, it builds an integrated automation system that performs the protection functions, validates models, integrates monitoring and control, and provides automated disturbance playback capabilities. The system interfaces with the control center to provide validated models of the protection zone and state estimation results. It can also provide validated models for any number of applications.

***Index Terms*--Nonlinear dynamic systems, dynamic state estimation, external and internal faults, component protection.**

I. 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. 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.

II. Proposed Approach

The overall proposed structure is shown in Figure 1. The system starts from the relays that monitor power apparatus (a protection zone) and performs dynamic state estimation at the apparatus level. The dynamic state estimation is performed a few thousand times per second depending on the sampling period of the data acquisition systems. For example, if the relay samples 4000 times per second, the dynamic state estimation is executed 2000 times per second. This process is described in the section setting-less protection and it has been demonstrated with extensive numerical experiments and in the laboratory. The indicated relay is a numerical relay on which a number of new functions have been added. We will refer to this relay as Universal Monitoring Protection and Control Unit (UMPCU). The UMPCU provides the real time model of the component, estimated measurements and status of connectivity of the component at very fast speeds. These results are used to perform component protection (setting-less protection) [20]. The results of the dynamic state estimation over a period of one cycle are used to compute the state of the component in the “phasor domain”, see block “Conversion to Phasor Model”. These results include the following information for the power apparatus (protection zone): ((1) connectivity, (2) device model, and (3) measurements). Subsequently, this information is used to synthesize the substation state as shown in Figure 1. Note that the substation state is updated once per cycle. Finally the substation state is transmitted to the control center where the system state is synthesized. Note that the synthesis of the substation state as well as the synthesis of the system state at the control center, does not require additional computations since the component models are all in UTC time (due to the GPS synchronized measurements) and therefore they can be simply merged to provide the system wide model.

It should be stressed that the functional specifications of the

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UMPCU can be met by current top-of-the-line numerical protective relays. Specifically, the computational power of these relays is adequate to perform the analytics of the UMPCU, i.e. the state estimation based protection function and the extraction of the real time model of the component by appropriate programming. The UMPCUs are also able to receive commands from the control center and apply them to control power apparatus just as present relays are able to do.

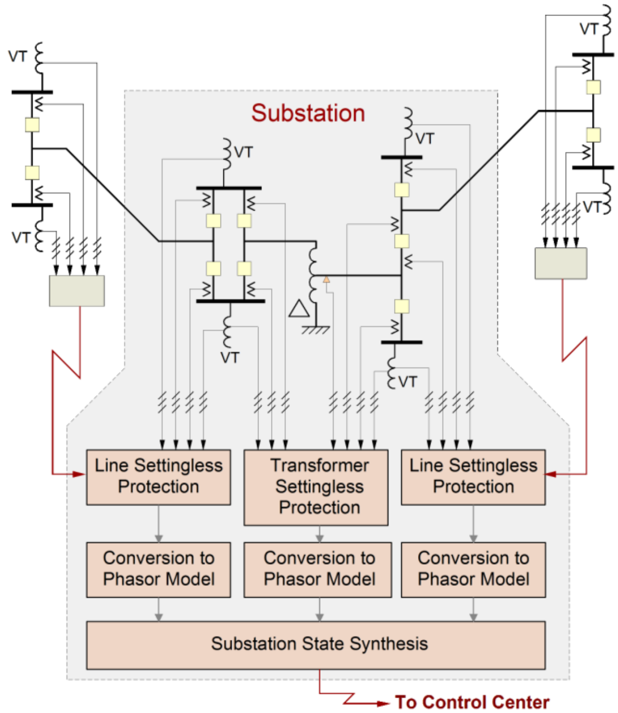

Figure 1: Illustration of Overall Approach

It is emphasized that the proposed approach facilitates efficient communications. Specifically, each substation sends to the EMS only its real time model which comprises a very small number of data. When connectivity changes, then connectivity data are transmitted by exception. Similarly if model changes occur, the new mathematical model will be transmitted by exception. The end result is that while the instrumentation may be collecting data at rates of hundreds of thousands of data points per second, the frequency domain state (phasors) are only a few tens of data points per second. Only the frequency domain component state is transmitted to the EMS.

The constituent parts of this approach are described next.

III. Zone Protection and Model Validation

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 [10-13]. 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 3 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.

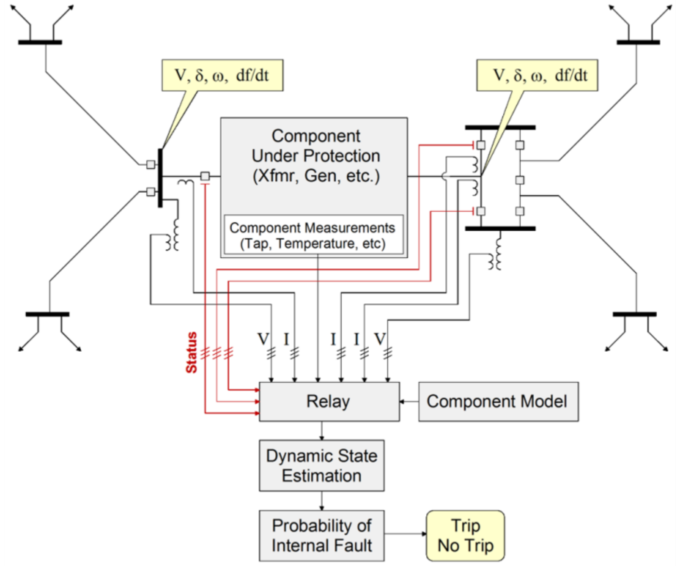

Figure 2: Illustration of Settingless Component Protection Scheme

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 3). In other words, this probability, which indicates the confidence level of the goodness of fit of the transformer 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. Furthermore, it does not degrade the security because a relay does not trip in the event of normal behavior 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 behavior 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.

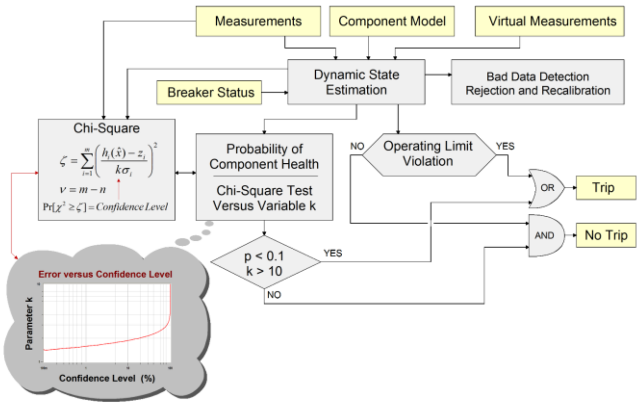

Figure 3: Illustration of Settingless Protection Logic

IV. Implementation of Setting-less Protection

The implementation of the setting-less protection 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 analog 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

The last task is fundamental for model verification and fine tuning the parameters of the models. It is done via online parameter identification methods. Conceptually the method is very 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. The overall process is shown in Figure 5.

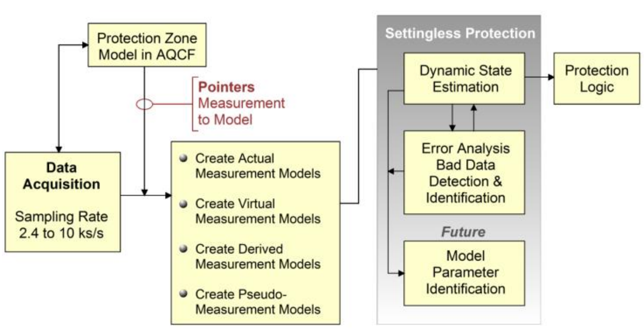

Figure 4: Setting-Less Protection Relay Organization

The details of this protection approach can be found in [11], [12]. Several user interfaces have been developed to visualize the operation of these relays. Figure 7 illustrates an example.

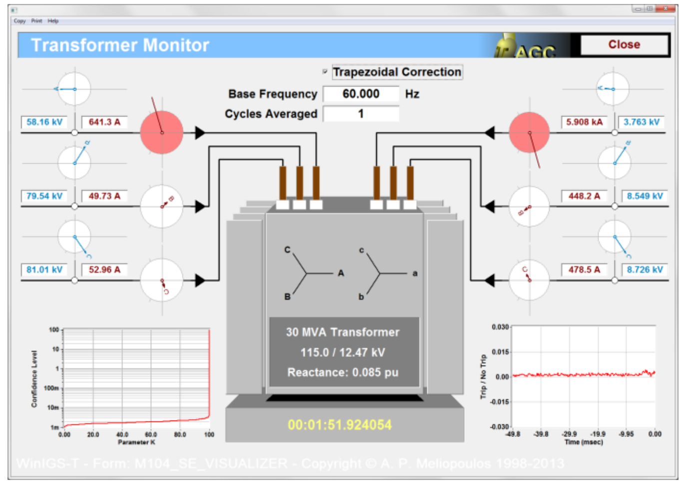

Figure 5: Visualization of Transformer Setting-Less Protection

V. Model Parameter Identification

The modeling issue is fundamental in this approach. For success the model must be high fidelity so that the component state estimator will reliably determine the operating status (health) of the component. For example consider a transformer during energization. The transformer will experience high in-rush current that represent a tolerable operating condition and therefore no relay action should occur. The component state estimator should be able to "track" the in-rush current and determine that they represent a tolerable operating condition. This requires a transformer model that accurately models saturation and in-rush current in the transformer. We can foresee the possibility that a high fidelity model used for protective relaying can be used as the main depository of the model which can provide the appropriate model for other applications. For example for EMS applications, a positive sequence model can be computed from the high fidelity model and send to the EMS data base. The advantage of this approach will be that the EMS model will come from a field validated model (the utilization of the model by the relay in real time provide the validation of the model). This overall approach is shown in Figure 6.

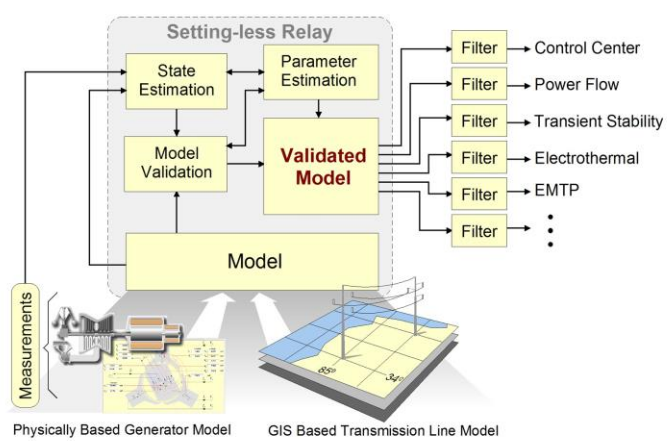

Figure 6: Illustration of Settingless Protection Logic

Since protection is ubiquitous, it makes economic sense to use relays for distributed model data base that provides the capability of perpetual model validation.

VI. Substation Model Synthesis

The results of the dynamic state estimation over a period of one cycle are in the time domain. Specifically, the point on wave data is available for each variable of the zone under protection. This data are converted into the frequency domain by applying Fourier transform on the time domain data over a user specified time interval, for example one cycle. Because the frequency of the system may vary in real time, the Fourier transform must estimate the frequency first and then perform the Fourier analysis. Otherwise issues of spectral leakage may appear. We have developed a generalized approach for the computation of the phasors that provide high accuracy in phasor computation under varying frequency and waveform distortion. We refer to this method as the "Standard PMU". The standard PMU is the subject of a paper to be released in the near future. The end result of these computations is the zone model in frequency domain. The over organization is shown in Figure 7. The phasor model is expressed in terms of four sets of data: ((1) connectivity, (2) device model, (3) measurements, and (4) time stamp). Subsequently, this information is used to synthesize the substation state estimate. This process is quite simple: the state estimates of each zone are aligned by the time stamp. The zone models of a specific time stamp are collected to form the substation state estimate. In our work we use a time interval of one cycle and therefore the substation state estimate is updated once per cycle. Finally the substation state is transmitted to the control center where the system state is synthesized. Note that the synthesis of the substation state does not require additional computations since the component models are all in UTC time (due to the GPS synchronized measurements) and therefore they can be simply merged to provide the substation model.

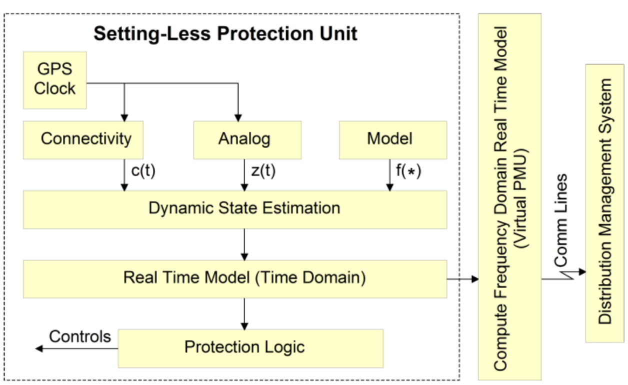

Figure 7: Functional Diagram of Setting-less Protection Unit

VII. System Wide Model Synthesis

The substation state estimate (in frequency domain) is used to directly synthesize the state of the entire system. This process is similar to the synthesis of the substation state estimate with the only difference that since the substation states are already in frequency domain this synthesis is straightforward and does not require any model conversions. The synthesis of the system wide state estimate is illustrated in Figure 8. Figure 8 illustrates how the EMS synthesizes the system wide model from substation state estimates. Each component's connectivity data is used to compose the topology of the substation. Using that topology, state estimates from each component that have the same GPS time stamp are immediately combined (with no additional calculations) to obtain the system wide state estimate.

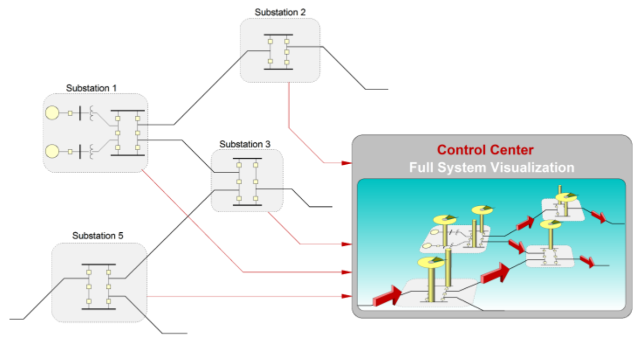

Figure 8: Synthesis of System Wide State Estimate from Substation State Estimates

VIII. Applications

The proposed infrastructure provides in an autonomous manner the real time model of components (zones), substation and system wide. We have seen that the results of the dynamic state estimation are used directly for the protection of the particular zone. The real time model can be used for a variety of other applications. Some examples are discussed here.

First the real time model can be used on demand for a number of off line applications. For example if a transient stability analysis is needed, then the real time model can be extracted in the form that is required from the particular analysis program to be used via a filter that takes the three phase real; time model and creates the model in the form required. This is illustrated in Figure 6. It is important to note that any standard analysis program can be supported by simply building the filters from the real time model to the model required by the analysis program.

The important of the proposed infrastructure is that it enables the seamless integration of real time applications. The applications use the real time model which is also characterized with the accuracy or the expected error in the real time model. Normally the expected error in the real time model is quite low providing a high confidence level on the results of the real time applications. We have developed the following real time applications:
(a) system protection (already demonstrated earlier),
(b) stability monitoring, and
(c) voltage/var control.
The last two applications have been implemented in a fully autonomous and object oriented manner. The only user interface is the selection of specific objectives, for example for

the voltage/VAR control problem, the user may specify voltage profile optimization, minimum losses, or minimum operating cost. The implementation of these applications is beyond the scope of this paper.

IX. Further Work

The proposed infrastructure enables a fully autonomous monitoring, protection and operation of a wide area system. The approach is based on equipping the basic data acquisition systems with intelligence to collect not only data but also the component model as well as the connectivity of the component. GPS time synchronization is a requirement of the approach since the analytics require that the derived models and state estimates by time stamped with accuracy of microseconds.

Further work is need to perfect the infrastructure and to demonstrate a number of basic applications of this system. On-going research projects are focused on these tasks.

X. Conclusion

The basic concept and objectives of the smart grid 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 an infrastructure that practically eliminates human input in the process of extracting the real time model of the system and using the real time model for (a) protection and (b) model based control. The technology required for the implementation of the proposed scheme exists today.

XI. Acknowledgments

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XIII. Biographies

A. P. Sakis Meliopoulos (M '76, SM '83, F '93) was born in Katerini, Greece, in 1949. He received the M.E. and E.E. diploma from the National Technical University of Athens, Greece, in 1972; the M.S.E.E. and Ph.D. degrees from the Georgia Institute of Technology in 1974 and 1976, respectively. In 1971, he worked for Western Electric in Atlanta, Georgia. In 1976, he joined the Faculty of Electrical Engineering, Georgia Institute of Technology, where he is presently a professor. He is active in teaching and research in the general areas of modeling, analysis, and control of power systems. He has made significant contributions to power system grounding, harmonics, and reliability assessment of power systems. He is the author of the books, Power Systems Grounding and Transients, Marcel Dekker, June 1988, Ligthning and Overvoltage Protection, Section 27, Standard Handbook for Electrical Engineers, McGraw Hill, 1993, and the monograph, Numerical Solution Methods of Algebraic Equations, EPRI monograph series. Dr. Meliopoulos is a member of the Hellenic Society of Professional Engineering and the Sigma Xi.

George Cokkinides (M '85) was born in Athens, Greece, in 1955. He obtained the B.S., M.S., and Ph.D. degrees at the Georgia Institute of Technology in 1978, 1980, and 1985, respectively. From 1983 to 1985, he was a research engineer at the Georgia Tech Research Institute. Since 1985, he has been with the University of South Carolina where he is presently an Associate Professor of Electrical Engineering. His research interests include power system modeling and simulation, power electronics applications, power system harmonics, and measurement instrumentation. Dr. Cokkinides is a member of the IEEE/PES.

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