

CHAPTER 1

INTRODUCTION

Computers have been widely used in the electric power engineering field since the 1950s. The applications include a variety of off-line or on-line tasks. Examples of off-line tasks include fault studies, load-flow studies, transient stability calculations, unit commitment, and relay settings and coordination studies. Examples of on-line tasks are economic generation scheduling and dispatching, load frequency control, supervisory control and data acquisition (SCADA), sequence-of-events monitoring, sectionalizing, and load management. The applications to computers in protective relaying have been primarily in relay settings and coordination studies and computer relaying.

1.1 Historical note

The great technical advances in the design and production of commercial and scientific general-purpose digital computers since the early 1950s have placed a powerful tool at the disposal of the engineering profession. This advancement has made economically feasible the utilization of digital computers for routine calculations encountered in everyday engineering work. In addition, it has provided the capability for performing more advanced engineering and scientific computations that were previously impossible because of their complex or time-consuming nature. All these trends have increased immensely the interest in digital computers and have necessitated a better understanding of the engineering and mathematical bases for problem solving.

The planning, design, and operation of power systems require continuous and comprehensive analysis to evaluate current system performance and to ascertain the effectiveness of alternative plans for system expansion. These studies play an important role in providing a high standard of power system reliability and ensuring the maximum utilization of capital investment.

The computational task of determining power flows and voltage levels resulting from a single operating condition for even a small network is all but insurmountable if performed by manual methods. The need for computational aids in power system engineering led in 1929 to the design of a special-purpose analog computer called an ac network analyzer. This device made possible the study of a greater variety of system oper-

ating conditions for both present and future system designs. It provided the ability to determine power flows and system voltages during normal and emergency conditions and to study the transient behavior of the system resulting from fault conditions and switching operations. By the middle 1950s 50 network analyzers were in operation in the United States and Canada and were indispensable tools to planning, relaying, and operating engineers.

The earliest application of digital computers to power system problems dates back to the late 1940s. However, most of the early applications were limited in scope because of the small capacity of the punched card calculators generally in use at that time. The availability of large-scale digital computers in the middle 1950s provided equipment of sufficient capacity and speed to meet the requirements of major power system problems. In 1957 the American Electric Power Service Corporation completed a large-scale load flow program for the IBM 704 which calculated the voltages and power flows for a specified power system network.

The initial application of the load flow program to transmission planning studies proved so successful that all subsequent studies employed the digital computer instead of the network analyzer. The success of this program led to the development of programs for short circuit and transient stability calculations. Today the computer is an indispensable tool in all phases of power system planning, design, and operation.

1.2 Impact of computers

The development of computer technology has provided the following advantages to power system engineering:

1. More efficient and economic means of performing routine engineering calculations required in the planning, design, and operation of a power system
2. A better utilization of engineering talent by relieving the engineer from tedious hand calculations and permitting him to spend more time on technical work
3. The ability to perform more effective engineering studies by applying calculating procedures to obtain a number of alternate solutions for a particular problem to provide a broad base for engineering decisions
4. The capability of performing studies which heretofore were not possible because of the volume of calculations involved

Two major factors which have contributed to the realization of these benefits are the declining cost of computing equipment and the development of efficient computational techniques. Now that a substantial reduction in computing cost has been effected, principal effort must be directed toward the orientation of engineering problems to computer solutions.

COMPUTERS IN POWER SYSTEM ENGINEERING

As electric utilities have grown in size and the number of interconnections has increased, planning for future expansion has become increasingly complex. The increasing cost of additions and modifications has made it imperative that utilities consider a range of design options, and perform detailed studies of the effects on the system of each option, based on a number of assumptions: normal and abnormal operating conditions, peak and off-peak loadings, and present and future years of operation. A large volume of network data must also be collected and accurately handled. To assist the engineer in this power system planning, digital computers and highly developed computer programs are used. Such programs include power-flow, stability, short-circuit, and transients programs.

Power-flow programs compute the voltage magnitudes, phase angles, and transmission-line power flows for a network under steady-state operating conditions. Other results, including transformer tap settings and generator reactive power outputs, are also computed. Today's computers have sufficient storage and speed to efficiently compute power-flow solutions for networks with 100,000 buses and 150,000 transmission lines. High-speed printers then print out the complete solution in tabular form for analysis by the planning engineer. Also available are interactive power-flow programs, whereby power-flow results are displayed on computer screens in the form of single-line diagrams; the engineer uses these to modify the network with a mouse or from a keyboard and can readily visualize the results. The computer's large storage and high-speed capabilities allow the engineer to run the many different cases necessary to analyze and design transmission and generation-expansion options.

Stability programs are used to study power systems under disturbance conditions to determine whether synchronous generators and motors remain in synchronism. System disturbances can be caused by the sudden loss of a generator or transmission line, by sudden load increases or decreases, and by short circuits and switching operations. The stability program combines power-flow equations and machine-dynamic equations to compute the angular swings of machines during disturbances. The program also computes critical clearing times for network faults, and allows the engineer to investigate the effects of various machine parameters, network modifications, disturbance types, and control schemes.

Short-circuits programs are used to compute three-phase and line-to-ground faults in power system networks in order to select circuit breakers for fault interruption, select relays that detect faults and control circuit breakers, and determine relay settings. Short-circuit currents are computed for each relay and circuit-breaker location, and for various system-operating conditions such as lines or generating units out of service, in order to determine minimum and maximum fault currents.

Transients programs compute the magnitudes and shapes of transient overvoltages and currents that result from lightning strikes and line-switching operations. The planning engineer uses the results of a transients program to determine insulation requirements for lines, transformers, and other equipment, and to select surge arresters that protect equipment against transient overvoltages.

Other computer programs for power system planning include relay-coordination programs and distribution-circuits programs. Computer programs for generation-expansion planning include reliability analysis and loss-of-load probability (LOLP) programs, production cost programs, and investment cost programs.

POWERWORLD SIMULATOR

PowerWorld Simulator (PowerWorld) version 15 is a commercial-grade power system analysis and simulation package that accompanies this text. The purposes of integrating PowerWorld with the text are to provide computer solutions to examples in the text, to extend the examples, to demonstrate topics covered in the text, to provide a software tool for more realistic design projects, and to provide the readers with experience using a commercial grade power system analysis package. To use this software package, you must first install PowerWorld, along with all of the necessary case files onto your computer. The PowerWorld software and case files can be downloaded by going to the www.powerworld.com/GloverSarmaOverbye webpage, and clicking on the **Download PowerWorld Software and Cases for the 5th Edition** button. The remainder of this section provides the necessary details to get up and running with PowerWorld.

EXAMPLE 1.1

Introduction to PowerWorld Simulator

After installing PowerWorld, double-click on the PW icon to start the program. Power system analysis requires, of course, that the user provide the program with a model of the power system. With PowerWorld, you can either build a new case (model) from scratch or start from an existing case. Initially, we'll start from an existing case. PowerWorld uses the common Ribbon user interface in which common commands, such as opening or saving a case, are available by clicking on the blue and white PowerWorld icon in the upper left-hand corner. So to open a case click on the icon and select **Open Case**. This displays the Open Dialog. Select the Example 1.1 case in the Chapter 1 directory, and then click Open. The display should look similar to Figure 1.6.

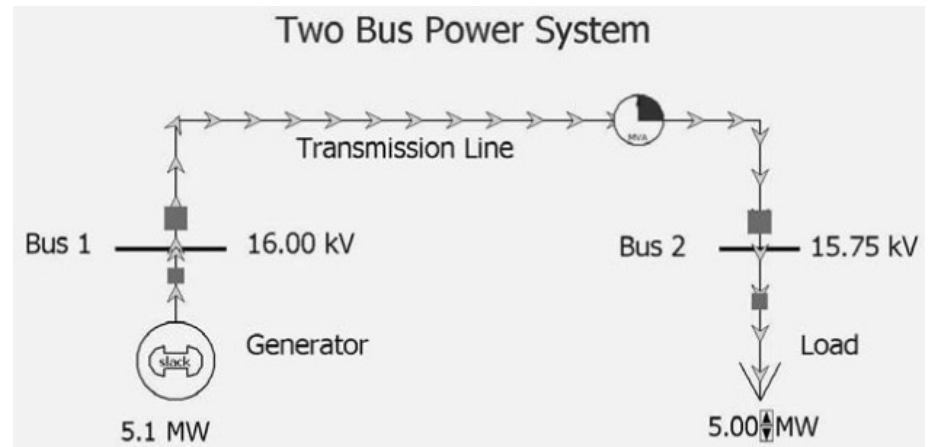
For users familiar with electric circuit schematics it is readily apparent that Figure 1.6 does NOT look like a traditional schematic. This is because the system is drawn in what is called one-line diagram form. A brief explanation is in order. Electric power systems range in size from small dc systems with peak power demands of perhaps a few milliwatts (mW) to large continent-spanning interconnected ac systems with peak demands of hundreds of Gigawatts (GW) of demand ($1 \text{ GW} = 1 \times 10^9 \text{ Watt}$). The subject of this book and also PowerWorld are the high voltage, high power, interconnected ac systems. Almost without exception these systems operate using three-phase ac power at either 50 or 60 Hz. As discussed in Chapter 2, a full analysis of an arbitrary three-phase system requires consideration of each of the three phases. Drawing such systems in full schematic form quickly gets excessively complicated. Thankfully, during normal operation three-phase systems are usually balanced. This permits the system to be accurately modeled as an equivalent single-phase system (the details are discussed in Chapter 8, *Symmetrical Components*). Most power system analysis packages, including PowerWorld, use this approach. Then connections between devices are then drawn with a single line joining the system devices, hence the term “one-line” diagram. However, do keep in mind that the actual systems are three phase.

Figure 1.6 illustrates how the major power system components are represented in PowerWorld. Generators are shown as a circle with a “dog-bone” rotor, large arrows represent loads, and transmission lines are simply drawn as lines. In power system terminology, the nodes at which two or more devices join are called buses. In PowerWorld thicker lines usually represent buses; the bus voltages are shown in kilovolts (kV) in the fields immediately to the right of the buses. In addition to voltages, power engineers are also concerned with how power flows through the system (the solution of the power flow problem is covered in Chapter 6, *Power Flows*). In PowerWorld, power flows can be visualized with arrows superimposed on the generators, loads, and transmission lines. The size and speed of the arrows indicates the

direction of flow. One of the unique aspects of PowerWorld is its ability to animate power systems. To start the animation, select the **Tools** tab on the Ribbon and then click on the green and black arrow button above **Solve** (i.e., the “Play” button). The one-line should spring to life! While the one-line is being animated you can interact with the system. Figure 1.6 represents a simple power system in which a generator is supplying power to a load through a 16 kV distribution system feeder. The solid red blocks on the line and load represent circuit breakers. To open, a circuit breaker simply click on it. Since the load is series connected to the generator, clicking on any of the circuit

FIGURE 1.6

Example power system



breakers isolates the load from the generator resulting in a blackout. To restore the system click again on the circuit breaker to close it and then again select the button on the **Tools** ribbon. To vary the load click on the up or down arrows between the load value and the “MW” field. Note that because of the impedance of the line, the load’s voltage drops as its value is increased.

You can view additional information about most of the elements on the one-line by right-clicking on them. For example right-clicking on the generator symbol brings up a local menu of additional information about the generator, while right-clicking on the transmission line brings up local menu of information about the line. The meaning of many of these fields will become clearer as you progress through the book. To modify the display itself simply right-click on a blank area of the one-line. This displays the one-line local menu. Select **Online Display Options** to display the Online Display Options Dialog. From this dialog you can customize many of the display features. For example, to change the animated flow arrow color select the “Animated Flows” from the options shown on the left side of the dialog. Then click on the green colored box next to the “Actual MW” field (towards the bottom of the dialog) to change its color.

There are several techniques for panning and/or zooming on the one-line. One method to pan is to first click in an empty portion of the display and then press the keyboard arrow keys in the direction you would like to move. To zoom just hold down the Ctrl key while pressing the up arrow to zoom in, or the down arrow to zoom out. Alternatively you can drag the one-line by clicking and holding the left mouse button down and then moving the mouse—the one-line should follow. To go to a favorite view from the one-line local menu select the **Go To View** to view a list of saved views.

If you would like to retain your changes after you exit PowerWorld you need to save the results. To do this, select the PowerWorld icon in the upper left portion of the Ribbon and then **Save Case As**; enter a different file name so as to not overwrite the initial case. One important note: PowerWorld actually saves the information associated with the power system model itself in a different file from the information associated with the one-line. The power system model is stored in *.pwb files (PowerWorld binary file) while the one-line display information is stored in *.pwd files (PowerWorld display file). For all the cases discussed in this book, the names of both files should be the same (except the different extensions). The reason for the dual file system is to provide flexibility. With large system models, it is quite common for a system to be displayed using multiple one-line diagrams. Furthermore, a single one-line diagram might be used at different times to display information about different cases. ■

EXAMPLE 1.2

PowerWorld Simulator—Edit Mode

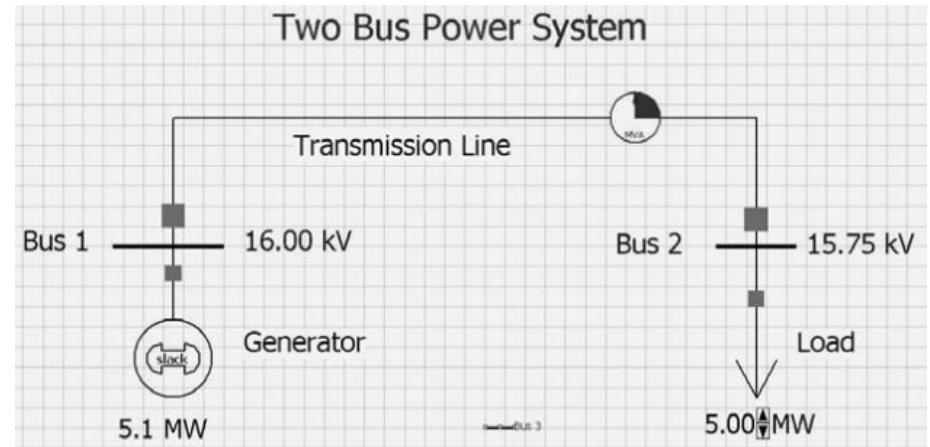
PowerWorld has two major modes of operations. The Run Mode, which was just introduced, is used for running simulations and performing analysis. The Edit Mode, which is used for modifying existing cases and building new cases, is introduced in this example. To switch to the Edit Mode click on the **Edit Mode** button, which is located in the upper left portion of the display immediately below the PowerWorld icon. We'll use the edit mode to add an additional bus and load as well as two new lines to the Example 1.1 system.

When switching to the Edit Mode notice that the Ribbon changes slightly, with several of the existing buttons and icons disabled and others enabled. Also, the one-line now has a superimposed grid to help with alignment (the grid can be customized using the Grid/Highlight Unlinked options category on the One-line Display Options Dialog). In the Edit Mode, we will first add a new bus to the system. This can be done graphically by first selecting the **Draw** tab, then clicking on the **Network** button and selecting **Bus**. Once this is done, move the mouse to the desired one-line location and click (note the **Draw** tab is only available in the Edit Mode). The Bus Options dialog then appears. This dialog is used to set the bus parameters. For now leave all the bus fields at their default values, except set Bus Name to "Bus 3" and set the nominal voltage to 16.0; note that the number for this new bus was automatically set to the one greater than the highest bus number in the case. The one-line should look similar to Figure 1.7. You may wish to save your case now to avoid losing your changes.

By default, when a new bus is inserted a "bus field" is also inserted. Bus fields are used to show information about buses on the one-lines. In this case the new field shows the bus name, although initially in rather small fonts. To change the field's font size click on the field to select it, and then select the **Format** button (on the Draw Ribbon) to display the Format dialog. Click on the **Font** tab and change the font's size to a larger value to make it easier to see.

FIGURE 1.7

Example 1.2—Edit Mode view with new bus



You can also change the size of the bus itself using the Format dialog, Display/Size tab. Since we would also like to see the bus voltage magnitude, we need to add an additional bus field. On the Draw ribbon select **Field, Bus Field**, and then click near bus 3. This displays the Bus Field Options dialog. Make sure the bus number is set to 3, and that the "Type of Field" is Bus Voltage. Again, resize with the **Format, Font** dialog.

Next, we'll insert some load at bus 3. This can be done graphically by selecting **Network, Load**, and then clicking on bus 3. The Load Options dialog appears, allowing you to set the load parameters. Note that the load was automatically assigned to bus 3. Leave all the fields at their default values, except set the orientation to "Down," and enter 10.0 in the Constant Power column MW Value field. As the name implies, a constant power load treats the load power as being independent of bus voltage; constant power load models are commonly used in power system analysis. By default PowerWorld

"anchors" each load symbol to its bus. This is a handy feature when changing a drawing since when you drag the bus the load and all associated fields move as well. Note that two fields showing the load's real (MW) and reactive (Mvar) power were also auto-inserted with the load. Since we won't be needing the reactive field right now, select this field and then select click **Delete** (located towards the right side of the **Tools** Ribbon) to remove it. You should also resize the MW field using the **Format, Font** command.

Now we need to join the bus 3 load to the rest of the system. We'll do this by adding a line from bus 2 to bus 3. Select **Network, Transmission Line** and then click on bus 2. This begins the line drawing. During line drawing PowerWorld adds a new line segment for each mouse click. After adding several segments place the cursor on bus 3 and double-click. The Transmission Line/Transformer Options dialog appears allowing you to set the line parameters. Note that PowerWorld should have automatically set the "from" and "to" bus numbers based upon the starting and ending buses (buses 2 and 3). If these values have not been set automatically then you probably did not click exactly on bus 2 or bus 3; manually enter the values. Next, set the line's Series Resistance (R) field to 0.3, the Series Reactance (X) field to 0.6, and the MVA Limits Limit (A) field to 20 (the details of transformer and transmission line modeling is covered in Chapters 3 through 5). Select OK to close the dialog. Note that Simulator also auto-inserted two circuit breakers and a round "pie chart" symbol. The pie charts are used to show the percentage loading of the line. You can change the display size for these objects by right-clicking on them to display their option dialogs. ■

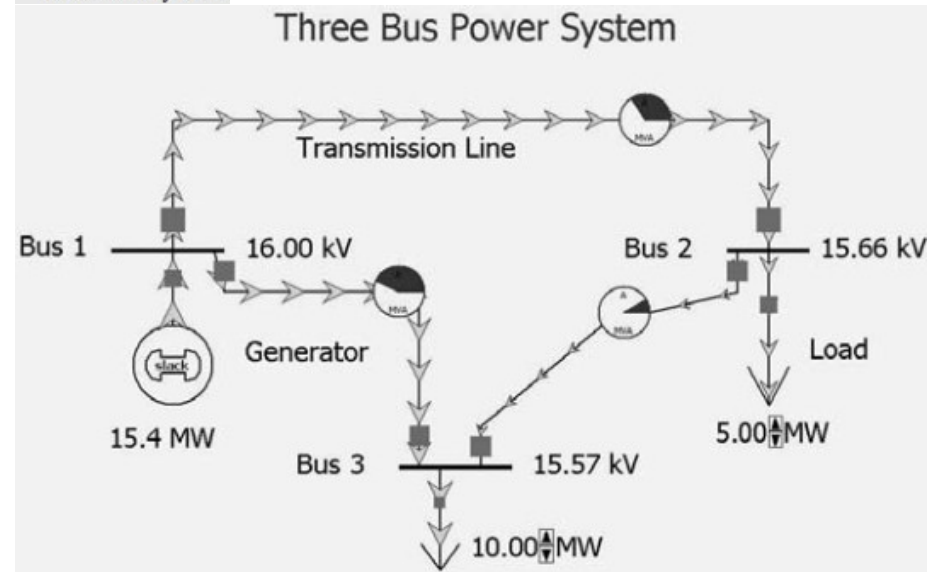
EXAMPLE 1.3 PowerWorld Simulator—Run Mode

Next, we need to switch back to Run Mode to animate the new system developed in Example 1.2. Click on the **Run Mode** button (immediately below the **Edit Mode** button), select the **Tools** on the ribbon and then click the green and black button above **Solve** to start the simulation. You should see the arrows flow from bus 1 to bus 2 to bus 3. Note that the total generation is now about 16.2 MW, with 15 MW flowing to the two loads and 1.2 MW lost to the wire resistance. To add the load variation arrows to the bus 3 load right click on the load MW field (not the load arrow itself) to display the field's local menu. Select **Load Field Information Dialog** to view the Load Field Options dialog. Set the "Delta per Mouse Click" field to "1.0," which will change the load by one MW per click on the up/down arrows. You may also like to set the "Digits to Right of Decimal" to 2 to see more digits in the load field. Be sure to save your case. The new system now has one generator and two loads. The system is still radial, meaning that a break anywhere on the wire joining bus 1 to bus 2 would result in a blackout of all the loads. Radial power systems are quite common in the lower voltage distribution systems. At higher

voltage levels, networked systems are typically used. In a networked system, each load has at least two possible sources of power. We can convert our system to a networked system simply by adding a new line from bus 1 to bus 3. To do this switch back to Edit Mode and then repeat the previous line insertion process except you should start at bus 1 and end at bus 3; use the same line parameters as for the bus 2 to 3 line. Also before returning to Run Mode, right click on the blue "Two Bus Power System" title and change it to "Three Bus Power System." Return to Run Mode and again solve. Your final system should look similar to the system shown in Figure 1.8. Note that now you can open any single line and still supply both loads—a nice increase in reliability!

FIGURE 1.8

Example 1.3—new three-bus system



SUPPLEMENTARY READING MATERIAL:

THE ENERGY CONTROL CENTER

8.1 INTRODUCTION

The following criteria govern the operation of an electric power system:

- Safety
- Quality
- Reliability
- Economy

The first criterion is the most important consideration and aims to ensure the safety of personnel, environment, and property in every aspect of system operations. Quality is defined in terms of variables, such as frequency and voltage, that must conform to certain standards to accommodate the requirements for proper operation of all loads connected to the system. Reliability of supply does not have to mean a constant supply of power, but it means that any break in the supply of power is one that is agreed to and tolerated by both supplier and consumer of electric power. Making the generation cost and losses at a minimum motivates the economy criterion while mitigating the adverse impact of power system operation on the environment.

Within an operating power system, the following tasks are performed in order to meet the preceding criteria:

- Maintain the balance between load and generation.
- Maintain the reactive power balance in order to control the voltage profile.
- Maintain an optimum generation schedule to control the cost and environmental impact of the power generation.
- Ensure the security of the network against credible contingencies. This requires protecting the network against reasonable failure of equipment or outages.

The fact that the state of the power network is ever changing because loads and networks configuration change, makes operating the system difficult. Moreover, the response of many power network apparatus is not instantaneous. For example, the startup of a thermal generating unit takes a few hours. This essentially makes it not possible to implement normal feed-forward control. Decisions will have to be made on the basis of predicted future states of the system.

Several trends have increased the need for computer-based operator support in interconnected power systems. Economy energy transactions, reliance on external sources of capacity, and competition for transmission resources have all resulted in higher loading of the transmission system. Transmission lines bring large quantities of bulk power. But increasingly, these same circuits are being used for other purposes as well: to permit sharing surplus generating capacity between adjacent utility systems, to ship large blocks of power from low-energy-cost areas to high-energy cost areas, and to provide emergency reserves in the event of weather-related outages. Although such transfers have helped to keep electricity rates lower, they have also added greatly to the burden on transmission facilities and increased the reliance on control.

Heavier loading of tie-lines which were originally built to improve reliability, and were not intended for normal use at heavy loading levels, has increased interdependence among neighboring utilities. With greater emphasis on economy, there has been an increased use of large economic generating units. This has also affected reliability.

As a result of these trends, systems are now operated much closer to security limits (thermal, voltage and stability). On some systems, transmission links are being operated at or near limits 24 hours a day. The implications are:

- The trends have adversely affected system dynamic performance. A power network stressed by heavy loading has a substantially different response to disturbances from that of a non-stressed system.

- The potential size and effect of contingencies has increased dramatically. When a power system is operated closer to the limit, a relatively small disturbance may cause a system upset. The situation is further complicated by the fact that the largest size contingency is increasing. Thus, to support operating functions many more scenarios must be anticipated and analyzed. In addition, bigger areas of the interconnected system may be affected by a disturbance.
- Where adequate bulk power system facilities are not available, special controls are employed to maintain system integrity. Overall, systems are more complex to analyze to ensure reliability and security.
- Some scenarios encountered cannot be anticipated ahead of time. Since they cannot be analyzed off-line, operating guidelines for these conditions may not be available, and the system operator may have to “improvise” to deal with them (and often does). As a result, there is an ever increasing need for mechanisms to support dispatchers in the decision making process. Indeed, there is a risk of human operators being unable to manage certain functions unless their awareness and understanding of the network state is enhanced.

To automate the operation of an electric power system electric utilities rely on a highly sophisticated integrated system for monitoring and control. Such a system has a multi-tier structure with many levels of elements. The bottom tier (level 0) is the high-reliability switchgear, which includes facilities for remote monitoring and control. This level also includes automatic equipment such as protective relays and automatic transformer tap-changers. Tier 1 consists of telecontrol cabinets mounted locally to the switchgear, and provides facilities for actuator control, interlocking, and voltage and current measurement. At tier 2, is the data concentrators/master remote terminal unit which typically includes a man/machine interface giving the operator access to data produced by the lower tier equipment. The top tier (level 3) is the supervisory control and data acquisition (SCADA) system. The SCADA system accepts telemetered values and displays them in a meaningful way to operators, usually via a one-line mimic diagram. The other main component of a SCADA system is an alarm management subsystem that automatically monitors all the inputs and informs the operators of abnormal conditions.

Two control centers are normally implemented in an electric utility, one for the operation of the generation-transmission system, and the other for the operation of the distribution system. We refer to the former as the energy management system (EMS), while the latter is referred to as the distribution management system (DMS). The two systems are intended to help the dispatchers in better monitoring and control of the power system. The simplest of such systems perform data acquisition and supervisory control, but many also have sophisticated power application functions available to assist the operator. Since the early sixties, electric utilities have been monitoring and controlling their power networks via SCADA, EMS, and DMS. These systems provide the “smarts” needed for optimization, security, and accounting, and indeed are really formidable entities. Today’s EMS software captures and archives live data and records information especially during emergencies and system disturbances.

An energy control center represents a large investment by the power system ownership. Major benefits flowing from the introduction of this system include more reliable system operation and improved efficiency of usage of generation resources. In addition, power system operators are offered more in-depth information quickly. It has been suggested that at Houston Lighting & Power Co., system dispatchers’ use of network application functions (such as Power Flow, Optimal Power Flow, and Security Analysis) has resulted in considerable economic and intangible benefits. A specific example of \$ 70,000 in savings achieved through avoiding field crew overtime cost, and by leaving equipment out of service overnight is reported for 1993. This is part of a total of \$ 340,000 savings in addition to increased system safety, security and reliability has been achieved through regular and extensive use of just some network analysis functions.

8.2 OVERVIEW OF EMS FUNCTIONS

System dispatchers at the EMS are required to make short-term (next day) and long-term (prolonged) decisions on operational and outage scheduling on a daily basis. Moreover, they have to be always alert and prepared to deal with contingencies that may arise occasionally. Many software and hardware functions are required as operational support tools for the operator. Broadly speaking, we can classify these functions in the following manner:

- Base functions
- Generation functions
- Network functions

Each of these functions is discussed briefly in this section.

Base Functions

The required base functions of the EMS include:

- The ability to acquire real time data from monitoring equipment throughout the power system.
- Process the raw data and distribute the processed data within the central control system.

Data acquisition (DA) acquires data from remote terminal units (RTUs) installed throughout the system using special hardware connected to the real time data servers installed at the control center. Alarms that occur at the substations are processed and distributed by the DA function. In addition, protection and operation of main circuit breakers, some line isolators, transformer tap changers and other miscellaneous substation devices are provided with a sequence of events time resolution.

Data Acquisition

The data acquisition function collects, manages, and processes information from the RTUs by periodically scanning the RTUs and presenting the raw analog data and digital status points to a data processing function. This function converts analog values into engineering units and checks the digital function converts analog values into engineering units and checks the digital status points for change since the previous scan so that an alarm can be raised if status has changed. Computations can be carried out and operating limits can be applied against any analog value such that an alarm message is created if a limit is violated.

Supervisory Control

Supervisory control allows the operator to remotely control all circuit breakers on the system together with some line isolators. Control of devices can be performed as single actions or a line circuit can be switched in or out of service.

Alarm Processor

The alarm processor software is responsible to notify the operator of changes in the power system or the computer control system. Many classification and detection techniques are used to direct the alarms to the appropriate operator with the appropriate priorities assigned to each alarm.

Logical Alarming

This provides the facility to predetermine a typical set of alarm operations, which would result from a single cause. For example, a faulted transmission line would be automatically taken out of service by the operation of protective and tripping relays in the substation at each end of the line and the automatic opening of circuit breakers. The coverage would identify the protection relays involved, the trip relays involved and the circuit breakers that open. If these were defined to the system in advance, the alarm processor would combine these logically to issue a priority 1 alarm that the particular power circuit had tripped correctly on protection. The individual alarms would then be given a lower priority for display. If no logical combination is viable for the particular circumstance, then all the alarms are individually presented to the dispatcher with high priority. It is also possible to use the output of a logical alarm as the indicator for a sequence-switching procedure. Thus, the EMS would read the particular protection relays which had operated and restore a line to service following a transient fault.

Sequence of Events Function

The sequence of events function is extremely useful for post-mortem analysis of protection and circuit breaker operations. Every protection relay, trip relay, and circuit breaker is designated as a sequence of events digital point. This data is collected, and time stamped accurately so that a specified resolution between points is possible within any substation and across the system. Sequence of events data is buffered on each RTU until collected by data acquisition automatically or on demand.

Historical Database

Another function includes the ability to take any data obtained by the system and store in a historical database. It then can be viewed by a tabular or graphical trend display. The data is immediately stored within the on-line system and transferred to a standard relational data base system periodically. Generally, this function allows all features of such database to be used to perform queries and provide reports.

Automatic Data Collection

This function is specified to define the process taken when there is a major system disturbance. Any value or status monitored by the system can be defined as a trigger. This will then cause a disturbance archive to be created, which will contain a pre-disturbance and a post-disturbance snapshots to be produced.

Load Shedding Function

This facility makes it possible to identify that particular load block and instruct the system to automatically open the correct circuit breakers involved. It is also possible to predetermine a list of load blocks available for load shedding. The amount of load involved within each block is monitored so that when a particular amount of load is required to shed in a system emergency, the operator can enter this value and instruct the system to shed the appropriate blocks.

Safety Management

Safety management provided by an EMS is specific to each utility. A system may be specified to provide the equivalent of diagram labeling and paper based system on the operator's screen. The software allows the engineer, having opened isolators and closed ground switches on the transmission system, to designate this as safety secured. In addition, free-placed ground symbols can be applied to the screen-based diagram. A database is linked to the diagram system and records the request for plant outage and safety document details. The computer system automatically marks each isolator and ground switch being presently quoted on a safety document and records all safety documents using each isolator or ground switch. These details are immediately available at any operating position when the substation diagram is displayed.

Generation Functions

The main functions that are related to operational scheduling of the generating subsystem involve the following:

- Load forecasting
- Unit commitment
- Economic dispatch and automatic generation control (AGC)
- Interchange transaction scheduling

Each of these functions is discussed briefly here.

Load Forecasting

The total load demand, which is met by centrally dispatched generating units, can be decomposed into base load and controlled load. In some systems, there is significant demand from storage heaters supplied under an economy tariff. The times at which these supplies are made available can be altered using radio tele-switching. This offers the utility the ability to shape the total demand curve by altering times of supply to these customers. This is done with the

objective of making the overall generation cost as economic and environmentally compatible as possible. The other part of the demand consists of the uncontrolled use of electricity, which is referred to as the natural demand. It is necessary to be able to predict both of these separately. The base demand is predicted using historic load and weather data and a weather forecast.

Unit Commitment

The unit commitment function determines schedules for generation operation, load management blocks and interchange transactions that can be dispatched. It is an optimization problem, whose goal is to determine unit startup and shutdown and when on-line, what is the most economic output for each unit during each time step. The function also determines transfer levels on interconnections and the schedule of load management blocks. The software takes into account startup and shutdown costs, minimum up and down times and constraints imposed by spinning reserve requirements.

The unit commitment software produces schedules in advance for the next time period (up to as many as seven days, at 15-minute intervals). The algorithm takes the predicted base demand from the load forecasting function and the predicted sizes of the load management blocks. It then places the load management blocks onto the base demand curve, essentially to smooth it optimally. The operator is able to use the software to evaluate proposed interchange transactions by comparing operating costs with and without the proposed energy exchange. The software also enables the operator to compute different plant schedules where there are options on plant availability

Economic Dispatch and AGC

The economic dispatch (ED) function allocates generation outputs of the committed generating units to minimize fuel cost, while meeting system constraints such as spinning reserve. The ED functions to compute recommended economic base points for all manually controlled units as well as economic base points for units which may be controlled directly by the EMS.

The Automatic Generation Control (AGC) part of the software performs dispatching functions including the regulation of power output of generators and monitoring generation costs and system reserves. It is capable of issuing control commands to change generation set points in response to changes in system frequency brought about by load fluctuations.

Interchange Transaction Scheduling Function

This function allows the operator to define power transfer schedules on tie-lines with neighboring utilities. In many instances, the function evaluates the economics and loading implications of such transfers.

Current Operating Plan (COP)

As part of the generation and fuel dispatch functions on the EMS at a typical utility is a set of information called the Current Operating Plan (COP) which contains the latest load forecast, unit commitment schedule, and hourly average generation for all generating units with their forecast operating status. The COP is typically updated every 4 to 8 hours, or as needed following major changes in load forecast and/or generating unit availability.

Network Analysis Functions

Network applications can be subdivided into real-time applications and study functions. The real time functions are controlled by real time sequence control that allows for a particular function or functions to be executed periodically or by a defined event manually. The network study functions essentially duplicate the real time function and are used to study any number of “what if” situations. The functions that can be executed are:

- Topology Processing (Model Update) Function.
- State Estimation Function.
- Network Parameter Adaptation Function
- Dispatcher Power Flow (DPF)
- Network Sensitivity Function.
- Security Analysis Function.
- Security Dispatch Function
- Voltage Control Function
- Optimal Power Flow Function

Topology Processing (Model Update) Function

The topology processing (model-updating) module is responsible for establishing the current configuration of the network, by processing the telemetered switch (breakers and isolators) status to determine existing connections and thus establish a node-branch representation of the system.

State Estimation Function

The state estimator function takes all the power system measurements telemetered via SCADA, and provides an accurate power flow solution for the network. It then determines whether bad or missing measurements using redundant measurements are present in its calculation. The output from the state estimator is given on the one-line diagram and is used as input to other applications such as Optimal Power Flow.

Network Parameter Adaptation Function

This module is employed to generate forecasts of busbar voltages and loads. The forecasts are updated periodically in real time. This allows the state estimator to schedule voltages and loads at busbars where no measurements are available.

Dispatcher Power Flow (DPF)

A DPF is employed to examine the steady state conditions of an electrical power system network. The solution provides information on network bus voltages (kV), and transmission line and transformer flows (MVA). The control center dispatchers use this information to detect system violations (over/under-voltages, branch overloads) following load, generation, and topology changes in the system.

Network Sensitivity Function

In this function, the output of the state estimator is used to determine the sensitivity of network losses to changes in generation patterns or tie-line exchanges. The sensitivity parameters are then converted to penalty factors for economic dispatch purposes.

Security Analysis Function

The SA is one of the main applications of the real time network analysis set. It is designed to assist system dispatchers in determining system security under specified single contingency and multiple contingency criteria. It helps the operator study system behavior under contingency conditions. The security analysis function performs a power flow solution for each contingency and advises of possible overloads or voltage limit violations. The function automatically reviews a list of potential problems, rank them as to their effect and advise on possible reallocation of generation. The objective of SA is to operate the network closer to its full capability and allow the proper assessment of risks during maintenance or unexpected outages.

Security Dispatch Function

The security dispatch function gives the operator the capability of reducing or eliminating overloads by rearranging the generation pattern. The tool operates in real-time on the network in its current state, rather than for each contingency. The function uses optimal power flow and constrains economic dispatch to offer a viable security dispatch of the generating resources of the system.

Voltage Control Function

The voltage control (VC) study is used to eliminate or reduce voltage violations, MVA overloads and/or minimize transmission line losses using transformer set point controls, generator MVAR, capacitor/reactor switching, load shedding, and transaction MW.

Optimal Power Flow Function

The purpose of the Optimal Power Flow (OPF) is to calculate recommended set points for power system controls that are a trade-off between security and economy. The primary task is to find a set of system states within a region defined by the operating constraints such as voltage limits and branch flow limits. The secondary task is to optimize a cost function within this region. Typically, this cost function is defined to include economic dispatch of active power while recognizing network-operating constraints. An important limitation of OPF is that it does not optimize switching configurations.

Optimal power flow can be integrated with other EMS functions in either a preventive or corrective mode. In the preventive mode, the OPF is used to provide suggested improvements for selected contingency cases. These may be the worst cases found by contingency analysis or planned outages.

In the corrective mode, an OPF is run after significant changes in the topology of the system. This is the situation when the state estimation output indicates serious violations requiring the OPF to reschedule the active and reactive controls.

It is important to recognize that optimization is only possible if the network is controllable, i.e., the control center must have control of equipment such as generating units or tap-changer set points. This may present a challenge to an EMS that does not have direct control of all generators. To obtain the full benefit of optimization of the reactive power flows and the voltage profile, it is important to be able to control all voltage regulating devices as well as generators.

The EMS network analysis functions (e.g., Dispatcher Power Flow and Security Analysis) are the typical tools for making many decisions such as outage scheduling. These tools can precisely predict whether the outage of a specific apparatus (i.e., transformer, generator, or transmission line) would cause any system violations in terms of abnormal voltages or branch overloads.

In a typical utility system, outage requests are screened based on the system violation indications from DPF and SA studies. The final approval for crew scheduling is granted after the results from DPF and SA are reviewed.

Operator Training Simulator

An energy management system includes a training simulator that allows system operators to be trained under normal operating conditions and simulated power system emergencies. System restoration may also be exercised. It is important to realize that major power system events are relatively rare, and usually involve only one shift team out of six, real experience with emergencies builds rather slowly.

The interface to the operator appears identical to the normal control interface. The simulator relies on two models: one of the power system and the other represents the control center. Other software is identical to that used in real time. A scenario builder is available such that various contingencies can be simulated through a training session. The instructor controls the scenarios and plays the role of an operator within the system.