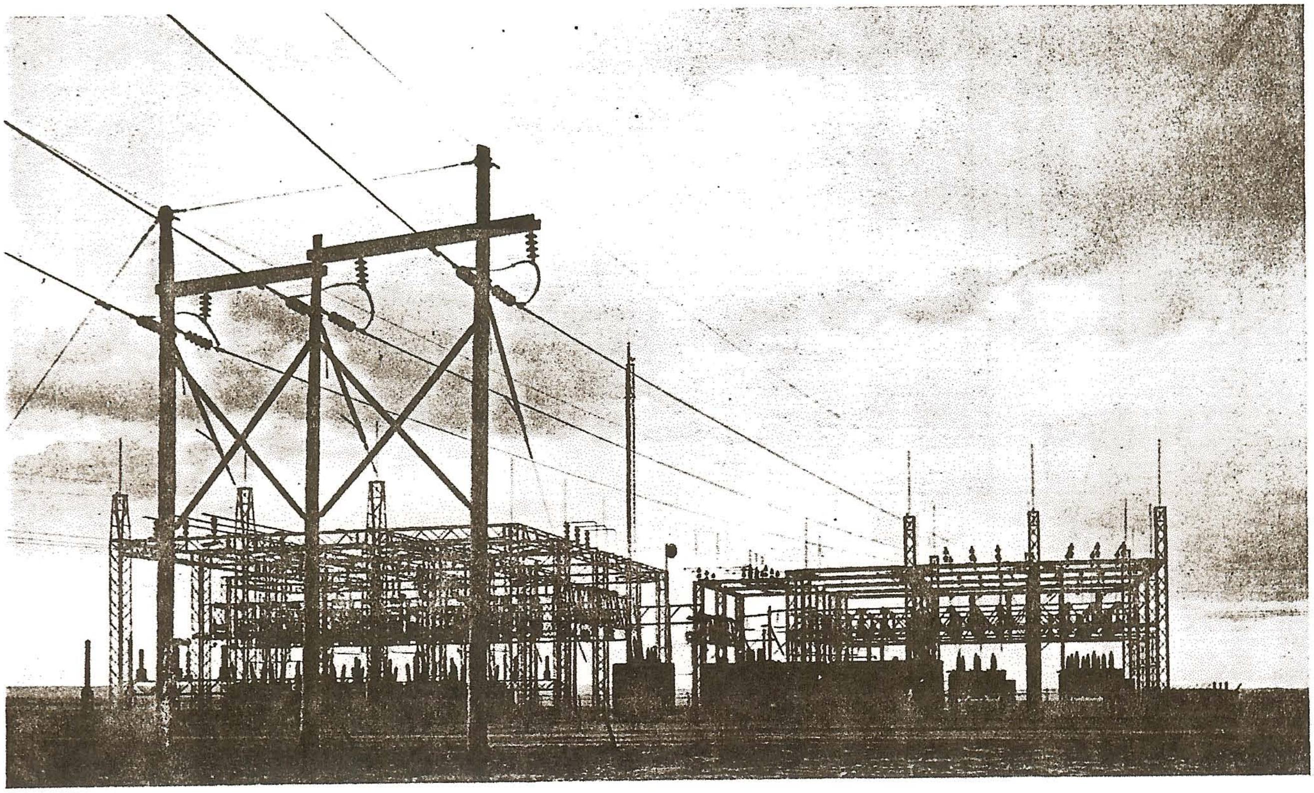

Fig. 2-9 Primary substation

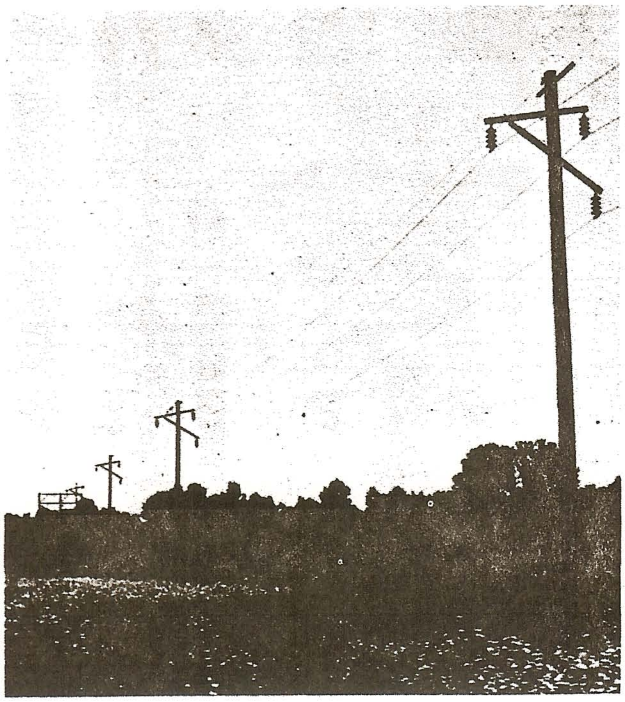

Fig. 2-11 Lower-voltage subtransmission line

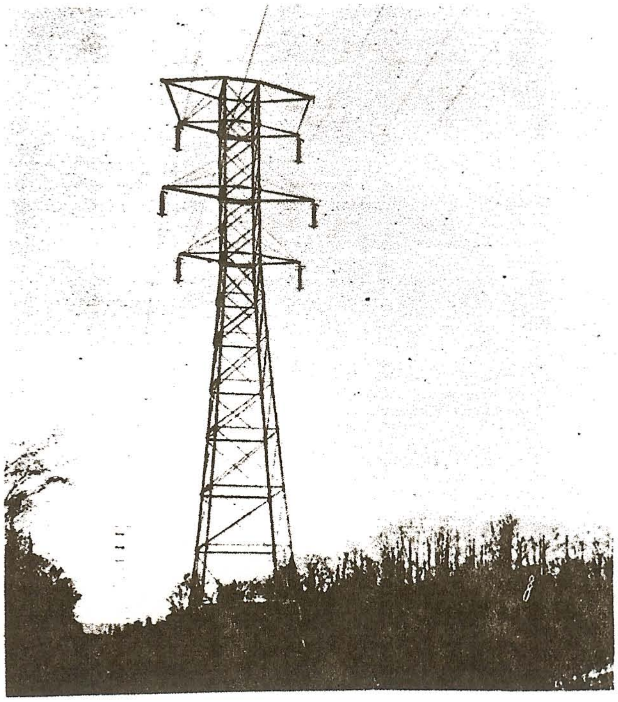

Fig. 2-10 (ST1) Double circuit subtransmission line

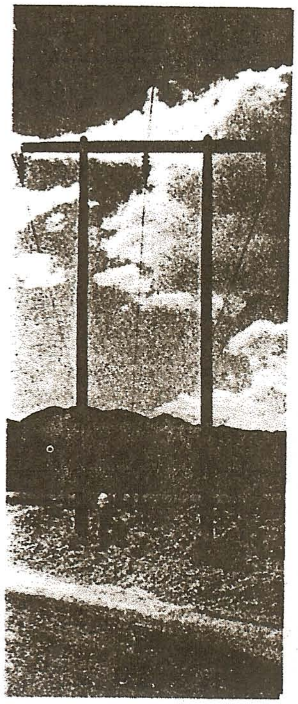

Fig. 2-12 Medium-voltage subtransmission line

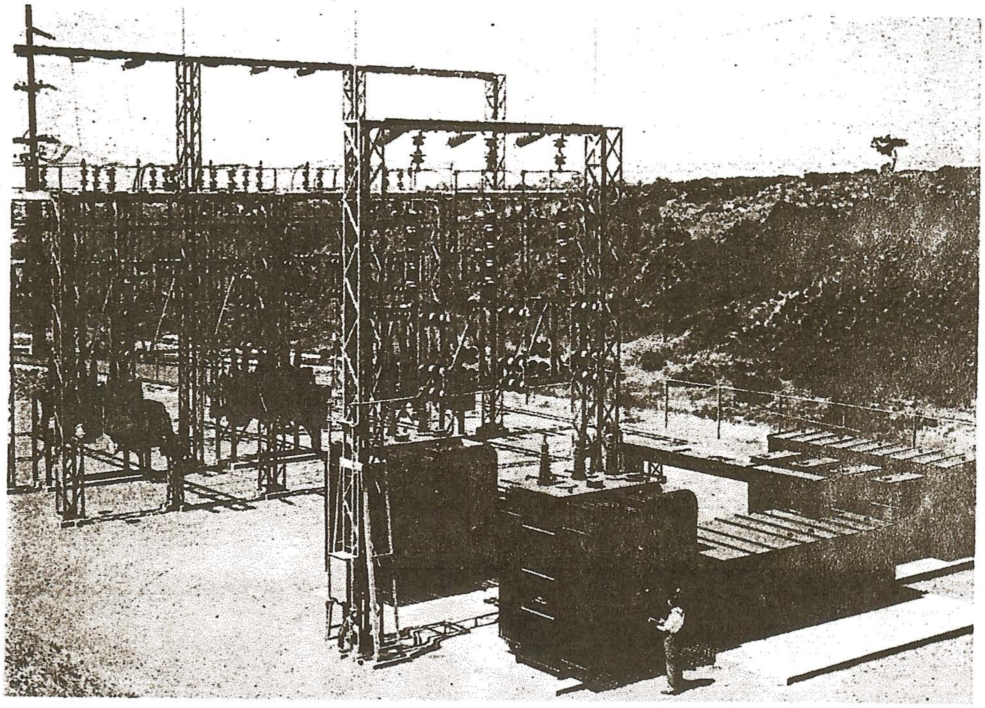

Fig. 2-13 Distribution substation

Fig. 2-14 Pole-type distribution transformer

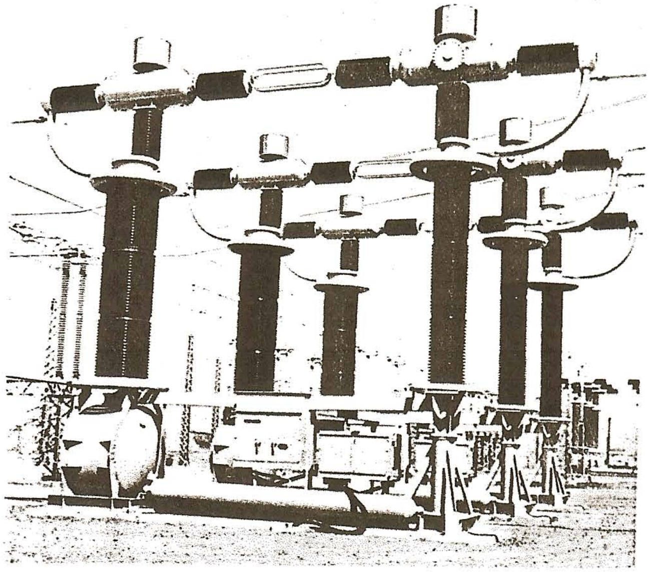

Fig. 2-15 500 kV switchyard with air-blast breaker in foreground

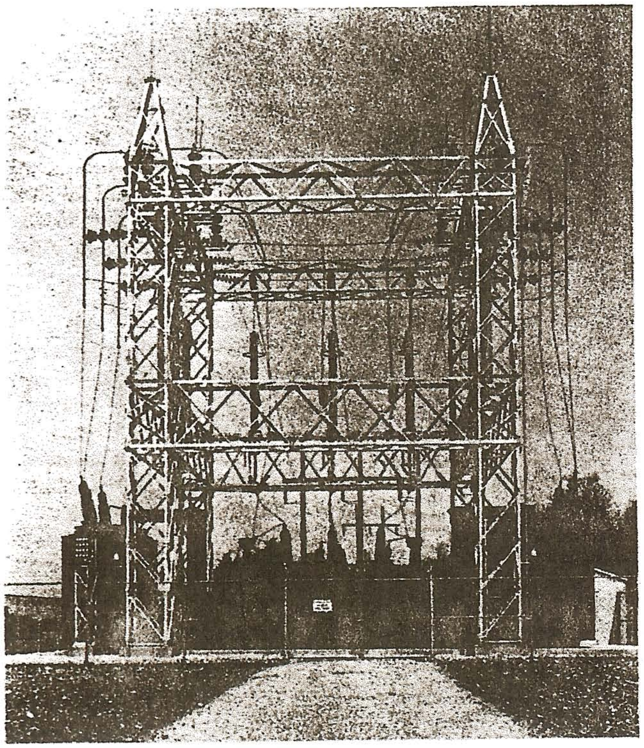

Fig. 2-16 Large industrial customer substation

RURAL LINES

Farms are served by long, lightly loaded Rural Lines. In the usual case, the line starts out as a 12.47-kV, three-phase, 4-wire circuit. Branches are 7200 volts, single phase. Toward the far end, the main circuit itself may become single phase, one-phase wire and neutral.

THE BULK POWER SUPPLY SYSTEM

Some utility people use this term to designate the wholesale part of the business. It includes generation, transmission, and primary substations; sometimes also subtransmission and distribution substations. This part of the system corresponds in function to that of manufacturer and wholesaler.

The bulk power supply system is under centralized control, both as to operation, routine maintenance, and construction of new facilities. It contains all the big pieces of apparatus on the system: the large steam-turbine generators, the high-voltage transformers, the waterwheel generators, and the power circuit breakers. It also provides problems of design and operation, such as protective relaying, stability, and control of system voltage, load, and frequency.

THE DISTRIBUTION SYSTEM

This is the retail part of the system. It serves the residential and commercial customers and some of the smaller industrials. It has the final responsibility for seeing that service is maintained to the customers, and at the correct voltage. On most systems, distribution represents from 35% to 45% of the total system investment and half the total system losses.

INVESTMENT

How much of the system investment is represented by these various components? The answer to this question varies considerably from one company to the next. A company whose generation is predominantly hydro has a larger proportion of its capital in generation than a company having no hydro, because hydro developments cost more per kilowatt than steam stations. A company that has several large industrial customers has less money invested per kilowatt in distribution than one that must deliver practically all its energy to many small customers. A company whose generation is close to its load has a relatively small investment in transmission. The following table shows the investment in each category in per cent of total electric plant for investor owned electric utilities for 1965. This is a national average and the numbers for any given utility can depart from those stated.

Type	Percent of Total
Generation	41
Transmission	17
Distribution	39
General and intangible	3
Total system investment (gross) per kW of installed capacity	$321

Source: Statistics of Electric Utilities in the United States — Federal Power Commission.

SYSTEM EVOLUTION

What factors determined the evolution of an existing system? The fact is that it was not designed — at least not in the sense that some one, starting from scratch, with no power supply facilities at all in the area, conceived and planned the present system. The present system may comprise what were originally separate operating companies, which have been consolidated into the present one big system. Throughout this process, the load in the area of each of the components was increasing, and adequate facilities for supplying it had to be available all the time. Each step taken in the evolution of the present system doubtless seemed to those who took it, at the time it was taken, as the most logical in view of:

a) Existing loads and current estimates of future loads; presently available apparatus, equipment, materials, knowledge, and techniques; economic conditions, current and predicted.

b) Limitations on freedom of choice imposed by policies adopted and actions taken previously (these limitations have sometimes constituted severe handicaps).

The present assembly of generating stations, substations, and transmission and distribution lines is probably rather different from what one would now select to serve the present load on the system, were he able, by a wave of a magic wand, to obliterate what now exists and instantaneously replace it with what he would like to have.

Tremendous gains have been made in the field of automated system planning — gains made possible by the development of computing devices. Calculating techniques are in use that provide optimum economic design solutions taking into account system expansion from the existing pattern, outages for whatever reason, interconnections with other utilities, and load characteristics. Included in these studies are considerations of reliability, adequacy of system under unusual circumstances, stability, short circuits, surge voltages, radio interference, protective relaying — in fact, all important aspects of system planning.

LOAD

The system load at any instant is the sum of the loads drawn by all the devices that happen to be in operation, plus the system losses. Some of the power-consuming devices are manually controlled (household radios and electric ranges). Some are controlled automatically (refrigerators). Some are both (flatirons and ovens). The amount of load at any instant is determined primarily by the customers and is sometimes referred to as demand. Demand may be measured in either kilowatts or kilovolt-amperes: it may apply to a single device or piece of apparatus, to a feeder, to a substation or generating station, or to the entire system. The utility can exert some influence on the demand, but not much. If the load is predominantly resistive (e.g., lighting and heating), a reduction in voltage reduces the demand, and vice versa. Motor load is affected only slightly by changes in voltage, but it may be sensitive to changes in frequency. How sensitive it is to frequency depends on the composite of the speed-load characteristics of all the driven devices in operation at the moment.

Emergencies can be created when insufficient generation is available to meet the load demand. This could be caused by unscheduled outages of any type generator or even other equipment. When companies operated an isolated system, some load reduction could be obtained by reducing voltage and/or frequency. However, with interconnected systems, frequency reduction on one system is not possible and any local voltage reduction can create undesirable var conditions. The most effective and direct way of reducing load in an emergency is "load shedding" wherein selected loads are automatically disconnected according to a planned schedule.

Turning on or off any energy-consuming device affects the system frequency and voltage. Even lighting a 25-watt lamp tends to reduce the voltage at the lamp socket. The effect of a 25-watt lamp is infinitesimal, of course, and is completely masked by the simultaneous starting and stopping of other devices all over the system. Large rolling mills, on the other hand, cause large, sudden, and frequent variations in load. In some cases they cause undesirable changes in tie-line load between systems. Welders, arc furnaces, sawmills, mine hoists and shovels are other loads having extremely variable demands. Sometimes they are merely a nuisance to other customers on the same feeder because of the voltage fluctuations and light flicker they cause; sometimes they present the utility with major problems of load, voltage, and frequency control.

Despite these occasional difficulties, the load on most systems is relatively free from objectionable fluctuations throughout most of the twenty-four hours. Major changes in load occur only with changes in the tempo of industrial activity, that is, at the beginning and end of the morning and afternoon shifts in the factories: and with the approach of daylight, of darkness, and of bedtime.

LOAD CURVES

A plot of the kilowatt demand, or load, over a given period of time is known as a load curve. The period most often used is a day, from midnight to midnight. Under normal conditions the system load curves for Monday through Friday are about the same. The Saturday and Sunday load curves of companies that have a considerable commercial or industrial load, or both, show the effects of the weekend shutdown of shops and factories. The system load curves will generally vary with the season depending upon such considerations as: darkness occurring earlier in winter, air conditioning load on a hot summer day, irrigation pumping, etc. One daily load curve may be represented by the power vs. time curve of Fig. 2-17. Another, showing a higher system peak, is shown in Fig. 2-18.

These curves bring out the difference between power and energy (see Appendix III of Chapter 1). The area under the curve represents energy, the kilowatt-hours which must be generated during each 24-hour period. The ordinates of the curve show the rate at which the energy must be generated. The highest ordinate shows the maximum rate, that is, the maximum power for the day. It is stated in kilowatts and is known as the peak load.

The ratio between the actual area under the load curve expressed in kilowatt-hours, and the kilowatt-hours that would be generated if the load were constant at peak value during the entire 24-hour period is called the load factor.

For the system whose loads conform to Fig. 2-17 and 2-18, the system peak is about 1.15 million kilowatts in one and 1.4 million kilowatts in the other. The utility must have available firm generating capacity (which may include purchased power, if it is firm) to carry these peaks. Although the higher peak requires 250,000 kW more generation than the lower peak, this quarter-million kilowatts is needed for less than three hours a day — a very low load factor. The energy is represented by area A of Fig. 2-18. Many systems have old steam units which have become too inefficient to be operated continuously. These units are still valuable for low-energy loads like A, where high economy is not very important, and for emergencies. The practice is growing of purchasing gas-turbine units intended specifically for peaking. Such units are characterized by their ability to be started and put into service quickly. Considerably lower investment costs and their easy adaptability to automatic control more than offset their higher fuel cost. Pumped hydro installations are becoming popular for peaking generation for those utilities with low-cost sites available Also conventional hydro units may be used for peaking, depending on the characteristics of the river flow and the storage available. It also may be economical to install additional generation at an existing dam site to obtain peaking capacity.

INSPECTION AND MAINTENANCE

Utility equipment such as switchgear, transmission lines, boilers, turbines, etc., require inspection and maintenance. A circuit breaker can be taken out of service, inspected, and even maintained without any service interruption to customers. However, when a boiler is taken out of service for scheduled maintenance, the associated generator is not available. Thus, maintenance should be done on a unit when it is not needed to carry the load.

The load curves shown in Figs. 2-17 and 2-18 show the difference between an off-peak load and a peak load. Maintenance would be scheduled for the off-peak season. During the time of system peak all units should be available. This was easy to schedule when the system peak occurred during the winter, probably in December, and the load dropped markedly after the peak. However, air conditioning load during the summer has now reversed the season for peak loads on several utilities. Many times the "system peak" might occur every six months. There are systems where the load does not drop substantially between system peaks, or one might say the system peak is difficult to determine. With such a load characteristic, maintenance cannot be scheduled during the "off peak" season. Thus the system design must be such that a reserve (extra capacity) is available so a necessary maintenance schedule can be kept.

PREVIEW OF STABILITY

Even though the analogy is not perfect, it is helpful to imagine that all the energy-consuming devices connected to the system are so many vehicles being pulled along by the generators. Resistive loads can

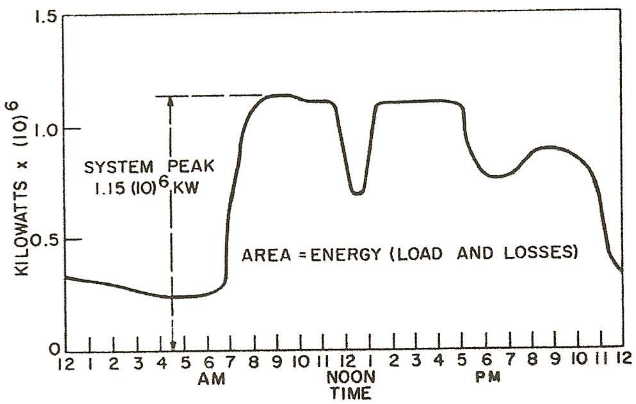

Fig. 2-17 Typical load curve for a weekday

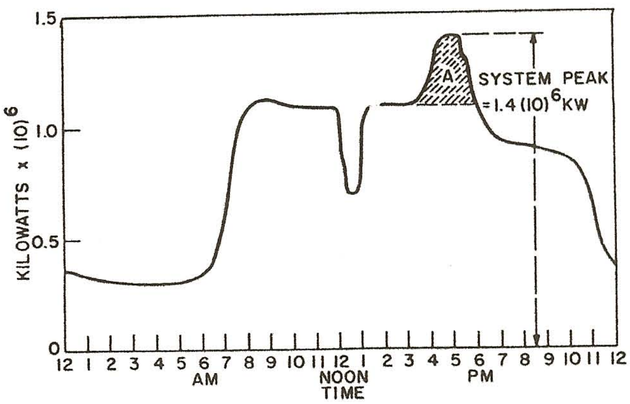

Fig. 2-18 Typical load for a weekday during the time of system peak load

be represented by stoneboats, or even plows. Motors, or "live load," can be represented by vehicles on wheels. These vehicles on wheels also have inertia, so that they do not stop moving instantly, even if the generators stop pulling. Each vehicle moves over its own road, and the roads are not level, nor are they equally steep.

We can further imagine that the generators pull the loads by means of elastic, ropelike members which stretch out in proportion to the pull exerted by the generators. These "ropes," however, also have stiffness, so that they can transmit a push as well as a pull. Therefore, if a generator starts to loaf on the job, the motors it has been pulling can push it along and make it keep up. One further point — these "ropes," each of a different length and stiffness, not only connect the generators to the loads, but also the generators to each other, and the loads to each other. The "ropes" are related to the impedances of the electrical connections between the various parts of the system.

The characteristic of a power system syggested by this analogy is further considered in Chapter 12, "Stability." For the present, however, the analogy may help you understand one important characteristic of a power system.

SYSTEM DESIGN

As long as loads continue to increase, systems must also continue to grow. This requires what is known as "system planning." System planning is management's defense against ever being caught with not enough generation to carry the load; or with a system which cannot maintain proper continuity or voltage in some areas. Loads have been growing at a rate to double about every 10 or 11 years, but that cannot keep up forever. Saturation will set in some time. Furthermore, that is an average rate of growth: it is subject to increase or decrease by business conditions and world outlook. Although it is necessary to maintain the ability of the system to carry any load which may be demanded, it is courting financial diaster to have facilities on hand too long before they are needed and, therefore, before they can begin to earn their keep. It is easy to see that management must be alert and exercise good judgment to keep out of trouble, especially when orders for new generation must be placed two to four years before it will be needed.

The emphasis in system design has been changing gradually over the years. This change is caused primarily by three factors:

a) Experience and development have greatly increased the reliability of each component part of the system.

b) As systems get bigger and bigger, any one piece of equipment becomes less and less important to the successful operation of the whole system

c) The increasing use of interconnections between neighboring systems has had the effect of making each system larger, and hence less dependent on any one component.

Many engineers feel that it is no longer necessary to resort to the duplication of former years. On recently built parts of the system, there are not so many double buses, double circuit breakers, spare transformers, or spare exciters as in stations built twenty-five or more years ago. Nowadays two transmission lines are built because two lines are needed, not primarily to be sure of having one of them in service. Because duplication is no longer so essential, complication is giving way to simplicity; therefore, costs are lower and there is less chance for the operators to make mistakes.

Utility planners have learned that it is of supreme importance to build into the system as much flexibility as possible. "Flexibility" means several things. It means freedom to grow without embarrassment, as necessary to serve ever-increasing loads. It means ability to serve new loads, whatever their nature and whenever they may appear. It means ability to take advantage of new tools and devices, new methods and techniques, and new operating, construction, and design practices, as they may be developed, invented, or discovered.

For example, the development of a successful automatic reclosing relay changed completely the philosophy of distribution system design. As already noted, this relay made practical an unattended substation. When the substation no longer required operators, it could economically be made smaller and located nearer the load. Primary distribution feeders could be shortened, and the power could be brought nearer its destination over the more economical subtransmission system. The large distribution substation feeding a large load area over many primary feeders became a relic of the past. Many are still in operation, of course, but most of them have been made automatic (and unattended). This is only a small part of the whole story of the effect of automation on system design and operation, resulting in great savings in capital investment and in operating costs. This subject will be treated in much more detail later.

SUMMARY

A modern power system consists of generating stations, transmission and subtransmission systems to convey the energy to the load areas, and distribution systems to deliver it to the customers. A utility must keep its system in condition to serve its present load adequately. It must, at all times, have enough generation available for service, and enough of the transmission, subtransmission and distribution systems in operation to assure continuity and good voltage to every customer despite planned outages for inspection and maintenance. It must meet these technical requirements, while at the same time operating the system so as to realize the maximum economies. Finally, it must plan and provide additions to the system to care for load growth.

ADDITIONAL REFERENCES:

Philip Sporn. The Integrated Power System. New York: McGraw-Hill Co., 1950.