CHAPTER TWO

Technical Construction and Operation of Electric Grids

2-1: Introduction

An electric power system is a network of electric components used to supply, transfer and use electric power. A grid can be broadly divided into the generators that supply the power, the transmission system that carries the power from generating centers and the distribution systems feed the power to nearby homes and industries. The majority of this system relies upon three-phase AC power, the standard for large scale power transmission and distribution system.

Sudan National (NEC) Grid is small grid compared with neighboring countries grid, and it consist of:

- Five large thermal generating stations:
  - ✓ *Khartoum North Steam Power Station (KHN):* consist of 6 steam turbines, total capacity is 400 MW, located on load center in Khartoum state.
  - ✓ *Khartoum North Gas Power Station (KHNG):* consist of 6 gas turbines, total capacity is 150 MW, located on load center in Khartoum state.
  - ✓ *Gari 1,2 Power Station:* consist of 8 gas turbines associated with 4 steam turbines operated in combine cycle, total capacity is 446 MW, located on load center in Khartoum state.
  - ✓ *Gari 4 Power Station:* consist of 2 steam turbines, total capacity is 120 MW, located on load center in Khartoum state.
  - ✓ *Kosti Power Station:* consist of 4 steam turbines, total capacity is 500 MW, located at 200km from load center in Khartoum state.
- Three Hydro generating stations:

- ✓ *Merwe Hydro-Electric Power Station (MWP):* consist of 10 Francis turbines, total capacity is 1250 MW, located at 346 km from load center in Khartoum state.
- ✓ *Rosieris Hydro-Electric Power Station:* consist of 7 Kaplan turbines, total capacity is 280 MW, located at 453 km from load center in Khartoum state.
- ✓ *Sennar Hydro-Electric Power Station:* consist of 2 Kaplan turbines, total capacity is 15 MW, located at 236 km from load center in Khartoum state.

- Small generating stations:
  - ✓ *Algirba Dam Hydro-Electric Power Station.*
  - ✓ *Jabal Awlia Dam Hydro-Electric Power Station.*
  - ✓ *White-Nile Sugar Thermal Power station.*
  - ✓ *Portsudan Thermal Power stations.*
- Transmission line:
  - ✓ *46 transmission circuits at 110kV voltage level.*
  - ✓ *71 transmission circuits at 220kV voltage level.*
  - ✓ *4 transmission circuit at 500kV voltage level.*
- 123 transmission three-winding transformers.
- 26 shunt reactors.
- 487 High voltage bas-bar.

2-2: General Benefits of Grid Interconnections

Due to the rapid increase in electricity demand, the need arises for the interconnection of power networks distributed in different areas to increase supply reliability, and to facilitate power exchange between areas. The interconnection of separated networks results in a large power system expanding hundreds of kilometres.

In this large power system, high-voltage alternating current lines (HVAC) are used to accommodate the power over long distances between the different networks. The technical rationales for grid interconnections include:

- *Improving reliability and pooling reserves:* The amount of reserve capacity that must be built by individual networks to ensure reliable operation when supplies are short can be reduced by sharing reserves within an interconnected network.
- *Reduced investment in generating capacity:* Individual systems can reduce their generating capacity requirement, or postpone the need to add new capacity, if they are able to share the generating resources of an interconnected system.
- *Improving load factor and increasing load diversity:* Systems operate most economically when the level of power demand is steady over time, as opposed to having high peaks. Poor load factors (the ratio of average to peak power demand) mean that utilities must construct generation capacity to meet peak requirements, but that this capacity sits idle much of the time. Systems can improve poor load factors by interconnecting to other systems with different types of loads.
- *Diversity of generation mix and supply security:* Interconnections between systems that use different technologies and/or fuels to generate electricity provide greater security in the event that one kind of generation becomes limited (e.g., hydroelectricity in a year with little rainfall). Historically, this complementarity has been a strong incentive for interconnection between hydro-dominated systems and thermal-dominated systems. A larger and more diverse generation mix also implies more diversity in the types of forced outages that occur, improving reliability.
- *Economic exchange:* Interconnection allows the dispatch of the least costly generating units within the interconnected area, providing an overall cost

savings that can be divided among the component systems. Alternatively, it allows inexpensive power from one system to be sold to systems with more expensive power.

- *Environmental dispatch and new plant siting:* Interconnections can allow generating units with lower environmental impacts to be used more, and units with higher impacts to be used less. In areas where environmental and land use constraints limit the siting of power plants, interconnections can allow new plant construction in less sensitive areas.
- *Coordination of maintenance schedules:* Interconnections permit planned outages of generating and transmission facilities for maintenance to be coordinated so that overall cost and reliability for the interconnected network is optimized.

2-3: Technical Objectives of Interconnected Systems

The ultimate objective of an interconnection is to provide power to customers economically, safely, reliably, efficiently, and with minimal environmental impact. Each of these aspects has one or more quantitative measure, such as price per kilowatt-hour, number of deathly accidents, frequency and duration of service interruptions, generating plant heat rate, transmission and distribution losses, and emissions factors. Interconnections are designed, and their individual components selected, with all of these objectives in mind, though they may be optimized differently in different systems.

2-4: Transmission Line Conductors

Conductors of overhead transmission and distribution lines typically consist of aluminum, which is light weight and relatively inexpensive, and are often reinforced with steel for strength. Copper is the material of choice for underground cables because, while it is more expensive, it has a lower resistance than aluminum.

Low resistance is generally desirable for power lines to minimize energy losses, but also because heating limits the conductor's ability to carry current. Resistance is given by $R = \rho.L/A$, where A is the cross-sectional area, L is the length of the conductor, and ρ (rho) is the resistivity.

The electrical resistance of a power line thus increases linearly with distance and decreases with the conductor cross section. However, resistance must be weighed against other factors, including the cost of the conductor itself and its weight that needs to be supported by the towers. Because even aluminum conducts so well, this trade-off comes out in favor of surprisingly slender lines considering the amount of current and power transferred.

Note that while resistance of lines is critical in the context of line losses, it is less important in the context of power flow and stability. This is because the overall impedance of a line tends to be dominated in practice by its inductive reactance, to such an extent that it is sometimes appropriate in calculation to make an approximation where a line has zero resistance and only reactance the lossless line. Inductance is based on magnetic flux lines linking a loop of wire. This notion extends to a straight wire, which can be considered an infinitely large loop, and the magnetic flux around the wire does link it. Indeed, there are two contributions to line inductance: the self-inductance, which is just a property of the individual conductor, and the mutual inductance, which occurs between the conductors of the three different phases.

Transmission lines have capacitance, too. It is a bit easier to see how two lines traveling next to each other would vaguely resemble opposing plates with a gap in between. In fact, there is also capacitance between a conductor and the ground. Because the lines are small and the gap wide, the capacitance tends to be fairly small. In describing transmission-line parameters, the inductance is generally considered to be in series and the capacitance in parallel.

Figure 2.1 illustrates the modeling of a transmission line. We can appreciate qualitatively that a line can be characterized in terms of an equivalent resistance, inductance, and capacitance on a per-kilometer basis. As the length increases, inductance and capacitance both increase, as does resistance.

The ratio of series impedance (the combination of resistance and reactance) and shunt admittance (the inverse of impedance) determines a quantity called the characteristic impedance. In the case where resistance is negligible, this reduces to the ratio of inductance to capacitance (actually, the square root of this ratio) and is called the surge impedance of a line. For power transmission, it is more common to speak of a line's surge impedance loading (SIL), an amount of real power in MW that is given by the square of transmission voltage divided by the surge impedance. The SIL does not measure a line's power carrying capacity, but rather states the amount of real power transmission in the situation where the line's inductive and capacitive properties are completely balanced. To system operators, this provides a benchmark: if the power transmitted along a line (at unity power factor) is less than the SIL, the line appears as a capacitance that injects reactive power (VARs) into the system; if transmitted power exceeds the SIL (the more common situation), the line appears as an inductance that consumes VARs, and thus contributes to reactive losses in the system.

The fact that the inductive property dominates at higher loading makes sense because the line's reactive power consumption is a function of the line current, whereas the capacitive property of injecting reactive power is a function of the voltage at which the line is energized as shown by equations (2.1) and (2.2).

$$Q_{loss} = I^2 X_L \quad \text{.......... (2.1)}$$

$$Q_{prod} = \frac{V^2}{X_C} \quad \text{.......... (2.2)}$$

When $X_L * X_C = V^2/I^2$ that mean $Q_{loss} = Q_{prod}$. Substituting $X_L = \omega L$ and $X_C = 1/\omega C$, this gives the characteristic or surge impedance.

$$Z_C = \sqrt{\frac{L}{C}} \quad \text{(2.3)}$$

The surge impedance loading is then given by

$$\text{SIL} = {V_o}^2/Z_C \quad \text{(2.4)}$$

Where V_o is nominal voltage of transmission line.

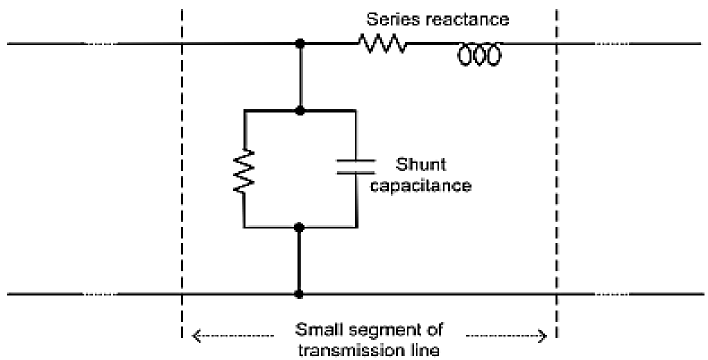

Figure 2.1: Transmission-line modeling.

Table 2.1: Sample of transmission line data*

	Line Voltage (kV)		
	138	**345**	**765**
Conductor per phase	1	2	4
Number of strand aluminum/steel	54/7	45/7	54/19
Diameter (cm)	2.48	2.96	3.617
Conductor geometric mean radius (cm)	1.003	1.1765	1.46
Current-carrying capacity per conductor (A)	770	1010	1250
Geometric mean diameter phase spacing (m)	6.7208	9.985	17.282
Inductance (H/m x10^{-7})	13.02	9.83	8.81
Inductive reactance x_L(Ω/km)	0.49	0.37	0.332
Capacitance (F/m x10^{-12})	8.84	11.59	12.78
Capacitive reactance x_C (MΩ/km)	0.115	0.088	0.08
Resistance (Ω/km)	0.10488	0.035	0.01249
Surge impedance loading (MVA)	50	415	2268

* Sourse: Bergen, Arthur R.; Vittal, Vijay, Power System Analysis, 2nd Edition, 2000, p. 85. Adapted by permission of Pearson Education, Inc., Upper Saddle River, NJ.

2-5: Communications, Monitoring, and Control Systems

System operations are co-ordinated by a central control center (National Load Dispatch Centre in Sudan (NLDC)), the responsibility of which it is to keep the entire system running safely and reliably. This entails continuously monitoring system conditions and managing system resources as the situation requires. These activities are automated by Supervisory Control and Data Acquisition (SCADA) systems combine remote sensing of system conditions with remote control over operations. For example, control center SCADA system controls key generators through automatic generator control (AGC), and can change the topology of the transmission and distribution network by remotely opening or closing circuit breakers. This monitoring and control is enabled by fiber-optic based.

2-6: General Requirements for AC Interconnection

AC interconnection usually provides the greatest interconnection benefits, except in certain cases for which DC is the preferred option. Synchronous interconnection of different systems is, however, technically demanding. At a general level, the first requirement is that the systems share the same nominal frequency, (50 Hz in Sudan). Then, they must regulate frequency so that they achieve and remain in synchronism. They must also interconnect at a common voltage level [4]. Other, more specific technical issues are discussed in the remainder of this chapter.

2-7: Transmission Issues

For proper operation without create any operational problem the transmission line must operate within the following limits:

- **Thermal limits:**

The flow of electrical current in a conductor causes heating of the conductor. Thermal limits, is the maximum amount of current over a specified period that a transmission line can conduct before it sustains permanent damage by overheating or violates public safety ground clearance requirements due to conductor sag [5].

- **Voltage limits:**

Adequate voltage must be maintained on the transmission systems at all times, including during and after a system contingency (facility outage). As electricity is transmitted along a transmission line, resistive and reactive power losses are incurred and a voltage drop occurs. As an increasing amount of electricity is transferred, resistive losses increase and increasing amounts of reactive power are required to support system voltages [5].

- **Stability limits:**

A basic advantage of reliable system design is that the interconnected systems should be capable of surviving disturbances, coincident with safe maximum electric power transfers, through the transient and dynamic time periods (from milliseconds to several minutes, respectively) [5].

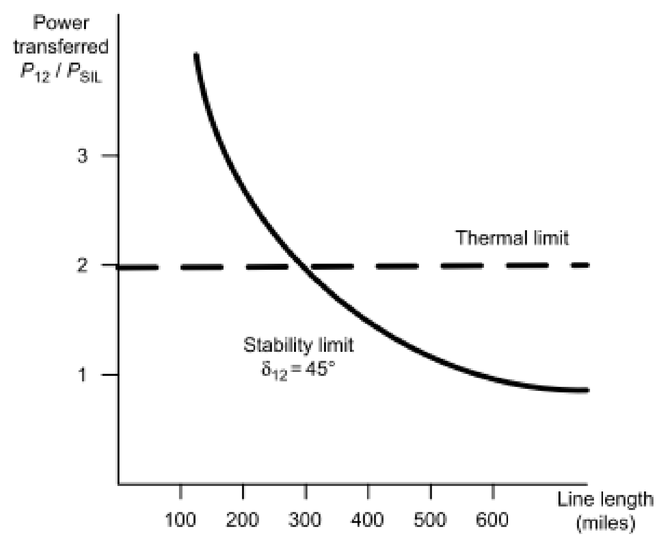

Figure 2.2: Thermal and stability limits.

Figure 2.2 shows the stability limit and thermal limit as a function of length for a hypothetical transmission line. The label P_{12}/P_{SIL} is a measure of the real power transmitted between the two ends of the line, expressed as a ratio of the actual power and the surge impedance loading, which is a characteristic of a given line.

- **Security:**

Security describes how many things can go wrong before service is actually compromised. A system in a secure operating state can sustain one or several contingencies, such as a transmission line going down or a generator unexpectedly going off-line, and continue to function without interruption, by transitioning into a new configuration in which the burden is shifted to other equipment (the load on other lines and/or generators is suddenly increased). Such a transition also requires transient stability, which, in the most general analysis of security, is assumed as given: the focus here is not on whether the system is capable of making a smooth transition to an alternative configuration, but on whether such alternatives exist at all [3].

2-8: Power Flow

The power-flow study, or load-flow study, is a numerical analysis of the flow of electric power in an interconnected system. A power-flow study usually uses simplified notation such as a one-line diagram and per-unit system, and focuses on various aspects of AC power parameters, such as voltages, angles, real power and reactive power. It analyzes the power systems in normal steady-state operation.

Power-flow or load-flow studies are important for planning future expansion of power systems as well as in determining the best operation of existing systems. The principal information obtained from the power-flow study is the magnitude and phase angle of the voltage at each bus, and the real and reactive power flowing in each line. They also necessary for planning, operation, economic scheduling and exchange of power between utilities and required for many other analyses such as transient stability and contingency studies [6].