Wide-Area Protection and Control: Present Status and Key Challenges

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Abstract—The electricity supply industries need tools for dealing with system-wide disturbances that often cause widespread blackouts in power system networks. When a major disturbance occurs, protection and control measures assume the greatest role to prevent further degradation of the system, restore the system to a normal state, and minimize the impact of the disturbance. Continuous technological development in communication and measurement have promoted the utilization of Phasor Measurement Unit (PMU) based Wide-Area Measurement Systems (WAMS) in power system protection and control for better management of the system security through advanced control and protection strategies. In this paper, a comprehensive survey is made on recent developments in this field. Focus of the survey is on WAMS based adaptive relaying and control applications and highlights key issues and challenges.

I. INTRODUCTION

Modern power systems are in the process of continuous development which has led to complex interconnected networks. Financial pressure on the electricity market and on grid operators forces them to maximize the utilization of high-voltage equipment, which very often lead their operation closer to the limits of the system. This approach of ensuring economic operation is possible provided the system is equipped with a well designed and coordinated protection and control strategy to deal with wide spread disturbances in the system.

Traditional power system protection and control measures are based on local measurements. However, it is quite difficult to maintain the stability and security of the system on the whole, if only local measurements are employed in the protection and control schemes. One promising way is to provide a system wide protection and control, complementary to the conventional local protection strategies. While it is not possible to predict or prevent all contingencies that may lead to power system collapse, a wide-area monitoring and control system that provides a reliable security prediction and optimized coordinated action is able to mitigate or prevent large area disturbances. The main tasks, which can be accomplished through wide-area based monitoring and control system, are early recognition of large and small scale instabilities, increased power system availability through well coordinated control actions, operation closer to the limit through flexible relaying schemes, fewer load shedding events and minimization of the amount of load shedding.

The main disadvantage of the present conventional method of system monitoring is the inappropriate system dynamic view, or the uncoordinated local actions, like that in decentralized protection devices. Solution to the above can be achieved through dynamic measurement system using synchronized phasor measurement units. A system comprising of synchronized phasor measurements and performing the tasks of stability assessment with adaptive relaying is called a Wide-Area Monitoring and Control (WAMC) system [1].

This paper provides a comprehensive survey of power system applications related to protection and control based on wide area measurements. The paper is organized as follows: section II describes the requirements for a wide-area protection system. In Section III architecture of wide-area protection system is discussed. Section IV critically reviews the research work carried out in the field of wide area based adaptive protection and categorizes the application fields. In section V, control schemes for small signal stability analysis based on wide area measurements are reviewed and are classified based on controller structures. Section VI lists a few key issues and research challenges in the wide area based protection and control schemes. Finally section VII presents the main conclusions.

II. REQUIREMENTS FOR A WIDE AREA PROTECTION SYSTEM

Wide-area protection system is employed to fulfill the two main objectives of increasing transmission capability as well as system reliability. Closer analysis on the above two broad objectives require the focus on the following [1]:

- Coordination with existing local protection system with a view to enhance the system reliability and security by appending the protection system with system wide information
- Identification of critical situations and determining appropriate remedial actions with regard to the following physical phenomena:
  a. Transient (angle) instability (first swing)
  b. Small signal angle instability mainly due to poor damping
  c. Frequency instability
d. Short-term voltage instability

e. Long-term voltage instability

These phenomena are now-a-days partly covered by pure local actions as part of the classical protection schemes or manually utilizing the Supervisory Control and data Acquisition (SCADA)/Energy Management System (EMS) view.

The major drawbacks of these conventional solutions are that local protection devices do not consider a system wide view and are, therefore, not able to take optimized and coordinated actions. The SCADA/EMS system instead is not able to directly catch the dynamics of the system and is, therefore, focused on the steady state operational requirements. These drawbacks define the following major requirements for wide-area protection systems.

- Dynamic measurement and representation of events
- Wide area system view
- Coordinated and optimized stabilizing actions
- Adaptive relaying in coordination with local protective devices
- Handling of cascaded outages

Benefits of using wide area measurement, protection and control schemes have been discussed in [2], which has classified the major application areas in eleven categories dealing with the important steady state and transient issues in the power system. Reference [2] also reviewed the phasor technology and identified the implementation gap, at present, with respect to each of the identified power system issues.

III. ARCHITECTURE OF WIDE-AREA PROTECTION SYSTEM

The requirements of a wide-area protection system and the current technological levels vary among different power utilities. Hence, the architecture for the protection system may also be different. Three major design architectures, normally adopted are discussed as follows [3]-[5]:

A. Enhancements to SCADA/EMS

At one end of the spectrum, enhancements to the existing EMS/SCADA can be made. These enhancements are aimed at two key areas: information availability and information interpretation. Information availability may be enhanced by providing system dynamic information through PMUs [6] from all over the grid. Based on these measurements, improved state estimation can be performed which result in improved accuracy of power system states prediction. Since the possibilities of new functions in the SCADA/EMS system tend to be limited, it is better to provide them as “stand alone” solutions.

B. “Flat Architecture” with System Protection Terminals

Protection devices or terminals are traditionally used in protecting equipments (lines, transformers, etc.). Modern protective devices have sufficient computing and communications capabilities that they are capable of performing beyond the traditional functions. When connected together via communications links, these devices can process intelligent algorithms (or “agents”) based on data collected locally or shared with other devices.

Powerful, sensitive, and robust, wide-area protection systems can be designed based on decentralized interconnected system protection terminals. These terminals are installed in substations, where actions are to be made or measurements are to be taken. Actions are preferably local to increase system security. Relevant power system variable data are transferred through the communication system that ties the terminals together. Different system protection schemes can be implemented in the same hardware.

C. Multilayered Architecture

While the above two designs attempt on extending the “reach” of existing control domains (protection terminal being one domain and EMS being the other), there is no guarantee that the end solution will be comprehensive. A comprehensive solution is one that integrates the two control domains, protection devices and EMS. Such a solution is depicted in Fig.1 [3].

![Multilayered wide-area protection architecture](image)

Fig. 1. Multilayered wide-area protection architecture [3]

There are up to three layers in this architecture. The bottom layer is made up of PMUs. The next layer up consists of several Local Protection Centers (LPCs), each of which interfaces directly with a number of PMUs. The top layer, the System Protection Center (SPC), acts as the coordinator for the LPCs. This kind of wide area protection systems will most likely be common in the future.

To design a three layered architecture for a wide-area protection system, the first step generally aims at achieving wide-area monitoring capability. For this WAMS, PMUs are widely employed. In WAMS applications, many PMUs are connected to a personal computer called data concentrator, so that the dynamic behaviour of a power system could be obtained from the concentrator. However, the quantities to be measured by PMUs and the locations for installations of PMU are dependent on many factors. Several publications had appeared in solving Optimal PMU Placement (OPP), i.e., a scheme with minimum PMUs meeting the requirement of the system observability in a monitoring system [7]-[15].

A reliable and fast communication system is an indispensable element for effective wide-area protection system. The important factors, which are considered in building a robust and reliable communication network, are media, communication protocols and topology of the network. Currently a combination of power line carrier, radio, microwave, leased phone lines, satellite systems, and optical fiber is being utilized in protection systems [3]. These
systems are also associated with communications delay or latency. It is defined as the time required for transmitting data from the measurement location to a control center or data concentrator, and the time required ultimately to communicate these data to control devices.

Delays in communication are mainly due to the following factors [16]:
- Transducer delays
- Window size of Discrete Fourier Transform (DFT)
- Processing time
- Data size of PMU output
- Multiplexing and transitions
- Communication links involved
- Data concentrators

It is imperative for the utility to choose a right communication link depending upon the control action to be performed.

IV. Adaptive Relaying Based on Wide Area Measurement System

It has been recognized that many relay settings are often compromise settings, which are reasonable for many alternative conditions that may exist on a power system, which may not be the best setting for any one condition. Thus, many relay settings are compromises in terms of sensitivity or speed of response to faults, in order that they are adequate for all possible faults. A definition of adaptive relaying, which embodies this idea, is as follows [17], “Adaptive protection is a protection philosophy which permits and seeks to make adjustments in various protection functions automatically in order to make them more attuned to prevailing power system conditions.” The need of adaptive relaying and concepts of adaptive relaying are clearly depicted in [18], where on line settings for conventional relays are worked out under system configuration changes. Adaptive relaying may include schemes for various protection functions, such as fault location, fault classification and adaptive adjustments of relay settings.

Application of microprocessor based phasor measurements to adaptive protection was investigated in [19]-[20] and Reference [20] brought out a scheme for working out adaptive settings for out-of-step blocking and tripping.

IEEE Working group has recommended the usage of coordinated wide-area adaptive protection for reducing the power system disturbances. Research in this area suggests that the wide area adaptive protection should progress in two forms, which are anticipatory and responsive [5]. In anticipatory schemes, protection system characteristics are altered at the time of system stress. In responsive schemes, protection system reacts to an emergency state by taking additional switching actions to restrict the impact of a protective devices’ maloperation.

Hence wide-area protection can be coordinated with the conventional protection through the following:
- Fault location based on wide-area measurement system
- Adaptive relay settings based on wide-area information
- Adaptive back-up protection schemes utilizing wide area measurements

A. Wide Area Measurement System Based Fault Location

Fault location may be based upon phasor measurements or on traveling wave concepts. If phasor measurements are used, it is possible to make the best possible estimates of fault location from each end, and then average the two results to obtain the double-ended fault location result [19]. In [21-23] a protection scheme is suggested for fault detection, direction discrimination, classification and location based on synchronized phasor measurements. Fault detection index, in terms of Clarke’s components of the synchronized voltage and current phasors, is derived. The fault detection index is composed of two complex phasors and the angle difference between the two phasors determines whether the fault is internal or external to the protected zone. On line parameter estimation is carried out for ensuring the performance of the protection scheme. Proposed protection scheme is shown in Fig 2. [23]

![Block diagram of a wide area protection scheme](image)

Applying series compensation in power systems can increase power transfer capability, improve transient stability and damp power oscillations. However, since the variation of series compensation voltage remains uncertain during the fault period, the protection of power systems with series compensated lines is considered as one of the most difficult tasks and is an important subject of investigation for relay manufacturers and utility engineers. Effect of series compensation on line protection is well analyzed in [24-26]. Solution, in the case of lines, protected with fixed and controllable series capacitors in combination with Metal Oxide Varistor (MOV), is suggested in [27]. Wide-area measurement system based fault location scheme is worked out in [28] in a system comprising of a series Flexible Alternating Current Transmission System (FACTS) controller. Traditional approach in computing voltage drop across the series compensation device is by using the device model. Algorithm proposed in [28] utilizes only synchronous measurement data at both ends of the transmission line, to estimate fault location of a line employed with Thyristor Controlled Series Compensator (TCSC).

B. Wide Area Back-up Protection Schemes

As wide-area measurements are adopted, long-time delay is no longer necessary to ensure the coordinated selection between primary protections and backup ones, while it is necessary in the conventional protections. As a result, the delay for isolating faults by backup protection could significantly be reduced. Wide-area differential backup protection schemes are described in [29]-[30]. A strategy to prevent cascaded outages is presented in [31-32] through a wide area Backup Protection Expert System (BPES). The role of substation based wide-area backup protection system is to
monitor the existing conventional protection relays and to provide appropriate backup protection to all lines, busbars and circuit breakers in an intelligent way, with minimized impact on the network. With its global view of the protected network, the wide-area based backup protection device is capable of locating a fault precisely to trip only the circuit breakers necessary to isolate a fault.

V. ADAPTIVE CONTROL BASED ON WIDE AREA MEASUREMENT SYSTEM

Damping of power system oscillations between interconnected areas is very important for secure operation of the system. The oscillation of one or more generators in an area with respect to the rest of the system are called local modes, while those associated with groups of generators in different areas oscillating against each other are called inter-area modes [33]. Local modes are largely determined and influenced by local area states and the control measures for the same are relatively simple, and a conventional Power System Stabilizer (PSS) may be sufficient to solve the problem. However, control measures for the inter-area modes are rather complicated and, therefore, extensive concerns arise in this area. The effectiveness in damping inter-area modes is limited because inter-area modes are not as highly controllable and observable in the generator’s local signals as local modes. However, local controllers are tuned in a non-optimum fashion to damp both inter-area and local plant modes. Hence, an alternative technique to provide effective damping of the inter-area modes is desirable. Analysis of the inter-area phenomenon has shown that certain signals measured at electrical centers of the group of generators separated from the rest of the system provide more effective control. These signals could be measured by the wide-area measurement system and then transmitted to an optimally located PSS/FACTS controller to damp out the oscillation [34].

Application of wide-area measurements for control of inter-area modes broadly fall in the three categories of controller design as mentioned below:
- De-centralized controllers
- Centralized Controllers
- Multi-agent Controllers

Figs. 3 and 4 shows the general architecture of the above types of control structures [35], which are discussed in following subsections.

A. De-Centralized Controllers

Decentralized design of controller design consists of providing an additional global signal to the existing local controllers with a view to provide enhanced damping to inter-area modes.

A two-level PSS design strategy is described in [36], where the first level of control is derived from local signals and is designed to deal with the local modes. The second level of control is supplied from a coordinator using selected global states to deal with the poorly damped inter-area modes. The global signals have also been employed in SVCs for enhancement of damping the inter-area modes. Local and inter-area modes are identified through the eigen value analysis. Location of the PSSs is determined using participation factors or transfer function residues [37]. In this work, interaction between sub-systems (i.e. generators) is neglected and also the time delay in obtaining the global signal is not considered. A group headed by I. Kamwa has carried out a series of research work on wide-area control for inter-area modes [38]-[41].

The state space system identification technique is first applied to build a large-scale small-signal model in the Hydro-Quebec’s system, and then used to design global stabilizing controllers [38]. Once the state space model was obtained, observability and controllability measures were computed and subsequently five control sites were paired with remote PMUs spread over nine electrically coherent areas. These PSSs have two control loops, a speed sensitive local loop operating in the usual way, and a WAMS-based global loop using a single differential frequency signal between two suitably selected areas. The tuning and coordination technique for the complex multiple controllers and their impacts on power system operation are also discussed in the paper. Extensive studies for this control system were carried out in [39], and specifically the decentralized/hierarchical architecture, system modeling, tuning and coordination technique, and simulation and assessment of impacts on the system are described in more detail. Sequential tuning method has been employed for tuning the PSSs. However, the processing and communication delay was not discussed.

A detailed analysis of the control loop selection is presented in [40], and a straightforward and easy-to-implement methodology for loop selection has been proposed. Two complementary measures are employed in the measurement and control-signal selection. One is the geometric measure for maximizing the controllability and observability of inter-area
modes, the other is the singular-value based total interaction measure for minimizing the interactions between the local or global loops at the inter-area natural frequency. An assessment on wide-area damping control over local control is presented in [41] through numerical simulations of a three-area test system and a revised Hydro-Quebec network. The results suggest that the wide-area damping control has obvious technological advantages [42].

B. Centralized Controllers

Centralized design of controllers use a large amount of information from the system to be controlled for providing conservative and more efficient solutions compared to conventional approach. In [43], a remote feedback centralized controller is proposed. The application of Linear Matrix Inequalities (LMI), to the tuning and optimization of the controller, makes it be able to deal with the time delay in its input signals. A two-loop framework, of a wide-area stability control system, has been proposed in [44], wherein the inner loop generates real-time damping control actions using wide-area feedback signals, while the external loop adjusts the controllers’ parameters in a near-real time to accommodate the variation in the operating conditions. In this work, a modal reduction method based on the disturbance injection technique and an improved proxy algorithm is suggested. Comprehensive controllability and observability indices are used to properly locate the observers (PMUs) and controllers. Controller parameters are obtained through the solution of an information-structured-constrained Linear Quadratic Regulator (LQR) problem. Signal transmission delay has been modeled using a least-squares based polynomial prediction algorithm. Test results of the proposed wide-area control system show the advantages of the scheme over traditional local PSSs.

In [45], a two level hierarchical structure is proposed to improve the stability of multi-machine power systems. It consists of a local controller for each generator at the first level helped by a multivariable central one at the secondary level. The secondary level controller uses remote signals from all generators to synthesize a decoupling control signal that improves the local controllers’ performances. In this work, problems of voltage regulation and rotor oscillations damping are addressed simultaneously. The proposed secondary level controller continuously adapts its parameters through a gain scheduling algorithm. An extension to the above work is reported in [46] in which Smith prediction approach is used to preserve the controller performance in presence of remote measurements delays and communication delays between the central and the local controllers. It has been reported that the local controllers’ performances are considerably increased by the secondary control action and system stability is improved in presence of severe contingencies.

A Multiple input single output controller is designed in [47] for a TCSC to improve the damping of the critical inter-area modes. The proposed work employs local as well as remote stabilizing signals for damping out the inter area oscillations. The stabilizing signals are obtained from remote locations based on the observability of the critical modes. A \( H_\infty \) damping control design based on the mixed-sensitivity formulation in a LMI framework is carried out. In [48], the work reported in [47] is extended to model the signal transmission delay. A predictor based \( H_\infty \) controller is proposed to take care of time delayed systems. A unified Smith predictor approach is used in this work to formulate the damping controller design problem for a power system having a signal transmission delay of 0.75s. Difficulty in \( H_\infty \) based control approach is in the selection of the weighting matrices.

C. Multi-agent Controllers

A Supervisory level PSS (SPSS) is proposed in [49] using wide-area measurements. The coordination of the robust SPSS and local PSS is implemented based on the principles of multi-agent system theory. LMI based \( H_\infty \) controllers using selected wide-area measurements are embedded into the SPSS control loop to accommodate power system non-linear dynamic performance and model uncertainties. The supervisory PSS operates as a software agent and is composed of three main components that are agent communications, fuzzy logic controller switch and robust control loops. Fuzzy logic controller switch selects the appropriate robust controller for the corresponding system operating condition. The control signals are sent to local machines to damp system oscillations through the machines’ excitation systems. In this work, the control loops are designed off line, which may cause problems when the operating conditions are varied to a larger extent. Also, signal transmission delays are not considered in this work. However, the test results of the proposed algorithm show promising results over conventional PSS approach for damping inter-area oscillations.

In recent years, various defense plans have been framed for utility to protect the grid against various power system threats [50]. The power system frequency and voltage monitoring tasks in Hydro– Quebec is performed using programmable load shedding scheme, which offers customized solution to the power system protection [51]. Electricite de France (EDF) had introduced French defense plan for predicting transient instabilities in the system through the phasor measurements. This coordinated defense plan strategy utilizes a decision making centre called ‘central point’, which has a global view of the power system operation with real time knowledge of the phase angles over all the areas [52]. The Tokyo Electric Power Company (TEPCO) has been operating the islanding protection scheme based on the phasor angle difference obtained from the phasor measurements since 1984 [53].

VI. KEY ISSUES AND CHALLENGES

Several control algorithms, which are listed in the previous sections, have been applied in power system as an additional protection measure. However, the practical applications of WAMS, integrated with the conventional protection, are only
reported in the area of WAMS based fault location. Some of the key issues and challenges in the wide area protection and control are as follows:

- A lot of WAMS based designs are available to protect system’s security. However, a comprehensive defense plan, which could handle all possible kinds of instabilities, is yet to be developed. Hence, OPP, which is presently viewed on the basis of special protection/ control function considered, is required to be tackled as a problem which provides complete topological observability as well as numerical observability of the system.

- Selection of proper architecture of wide-area protection system is important in terms of system reliability and speed of information exchange between system components. Three possible architectures are discussed in section III of this paper for wide area protection system. However, a combination of these architectures may be preferred in the case of comprehensive defense plan. This is because, comprehensive plan intends to find solutions for system security problems, which are local (e.g. adaptive relaying for primary protection, long term voltage instability) or global (frequency instability, angular instability, control coordination for small signal stability) in nature.

- Dynamics of loads are not being considered in frequency instability protection measures based on WAMS, to the best of authors’ knowledge. For a realistic solution for frequency instability, it is inevitable to consider the same though considerable challenge is involved in obtaining dynamic loading characteristics.

- Events of cascaded tripping are reported due to the operation of overreaching zones of distance relay under stressed situation of power system. It may be a challenging task to employ WAMS based anticipatory adaptive relaying schemes to tackle the situation.

- Flexible protection scheme will be a potential solution for dealing with uncertainties involved in distance protection of transmission lines containing series FACTS devices. This scheme demands the knowledge of control parameters of FACTS devices for zone classification in distance relays. WAMS can be employed to obtain the control parameters of FACTS devices in a very short time span.

- The wide area measurement based protection and control strategy should be designed to account for time delayed information exchange from PMUs to Phasor Data Concentrator (PDC) and from PDCs to control centers. Fixed delays and polynomial prediction algorithm for delays are already incorporated in the adaptive control schemes. However, the real time adaptive identification techniques of (varying) delays need to be developed.

VII. CONCLUSION

Wide-area protection, currently, is a highly demanding research area. A comprehensive survey of present status of wide area protection and control applications in power system is carried out in this paper. This paper critically analyzes presently employed local protective measures along with SCADA/EMS system and identifies the bottlenecks in the system. Requirements of a wide-area protection system have been identified in order to overcome these shortcomings. Three possible architectures are discussed for wide area protection scheme either as an extension to the present SCADA/EMS system or as a dedicated multilayered structure. This paper brings out a categorical classification of relaying and control schemes reported in the literature. One of the major issues in the application of this relatively new technology is integration of WAMS based adaptive relaying schemes with conventional protection schemes comprising of fault detection, fault identification and fault location. Control algorithms incorporating wide area based control schemes are already available for various system stability problems like small signal stability, voltage instability, angular instability etc. Further improvements on the same could be in the methods of dealing with signal transmission delays in an adaptive manner.

REFERENCES


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