Review of PMU-based Online Applications for Dynamic Simulation, Fault Detection, and Cascading Failure Prevention

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Abstract: - Power systems are extraordinary dynamic and complicated systems with various components and tools of generation, transmission, distribution, protection and control to guarantee the nation-wide interconnected grid's daily operation and safety. This paper reviews the latest Phasor Measurement Unit (PMU) technology development and applications in power system dynamic analysis and reduced model parameter estimation, event and fault location, and novel control strategies and algorithms employed in validating relay operations to prevent cascading failure. The methods and algorithms in the reviewed works are all in accordance with NERC recommendations and fit well in the new trend of wide-area protection and control. The reviewed technology can be utilized and combined in the future to address power system online dynamic simulation, control and protection.

Key-Words: - PMU, real-time data, fault diagnosis, event tree analysis, self-healing grid, cascading failure.

1 Introduction to PMU

It is well known that power systems are so complicated that it is very challenging to simulate system-wide dynamics in great details. In recent years, Phasor Measurement Unit (PMU) data has been employed to facilitate the investigation on system states of interest. PMU is novel measurement technique to track voltage phasors, local system frequency, and rate of the change of frequency. Its popularity has been sharply growing, as evidenced by the world-wide deployment and installation. This is because of its attractive features such as GPS-based synchronization, high sampling rate of 30-60 samples/second presently, and so on [1-2].

This paper reviews several emerging techniques to apply PMU for dynamic simulation, control and protection. It first briefly reviews the previous works in grid dynamic simulation, then discusses the model reduction for dynamics parameters. Next, this paper discusses the PMU-based technology for fault location and cascading failure prevention. The reviewed technology can be utilized and combined in some way in the future to address power system online simulation, control and protection. Therefore, this is the motivation of this review paper.

2 PMU-based Dynamic Simulation and Reduced System Modeling

2.1 PMU-based Grid Dynamic Studies

A number of previous works discusses PMU-based grid dynamic studies. Reference [3] demonstrated PMU-based energy function analysis of dominant power transfer paths in large power system. The PMU-based real-time data is used to calculate system reactances and equivalent inertia. This differs from the out-of-step relay studies in [4-5], which relies on known or pre-computed system reactances to simulate system dynamics. In WECC, dynamic analysis of system response to disturbances or staged tests is based on synchronized phasor data to study the low-frequency interarea damping characteristics [6], transfer function identification [7], and system model validation [8].

2.2 PMU-based Model Reduction

Power system is usually simplified in simulation research to approximate system dynamics. For instance, the terminal bus aggregation approach is presented in [9-10], while the slow-coherency method is presented in [11-13]. Both methods retain the original power network structure.

In addition, internal node generator can be applied to represent each coherent group of close-by or strongly-connected generators based on observation. A two-area, four-generator, and 13-bus power system modified from the one used in [14] and [15] is studied in [16]. The system is shown in Fig. 1.

In this system $G_{11}$and G_{12} are strongly connected in Area 1, while G_{21} and G_{22} are strongly connected in Area 2. Each area is called a coherent group. According to the previous studies, interarea modes of oscillations are lower in frequency than the local mode of oscillations between machines in the same coherent area. For example, with 300MW power transfer from Area 1 to Area 2, the interarea oscillation frequency is 0.5735Hz, and the local mode frequencies within the coherent areas are 1.2930Hz and 1.3076Hz.

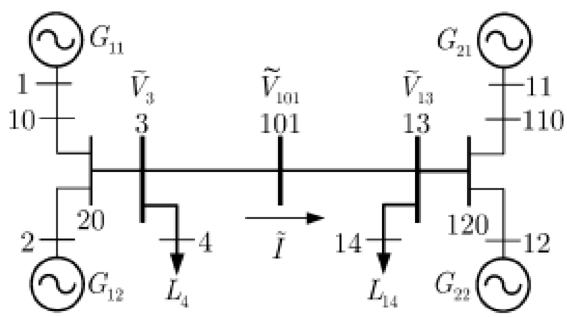

Fig. 1. The two-area study system in [16].

After obtaining PMU measured phasor data V_3, θ_3, V_{13}, θ_{13}, I, and θ_i, E_i, δ_i, z_i, H_i, (i=1, 2) and z_e can be computed to construct a reduced-order two-generator 3-bus system of [16] to represent the interarea dynamic behavior of the two-area power system. Using reactance extrapolation algorithm, the voltage at any bus, which has no PMU measurement and is located between the two generator buses, can be calculated by system dynamic differential equations and Jacobian equation, given the line current phasor. While using inertia extrapolation algorithm, from the linearized model and by measuring the frequency of the swing mode in the PMU voltage measurement, the interarea frequency in Hz and the equivalent inertia constant H can be obtained. Also frequency deviation at both ends of transmission line of interest can be calculated by the dynamic model containing rotor speed, power angle, angular frequency, and voltage magnitudes.

To examine the robustness of this reduction approach based on GPS synchronized phasor measurement, the simulation results of a same disturbance are compared for three models: the Inter-area Model Estimation (IME), the fully detailed system simulation, and the Inertia-aggregation (INA) technique [11]. The disturbance is a three-phase short-circuit fault applied at Bus 101 with 300 MW of power transfer. No line is switched out, which would require using a different IME model. Study results shows all the three traces and the IME model response can approximate the other two models quite well.

The disturbance response investigation shows that the IME model can be used to assess system stability margins. In particular, the power angle plot of the reduced system can be obtained using the IME model and be used to estimate critical clearing time and the impact of loss of transmission capacity. In [3], synchronized phasor measurement from severe oscillation events was used to establish power-angle curves of two power transfer paths in WECC, without performing reactance extrapolation to the equivalent generator internal node. In [16], new extrapolation techniques are applied. Also, the IME model of Transfer Path 1, which is compensated by series capacitors, is re-computed. Compared to the previous results, the new results show much better alignment with the actual system parameters.

3 Cascading Failure Issue in Power Systems

As a result of the U.S. northeast and the connected Canada area's blackout due to large cascading failures on August 14, 2003, system-wide disturbance issue and stability concern become an even more critical issue to power systems research than before. The causes for such large scale blackout are mainly due to the complexity of power system and lack of proper coordination, look-ahead simulation, and contingency analysis. According to historical data [17], relay misoperation [18] is a contribute factor of 70 percent of the major disturbances in the U.S. The major problem with conventional relays is that they make decisions based on local measurements instead of a global standing point. Neighboring area's operation condition and stability margin is neglected, therefore system operators may not be able to make an informed decision and issue corrective controls timely.

In the final report [19] on the August 13, 2003 blackout, NERC proposed several guidelines to

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solve such kind of problem, including prevention of cascading failure to achieve more reliable power system. In [20], the idea of wide-area protection and control was proposed as a recommendation to prevent system-wide blackout. More intelligent methods such as the Neural Network based Fault Detection and Classification (NNFDC) algorithm [21-22] and Synchronized Sampling based Fault Location (SSFL) algorithm [23] are combined to provide more reliable real-time fault analysis tool than traditional distance relay protection. The Event Tree Analysis (ETA) was used as an effective tool monitoring actual relay operations and providing event diagnosis support. They are developed using MATLAB and validated by Alternative Transients Program (ATP) [21-24].

3.1 Real-time Fault Analysis

Conventional protection focused on adding many backup strategies to guarantee protection dependability [25]. However, when the system is experiencing overload or oscillation, unnecessary trip or false trip by relays may occur. These activities may even worsen system stability and initiate cascading failure leading to wide-area blackout.

Neural network based fault detection and classification uses time domain measurement from transmission lines as patterns. The ART neural network algorithm [21] allocates the training patterns into homogeneous clusters by some grouping technique. Then, the clusters are assigned to classes representing fault events in power system. In this approach, the prototype and position of each cluster is stored and used for identifying and classifying unknown events like a rule table.

Synchronized Sampling Based Fault Location (SSFL) algorithm is developed in [23] to implement precise fault location. This algorithm demands raw samples of voltage and current data synchronously taken from both ends of a transmission line. It becomes more popular because the use of GPS time-synchronized data acquisition units PMU is an emerging trend in the utility industry, as already elaborated previously.

The principle of SSFL relies on the fact that the voltage and current at the faulted point can be represented by both sending data and receiving data. Here, traveling wave method and linear relationship are employed. The fault location is calculated by finding the point that has minimum voltage difference calculated using data from both two ends. The square of difference is plotted for each discretized point on a transmission line. It shows obvious difference between a faulted and unfaulted line. Using this method, the protection system can be prevented from tripping overload, power swing, or other no-fault abnormal situations [24], which may otherwise initiate or facilitate cascading blackouts resulting in huge loss in industry and society. A software package incorporating the NNFDC and SSFL algorithms is developed using MATLAB [26].

3.2 Validating Relay Operation Reliability

There are different types of relays in power system such as distance relay, overcurrent relay and differential relay. Their operations are critical for system reliability. There are two important causes of the August 14, 2003 blackout shown as follows [19]:

- Inadequate situational awareness
- Inadequate diagnostic support

In order to improve this situation, Event Tree Analysis (ETA) can be used for relay monitoring purpose since it is a commonly used event/response technique in industry for identifying the consequences following an occurrence of the initial event [27-28].

ETA takes the structure of a forward symbolic logic modeling technique, which links system responses to an initial challenge and enables assessment of the probability of an unfavorable or favorable outcome [28]. The explanation of each node in the event tree and its corresponding reference actions are given in a table. This table is set up along with the design of the event tree. The other two example event trees matching the case (2) and case (3) are described in [29] for a typical relay system. Implementation of real-time fault analysis and relay monitoring becomes feasible with such fault analysis tool and event analysis tool.

A 9-bus system [24] shown in Fig. 2 is modeled in ATP using dynamic generator parameters [30]. The detailed performance evaluations for NNFDC and SSFL are implemented in [21-24]. The accuracy of both algorithms is confirmed under a variety of fault scenarios, system-wide disturbances, and power swing conditions. When a three-phase fault occurrs at middle of Line 4-5, with the assumption that the trip signal is delayed for some reason, the circuit breakers at Line 4-5 have opened very close to its critical clearing time (CCT). After the fault is cleared, the system experienced a power swing. The voltage and current for Line 9-6 at bus 9 have the profile with an oscillation.

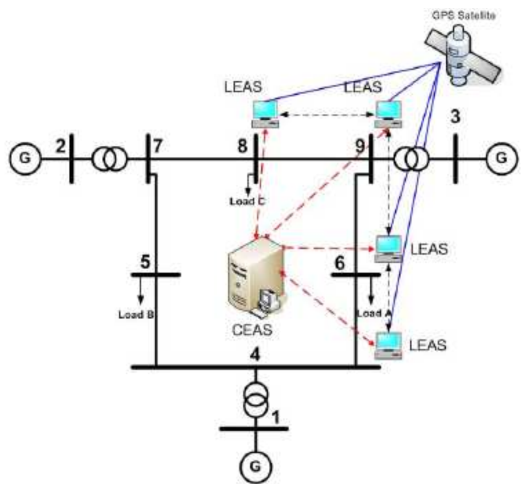

Fig. 2. A 9-bus test system with LEAS and CEAS [24].

At a certain time, low voltage and high current are observed by this relay. The impedance calculated by this relay will float into the relay setting areas, thus the relay will detect the event as the Zone 3 fault. If the timer of Zone 3 expires, the relay will trip the healthy Line 9-6 that should not be tripped. This will further worsen system stability. If such a scenario happens in a large system, a probable blackout may be initialized in cascading failure mechanism.

For this scenario, the conclusions of both NNFDC and SSFL indicate that there is no fault either in the primary zone or backup zones. An event tree should be activated for the Local Event Analysis System (LEAS) at Bus 9 to monitor its relay system activities. Depending on the priority of the LEAS to intervene relay operations, the trip signal may be blocked by LEAS at the local level, or Line 9-6 may be tripped. In the latter case, the Central Event Analysis System (CEAS) will be informed to attempt to reclose Line 9-6 to solve the problem, once it is confirmed that there is no fault on Line 9-6. Hence, the relay misoperation can be successfully prevented.

4 Conclusion

In this paper, the innovative PMU GPS-based measurement and its real-time control application are introduced and elaborated to show its effectiveness in power system:

(1) Estimation of radial power system transfer path dynamic parameters and grid dynamics simulation;
(2) Clustering-based dynamic event or fault location using wide-area phasor measurements;
(3) Improving real-time fault analysis and validating relay operations to prevent or mitigate cascading failure blackout.

In summary, the methods and algorithms in the reviewed works are all in accordance with NERC recommendations and fit well in the new trend of wide-area protection and control. The reviewed technology can be utilized and combined in the future to address power system online dynamic simulation, control and protection.

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