CHAPTER 1

Why Do Lights Go Out ?

"If anything can wrong, it will."
Murphy's Law

1.1 Introduction

Just as food, clothing and shelter are considered as basic necessities for every citizen, so is electrical energy. The first application of electrical energy was for street lighting which then spread to homes, offices and practically everywhere people lived and worked. Electricity also provided a clean alternative to steam engines in factories for providing motive power. It is a versatile form of energy that can be used for cooking, heating and cooling, appliances and gadgets that are used for cutting down manual labour and improving the quality of service in many spheres of life including health care, education and entertainment. In modern times, electricity drives communication equipment and information technology. The application of electrical drives in rail and road transportation can reduce environmental pollution and improve efficiency of energy usage. About 40 % of the total energy used in developed countries is electrical energy.

We expect the lights to turn on at the flick of a switch and it is quite frustrating when the lights go out suddenly and darkness descends due to unexpected power supply interruptions. In this chapter, we will look into the causes of power blackouts that may be temporary (lasting only few minutes) or prolonged (lasting several hours or even days). The blackout may occur only in a localized area (say in a street, affecting few people) or in a wide area affecting thousands of people. The historic blackout on November 9, 1965 in

New York and New England states in U.S.A affected 30 million people in an area of 83,000 square miles. The consequences of this were to introduce major changes in the grid operation and in energy control centres that saw the application of computers for SCADA (Supervisory Control and Data Acquisition). The computers are also used for security monitoring and to provide guidance to system operators to implement preventive control (to prevent the occurrence of blackouts). However, these measures were applied primarily for bulk power systems made up of generating stations and high voltage transmission networks. Subsequent developments in the eighties, have led to the introduction of Distribution Automation and Control (DAC) for monitoring facilities in the distribution substations (such as transformers and switches) and load management.

1.2 Present Status of Electricity Supply Industry (ESI)

Supplying reliable power at affordable costs has been the guiding principle in planning power (supply) systems, all over the world. Till the nineties, the Electricity Supply Industry (ESI) was a regulated monopoly in which each utility took care of planning, design and operation of the generation, transmission and distribution facilities under its control in the designated area. The tariff was decided on the basis of an equitable rate of return on investment, taking into account the capital and operating & maintenance costs. Such utilities are essentially Vertically Integrated Utilities (VIU). The exchange of energy among VIUs was based on mutual needs with the help of tie lines (interconnections). While most of the utilities in U.S.A. were privately owned, in UK, India and elsewhere, they were publically owned. The desire to introduce competition in generation of power with the expectation of providing a choice for the customers and reducing the costs, led to the unbundling of generation, transmission and distribution. Also, deregulation was introduced where a large customer can buy power from any competing supplier who had access to transmission facilities irrespective of its ownership. The jury is still out on the impact of these momentous changes in the operation of electricity supply industry (ESI). While it was anticipated that the electricity rates will drop without affecting the system reliability, the actual experience showed that it led to higher rates and rolling or rotating blackouts. However, on the positive side, it also opened the door to greener forms of electricity generation (See the article in

December 2010 issue of IEEE Spectrum-"How Free Market rocked the Grid" by Seth Blumsack). In India, the 2003 electricity act has led to the unbundling of generation, transmission and distribution and introduction of open access to transmission facilities and power trading.

In another article (by S.M. Amin published in the January 2011 issue of IEEE Spectrum), entitled "U.S. Electrical Grid Gets Less Reliable", it is stated that the U.S. electrical grid has been plagued by ever more and ever worse blackouts over the past 15 years. "In an average year, outages total 92 minutes per year in the Midwest and 214 minutes in the Northeast. Japan, by contrast, averages only 4 minutes of interrupted service each year." The author states that "Starting in 1995, the amortization and depreciation rate has exceeded utility construction expenditures. In other words, for the past 15 years, utilities have harvested more than they have planted. The result is an increasingly stressed grid." It is also interesting to note that R&D spending for the electric power sector has dropped 74% from a high in 1993 of U.S.$ 743 million to $193 million in 2000. The R &D declined from 0.3% of the revenue in 2000 to 0.17% in 2006.

"Even the hotel industry spends 0.7%. on R&D." Incidentally, a major blackout on August 14, 2003 affected large portions of U.S. Midwest and Northeast, and Ontario in Canada. The power outage affected 50 million people and 61,800 Mega Watts (MW) of load. The power was not restored for 4 days in some parts of U.S. In parts of Ontario, there were rolling blackouts that lasted for more than a week. The estimates of the total costs of the blackout range from $ 6 billion to about $12 billion.

In India, there are no accurate records of the power outages kept. The public seem to consider interrupted power supply as their fate! (Although, it must be admitted that the reliability of power supply in Mumbai had been comparable to that in Europe). It is important to outline the causes that lead to a local or widespread blackout. The basic configuration of an electric power system is shown in Fig.1.1. The electricity is produced in generating stations at voltages from 10 to 25 kilo Volts (kV) from various energy sources such as coal, oil, gas, nuclear, hydo, solar, wind, geothermal and tidal. The electrical power is generated in a three-phase, alternating current (AC) form. The renewable energy sources such as solar and wind are desirable although unsteady and costly. For long distance transmission of power, the generated power is transformed to a higher voltage using a step-up transformer. The transmission voltages range from 220 kV to 800 kV. A 400 kV, three phase AC transmission line can transmit power levels up to 1000 MW. In general, the power rating of an AC line is inversely proportional to its length for reasons that will be mentioned in a later chapter. The maximum rating is determined by the temperature rise of the aluminum conductor that is a function of the ambient temperature and the current carried by the conductor. At higher temperatures the conductor sags and the clearances from the vegetation below the line may become insufficient leading to faults that are cleared by tripping the line. It is possible to transmit power by converting it to direct current (DC) using power electronic converters at the two ends of the line. (It is to be noted that the low voltage (230/400 V) distribution of power is invariably in the AC form).

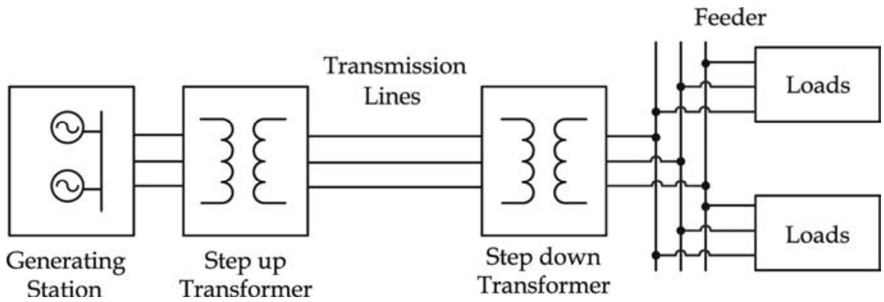

Fig. 1.1 Basic configuration of an electric power system

From cost considerations, the transmission lines are primarily overhead lines that are exposed to vagaries of the nature and susceptible to failures caused by storms and lightning surges. The failures can be of mechanical nature (the worst could be damage to towers) or electrical breakdowns caused by failure of air insulation. Fortunately, the air can recover its insulation strength, once the factors that lead to ionization are absent. Thus, tripping of a line following flashovers permits the air insulation to regain its strength and the line can be reclosed after few seconds. In any case, the grid operation requires the power transfers to be unaffected after the loss of any single line. Thus, the transmission network is a complex electrical circuit containing several meshes (loops).

The distribution network is usually radial with primary feeders operating at voltages of 11 kV to 66 kV (in India) depending on the load (power demand) requirement. Large customers can receive power at 66 kV or sometimes even at 110 kV. The low voltage, secondary distribution network operating at 230/400 V is used to supply residential and small commercial loads. A distribution substation supplies power to feeders by stepping down the voltage by using step down transformers. Further reduction in voltage is provided by pole mounted transformers that supply power to a group of houses or units that may consume power of 3 to 6 kW (peak load) each.

While we will discuss the organization of electricity supply and its operation separately in a following chapter, it is worth noting that electric power utilities were started more than a century ago to primarily supply a local area or a town/city. Historically, the credit for developing electric lights (incandescent lamps) goes to Thomas Edison who also started a power station using DC generators driven by steam engines to supply street lighting in Pearl street in New York city, U.S.A.in 1882. It was soon found that long distance transmission was not feasible unless voltages can be raised. This led to the development of AC generation and transmission as transformers can be built to operate at very high efficiencies and thus, stepping up or down of voltages became feasible. It is to be noted that for a given power level, the current flow in a line is inversely proportional to the voltage level. The power losses in a conductor are proportional to the square of the current and hence the combined losses in the transmission and distribution networks can be kept below 10% of the power generated. AC generators could be built also for high power ratings unlike DC generators where commutator and brushes limit the power level.

The discovery of AC induction motor by Nicola Tesla also spurred the utilization of power in the AC form. As the power utilities increased in number, it was found desirable to interconnect them using tie lines for improved economy and reliable operation. (It is to be noted that there is no difference physically between a line evacuating power from a generating station and a tie line. In the latter, the power can flow in both directions). This has led to the growth of large interconnected systems, spread over a large geographic area. In India, there are five regional grids-Northern, Southern, Western, Eastern and North Eastern. Except for the Southern regional grid, all other regional grids have now been connected using AC tie lines. Even the Southern regional grid has been connected to the Western and Eastern grids using DC ties that don't have the problems associated with the AC ties. However, DC ties are more expensive than AC ties in general. In North America, only Texas State in U.S.A. is not interconnected (except using DC ties). The rest of the states/provinces are organized into two major Interconnections-Western and Eastern. These two major areas are also connected by small DC ties.

1.3 Certain Facts that Govern Electricity Supply

Before we analyze the causes that can result in blackouts (localized or widespread) and the remedies, let us look at some important facts that affect the planning, operation and control of interconnected AC power systems.

FACT 1: At any instant of time, there is a power balance-that is, the power supplied to customers = power generated – losses in the system.

FACT 2: It is not economically feasible to store electric energy in large quantities.

FACT 3: It is not possible to distinguish between the energy received from different generating stations. (The concept of green (renewable) power is only conceptual in the sense that nobody can claim that they receives only green power unless they are not connected to the grid).

FACT 4: The power flow in an AC line cannot be controlled unless special control equipment is used.

FACT 5: The electricity travels over transmission lines at speeds approaching that of light (300,000 kilometers/second).

FACT 6: The rate at which power can be ramped up is limited by prime-mover characteristics.

Let us first discuss the implications of these facts. While economists wish to consider electrical energy as a product and encourage competition among generators, and power trading, FACT 3 indicates that the products of all manufacturers (generators, in this case) are identical. Also, power delivered to a distribution substation generally comes from more than one generating station and their contribution is determined from the network configuration and Kirchhoff's laws (that determine flows of current in individual lines).

FACT 1 and FACT 2 indicate that variations in the load (power demand) require prompt adjustments in the generated power to maintain power balance without affecting the frequency. FACT 5 implies that the adjustments in the generation have to be done instantaneously to avoid fluctuations in the frequency. However, FACT 6 indicates that this is not feasible. It is to be noted that a sudden increase in load results in deceleration of the rotors of generators and a drop in the frequency. We can also say that the increased energy demand is initially met by the stored kinetic energy in the spinning generator rotors. The speed governor action results in opening of the valves (carrying steam or water to the steam or hydro turbines) causing increase in the generated power. To restore frequency to the original (nominal) value, the power setting has to be changed to the desired new value determined from Automatic Generation Control (AGC), also called as Load Frequency Control (LFC). A large increase in the load requires adequate spinning reserve at the generators already in service.

The system consisting of generating stations and high voltage transmission network is generally called as bulk power system. The load on the system is determined by the customer requirements and has typically, a cyclic variation during a period of 24 hours. The load is generally minimum during the nights and picks up during the day reaching a maximum value which can be more than twice the minimum value. There could also be more than one peak (one in the morning and other in the evening). The maximum load can also vary depending on the seasonal variations, holiday periods etc. However, the trend is for the peak daily load to increase with time as the economy and population expands. The annual load growth is generally high in a developing country like India (7-10%). If energy storage in large quantities is feasible, it is adequate to plan generation facilities to provide only average load on the system rather than the peak load. The blackouts in India are primarily due to the FACT 2 and the installed capacity is perennially insufficient to meet the peak load.

Apart from the normal variations in the load (that are represented by a daily load curve), there can be disturbances caused by sudden tripping of generators and transmission lines, connection/ disconnection of large loads. This will affect normal power flows in the lines and it is possible that some lines can be overloaded. (It is to be noted that the power flow in transmission lines is determined by injections of power at generating and load nodes in addition to Kirchhoff's laws). To prevent abnormal rise in the conductor temperature, it is necessary to trip the line. Since all lines are not overloaded (some lines operating with sufficient margins), it would be desirable to control power flows in the overloaded lines to ensure they don't trip. However, FACT 4 shows that this is not possible unless special control equipment is provided which involves additional investment (although it may be cheaper than putting up a new line). Interestingly such controllers (based on power electronics) are called as FACTS Controllers. Here, FACTS is an acronym for Flexible AC Transmission System.

It is to noted that from the customer's point of view, the major facet of Power Quality (that is assuming importance) is reliability (availability of uninterrupted power). In addition, regulation of voltage and frequency is also significant. The speed of regulation of voltage (how fast the voltage is brought back to the normal value) can be important for critical loads such as paper mills and semiconductor manufacturing plants.

Additionally, the deviation of the voltage waveform from the (ideal) sinusoidal can affect motor loads.

1.4 Causes for Lights Going Out

1. ***Inadequate Spinning Reserve*:** The spinning reserve takes care of the contingencies involving sudden tripping of a generator or connection of a large load. Normally, load variation tends to be slow as the total load is made up of a large number of small loads and there is diversity among them. Typically, the size of the spinning reserve should not be less than the rating of the largest generator in service. If the spinning reserve is inadequate, the loss of a large generator can result in decay of frequency which is arrested by frequency activated load shedding (to restore the balance between the supply and demand).

   In developing countries, the installed generation capacity may not be adequate to meet the peak load. In such cases, it is necessary to resort to rolling (rotating) blackouts where the supply to a set of customers is deliberately switched off for the required duration to reduce the peak load. Even if the installed generation capacity is adequate, there could be shortage (non-availability) of fuel (fossil or nuclear) that results in power cuts. Also, in hydroelectric power plants, there could be deficiency of storage in reservoirs due to draughts or insufficient rain fall in catchment areas.

It is to be noted that even under generation shortage conditions, it is important to maintain the required minimum spinning reserve. While it may be tempting for the system operator to have zero reserve to avoid customer complaints, this is not advisable as most of the customers would plan for scheduled outages, rather than be rudely surprised by the sudden random outages that can lead to power blackouts.

2. ***Inadequate transmission capacity*:** For the specified locations of generators and loads, there is an upper limit on the aggregate load that can be supplied by a transmission network. For a specified loading condition and the power flow in a transmission line, it is possible to estimate the Available Transfer Capacity (ATC) that cannot be exceeded. This implies that even if the generation is adequate to meet the required load, the transmission is inadequate. In the economist's language, it is called 'congestion' (as the transmission network is compared with the transportation network). However, while the transportation network is subjected to only KCL (Kirchchoff's Current Law), the electrical transmission network is also subjected to KVL (Kirchchoff's Voltage Law) which puts additional constrains. For example, when an overlay of EHV lines is designed to carry the required power (for a 765 kV line of 150 miles length, 3800 MW can be transmitted if there are no other constraints), it has been observed that underlying lower voltage lines carry higher power because of the increase in the impedance of the EHV line due to the autotransformers at the two ends of the line used for raising the voltage (say, from 345 kV to 765 kV).

3. ***Faults (Short Circuits) in the Distribution Feeders*:** The breakdown of insulation in cables or overhead distribution feeders (at medium voltage levels) result in interruption of power flows to loads. Since the faults have to be cleared by opening of circuit breakers, the supply is affected until the circuit breaker is reclosed after the fault is cleared. For overhead conductors, the insulation is provided by

the air which can break down due to lightning or insufficient clearance to a grounded conductor (of electricity). However, when the causes resulting in a fault are removed, the air insulation recovers and hence the breaker is reclosed after some time (of clearing the fault). If the fault is still persisting, 3 or more attempts are made to clear the fault and reclose after some time delay. For a permanent fault, the restoration of the supply requires another healthy feeder (to which the load can be connected).

4. ***Major Disturbances in the System*:** A power system is normally designed to withstand a single major contingency. However, unforeseen events can occur that can result in cascading outages (tripping of several lines and generators due to overloads and under frequency or loss of synchronism) that causes major blackouts which can be widespread over a large geographical area. (as one that happened on 14th August 2003 in Canada and USA or the one that happened on 31st July 2012 in India).

5. ***Improper Coordination of Protection*:** An electrical circuit, even at low voltages (110 or 220 V) and carrying 10 amperes has to be protected against faults (short circuits resulting from failure of insulation). In the past, fuses that would blow at high currents resulting from faults, were used. Now a days, miniature circuit breakers (MCB) and earth leakage circuit breakers (ELCB) are used for protection. In the absence of such protection, the fault currents would continue to flow in the distribution wires and this can result in the pole fuses blowing out, resulting in the interruption of power to several customers. In the worst case, the breaker/recloser at medium voltages (11 to 33 kV) can operate inconveniencing a large number of customers in a locality.

   It should be noted that the protective device at a customer premise must be carefully chosen based on the connected load and the peak load demand.

6. ***Fluctuating Power Generation with Renewable Energy Sources (RES)*:** Both wind and solar power are useful and viable renewable energy sources. However, wind velocity fluctuates and the power output of a wind turbine is proportional to the cube of wind velocity. Thus, a 10 % reduction of rated wind speed results in 30 % reduction of power output. Also, there is a cut-out wind speed (20 to 25 m/sec) above which the wind turbine needs to shut down

to protect the turbine. Similarly, photo voltaic (PV) solar power generation suffers from the variation of sunshine due to clouds and earth's rotation. The only solution to the variable RES is to install adequate electric energy storage (EES) facilities. However, this adds to the cost of generation. At present, several types of EES technologies are under development.

1.5 Reliability of Electricity Supply

For the customers connected to low or medium voltage feeders, the reliability indices are the frequency and duration of the power outage. We can also define average service availability index (ASAI) which considers the total duration of power interruptions in a year. In U.S.A. prior to restructuring, the best index was 1 hour in a year (which translated to 99.99% availability). Of course, in the present times when lighting is only one of the various uses of electrical energy, the power quality (PQ) which encompasses issues such as frequency, slow or fast variations of voltage magnitude (sags and swells), voltage flicker ad departure from sinusoidal waveform (that results in the harmonics which can affect motor loads) is becoming important. In the past, steady state voltage magnitude remaining within a band (+/- 5 % of the nominal) and frequency close to the nominal were considered adequate.

Power Quality (PQ) is fast becoming a major issue in power distribution. One of the PQ problems is the generation of harmonic currents by nonlinear loads caused by introduction of power electronic control for efficient energy utilization. The presence of harmonics (resulting in the departure of the current wave form from being sinusoidal) causes increased losses in the lines and motors. The presence of harmonics injected by a load results in the distortion of the voltage wave form at other locations due to the impedance of the distribution lines. Active filters based on reactive power compensation principle are being applied to overcome this problem. The fast variations in the voltage magnitude (including momentary interruptions of power) are also deleterious to the critical and sensitive loads such as paper and steel mills and semiconductor fabrication plants.

1.6 Scope of this Book

The basics of DC and AC circuits (both single phase and three phase) are introduced in chapter 2 with definitions of three circuit elements-resistance, inductance and capacitance. This chapter is intended for beginners and can be skipped by those familiar or not interested in circuit analysis. The electrical quantities are defined mathematically in this chapter.

The basic structure of the electricity supply system (also called as electrical power system in technical parlance) including generation and delivery of power, and the normal control functions during system operation are explained in chapters 3 to 5. The protection against faults (short circuits) mainly caused by lightning discharges affecting overhead lines, is described in chapter 6 along with the collapse of the system caused by contingencies that lead to the system transition to an emergency state where the system operator has no time to react in real time. Chapter 7 describes the various technological solutions to enhance system security and eliminate widespread blackouts. The emphasis is to enable the creation of self-healing transmission grids.

In this context, the present developments on smart grids which are mainly aimed at low or medium voltage microgrids is presented with a discussion on their relevance in improving the system operation that should provide desired reliability without sacrificing cost effectiveness.

Chapter 8 presents various types of renewable energy sources (RES), the predominant being wind and solar. Since their application also involves the use of energy storage technologies, these are discussed in this chapter. Finally, the issues of restructuring of electrical supply industry (ESI) and competition are discussed in detail with some suggestions for system planning in the present regime of reregulation or restructuring.

The Appendices cover the unit system in general, the electrical shock and safety issues, nuclear energy and glossary.