Future Trends in Power System Control

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1. Introduction

With the premise that transmission system loading will continue to increase and the trend will be toward maximum utilization of transmission systems close to thermal capacity, coordinated real-time control of power injection and flow on transmission lines will be an important issue. Minimization of operating margins or maximum utilization of existing transmission assets with increased system security and reliability will rely heavily on traditional as well as new control equipment. This short article looks into the future state of *power system operations and control* based on a number of assumptions and provides an analysis of the direction that this area might take over the next decade. Issues related to development of techniques and requirements for fully coordinated, high-bandwidth, and robust controls for power systems are presented. Proceeding toward this ultimate goal, system-wide automatic voltage control (SAVC), system-wide automatic power control (SAPC), and the integrated system-wide automatic control (SAC) concepts are introduced for coordination of injection and routing controllers for both real and reactive power.

Fig. 1 Power System Control Center

2. Ideal Control Scenario

The ideal scenario for control of a power system would be to have the capability to instantly compute an optimum operating condition and keep the system at that operating condition using the available controls. This will require instant knowledge of system topology information and the system real and reactive load. Optimum operating conditions consist of maintaining a constant frequency while supplying the system load, maintaining desired voltage profiles and line flows, respecting the physical limits of the equipment, and observing a defined set of security and economy criteria. Of course, stable system operation despite disturbances is of paramount importance and the premiere objective. Considering a model-based control algorithm for example, upon occurrence of a system contingency, the change in system topology will be instantly detected or estimated at a central location, and the sys- tem model will be updated accordingly. Then, the trajectory to the final operating point will be planned instantly starting from the initial system state, taking into account all constraints, and the controllers will be driven to achieve tracking of the planned trajectory. Here, the existence of accurate and validated power system models must be assumed. This fully coordinated centralized (using global state and parameter information either synchronously measured or estimated) high-bandwidth model-based control scheme is shown in Figure 2. To realize this ideal scenario, sophisticated, robust, and redundant control and communications systems with adequate bandwidth are needed.

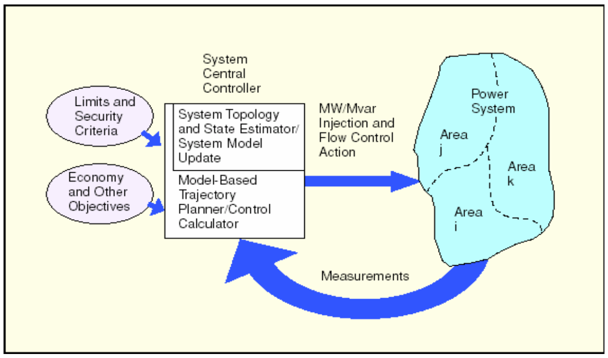

Figure 2. The ideal centralized system-wide high-bandwidth model-based power system controller

Power systems are viewed as large-scale, multi- input/multi-output, nonlinear systems distributed over large geographic areas. Therefore, the complexities associated with control of such systems apply. In many other large dynamic systems, the signals required for feedback are generally available locally and the computed actuating signals need not travel a long distance to reach the actuators. In power systems, however, the controllers are dispersed geographically throughout the system, thus prohibiting implementation of a centralized adaptive high-bandwidth control scheme. This scheme cannot be implemented in large power systems with today's technology, mainly due to excessive computation time requirements and unavailability of dedicated robust and redundant communication links. Striving for performances close to that of the centralized controller, historically one has resorted to centrally- coordinated decentralized control. Decentralized control in the strict sense is defined as a control where only local state information is utilized. Although attractive due to their simplicity and operation without the need for remote communication, decentralized control schemes are mostly practical in systems with special structures, such as weak couplings, or when couplings can be appropriately handled.

Power systems are naturally decentralized in structure and, therefore, in need of central coordination to achieve the desired performance objectives. However, to buy time for online computations necessary for central coordination and to attain wider-area objectives for optimum operation, one has had to resort to decomposition and, therefore, multilevel hierarchical control schemes. A multilevel hierarchy can be defined as a vertical arrangement of a number of subsystems with defined priority of action and rights of intervention helping to achieve system-wide goals. Higher level subsystems in the supervisory role are concerned with a larger portion or broader aspects of the system behavior, dealing with slower phenomena and affording more time for decision-making and control computation. Depending on the system-wide objectives and the structure of the system, the subsystems may have cooperative or competitive objectives. Higher level controllers can serve in a conflict resolution role. Reasons such as the following make power systems prime candidates for use of hierarchical control schemes:

- Complexity and size of the system
- System natural structure
- Limited vision and inability of a subsystem to achieve system-wide goals

- Specialized subsystems designed to perform a specific task well
- Limited or no communications among subsystems
- Cost, delay, or distortion in information transfer.

Figure 3 depicts a multilevel hierarchical control structure where a power system is divided into a number of areas. The area central controllers exchange information with the higher level (and possibly with each other) to jointly compute the control action required to achieve area-wide and system- wide performance objectives. The system-wide controller/coordinator may reside on a satellite, for example, or can be embedded in one of the areas. This scheme can be used to control inter- and intra-area line flows and bus voltages in the system. Historically, in power systems, inherent multiple time scales and weak coupling between real and reactive power dynamics has allowed a simplified form of this hierarchical centralized coordination. This is referred to as the centralized set-point coordination scheme, where the actual real-time control action is performed locally and autonomously in a decentralized manner, given the less-frequent centrally-computed/supplied set points. An online automatic (closed-loop) centralized MW set-point coordination scheme has been implemented and used successfully in the existing automatic generation control (AGC) and load frequency control (LFC) systems since the introduction of interconnected power systems. AGC/LFC constitutes the slower and the faster control loops, respectively. This control structure has been feasible due to the slower available controls and slower dynamic requirements due to turbine/generator/governor inertia. In general, a typical control function for today's power systems can be categorized as a faster disturbance rejection/stabilization function superimposed on a load-trajectory following function. The system initially tries to follow the changes that occur in generation, load, or system topology, mainly by reacting to frequency and/or voltage changes via preset feedback mechanisms. Then a slower reset action or trajectory correction is enacted to respect security and economy criteria. In summary, the slower control functions dealing with slower system dynamics have been implemented as online, coordinated, and closed loops and have worked successfully. This coordination has not in general been possible for faster phenomena. To deal with scenarios where the size of the system disturbance becomes larger as compared to the system capacity, such as loss of connectivity and islanding or very large disturbances resulting from cascading out- ages, more system control capability with superior performance is needed for survival. To achieve further enhancements, the trend in power system control technology must be in the direction of centralized real-time and online coordination of decentralized controllers.

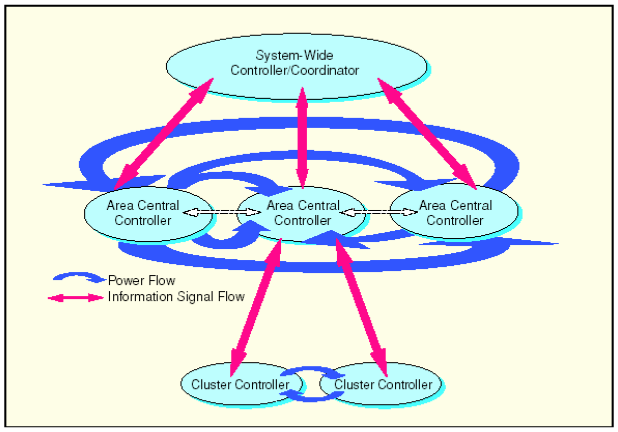

Figure 3. Power system area and cluster controllers in a multi level hierarchical arrangement: an example of decomposition in the control functionality

3. Requirements for Enhanced Control

In general, the control actions in power systems can be categorized as on/off or continuous. The continuous controls for example, can also be categorized as either generation based or network-impedance based. To achieve enhanced performance, adequate proliferation of high-speed MW/Mvar injection/flow controllers (such as FACTS controllers combined with energy sources or other fast-dynamics generators and controllable loads, as well as storage devices) in power systems is required. Utilizing these fast controllers, a new general centrally coordinated hierarchical control framework for both real and reactive power injection and flow control called the system- wide automatic control(SAC) for the entire range of power system dynamic response frequencies can be implemented However, the most likely trend in the evolution of the power system controls will be that large high-speed real power control devices will be slow in coming. This is precisely the reason for the use of PSSs for power system damping enhancement For example, if high- speed real power injection and flow controllers were available, direct control of real power related oscillations could be more effectively done as opposed to utilizing the inherently weak coupling between the real power related inputs and reactive power related outputs. In the interim and until SAC can become a reality, system-wide automatic power control (SAPC) and sys- tem-wide automatic volt- age control (SAVC) functions can be implemented in separate loops and timeframes based on preserving the traditional notion of decoupled real and reactive power control.

The SAPC will not only include functions similar to the existing LFC and AGC functions but will achieve enhanced performance ranging from stabilization to MW flow control and satisfy additional security/economy objectives. Frequency is the omnipresent system-wide feedback quantity indicative of system real power changes. For real power flow control, phase-angles across or flows in designated transmission lines must be measured for feedback and criteria for selection of these lines must be developed. The SAVC will provide centrally coordinated hierarchical voltage control across the system as well as Mvar flow control. Again additional security/economy objectives can be satisfied via the use of SAVC. SAVC will include functions similar to LFC/AGC but for voltage/reactive power control which are called automatic voltage regulator (AVR) and automatic voltage controller (AVC). AVR consists of the existing local volt- age control loops implemented on generators and other voltage regulators such as SVCs, STATCOMs, etc. The AVC provides the set points for all or designated AVRs. For voltage/reactive power control, the voltage and/or Mvar flow feedback quantities must be selected, and the criteria and the mechanism for their selection must also be developed. Similar to LFC/AGC functions, AVR/AVC constitute faster (AVR) and slower (AVC) controls but deal with reactive power injection and flow instead.

4. Hierarchical Set-Point Coordination of Power Systems

4.1 Current State

Figure 4(left) shows a schematic of today's hierarchical control structure for power systems with the associated timeframes for each level. At the highest level or the tertiary level, a scheduling function ensures that loads are supplied, adequate reserves for ancillary services are in place, network operating constraints and transmission contracts are respected, and maximum possible efficiency prevails. The timeframe for the tertiary level is from one to several hours to the day ahead. This function is performed at a coordinating level such as a power pool or an ISO. At the secondary level, a voltage/Mvar control function also exists. The system operator is generally in the loop and based on offline studies, experience, and actual system conditions observed via telemetry, and state-estimator output decides on the capacitor and reactor bank on/off status and set-points for generator AVRs and other voltage regulators, such as SVCs and STATCOMs. Generally, there is no capability to rapidly change these set-points in an online and coordinated manner to achieve further improved performance. This loop has not been closed or automated due to fast response requirements and has not been feasible until recently. At the primary level, the controllers basically regulate to their given set-points, and the appropriateness of these set-points is determined mainly based on offline studies. Currently, there are no fast real power injection/flow controllers installed. Full online coordination between the two loops is mainly nonexistent, and the only recourse is to the results of offline studies. MW flow control is mainly accomplished through slow generation control, and system-wide high-bandwidth power flow control is also nonexistent. Generally, there is no capability to rapidly change these set-points in an online and coordinated manner to achieve further improved performance. This loop has not been closed or automated due to fast response requirements and has not been feasible until recently.

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4.2 Future

Figure 3(right) shows a multi-area centrally coordinated hierarchical control schemes for a power system consisting of SAPC, SAVC, and the combined SAC. In the transition to achieve fully integrated SAC, the following discussion still preserves separate real/reactive power control loops, although they can be fused. The third level has a timeframe of minutes and provides complete optimal real and reactive injection/flow schedule for the entire system, considering all constraints and security and economy criteria. The secondary level has a timeframe of seconds. The main task of the secondary level in the hierarchy related to the SAPC would be to determine the MW set points for the generators and control devices. The criteria for determination of these set-points must guarantee stability and security of the system while considering the economic and contractual issues. The primary criteria for implementation of the SAPC can be power system phase angle equalization and overall reduction of angles across the system for added stability and load- ability for maximum utilization of transmission assets. Secondary criteria such as minimizing system losses, etc. can also be considered. Once the generator MW output and MW-flow controller set-points are determined by the secondary level, they are transmitted to the local controllers constituting the primary or the fastest response level of the hierarchy with the timeframe of milliseconds. Each controller then regulates its own output or flow to the received set-point. Since the reactive power/voltage relationship is a more local phenomenon and a global feedback quantity similar to frequency for LFC/AGC does not exist, specific feedback quantities must be made avail- able to the SAVC function.

To this end, a set of load bus voltages called pilot buses and/or line Mvar flow levels must be selected such that through direct control of these voltages and/or flows a desirable voltage profile at all system load buses is achieved. The number of selected voltages and line flows to be controlled must match the number of the controllers available. The set of indicative or pilot voltages and/or var-controlled lines may be selected based on an offline analysis, and, if redundancies exist, the priority and weights for the use of these controlled quantities must be established. The main task of the secondary level related to the SAVC is to determine the set-points for the shunt and series devices capable of Mvar control. These include the generator AVR set points, SVC and STATCOM set- points, ULTC set-points, synchronous condenser/motor reactive output levels, and capacitor and inductor bank status, as well as any Mvar flow control device set- points. The algorithm utilized for determination of these set-points must strive to achieve an acceptable bus volt- age profile such that stability and security of the system is guaranteed. Other optimization criteria, such as maximizing the distance of the system operating point (in the sense of load increase on a number of buses or power transfer increase in a transmission corridor) from the point of voltage collapse, can also be considered. Once the voltage control/Mvar flow control set-points are determined by the secondary level, they are transmitted to the controllers at the primary level of the hierarchy. Each controller then regulates its own voltage or MVAR flow to the received set-point. The timeframe for the response in the primary level is in the millisecond range. An historic perspective encompassing the past as well as the future evolution of power system controls under the general framework presented here is shown in Figure 5.

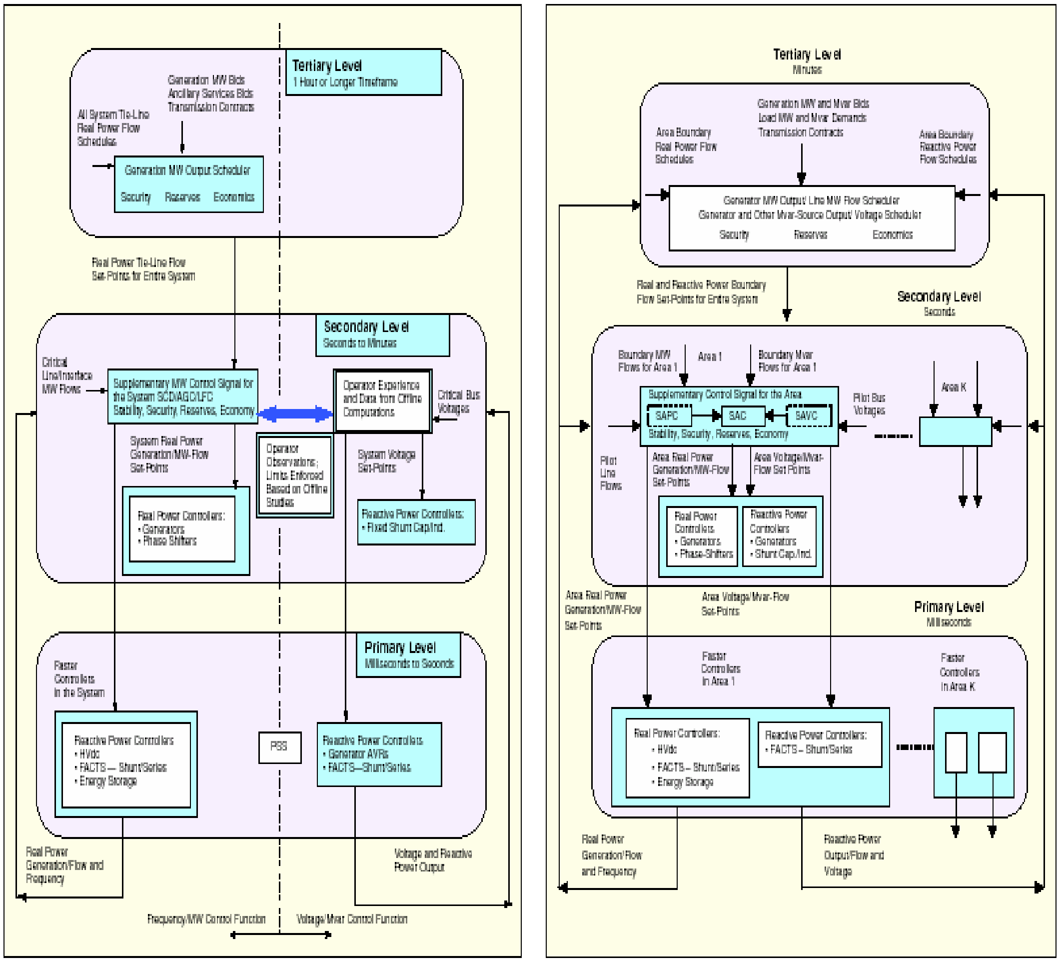

Figure 4. Current(left) and Future(right) Control and Coordination in Power Systems

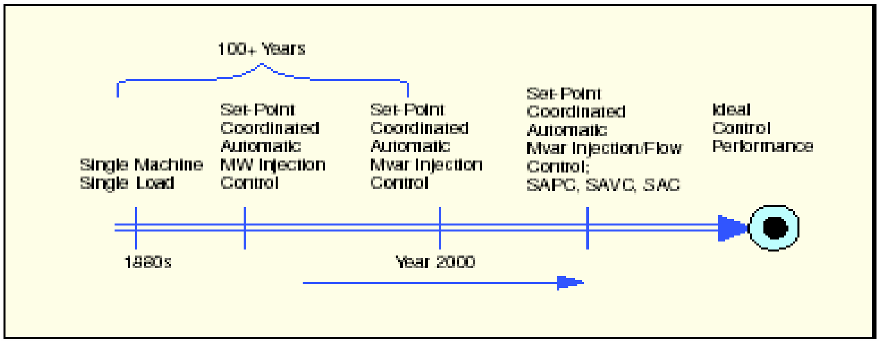

Figure 5. Evolution of power system control with increased computation and communication capability and controller bandwidth

For Further Reading

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