New Paradigm in Energy Cyber-Physical Systems: Automated Disturbance Detection, Analysis and Mitigation

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Power systems operate most of the time in a normal state with only small relative variations of the basic power system parameters such as current, voltage and frequency. During disturbances, particularly faults, the power system parameters may change abruptly creating transients (faults) or slowly changing phasor variations (various stability violations). In such instances, existing protective relaying system and the System Integrity Protection Scheme (SIPS) are used for an automated control action to remedy the situation. Operators may or may not be able to differentiate or even see some of the disturbances since the Supervisory Control and Data Acquisition (SCADA) Systems, typically used to feed energy management system application used by the operators, is not designed to capture abrupt changes in the system parameters, including fast changes in the switching status. Quite often, operators are unable to react appropriately even for slowly changing conditions such as cascading events and small signal or voltage stability violations due to SCADA limitations. As a result of this inability to track the system parameter and switching state changes as closely as needed, and due to the inappropriate or ineffective action caused by lack of situational awareness, systems may develop oscillations or voltage instability that can results in a blackout. The automated actions of relays and SIPS, which are unfolding in sub second time intervals, may also be executed incorrectly leading to transient instability and collapse of the system. The outcome of the power system not performing reliably, and eventually even collapsing, is unacceptable. Over the last decade, blackouts around the world have caused power outages affecting millions of people and have resulted in billions of dollars in economic and physical damage; this is unsustainable. New, fundamental research is needed to find alternative ways of protecting power systems from the impact of disturbances, including faults and undesirable and mal-intended intrusions. This creates challenges in the fundamental and applied research, as well as the need for new technologies for implementation of the adequate cyber-energy systems for energy applications.

The new paradigm for monitoring, control and protection of power systems under disturbances will have to take into account new developments. A few examples include [1]: a) High penetration of renewable generation, which has unique impacts on system dynamics during various disturbances including faults; b) Possible high concentration of the use of electrical vehicles of various designs, which impacts power systems in many ways through both the G2V and V2G interactions; c) System overloading due to sudden changes in load/generation leading to more frequent occurrence of cascades, d) Expansion of the grid in the customer domain with flexible load and microgrids providing local generation, storage and control of power usage; and e) appearance of sophisticated malicious attacks on power infrastructure . A new paradigm, mostly based on automated disturbance detection, analysis and mitigation, is needed. This requires new theoretical approaches, as well as energy cyber-physical system requirements, technologies and design implementations. The theoretical approaches may rely on emergence of three key components not readily available before: abundance of data, advances in the mathematical approaches to modeling power system dynamics, and advanced technology that allows enhanced sensing, processing, communication and visualization. Combined, they allow totally new approaches to monitoring, control and protection that can replace the existing paradigm and open new opportunities for running power systems much more reliably in the future. Translational research that will transcend the traditional power system view and integrates concepts from many engineering disciplines is needed.

Disturbance monitoring. An “explosion” of captured data drives the change in the monitoring paradigm and can bring new light to understanding power system behavior during disturbances. Such expansion in the data comes from the new intelligent electronic devices (IEDs) that have been introduced to power system substations, along transmission lines and feeders, and to generating plants and customer interfaces and premises over the last couple of decades. Besides the abundance of data available from such points in the power system, extensive data sets describing events that cause changes in power systems (e.g., weather data, lightning data, seismic data, animal migration data, etc.) are also readily available. The research challenge is how to integrate and correlate such data, which may be translated into the data analytics for big data but with clear constraints unique to power system monitoring: strong spatial-temporal correlation, need for real-time processing, requirement for compressed visualization, and challenges in storing large volumes of historical data. The integration of such data and an ability to correlate the data effectively across time and space is the key to the future monitoring solutions [2].

Effective control. The control paradigm in existence today clearly differentiates between two goals: to maintain power system operation during faults (Protective relays), and to steer power system back to normal operation during major disturbances (Energy Management Systems). The two approaches have some distinct differences: protective relaying reacts in sub second range where humans do not have a capability to make decisions and react fast enough to save the system before it collapses while the EMS solution supports operators, which may react in minutes and hours. Besides the two approaches, power system control is also implemented through Automatic Generation Control (AGC) to maintain desirable dynamics at the points of generation and through myriad of hardware controllers distributed throughout the network to alter power flow and voltage conditions (FACTS, UPFC, “Smart wires”, etc.). The new paradigm needs to put all such solutions into a different framework where they interact to produce a desirable match between measured data and model behavior, leading to the controls that are based on the best match between data and model [3].

Flexible protection. Protection systems have evolved over the years in its flexibility, but primarily associated with basic localized algorithms to recognize faults on individual power systems apparatus. The relaying action is considered today as a reactive, localized remedy. That very approach needs to be revisited by introducing pro-active methods leading to adaptive, corrective and predictive protection. An example is the new protection requirement imposed by introduction of renewable resources. It is an imperative that wind generation protection has ride-through capabilities for the faults in the power system causing voltage dips, and it is also essential that fault current increase is not used as the relaying parameter since in some wind turbine interfaces such currents are severely limited by the design. To implement the new paradigm, both localized and system-wide protection are needed. Additionally, new automated means of tracking protective relay operation and performance are essential to developing restoration strategies. Such automation is readily possible but requires interdisciplinary research which combines intelligent system approaches and real-time processing capabilities [4].

In summary, new paradigm for automated monitoring, control and protection is needed, which in turn requires a holistic, big picture view of power systems development going forward[5]. This leads to the need to define the new energy cyber-physical system solutions that can support such a paradigm [6,7]. All of this is leading to advanced data analytics and supporting communication and information processing (CIP) technology [8]. The key research challenges are how to match new technologies, new applications and new business models that can produce sustainable solutions.

Impact on Energy Cyber-physical Systems' research and design. There are several areas of research that are traditionally explored by the CPS community but now may have a different problem formulation and requirements as a consequence of being considered for energy applications:

- *Sensor networks and embedded systems, scalable architectures, agent-based architectures*: The introduction of energy management systems at customer premises introduces mega-scale computational and communication problem requiring advanced architectures for coordination.
- *Hybrid reconfigurable communication networks, pervasive energy mobile computing*: The variety of communication media and protocols is going to grow as the power systems expand, hence flexible network interfaces and Quality of Service (QoS) characteristics will be highly desirable
- *Dissemination of time-reference for system-wide data sampling*: Time reference clock signal is essential for future development of synchrophasor and other metering systems, hence providing for reliable and versatile clock signal dissemination is pivotal for such development
- *Peta-scale computing and data storage, cloud computing, big data analytics*: The data availability is going to expand, and the need to have high performance computational and storage retrieval options will be an imperative that needs to be met by variety of solutions
- *Agile and open source software development, software testing and troubleshooting*: The use of software will grow and outpace hardware developments, hence new approaches to managing large scale complex software projects will be a daunting challenge
- *Distributed and coordinate control architectures, and real-time control*: The tendency to reverse the traditional centralized control, and uncoordinated local control will require new architectures and algorithms for real time coordinated and distributed control.
- *Intelligent systems, real-time data mining and on-line learning*: Extracting knowledge from large volumes of data will have to rely on new heuristics leading to extensive learning capabilities from historical data and model-less approaches to event detection
- *Cyber-physical security, metrics, penetration testing and privacy*: Energy cyber-physical systems vulnerability will have to be judged by the impacts of the loss of security on other systems and risk will have to evaluated against major damage to the infrastructures and loss of privacy
- *Virtual reality and web-based training*: The sheer size of the education and training effort, and its complexity will have to engage the state of the art solutions in animation, image exploration and graphics analytics to provide virtual reality for comprehensive training and education

While the above are just samples, future research along the mentioned disciplines is inseparable from being able to further develop a new paradigm for automated monitoring, control and protection.

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