CHAPTER THREE

Technical Solutions and Options for Transmission Line Enhancement

3-1: Problem Formulation

The problem formulation for total power transfer capability used to determine the maximum power that can be transferred from a specific set of generators in source area to loads in sink area within real and reactive power generation limits, line flow limits, voltage limits, stability limits. Some FACTS device is used to enhance the load-ability of the transmission line, control bus voltage, reactive power injection, stability control, oscillation damping and unbalanced compensation [7]. An important issue to study stability limit is to study the relation between line impedance and voltage at end-point of radial feeder, consider a two bus system as shown below.

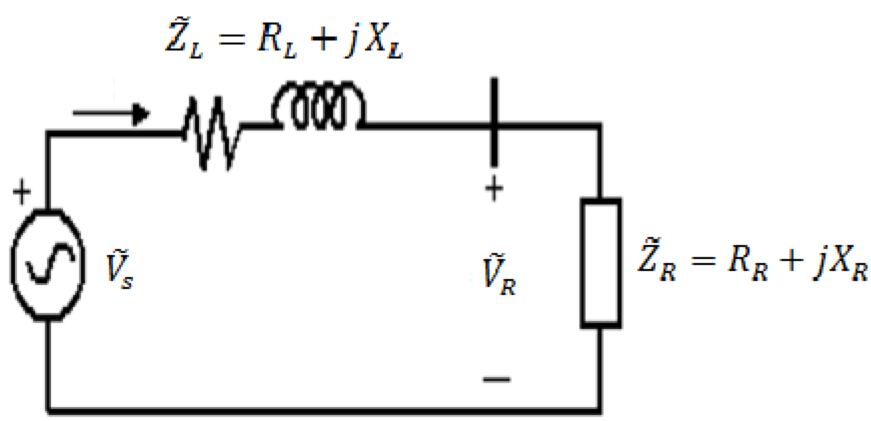


Figure 3.1: A small power system.

The equivalent transmission line impedance is:

$$\tilde{Z}_L = R_L + jX_L = Z_L\angle\theta_L \quad (3.1)$$

The equivalent receiving-end impedance is:

$$\tilde{Z}_R = R_R + jX_R = Z_R\angle\theta_R \quad (3.2)$$

Hence

$$\tilde{Z}_{ratio} = \frac{\tilde{Z}_L}{\tilde{Z}_R} = \frac{|Z_L|}{|Z_R|}\angle(\theta_L - \theta_R) \quad \text{(3.3)}$$

Hence the receiving-end voltage according to $\tilde{V}_S = 1\angle 0^o$

$$\tilde{V}_R = \frac{1}{1+Z_{ratio}\angle(\theta_L-\theta_R)} \quad \text{(3.4)}$$

The transmission line impedance is fixed for a given line. Therefore Z_{ratio} decreases as the load impedance increases. The maximum power occurs when the load and line impedances are same. The power decreases after that and the voltage monotonically decreases.

$$P_R = \frac{2Z_{ratio}^2(1+\cos(\theta_L-\theta_R))}{1+Z_{ratio}^2+Z_{ratio}\cos(\theta_L-\theta_R)} \quad \text{(3.5)}$$

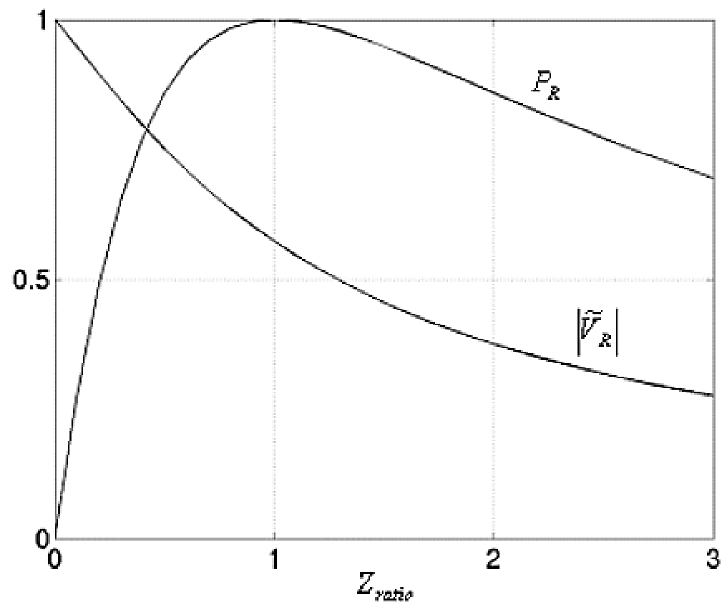


Figure 3.2: Representation of relation between Z_{ratio} and amount of power transfer and receiving end voltage.

3-2: Power-Voltage (PV) Characteristic for Radial Line

Corresponding to a load of $P_R + jQ_R$ at the receiving end, we have:

$$\tilde{I}_R = \frac{P_R - jQ_R}{\tilde{V}_R^*} \quad \text{(3.6)}$$

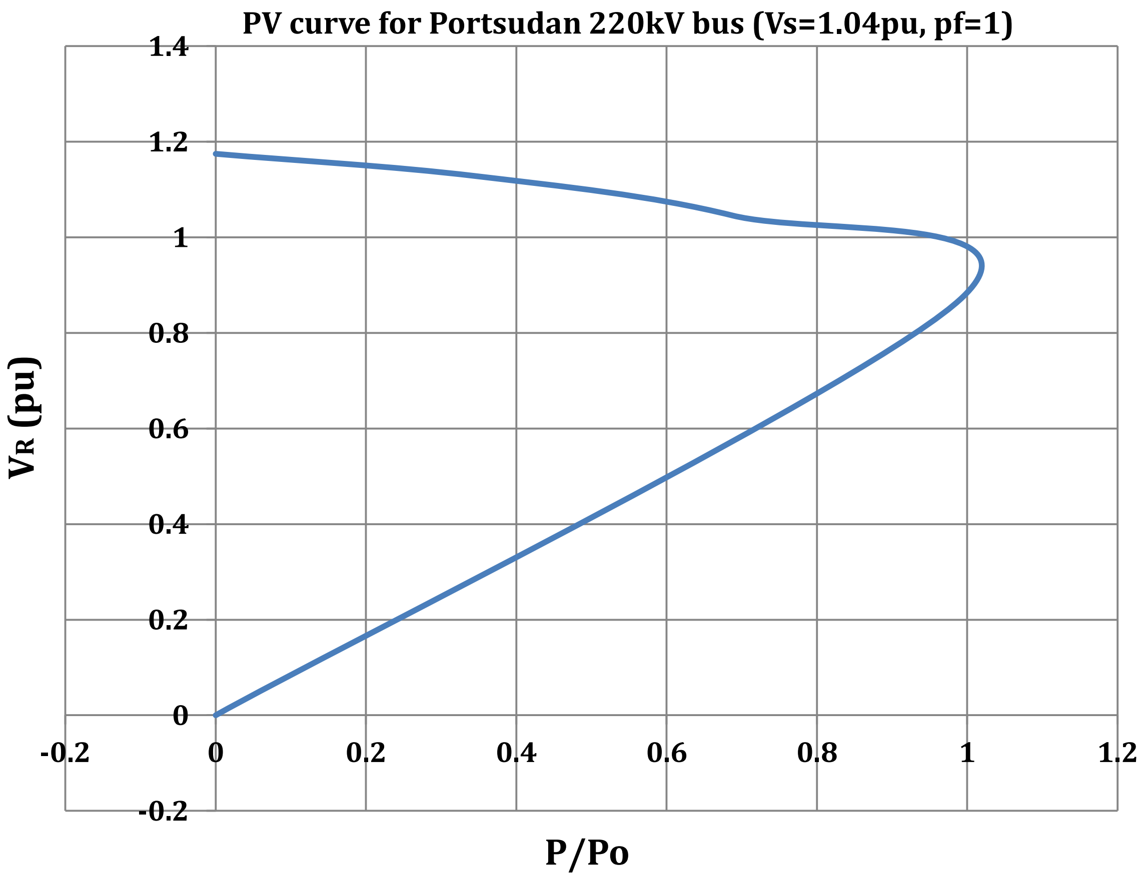
The voltage in sending end will be:

$$\tilde{V}_s = \frac{\tilde{V}_R + Z_C\tilde{I}_R}{2} e^{\gamma l} + \frac{\tilde{V}_R - Z_C\tilde{I}_R}{2} e^{-\gamma l} \quad \text{...} (3.7)$$

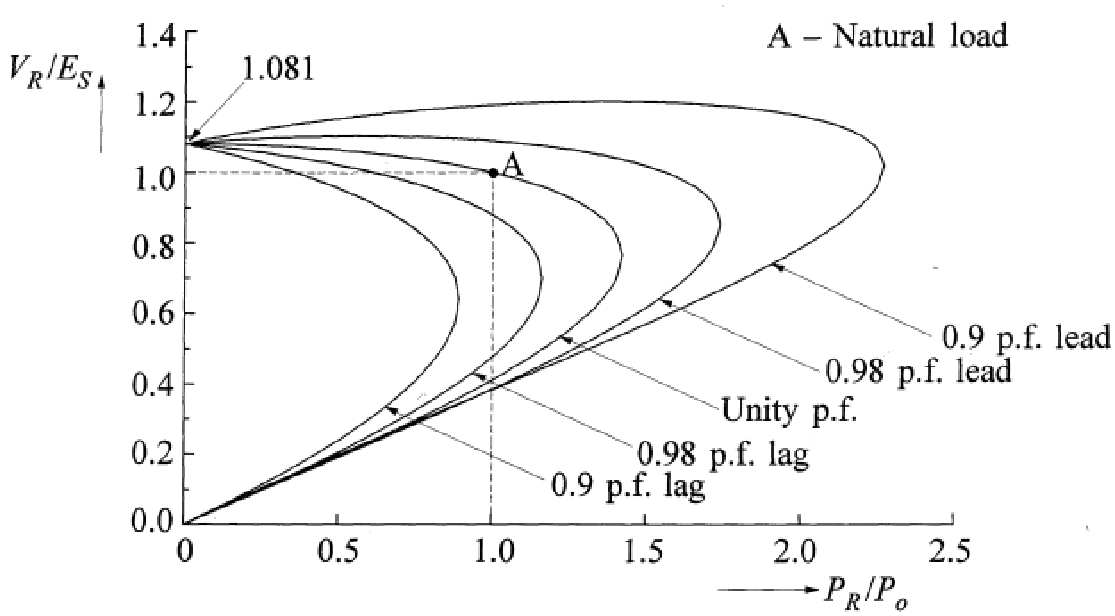
Re-arranging equation 3.7, sending end voltage will be:

$$\tilde{V}_s = \tilde{V}_R \frac{e^{\gamma l} + e^{-\gamma l}}{2} + Z_C\tilde{I}_R \frac{e^{\gamma l} - e^{-\gamma l}}{2} \quad \text{...} (3.8)$$

Where $\gamma \equiv$ Propagation constant $= \sqrt{zy}$ and $l \equiv$ is the line length in km. we can easily plot a curve between receiving end power and receiving end voltage at specified power factor and sending end voltage.



(a)



(b)

Figure 3.3: (a) PV characteristic for ATB220kV-POR220kV radial line (Po =128MW), (b) PV characteristic sample lossless radial line with a different power factor (Vs = 1 pu).

Through the above Figure 3.3 its clear that whenever the nature of the load is to be good power factor or capacitive the transmission line capacity to be increase.

3-3: System Studied Description

The Sudan national grid (also called NEC grid) system is used in this thesis to demonstrate the effect of FACTs, reconfiguration scenarios to increase Available Transmission Capacity (ATC) of Atbara-Portsudan transmission line. Data of the system can be accessed in appendix (A). The simulation software used is NEPLAN. Only the thermal limit of transmission lines, line loading and voltage magnitude and voltage angle limit of each bus are considered. The voltage magnitude limit in transmission level is to be within (±5% for 500kV level, ±5% for 220kV, ±7% for 110kV level).

The transmission line studied is situated between Atbara and Portsudan in Sudan. The 3-phase, 220kV, 449 km long transmission line having a load of 82 MW in peak of July 3rd 2016. The transmission line having a resistance of 0.076 Ω/km, reactance of 0.403 Ω/km and capacitance of 9.02 nF/km. The transmission line is fed from Atbara 220kV bus. Figure 3.4 below shows a part of Sudan National Grid represent the case studied.

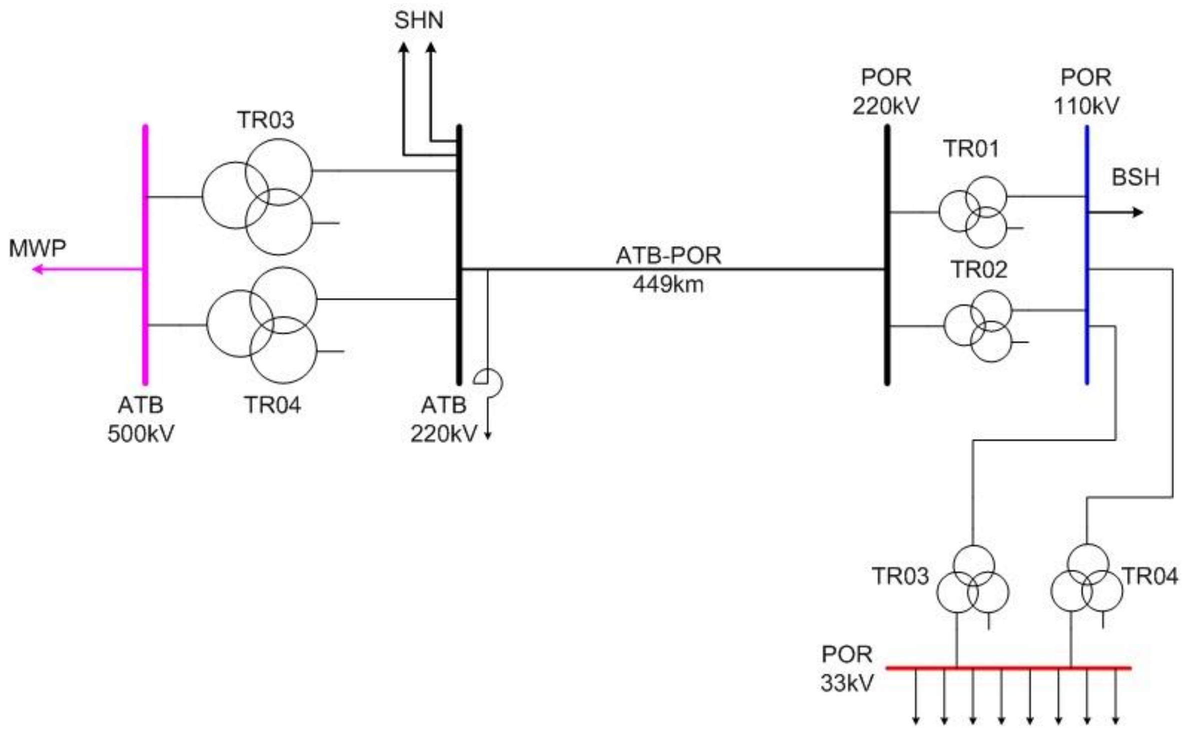


Figure 3.4: Part of Sudan National Grid.

3-4: Arranging of 220kV Transmission Line

Table 3.1, gives the all 220 kV transmission line arranged according to official reactance, while Table 3.2 shows the transmission line arranged according to active power losses during peak load.

Table 3.1: 220kV transmission lines ranked according to line reactance.

LINE	Length (km)	R (Ω/km)	X (Ω/km)	C (uF/km)	R (Ω)	X (Ω)	Z (Ω)
ATB-POR	448.92	0.076	0.403	0.00902	34.11792	180.9148	184.1037
ROS-SNG	178	0.076	0.403	0.00902	13.528	71.734	72.99845
WAW-WHL	205	0.067	0.302	0.01306	13.735	61.91	63.41528

DEB-DON	139.38	0.076	0.403	0.00902	10.59288	56.17014	57.16025
MWT-DEB	139.3	0.076	0.403	0.00902	10.5868	56.1379	57.12744
RBK-RNK	172.8	0.067	0.302	0.01306	11.5776	52.1856	53.45444
ROS-RNK	172.8	0.067	0.302	0.01306	11.5776	52.1856	53.45444
DON-WAW	166	0.067	0.302	0.01306	11.122	50.132	51.35091
SHN-ATB	140	0.067	0.302	0.01306	9.38	42.28	43.308
UMR-OBD	126	0.067	0.302	0.01306	8.442	38.052	38.9772
FRZ-SHN	115	0.067	0.302	0.01306	7.705	34.73	35.57443
SNJ-MAR	84	0.076	0.403	0.00902	6.384	33.852	34.44871
GDF-HWT	110	0.067	0.302	0.01306	7.37	33.22	34.02771
MSH-RBK	100	0.067	0.302	0.01306	6.7	30.2	30.93429
JAS-MSH	100	0.067	0.302	0.01306	6.7	30.2	30.93429
HWT-SNG	90	0.067	0.302	0.01306	6.03	27.18	27.84086
RBK-TND	84	0.067	0.302	0.01306	5.628	25.368	25.9848
GAD-NHS	80.7	0.067	0.302	0.01306	5.4069	24.3714	24.96397
MAR-NHS	60.3	0.076	0.403	0.00902	4.5828	24.3009	24.72925
TND-UMR	78.3	0.067	0.302	0.01306	5.2461	23.6466	24.22155
GDF-SHK	75.12	0.067	0.302	0.01306	5.03304	22.68624	23.23784
KSL-GRB	74.5	0.067	0.302	0.01306	4.9915	22.499	23.04604
SNG-SNJ	50	0.076	0.403	0.00902	3.8	20.15	20.50518
GRB-SHK	62.54	0.067	0.302	0.01306	4.19018	18.88708	19.3463
GAR-IBA	60	0.067	0.302	0.01306	4.02	18.12	18.56057
KLX-GAD	43	0.076	0.403	0.00902	3.268	17.329	17.63446
GRB-HLF	48.87	0.067	0.302	0.01306	3.27429	14.75874	15.11759
MWP-MWT	34.55	0.076	0.403	0.00902	2.6258	13.92365	14.16908
MWP-DON	34.55	0.076	0.403	0.00902	2.6258	13.92365	14.16908
ARM-KSL	43.87	0.067	0.302	0.01306	2.93929	13.24874	13.57087
MRK-GAM	37	0.067	0.302	0.01306	2.479	11.174	11.44569
JAS-GAM	37	0.067	0.302	0.01306	2.479	11.174	11.44569
JAS-GAD	36	0.067	0.302	0.01306	2.412	10.872	11.13634
KBA-FRZ	34	0.067	0.302	0.01306	2.278	10.268	10.51766
KBA-IBA	30	0.067	0.302	0.01306	2.01	9.06	9.280286
MRK-MHD	21	0.067	0.302	0.01306	1.407	6.342	6.4962
IBA-KLX	14	0.067	0.302	0.01306	0.938	4.228	4.3308
GAR-FRZ	5	0.067	0.302	0.01306	0.335	1.51	1.546714

Table 3.2: 220kV transmission lines ranked according to line losses.

LINE	Length (km)	R (Ω/km)	X (Ω/km)	C (uF/km)	B (uS/km)	LOSS (MW)
ATB-POR	448.92	0.076	0.403	0.00902	2.834	6.0565

MSH-RBK-1	100	0.067	0.302	0.01306	4.103	3.781
JAS-MSH-1	100	0.067	0.302	0.01306	4.103	3.667
MWT-DEB	139.3	0.076	0.403	0.00902	2.834	2.0438
KBA-IBA-1	30	0.067	0.302	0.01306	4.103	2.2237
SNJ-MAR-1	84	0.076	0.403	0.00902	2.834	1.3704
GAR-IBA-1	60	0.067	0.302	0.01306	4.103	1.7769
ROS-SNG-1	178	0.076	0.403	0.00902	2.834	1.2391
SNG-SNJ-1	50	0.076	0.403	0.00902	2.834	1.0304
MRK-MHD-1	21	0.067	0.302	0.01306	4.103	1.3417
MWP-MWT	34.55	0.076	0.403	0.00902	2.834	0.9455
DEB-DON	139.38	0.076	0.403	0.00902	2.834	0.8442
MRK-GAM-1	37	0.067	0.302	0.01306	4.103	0.7132
SHN-ATB-1	140	0.067	0.302	0.01306	4.103	0.6703
GDF-SHK-1	75.12	0.067	0.302	0.01306	4.103	0.525
FRZ-SHN-1	115	0.067	0.302	0.01306	4.103	0.5076

3-5: Identification of Weakest Bus and Transmission Line:

In open literature there are serval effective methods for identification of weak bus-bar or transmission line.

3-5-1: Fast voltage stability index (FVSI)

Identification of weakest bus is for objective to identify the best location for reactive power compensation for the improvement of static voltage stability margin of the system. In this study a line based voltage stability index called Fast Voltage Stability Index (FVSI) is utilized as the indicator. The FVSI can be calculated for any of the lines of the network and depends, essentially of reactive power. The value of line index that is closed to the unity indicates that the respective line is closed to its stability limit. The calculated FVSI can also be used to determine the weakest bus. The determination of weakest bus is based on the maximum reactive power loading. The most critical bus or the weakest bus in system corresponds to the bus with smaller maximum reactive power loading. Figure 3.5 illustrates a single line of interconnected network where the FVSI is derived from.

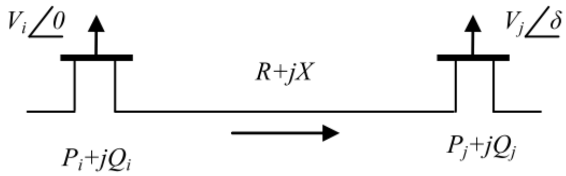


Fig 3.5: Model of simple branch for voltage stability research

By taking the sending bus (bus i) as the reference, the voltage of receiving end V_j can be calculated by:

$$V_j^2 - \left[\frac{R}{X}sin\delta + cos\delta\right]V_iV_j + \left[X + \frac{R^2}{X}\right]Q_j = 0 \ \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \ (3.9)$$

In equation (3.9), the condition for obtaining the real roots of V_j is that the discriminate must be set greater than or equal to 1, that is:

$$\frac{4Z^2Q_jX}{V_i^2(Rsin\delta + Xcos\delta)} \leq 1 \ \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \ (3.10)$$

Considering the angle difference δ is very small, i.e. δ ≈ 0, the index is formulated as:

$$FVSI = \frac{4Z^2Q_j}{V_i^2X} \leq 1 \ \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \ (3.11)$$

Where: Z is the line impedance, X is the line reactance, V_i is the voltage at the sending end and Q_j is the reactive power at the receiving end. The value of the index which is closed to unity indicates that the respective line is closed to its stability limit [8].

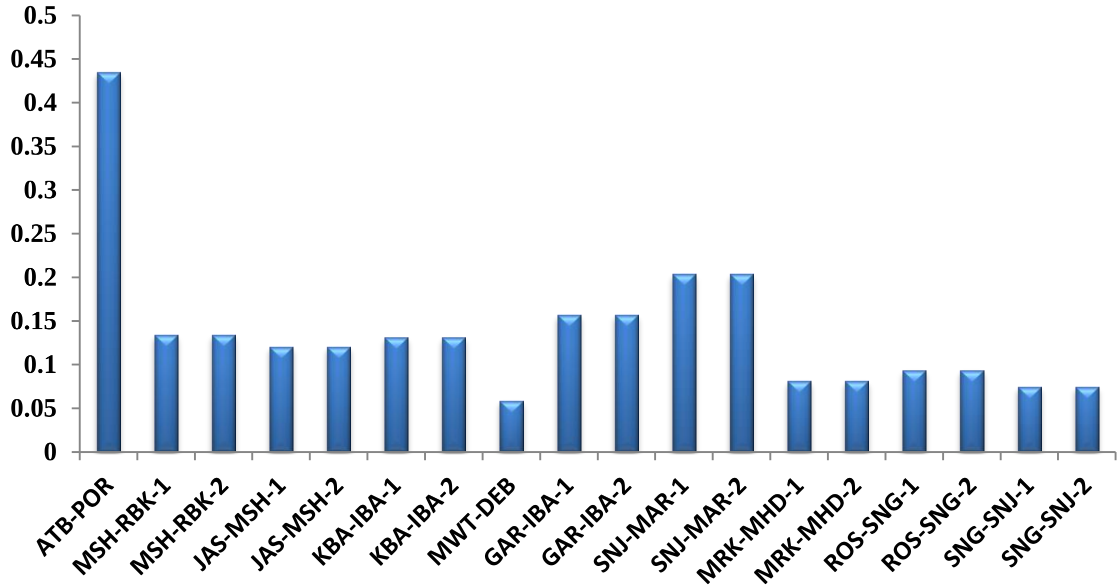


Figure 3.6: 220kV transmission line ranked according to FVSI.

3-5-2: Line stability index L_{mn}

This stability criterion is used to find the stability index for each line connected between two bus-bars in an interconnected network. This voltage stability criterion is based on a power transmission concept in a single line. Stability criterion is developed considering a single line of a network.

$$L_{mn} = \frac{4XQ_j}{(V_i \sin(\theta - \delta))^2} \quad \text{.......} \quad (3.12)$$

Where: θ is the line impedance angle; δ is the angle difference between the sending end and the receiving end voltage; X is line reactance; Q_j is the reactive power flow at the receiving end and V_i is the sending end voltage.

The system is said to be stable, in the sense of transmission lines, as long as L_{mn} remains much less than 1; and approaches 1 towards the point of bifurcation. The most critical line connecting the weak buses in the system can be easily identified from the value of L_{mn} closest to 1 [9].

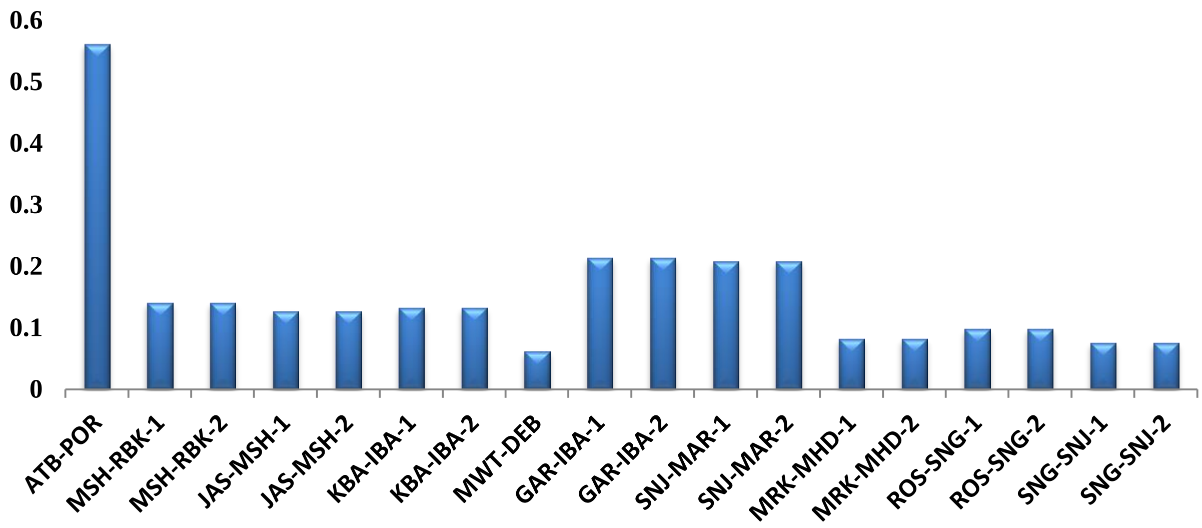


Figure 3.7: 220kV transmission line ranked according to L_{mn}.

3-6: Enhancing Long Transmission Line Load-ability

There are some methods to improve transmission line performance regarding voltage stability, line losses and line load-ability such as:

1. Line reconfiguration.
2. FACT's devices.
3. Distribution of generation.

3-6-1: Line reconfiguration

Reconfiguration of transmission line is one of old option used for improve line performance such as increase line capacity and reduce voltage drop. The following is some of the techniques used for reconfiguration of transmission lines:

- Phase reordering: this method is used rearranging of three phases to get new line parameter (L, C) and then reduce characteristic impedance and increase power transfer [10].
- Conductor bundling: a bundle conductor is a conductor made up of two or more sub-conductors and is used as one phase conductor to achieving of two

fold advantage of decreasing the series inductance, and increasing shunt capacitance of transmission line [10].

- Use of double circuit: to increase a transmission line load-ability, efficient use of transmission towers and security.

3-6-2: FACT's controllers:

The rapid development of power electronics technology provides exciting opportunities to develop new power system equipment for the betterment of the existing systems. In last two decades number of power devices have been proposed and implemented and put under the term Flexible AC Transmission System (FACTS). FACTS devices can be effectively used for power flow control, voltage regulation, improvement of power system stability, minimization of losses, and reduction of harmonics. There are two main objectives of FACTS devices which are increasing the power transfer capability of transmission system and restricting power flow over designated lines. In current power market, control of active and reactive power flow in a transmission line becomes a necessity aspect. Entry of more power generation companies has increased the need for enhanced secured operation of power systems, which are facing the threat of voltage instability leading to voltage collapse and also for minimization of active power loss leading to reduction in electricity cost. Also the stable operation of the power system networks revolves around improving voltage profile, minimizing power transmission loss. Power system operators ensure the quality and reliability of supply to the customers by employing system compensation and load side compensation for maintaining the load bus voltages in their permissible limits.

FACTS devices can be effectively used for the control of power flows, providing the possibility of operating the transmission grid with increased flexibility and efficiency. The comprehensive devices that originate from the FACTS technology are Static Var Compensator (SVC), Thyristor Controlled Series

Compensator (TCSC), Static Synchronous Compensator (STATCOM) and Unified Power Flow Controller (UPFC). To achieve good performance of SVC and TCSC, proper placement of the FACTS devices becomes a vital task [11]. In this case the SVC was already installed in Portsudan 110kV bus through (33/110 kV) transformer.

A. Modeling of SVC:

The Static Var Compensator (SVC) generates or absorbs shunt reactive power at its point of connections. SVC is also used primarily in power systems for voltage control as either an end in itself or a means of achieving other objectives, such as system stabilization. SVC is a general term for a thyristor-controlled or thyristor-switched reactor, and/or thyristor-switched capacitor or combination. SVC is based on thyristor without the gate turn-off capability. It includes separate equipment for leading and lagging vars; the thyristor controlled or thyristor-switched reactor for absorbing reactive power and thyristor-switched capacitor for supplying the reactive power [11].

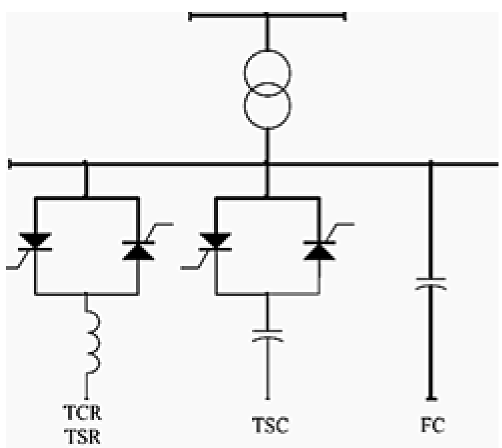


Figure 3.8: A schematic diagram of SVC.

The SVC regulates voltage at its terminals by controlling the amount of reactive power injected into or absorbed from the power system. When system voltage is low, the SVC generates reactive power (SVC capacitive). When system voltage is high, it absorbs reactive power (SVC inductive). SVC principle is supplying a varying amount of leading or lagging VAR to the lagging or leading system. The reactor power of SVC is [12]:

$$Q_{SVC} = \frac{V^2(X_C(2\pi - \alpha + sin2\alpha) - \pi X_L)}{\pi X_c X_L} \quad \ldots\ldots (3.13)$$

Where V is the rms voltage, X_L=ωL is the fundamental frequency reactance of the reactor; ω = 2πf, and α is the gating delay angle.

Generally, by changing the firing angle α, the fundamental reactance X_L of the reactor is changed. Conventional thyristor controlled compensator, the SVC, presents variable reactive impedance to, and thus acts indirectly on, the transmission network. The SVC functions as a controlled shunt reactive admittance that produces the required reactive compensating current. Frequency susceptance controlled by the conduction angle according to the law [12]:

$$B_L(\sigma) = \frac{\sigma - \sin(\sigma)}{\pi X_L} \quad \ldots\ldots (3.14)$$

Where σ is the conduction angle, related to α by the equation ($\alpha + \frac{\sigma}{2} = \pi$), Thus the total susceptance of SVC is:

$$B_{SVC} = B_{TSC} - B_{TCR} = B_C \frac{n^2}{n^2 - 1} - B_L(\sigma) \quad \ldots\ldots (3.15)$$

Where n is the per-unit natural frequency ($\omega_n = \frac{1}{\sqrt{LC}}, n = \sqrt{\frac{X_C}{X_L}}$).

B. Modeling of TCSC:

Thyristor controlled series compensator (TCSC) device is a series compensator to govern the power flow by compensating the reactance of transmission line. Both capacitive and inductive reactance compensation are possible by proper selection of capacitor and inductor values of the TCSC device which can be realized through reactance equation. A TCSC which consist of a series compensating capacitor (C) shunted by a Thyristor controlled reactor (TCR).

TCR is a variable inductive reactor (X_L (α)) tuned at firing angle α. The variation of X_L with respect to α can be given as [13]:

$$X_L(\alpha) = X_L \frac{-\pi}{\pi - 2\alpha - \sin(2\alpha)} \quad \text{(3.16)}$$

Where $X_L=\omega L$ is the reactance of the inductor, α is the firing angle, $X_L(\alpha)$ is the effective reactance of the inductor at firing angle.

$$X_C = \frac{1}{2\pi f C} \quad \text{(3.17)}$$

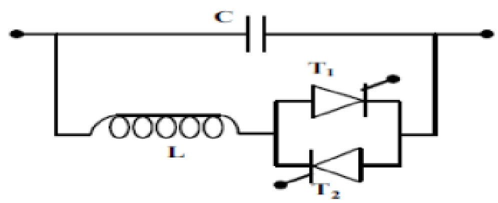


Figure 3.9: A schematic diagram of TCSC device.

For the variation of α from 90° to 180°, $X_L(\alpha)$ varies from infinity to actual reactance (X_L). This controlled reactor is connected across the series capacitor, so that the variable capacitive reactance, as Figure 3.9 is possible across the TCSC which modify the transmission line impedance. There exists a steady state relationship between the firing angle α and the reactance X_{TCSC}. This relationship can be described by the following equation [13].

$$X_{TCSC}(\alpha) = \frac{X_C X_L(\alpha)}{X_L(\alpha) - X_C} \quad \text{(3.18)}$$

The effective reactance (X_{TCSC} (α)) of TCSC operates in three region, inductive region, capacitive region and resonance region. Inductive region starts increasing from X_C value to infinity and decreasing from infinity to $X_L \| X_C$ for capacitive region. Between the two regions, resonance occurs [13].

- $90^o \leq \alpha \leq \alpha_{Llim}$: Thyristor valve bypass mode (inductive region operation).
- $\alpha_{Llim} \leq \alpha \leq \alpha_{Clim}$: Thyristor valve blocked mode (resonance region for inhibited operation).
- $\alpha_{Clim} \leq \alpha \leq 180^o$: Vernier control mode (capacitive region operation).

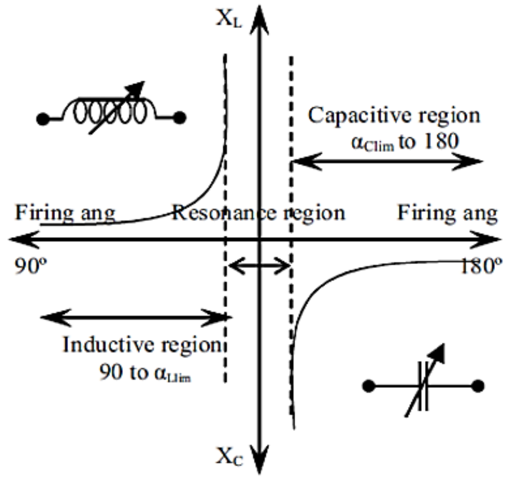


Figure 3.10: Regions of TCSC operation.

The effective series transmission impedance is given by:

$$X_{eff} = (1-k)X_{line} \quad (3.19)$$

Where k is the degree of series compensation;

$$k = \frac{X_{TCSC}(\alpha)}{X_{line}} \quad (3.20)$$

While choosing k, 100% compensation should not be provided to avoid series resonance in transmission line. Practically up to 75% of series compensation is chosen for line reactance compensation.

3-6-3: Distribution of generation

Distributed generation, is the distributed energy resources. Conventional power stations, such as coal-fired, gas and nuclear powered plants, as well as hydroelectric dams and large-scale solar power stations are centralized and often require electricity to be transmitted over long distances. By contrast, distributed energy resources systems are decentralized modular and more flexible technologies that are located close to the load they serve. These systems can comprise multiple generation and storage components. In this instance they are referred to as Hybrid power systems.

Some countries define distributed generation on the basis of the voltage level, whereas others start from the principle that distributed generation is connected to circuits from which consumer loads are supplied directly. Other countries define distributed generation as having some basic characteristic (for example, using renewables, co-generation).

The IEEE defines distributed generation as the generation of electricity by facilities that are sufficiently smaller than central generating plants so as to allow interconnection at nearly any point in a power system.

Distributed generation (DG) takes place on two-levels: the local level and the end-point level. Local level power generation plants often include renewable energy technologies that are site specific, such as wind turbines, geothermal energy production, solar systems (photovoltaic and combustion), and some hydro-thermal plants. These plants tend to be smaller and less centralized than the traditional model plants. They also are frequently more energy and cost efficient and more reliable. Since these local level DG producers often take into account the local context, the usually produce less environmentally damaging or disrupting energy than the larger central model plants [14].

The specific areas of potential benefits covered in this study include:

- Increased electric system reliability.
- An emergency supply of power.
- Reduction of peak power requirements.
- Offsets to investments in generation, transmission, or distribution facilities that would otherwise be recovered through rates.
- Provision of ancillary services, including reactive power.
- Improvements in power quality.
- Reductions in land-use effects and rights-of-way acquisition costs.

- Reduction in vulnerability to terrorism and improvements in infrastructure resilience.

Table 3.3: Matrix of distributed generation benefits and services*

	Benefit Categories							
	Energy cost saving	Saving of T&D losses and congestion costs	Deferred generation capacity	Deferred T&D capacity	System reliability benefits	Power quality benefits	Land use effects	Reduced vulnerability
Reduction in peak power requirements	**yes**	**yes**	**yes**	**yes**	**yes**	**yes**	**yes**	**yes**
Provision of ancillary Services: Operation reserve. Regulation. Black start. Reactive power control.	**yes**	**yes**	**yes**	**yes**	**yes**	**yes**	**yes**	**yes**
Emergency power supply.	**yes**	**yes**			**yes**	**yes**		

* T&D: Transmission & Distribution