J. Electrical Systems 20-9s (2024): 2370-2378

[1]Rozina R. Surani

[2]Hitendra B. Vaghela

[3]Nitinkumar R. Prajapati

Reactive Power Control (A Case Study)

Abstract: Power system interconnection is essential for energy reliability and security in power systems. However, the interconnections of many electric generating stations, micro generations, transmission lines, and loads can lead to voltage control and stability issues. Controlling real and reactive power between the lines or towards the load side may solve this issue. In addition to that, existing power transmission lines operate under huge stress and carry power nearer to their thermal limits. Reactive power management is therefore crucial. In this paper, a case study of a high voltage long-distance transmission line is considered in Matlab/Simulink to discuss the issues of voltage control considering various loading conditions, and to regulate the voltage, the FCTCR has been discussed with simulated results and waveforms.

***Keywords*:** Reactive Power, Voltage Control, Flexible AC transmission (FACT devices), Voltage Stability

I. INTRODUCTION

A. Reactive Power Basics

In alternating current (AC) systems, inductors and capacitors are energy storage elements that can store the energy in magnetic ($1/2Li^2$) and electric fields ($1/2Cv^2$). Transformers and Reactors absorb reactive power and Capacitors generate reactive power.

In India, most electric power is generated, transmitted, and consumed by Alternating currents. Active Power ($P=VI\cos\Phi$) or Real Power corresponds to useful work and Reactive power ($Q=VI\sin\Phi$) supports the voltage profile. Control of reactive power is essential for voltage stability and system reliability. Active power can be transported over long distances but reactive power is difficult to transmit (As $X/R > 7$). Therefore, there will be more IX drop in comparison to IR drop. Reactive power support can be given either by a system or at the load point. The capacitor bank is the conventional approach to manage reactive power deficiency at the load point.

Voltage control in an electric power system is important for an efficient and reliable electrical system. Reactive power support is necessary. Reactive power should be injected (leading VARs) whenever voltage drops, and during voltage rise conditions, it should be absorbed (lagging VARs) from the system. A voltage collapse occurs when the system tries to serve much more load than the system can support.

As voltage drops, current must increase to maintain the power supplied, causing the lines to consume more reactive power and the voltage to drop further. If the current increases too much, transmission lines trip or go off-line, overloading other lines and potentially causing cascading failures.

Some generators will automatically disconnect to protect themselves if the voltage drops too low. If the declines continue, these voltage reductions cause additional elements to trip, leading to further reductions in voltage and loss of load. The result is a progressive and uncontrollable decline in voltage, all because the power system is unable to provide the reactive power required to supply the reactive power demand.

B. Transmission line Behaviors and Reactive Power Compensation

Their inductive and capacitive characteristics complicate the reactive-power behavior of transmission lines. At low line loadings, the capacitive effect dominates, and generators and transmission-related reactive equipment must

---

[1] Electrical Engineering, Vishwakarma Government Engineering College Chandkheda Ahmedabad, India. rozina.surani@gmail.com

[2] Electrical Engineering, Vishwakarma Government Engineering College Chandkheda Ahmedabad, India hitenvaghela2015@gmail.com

[3] Instrumentation & Control Engineering, Vishwakarma Government Engineering College Chandkheda Ahmedabad, India nrp.prajapati@gmail.com

absorb reactive power to maintain line voltages within their appropriate limits. On the other hand, at high-line loadings, the inductive effect dominates, and generators, capacitors, and other reactive devices must produce reactive power. The thermal limit is the loading point (in MVA) above which real power losses in the equipment will overheat and damage the equipment. Most transmission elements (e.g., conductors and transformers) have normal thermal limits below which the equipment can operate indefinitely without any damage. These types of equipment also have one or more emergency limits to which the equipment can be loaded for several hours with minimal reduction in the life of the equipment. If uncompensated, these line losses reduce the amount of real power that can be transmitted from generators to loads. Transmission-line capacity decreases as the line length increases if there is no voltage support (injection or absorption of reactive power) on the line (Refer to Fig 1). At short distances, the line's capacity is limited by thermal (I^2R losses) considerations; at intermediate distances, the limits are related to voltage drop; and beyond roughly 300 to 350 miles, stability limits dominate.

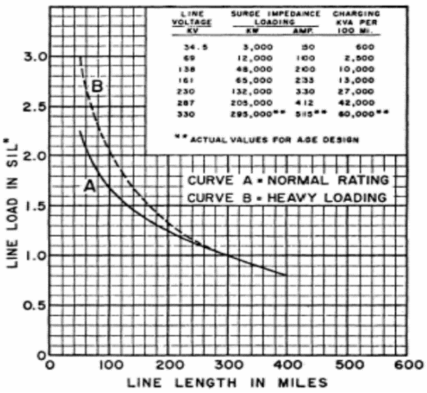
Transmission lines and cables generate and consume reactive power at the same time. The reactive power generation is almost constant, because the voltage of the line is usually constant, and the line's reactive power consumption depends on the current or load connected to the line which is dynamic in nature. So, under heavy load conditions transmission lines consume reactive power, decreasing the line voltage, and under light load conditions – generating reactive power, increasing the line voltage (known as the Ferranti effect).

When reactive power produced by line capacitance is equal to reactive power consumed by line inductance is called natural loading or surge impedance loading (SIL), meaning that the line provides exactly the amount of MVAr needed to support its voltage. The balance point at which the inductive and capacitive effects cancel each other is typically about 40% of the line's thermal capacity. Lines loaded above SIL consume reactive power, while lines loaded below SIL inject reactive power ($V_R > V_S$).

C. Reactive Power Compensation

Normally there are two types of shunt reactors – Line reactors and bus reactors. Line reactor's functionality is to avoid the switching and load rejection over voltages whereas Bus reactors are used to avoid the steady state over voltage during light load conditions. The degree of compensation is decided from an economic point of view between the capitalized cost of compensator and the capitalized cost of reactive power from the supply system over a while. In practice a compensator such as a bank of capacitors (or inductors) can be divided into parallel sections, each switched separately, so that discrete changes in the compensating reactive power may be made, according to the requirements of the load.

- Benefits of reactive power compensation:
  - ➢ New construction of overhead lines can be postponed
  - ➢ Return-on-investment of approximately two years
  - ➢ Easy supply of reactive power wherever needed
  - ➢ Lower reactive power demand of the transmission line during strong load conditions
  - ➢ Less emission of CO2 because of reduced power losses
  - ➢ Optimal workload on overhead lines



LINE VOLTAGE KV	SURGE IMPEDANCE LOADING KW	SURGE IMPEDANCE LOADING AMP.	CHARGING KVA PER 100 MI.
34.5	3,000	50	600
69	12,000	100	2,500
138	48,000	200	10,000
161	65,000	233	13,000
230	132,000	330	27,000
287	205,000	412	42,000
330	295,000**	515**	60,000**

** ACTUAL VALUES FOR AGE DESIGN

Fig. 1 Transmission line loading as a function of line length (St. Clair Curve) [4]

D. *Sources & Sinks of reactive power [1]*

Sources of Reactive Power		**Sink of Reactive Power**
Static	***Dynamic***	
Shunt Capacitors	Synchronous Generators	Transmission lines (Heavily loaded)
Filter banks	Synchronous Condensers	Transformers & Shunt Reactors
Underground cables	FACTS (e.g. SVC, STATCOM)	Loads (Inductive loads)
Transmission lines (lightly loaded)		Synchronous machines
Fuel cells		FACTS (e.g. SVC, STATCOM)
PV systems		Induction generators (wind plants)

E. *Methods of controlling reactive power*

The reactive power in the line can be controlled by the following methods.

Conventional methods

- Automatic generation control
- Excitation control
- Transformer tap changer control
- Phase shifting transformer
- Facts devices

F. *Reactive Power Control through Series and Shunt Capacitor (Voltage Control)*

Series and shunt capacitors in a power system generate reactive power to improve power factor and voltage, thereby enhancing the system capacity and reducing the losses. In series capacitors the reactive power is proportional to the square of the load current, thus generating reactive power when it is most needed whereas in shunt capacitors it is proportional to the square of the voltage. Series capacitor compensation is usually applied for long transmission lines and transient stability improvement. Series compensation reduces net transmission line inductive reactance (Xnet=X_L-X_C). The reactive generation I^2X_C compensates for the reactive consumption I^2X_L of the transmission line. This is the self-regulating nature of series capacitors. At light loads series capacitors have little effect.

G. *Reactive Power Control through FACT's devices:*

Flexible AC transmission systems are new and emerging power electronics-based static controllers that can control capacitive or inductive current from an electrical power system, thereby generating/or absorbing reactive power. As there are no rotating parts; less maintenance requirements, high reliability, and very fast control-response time are some of the benefits of FACT devices. Various FACT devices are available as per their connection in power systems such as Shunt, Series, and combination of shunt and series. SVC-shunt connected; TCSC-series connected variable impedance type FACT devices while STATCOM and SSSC are VSC based FACT devices. Refer to Figure 2 for modeling of FCTCR. If the bus voltage falls below the reference voltage, then SVC will inject the reactive power, and if the voltage of the bus increases, then SVC will absorb it. Hence regulate the bus voltage within limits as the loads are changing. In FCTCR the capacitor is fixed and the TCR current may vary by changing the firing angle of SCRs. If the firing angle increases then the inductive current decreases and vice versa.

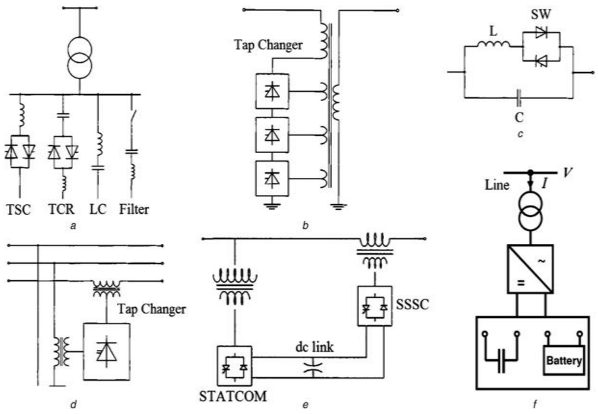


Fig. 2 FACTS Devices [1]

a. SVC b. TCVR c. TCSC d. TCPST e. UPFC f. STATCOM with energy storage

II. CASE STUDY [2]

For lossless transmission lines voltage and current are given by,

$$\bar{V}(x) = \overline{Vs}\cos\beta x - j\,Zo\,\overline{Is}\,sin\,\beta x,$$

$$\bar{I}(x) = \overline{Is}\cos\beta x - j\frac{\overline{Vs}}{Zo}\sin\beta x$$

These equations are used to calculate voltage and current anywhere on a transmission line, at x distance from the sending end, in terms of sending end voltage and sending end current, and the line parameters. Surge impedance is given by, $\sqrt{l/c}$ $\Omega\sqrt{l/c}\,Zo = \sqrt{l}/cZo = \sqrt{l}/c$

$$\beta = \omega\sqrt{lc}\,rad/km$$

$$\beta a = \omega\sqrt{lca}\,Rad/km$$

Where ll is the line inductances in (H/km), cc is the line shunt capacitance in (F/km) of the transmission lines. Here a represents the transmission line length. From eq. we get,

$$\overline{Is} = \frac{\overline{Vs}\,cos\beta a - \overline{Vr}}{jZ0sin\beta a}$$

Power at the sending end is given by,

$$Ps = -Pr = \frac{V^2}{Zosin\beta a}\,sin\delta$$

$$Qs = Qr = V^2cos\beta a - \frac{V^2cos\delta}{Zosin\beta a}$$

Therefore, Surge Impedance Zo=276.4Ω & Surge Impedance Loading (SIL) is given by,

$$Po = \frac{V^2 nom}{Zo} = \frac{(735\text{x}10^3)^2}{276.4} = 1954.5\, MW$$

For this line to operate as a symmetrical line, that is, Vs= Vr =735Kv,

$$Ps = \frac{Vs}{Zosin\beta a} sin\delta = \frac{735^2}{276.4\sin\left[(\omega\sqrt{lc})800\right]} sin\delta$$

$$= 2298.5 \sin\delta\, MW$$

$$= 1.176 Posin\delta\, MW$$

Table 1: Matlab/Simulink Model Parameters

Matlab/ (Simulink) Simulation Model Parameters:	
Transmission line voltage	735 KV
Line Inductance	0.932 mH/km
Line Capacitance	12.2 nF/km
Length of transmission line	800 km

Table 2 Calculated Pr and Qr for different loading conditions

Loading Condition	**Load Angle(δ)** **δ(degree)**	**Active Power (MW) Calculated as per the formula**	**Reactive Power (MVAR) Calculated as per the formula**
Lightly loaded Load <SIL	10	452.77	-842.0142
	20	891.79	-724.3804
	30	1303.71	-532.2996
	40	1676.01	-271.6080
Load = SIL	**48.56**	**1954.55**	**0.0000**
Heavily loaded Load > SIL	50	1997.39	49.7734
	60	2258.09	422.0796
	70	2450.17	833.9982
	80	2567.80	1273.0134
	90.00	2607.41	1725.7858

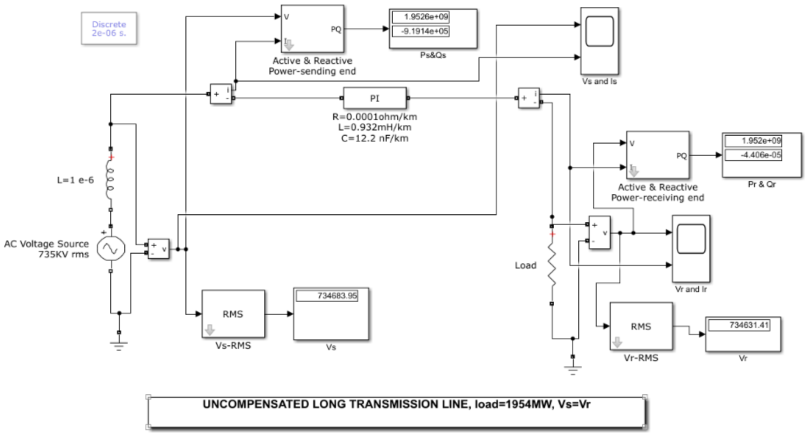


Fig. 3 Simulink Model 1: Uncompensated π section Transmission line

III. WAVEFORMS

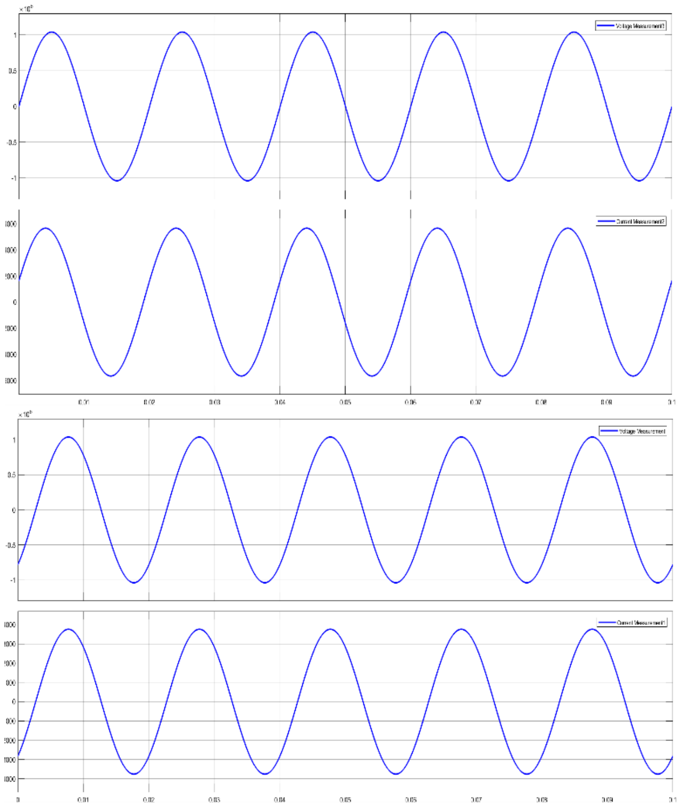


Fig. 4 Waveforms a and b: Sending end Voltage and Current waveforms, Receiving end Voltage and Current waveforms

IV. SIMULATED RESULTS

Table 3. Sending and receiving end voltage, current, active power and reactive power

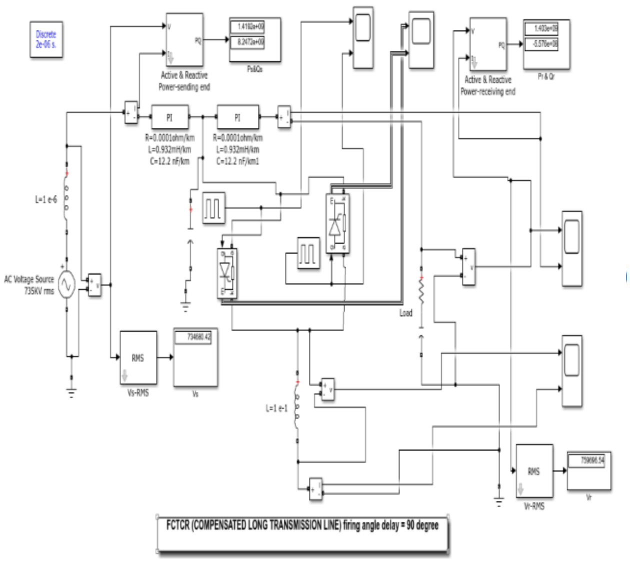
Vs KV	Is KA	Ps MW	Qs Mvar	Vr KV	Ir KA	Pr MW	Qr Mvar	Loading condition
734.7	265.8	1952.6	-93.863	734.6	265.7	1952	$7.262*10^{-12}$	Load = SIL
734.7	217.0	1579	221.81	614.5	261.3	1579	295.2	Load < SIL
734.7	729.7	3118.6	-4360.5	1928	341.2	3116	-5793	Load > SIL

Table 4 Variation of receiving end active and reactive power as per SIL

Load Angle δ in degree	Loading condition	Pr (Real Power) (MW)	Qr (Reactive Power) (Mvar)
48.56	Load = SIL	1954	0.00
10	Load < SIL	452	-841.85 (negative)
60	Load > SIL	2258.28	422.34

Table 5 FCTCR control with firing angle delay

Vs	**Ps**	**Qs**	**Vr-KV**	**Pr-**	**Qr-Mvar**	**Load**	**Firing angle delay**
734.7	1419	8249	759	1403	-568	Load < SIL	90
734.7	2471	9234	767	2459	459	Load > SIL	90
FCTCR is used to control Vr (Compensated transmission line)							



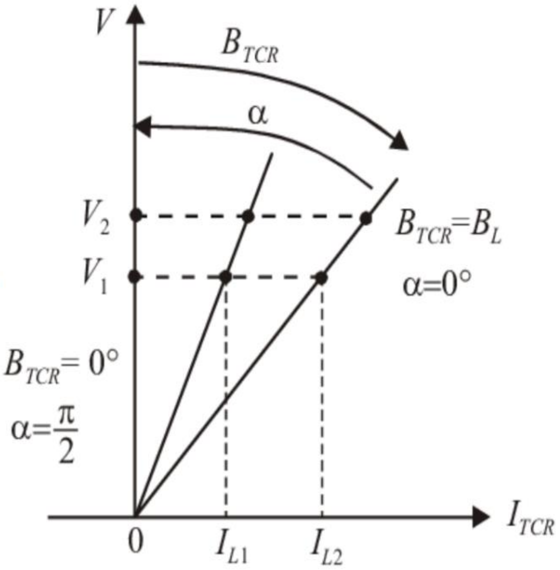


Fig. 5 Simulink Model 2 for LOAD<SIL,

Fig. 6 Voltage Current Characteristics for an open loop controlled TCR [7]

FCTCR is used to compensate leading reactive power

Note: (Two π-sections lines are used: Midpoint is used for FCTCR)

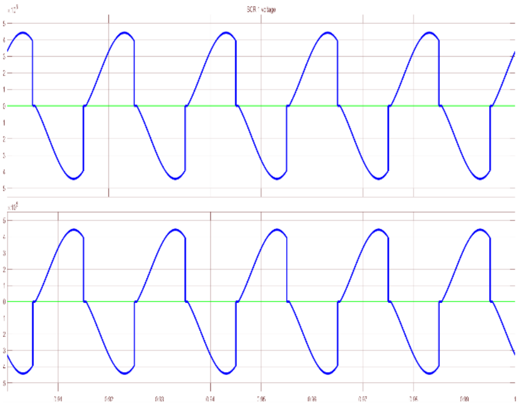
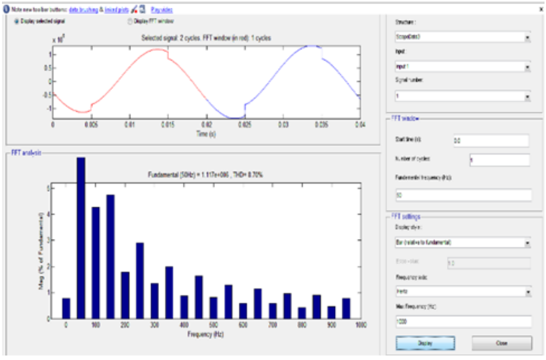


Fig. 7 Waveforms c: SCR1 and SCR2 Waveforms



Selected signal: 2 cycles. FFT window (in red): 1 cycles

Fundamental (50Hz) = 1.117e+006 , THD= 8.70%

Structure: ScopeData1

Input: input 1

Signal number: 1

Number of cycles: 1

Fundamental frequency (Hz): 50

Display style: Bar (relative to Fundamental)

Frequency axis: Hertz

Max Frequency (Hz): 1000

Fig. 8 Waveform d: TCR Voltage and Current Waveforms

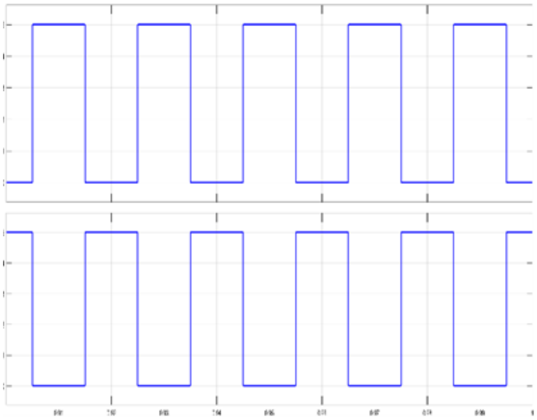


Fig. 9 FFT Analysis window

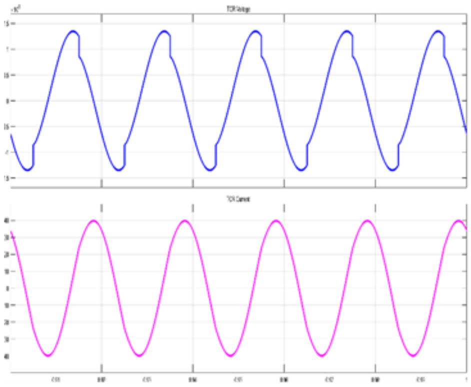


Fig. 10 Pulse generator 1 and Pulse generator 2 waveforms

V. CONCLUSION

Reactive power control is required to maintain rated voltages at every node in long-distance high-voltage transmission lines. In this research paper, the detailed case study has been modelled in Matlab/Simulink to find the receiving end voltage for different loading conditions. When the connected load on a transmission line is equal to surge impedance loading, sending end voltage V_s and receiving end voltage V_r both are equal. When the connected load on a transmission line is below surge impedance loading, V_r is greater than $V_{s,}$ and the shunt inductor should be connected to consume excess reactive power. When the connected load on a transmission line is more than surge impedance loading then V_r drops and the Shunt capacitor should be connected to increase voltages. FCTCR is used to compensate the transmission line when the connected load is less than SIL and vice versa. FFT analysis is done which shows total harmonic distortion THD is less than 9%. Recent developments in power electronics switching devices can be used in FACTs devices to solve the reactive power control issues in high voltage long-distance AC transmission lines to enhance power transfer capability.

DECLARATION

The authors declare no conflicts of interest. This research did not receive any financial support.

REFERENCES

[1] Hingorani, N.G., Gyugyi, L.: ‘Understanding FACTS: concepts and technology of flexible AC transmission systems’ (IEEE Press, 2000)

[2] Mathur, R.M., Varma, R.K.: ‘Thyristor-based FACTS controllers for electrical transmission systems’ (IEEE Press, Piscataway, 2002)

[3] Santosh Grampurohit, Rozina Surani, “Comparison of FACT devices to control reactive power in long distance high voltage transmission line”, IJERT,2013. ISSN 2278-0181 http://dx.doi.org/10.17577/IJERTV2IS121258,

[4] Rozina Surani, Reactive power Planning, Operation, Control and Management (Review Paper), JETIR, 2018, http://www.jetir.org/papers/JETIRK006061.pdf

[5] https://www.iitk.ac.in/npsc/Papers/NPSC2012/papers/12269.pdf

[6] CIGRE, “*FACTS Overview*”, IEEE Power Engineering Society, 95 TP 108, April 1995.

[7] Eremia, Mircea & Gole, Aniruddha & Toma, Lucian. (2016). Static VAr Compensator (SVC): HVDC, FACTS, and Artificial Intelligence. 10.1002/9781119175391.ch5.