Power System State Estimation:
Theory and Implementation

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Chapter 1

Introduction

Power systems are composed of transmission, sub-transmission, distribution and generation systems. Transmission systems may contain large numbers of substations which are interconnected by transmission lines, transformers, and other devices for system control and protection. Power may be injected into the system by the generators or absorbed from the system by the loads at these substations. The output voltages of generators typically do not exceed 30-kV. Hence, transformers are used to increase the voltage levels to levels ranging from 69-kV all the way up to 765-kV at the generator terminals for efficient power transmission. High voltage is preferred at the transmission system for different reasons one of which is to minimize the copper losses that are proportional to the ampere flows along lines. At the receiving end, the transmission systems are connected to the sub-transmission or distribution systems which are operated at lower voltage levels ranging from 115-KV to 4.16-KV. Distribution systems are typically configured to operate in a radial configuration, where feeders stretch from distribution substations and form a tree structure with their roots at the substation and branches spreading over the distribution area.

1.1 Operating States of a Power System

The operating conditions of a power system at a given point in time can be determined if the network model and complex phasor voltages at every system bus are known. Since the set of complex phasor voltages fully specifies the system, it is referred to as the static state of the system. According to [1], the system may move into one of three possible states, namely normal, emergency and restorative, as the operating conditions change.

A power system is said to operate in a normal state if all the loads in the system can be supplied power by the existing generators without violating any operational constraints. Operational constraints include the limits on the transmission line flows, as well as the upper and lower limits on bus voltage magnitudes. A normal state is said to be *secure* if the system can remain in a normal state following the occurrence of each contingency from a list of critical contingencies. Common contingencies of interest are transmission line or generator outages due to unexpected failures of equipment or natural causes such as storms. Otherwise, the normal state is classified as *insecure* where the power balance at each bus and all operating inequality constraints are still satisfied, yet the system remains vulnerable with respect to some of the considered contingencies. If the system is found to be in a normal but *insecure* operating state then, preventive actions must be taken to avoid its move into an emergency state. Such preventive controls can be determined typically by the help of a security constrained optimal power flow program which accounts for a list of critical contingencies.

Operating conditions may change significantly due to an unexpected event which may cause the violation of some of the operating constraints, while the power system continues to supply power to all the loads in the system. In such a situation the system is said to be operating in an emergency state. Emergency state requires immediate corrective action to be taken by the operator so as to bring the system back to a normal state.

While the system is in the emergency state, corrective control measures may be able to avoid system collapse at the expense of disconnecting various loads, lines, transformers or other equipment. As a result, the operating limit violations may be eliminated and the system may recover stability with reduced load and reconfigured topology. Then, the load versus generation balance may have to be restored in order to start supplying power to all the loads. Such an operating state is called the restorative state, and the actions to be taken in order to transform it into a normal state are referred to as restorative controls. The state diagram in Figure 1.1 illustrates the possible transitions between the different operating states defined above.

1.2 Power System Security Analysis

Power systems are operated by system operators from the area control centers. The main goal of the system operator is to maintain the system in the normal secure state as the operating conditions vary during the daily operation. Accomplishing this goal requires continuous monitoring of the system conditions, identification of the operating state and determination of the necessary preventive actions in case the system state is found to be *insecure*. This sequence of actions is referred to as the security analysis of the system.

The first step of security analysis is to monitor the current state of the system. This involves acquisition of measurements from all parts of the system and then processing them in order to determine the system state. The measurements may be both of analog and digital (on/off status of devices) type. Substations are equipped with devices called remote terminal units (RTU) which collect various types of measurements from the field and are responsible for transmitting them to the control center. More recently, the so-called intelligent electronic devices (IED) are replacing or complementing the existing RTUs. It is possible to have a mixture of these devices connected to a local area network (LAN) along with a SCADA front end computer, which supports the communication of the collected measurements to the host computer at the control center. The SCADA host computer at the control center receives measurements from all the monitored substations' SCADA systems via one of many possible types of communication links such as fiber optics, satellite, microwave, etc. Figure 1.2 shows the configuration of the EMS/SCADA system for a typical power system.

Measurements received at the control center will include line power flows, bus voltage and line current magnitudes, generator outputs, loads, circuit breaker and switch status information, transformer tap positions, and switchable capacitor bank values. These raw data and measurements are processed by the state estimator in order to filter the measurement noise and detect gross errors. State estimator solution will provide an optimal estimate of the system state based on the available measurements and on the assumed system model. This will then be passed on to all the energy management system (EMS) application functions such as the contingency analysis, automatic generation control, load forecasting and optimal power flow, etc. The same information will also be available via a LAN connection

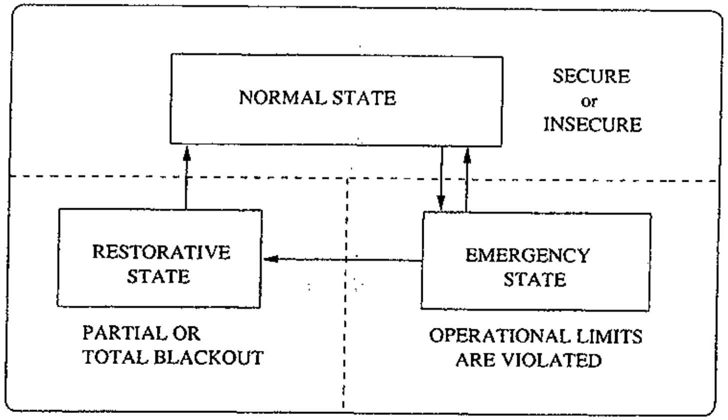

Figure 1.1. State Diagram for Power System Operation

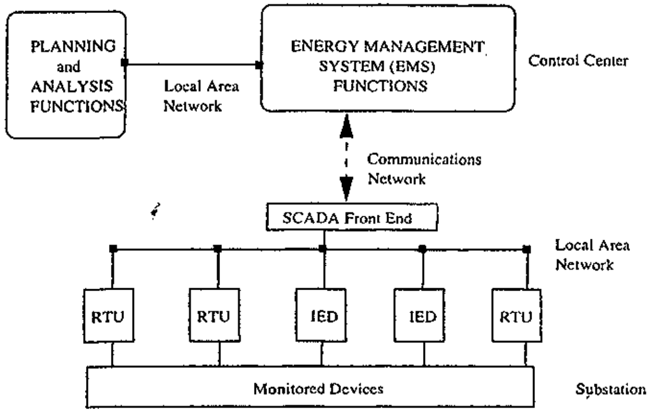

Figure 1.2. EMS/SCADA system configuration.

to the corporate offices where other planning and analysis functions can be executed off-line.

Initially, power systems were monitored only by supervisory control systems. These are control systems which essentially monitor and control the status of circuit breakers at the substations. Generator outputs and the system frequency were also monitored for purposes of Automatic Generation Control (AGC) and Economic Dispatch (ED). These supervisory control systems were later augmented by real-time system-wide data acquisition capabilities, allowing the control centers to gather all sorts of analog measurements and circuit breaker status data from the power system. This led to the establishment of the first Supervisory Control and Data Acquisition (SCADA) Systems. The main motivation behind this development was the facilitation of security analysis. Various application functions such as contingency analysis, corrective real and reactive power dispatch could not be executed without knowing the real-time operating conditions of the system. However, the information provided by the SCADA system may not always be reliable due to the errors in the measurements, telemetry failures, communication noise, etc. Furthermore, the collected set of measurements may not allow direct extraction of the corresponding A.C. operating state of the system. For instance, bus voltage phase angles are not typically measured, and not all the transmission line flows are available. Besides, it may not be economically feasible to telemeter all possible measurements even if they are available from the transducers at the substations.

1.3 State Estimation

The foregoing concerns were first recognized and subsequently addressed by Fred Schweppe, who proposed the idea of state estimation in power systems [2, 3, 4]. Introduction of the state estimation function broadened the capabilities of the SCADA system computers, leading to the establishment of the Energy Management Systems (EMS), which would now be equipped with, among other application functions, an on-line State Estimator (SE).

In order to identify the current operating state of the system, state estimators facilitate accurate and efficient monitoring of operational constraints on quantities such as the transmission line loadings or bus voltage magnitudes. They provide a reliable real-time data base of the system, including the existing state based on which, security assessment functions can be reliably deployed in order to analyze contingencies, and to determine any required corrective actions.

The state estimators typically include the following functions:

- Topology processor: Gathers status data about the circuit breakers and switches, and configures the one-line diagram of the system.
- Observability analysis: Determines if a state estimation solution for the entire system can be obtained using the available set of measurements. Identifies the unobservable branches, and the observable islands in the system if any exist.
- State estimation solution: Determines the optimal estimate for the system state, which is composed of complex bus voltages in the entire power system, based on the network model and the gathered measurements from the system. Also provides the best estimates for all the line flows, loads, transformer taps, and generator outputs.
- Bad data processing: Detects the existence of gross errors in the measurement set. Identifies and eliminates bad measurements provided that there is enough redundancy in the measurement configuration.
- Parameter and structural error processing: Estimates various network parameters, such as transmission line model parameters, tap changing transformer parameters, shunt capacitor or reactor parameters. Detects structural errors in the network configuration and identifies the erroneous breaker status provided that there is enough measurement redundancy.

Thus, power system state estimator constitutes the core of the on-line security analysis function. It acts like a filter between the raw measurements received from the system and all the application functions that require the most reliable data base for the current state of the system. Figure 1.3

describes the data and functional interfaces between the various application functions involved in the on-line static security assessment procedure. Raw measurements which include the switch and circuit breaker positions in the substations, are processed by the topology processor, which in turn generates a bus/branch model of the power system. This model not only includes all buses within the area of the control center EMS, but also selected buses from the neighboring systems. The information and measurements obtained from the neighboring systems are used to build and update the external system model. Furthermore, there may be unobservable pockets within one's own area due to temporary loss of telemetry, rejected bad data or other unexpected failures. Such areas whether physically located within the control area or part of the external system, will be estimated via the use of pseudo measurements. Pseudo measurements can be generated based on short term load forecasts, generation dispatch, historical records or other similar approximation methods. Naturally, they are assigned high variances (low weights) or they can be forced to be critical measurements by design. Definition and properties of a critical measurement will be discussed in detail in chapter 5. In addition, there may be passive buses with no generation or load, having net zero real and reactive power injection. Such bus injections, even though not measured, can be used as error free measurements in the state estimation formulation and referred to as "virtual" measurements. The results obtained by the state estimator will be checked in order to classify the system state into one of the three categories shown in Figure 1.1. If it is found to be in the *normal* state, then contingency analysis will be carried out to determine the system security against a set of predetermined contingencies. In case of insecurity, preventive control actions have to be calculated via the use of a software tool such as a security constrained optimal power flow. Implementing these preventive measures will move the system into the desired *normal and secure* state. Figure 1.3 also indicates the emergency and restorative control actions which will be deployed under *abnormal* operating conditions, however these topics are beyond the scope of this book and will not be discussed any further.

1.4 Summary

Power systems are continuously monitored in order to maintain the operating conditions in a normal and secure state. State estimation function is used for this purpose. It processes redundant measurements in order to provide an optimal estimate of the current operating state. State estimation problem has been investigated by several researchers since its introduction in the late 1960s. Being an on-line function, computational issues related to speed, storage and numerical robustness of the solution algorithms have been carefully studied. Measurement configuration and its effect on state estimation have been addressed by the developed observability analysis methods. State estimators also function as filters against incorrect measurements, data and other information received through the SCADA system. Hence, the subject of bad data processing has been investigated and detection/identification algorithms for errors in analog measurements have been developed. Special methods also exist for the identification of those errors related to the topology information and/or network parameters. On the other hand, the use of ampere measurements present some problems which do not exist in their absence from the measurement set. In the following chapters, these issues will be presented in more detail and methods which are developed to address them will be described.

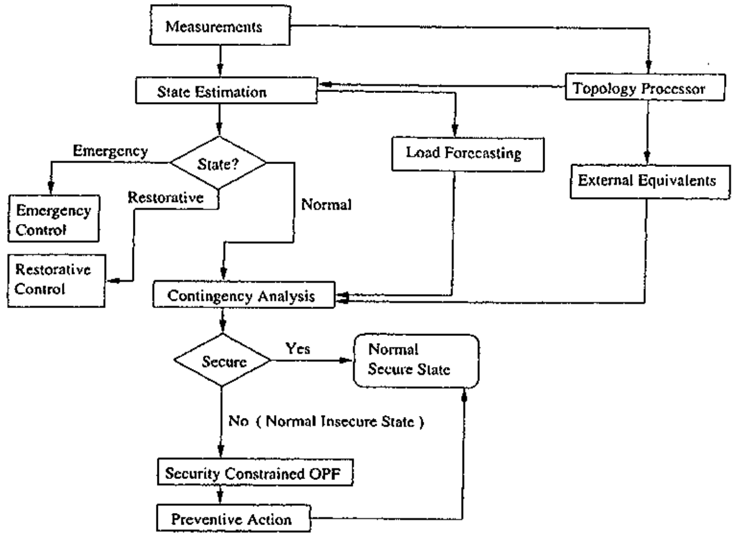

Figure 1.3. On-line Static Security Assessment: Functional Diagram

References

[1] Dy Liacco T.E., "Real-Time Computer Control of Power Systems", Proceedings of the IEEE, Vol. 62, No.7, July 1974, pp.884-891.

[2] Schweppe F.C. and Wildes J., "Power System Static-State Estimation, Part I: Exact Model", IEEE Transactions on Power Apparatus and Systems, Vol.PAS-89, January 1970, pp.120-125.