An Article on Flexible A.C Transmission System

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ABSTRACT - *Flexible AC transmission has now become a topic of interest for the designers and planners of the modern power systems. It enhances the controllability of the system as well as the power transfer capability. Increase in power production and its Transmission and Distribution has reflected itself in higher level of complexity. The problem of control and coordination of the power system has become difficult. Also the atmosphere of regular expansion is posing problem to the power engineers. Now-a-days the power lines are running near to their upper limits. Therefore, the power angle margin is less. Also, reactive power mismatch is affecting the voltage profile. FACT-system is very much efficient to reduce our existing problems and will increase both the power transfer capability and the techno-economic efficiency. The subject has become interesting after the advent of power electronic devices of large rating e.g. high voltage and high current thyristors, IGBTs, GTOs etc. The paper projects the work on FACTS and FACTS-devices is based on an over-all survey of this area, clarifying the concepts, noting the elements to control the system and finding out their specific fields of application.,*

***KEY WORDS*: FACTS, STATCOM, SVC, REACTIVE POWER, COMPENSATION**

1. INTRODUCTION

A flexible alternating current transmission system (FACTS) is a system composed of static equipment used for the AC transmission of electrical energy. It is meant to enhance controllability and increase power transfer capability of the network. It is normally a system based on power electronics. FACTS is defined by IEEE as a power electronic based system and other static equipment that provide control of one or more AC transmission system parameters to enhance controllability and increase power transfer capability.

1) Historically, the first FACTS installation was at the C. J. Slatt Substation in Northern Oregon. This was a 500 kV, 3-phase 60 Hz substation, and was developed by EPRI, GEC and Bonneville Power Administration. Later on, FACT-systems have been installed in several parts of the world.

In the case of a lossless line, voltage magnitude at the receiving end is the same as voltage magnitude at the sending end: $V_s = V_r = V$. Transmission results in a phase lag δ that depends on line reactance

$$\mathbf{V_S} = V\cos(\delta/2) + j.V\sin(\delta/2)$$

$$\mathbf{V_R} = V\cos(\delta/2) - j.V\sin(\delta/2)$$

$$\mathbf{I} = \frac{\mathbf{V_S} - \mathbf{V_R}}{j.X} = \frac{2V\sin(\delta/2)}{X}$$

As it is a no-loss line, active power P is the same at any point of the line:

$$P_S = P_R = P = \frac{V^2}{X}\sin(\delta)$$

Reactive power at sending end is the opposite of reactive power at receiving end:

$$Q_S = -Q_R = Q = \frac{V^2}{X}[1-\cos(\delta)]$$

As δ is very small, active power mainly depends on δ whereas reactive power mainly depends on voltage magnitude

2. LITERATURE SURVEY

Extensive literatures are available on generation, transmission, and distribution of electrical energy. These are also intimately connected with generation at the source end and utilization at the consumer end. Present day power system has become a gigantic complex, comprising of several power plants, transmission grids, distribution systems and the loads of several kinds. The economic and operational efficiency of such a system can be achieved by Flexible AC Transmission. It is a rather new area of interest but is of great importance in the present context. Literature survey has been made in this emerging area. **Ferranti effect**

This is an effect associated with unloaded line. The phasor diagram is shown in figure 1. It is noted that the voltage regulation is negative- the receiving end voltage is greater than the sending end voltage.

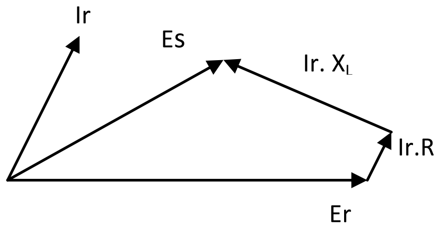

Fig. 1: Ferranti effect

This effect is more pronounced for cable lines as the cables have relatively larger capacitance compared to O/H lines. The effect was first observed by Ferranti in the later part of 19th Century. So the effect goes by his name.

3. Reactive compensation

It is very much necessary to maintain an acceptably good voltage profile in an interconnected grid system. The flow of current through the transmission/distribution system in D.C. causes only voltage drop but in A.C. there may be either voltage drop or voltage rise depending upon the load and its power factor. The voltage drop as well as rise is heavily influenced by the parameters of the line.

The voltage drop is quite obvious and was expected but the rise phenomenon was unknown to the engineers at a certain point of time. It was first noticed and explained by Ferranti. So the effect is called Ferranti effect.

Short transmission lines are characterized by a series-impedance only. The capacitive effects are generally negligible. For such lines the voltage drop is given as:

V.D. = R.cos (φ) + X_L.sin (φ)

Where, (R + j X_L) is the series impedance and φ is the angle of lag of the load current behind the voltage. This drop is dominated by the leakage reactance X_L as normally $X_L >> R$. The capacitive effect is quite appreciable for medium lines, and is very high for long lines. Such lines under unloaded or partially loaded conditions exhibit Ferranti effect. The receiving end voltage becomes higher than the sending end voltage, a phenomenon which is very much unwanted. In this case also the determining factor is the capacitive reactance of the line. So the voltage control problem is closely associated with the problem of reactive power flow.

4. SYNCHRONOUS COMPENSATORS

The power factor of a synchronous motor depends on its excitation. If it is under excited, it runs at lagging power factor. If it runs at leading power factor, it is over excited. This phenomenon has been utilized in making synchronous compensators. Synchronous motors may act either as a synchronous condenser (over-excited) or as a synchronous inductor (under excited). This is an advantage as a single device may act as either VAR-absorber or VAR-generator. But the disadvantage is its high cost, high maintenance charge and more space requirement.

5. STATIC VAR COMPENSATORS (SVC)

A static VAR-compensator (or SVC) is a fast-acting electrical device which provides reactive power on high-voltage transmission networks to regulate the voltage and stabilize the system. SVCs are part of the Flexible AC Transmission System. They are automated impedance matching devices, designed to bring the system closer to unity power factor. A flexible alternating current transmission system (FACTS) comprises of static equipment to enhance controllability and increase power transfer capability of the network. It is generally a power electronics-based system. SVCs are used in two main situations:

- Connected to the power system, to regulate the transmission voltage (Transmission type)
- Connected near large industrial loads, to improve power quality (Industrial type)

The basic types of SVCs are as follows:

- Saturated reactor (SR)
- SCR-controlled reactor (TCR)
- SCR-controlled capacitor (TC
- SCR-switched reactor (TSR)
- SCR-controlled transformer

- Self or line-commutated converter (SCC/LCC)

In transmission system, SVC is used to regulate the grid voltage. If the power system operates at leading power factor, the SVC will use thyristor-controlled reactors to consume VARs from the system, lowering the system voltage. Under lagging power factor, the capacitor banks are automatically switched in, thus providing higher system voltage.

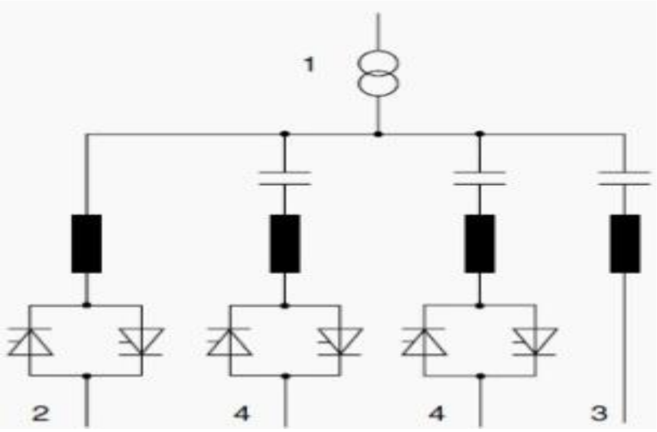

fig. 2:SVC

A load with a low power factor draws relatively more current for the same useful power, thus increasing the energy loss in the distribution system, and the cost of wires and other equipment. Hence, more tariffs are levied for the industrial or commercial consumer drawing power at a low power factor. The schematic view of an SVC is given in fig. 2

6. PRACTICAL APPLICATIONS

SVCs are finding increasing applications in power system from seventies. They are applied for the following:

A. To counteract transient over volt
B. To prevent voltage collapse
C. To enhance transient stability limit
D. To enhance system damping

7. STATIC SYNCHRONOUS COMPENSATOR (STATCOM)

It is known as a static synchronous condenser (STATCON). It is a regulating device used in A.C transmission networks. It is run by a voltage source inverter and can act as either a source or sink of reactive AC power. If connected to a source of power it can also provide active AC power. It is a member of the FACTS family. STATCOM is installed to improve the power factor and voltage regulation. This is also used to ensure voltage stability. A STATCOM is a voltage source converter (VSC) behind a reactor. The reactive power of the STATCOM depends on the voltage. If the terminal voltage of the VSC is more than the AC voltage at the point of connection, the STATCOM generates reactive power and if it is less then it absorbs reactive power. The response time of a STATCOM is smaller than that of an SVC, mainly due to the fast switching times provided by the IGBTs of the voltage source converter. The STATCOM also provides better reactive power support at low AC voltages than an SVC.

8. MATHEMATICAL ANALYSIS

In a long line the series resistance is much less than the series inductive reactance and the shunt conductance is much less than the shunt capacitive reactance. Therefore, the effects of resistance and the conductance may be neglected without appreciable loss of accuracy, except while calculating the efficiency of the line. For such an idealized lossless line, the characteristic impedance is given as:

$$Z_C = \sqrt{\frac{Z}{Y}} = \sqrt{\frac{R + j\omega L}{G + j\omega C}} \approx \sqrt{\frac{L}{C}}$$

And the propagation constant is given as:

$$\gamma = \sqrt{Y.Z} = \sqrt{(R + j\omega L)(G + j\omega C)} = \alpha + j\beta \approx \omega\sqrt{LC} \approx \beta$$ L =

inductance in Henry/unit length and C= capacitance in Farad/unit length

If uniform shunt compensation is added, then the effective shunt susceptance is given by:

$$B_C' = B_C - B_{SH} = B_C(1 - K_{SH})$$

Where K_{SH} is the coefficient of shunt compensation. It may be positive or negative depending upon the specific requirement. The modified value for the characteristic impedance becomes:

$$Z_C' = Z_C / \sqrt{1 - K_{SH}}$$

and that for the phase constant becomes:

$$\beta' = \beta\sqrt{1 - K_{SH}}$$

If uniform series compensation is added, then the effective series inductance is given by:

$$X_L' = X_L - X_{SE} = X_L(1 - K_{SE})$$

The corresponding value for the modified characteristic impedance is given as:

$$Z_C' = Z_C\sqrt{(1 - K_{SE})}$$

and that for the phase constant becomes:

$$\beta' = \beta\sqrt{1 - K_{SE}}$$

If both shunt and series distributed compensation are added, then the expression for characteristic impedance is given as:

$$Z_C' = Z_C\sqrt{(1 - K_{SE}) / (1 - K_{SH})}$$

and that for the phase constant becomes:

$$\beta' = \beta\sqrt{(1 - K_{SH})(1 - K_{SE})}$$

With both of these compensations, the effective phase angle and the natural load are given as:

$$\theta' = \theta\sqrt{(1 - K_{SH})(1 - K_{SE})}$$

$$P_O' = P_O\sqrt{(1 - K_{SE}) / (1 - K_{SH})}$$

8. Series Compensation

In series compensation, capacitors are connected in series with the transmission line. It works as a controllable voltage source. It partially compensates the series inductance of the line.

Figure 3, below shows the diagram of no loss line and Figure 4 and 5 shows series and shunt compensation,

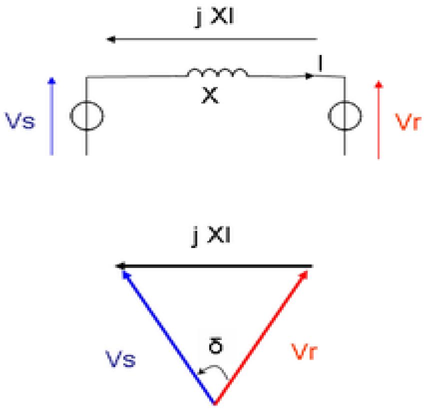

Fig.3: **Transmission on a no-loss line**

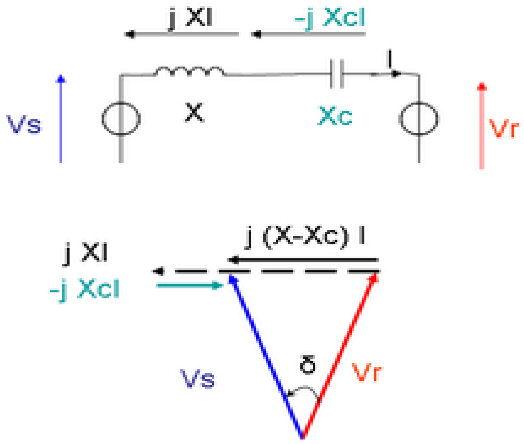

Fig. 4: **Series compensation**

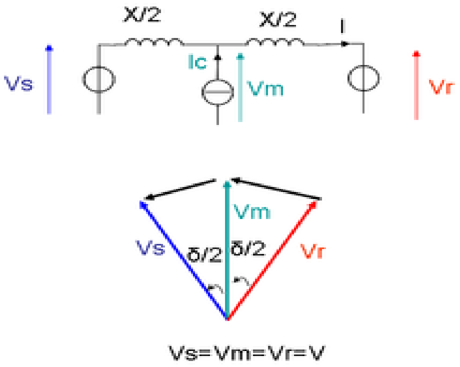

Fig.5: Shunt compensation

9. SHUNT COMPENSATION

In shunt compensation, power system is connected in shunt (parallel) with the FACTS. It works as a controllable current source. Shunt compensation is of two types:

10. SHUNT CAPACITIVE COMPENSATION

This method is used to improve the power factor. Whenever an inductive load is connected to the transmission line, power factor lags because of lagging load current. To compensate, a shunt capacitor is connected which draws current leading the source voltage. The net result is improvement in power factor.

11. SHUNT INDUCTIVE COMPENSATION

This method is used either when charging the transmission line, or, when there is very low load at the receiving end. Due to very low or no load a low current flows through the transmission line. Shunt capacitance in the transmission line causes voltage amplification (Ferranti Effect). The receiving end voltage may become double the sending end voltage (generally in case of very long transmission lines). To compensate, shunt inductors are connected across the transmission line. The power transfer capability is thereby increased depending upon the power equation

$$P = \frac{EV}{X}\sin(\delta);\delta = power\ angle$$

12. SERIES COMPENSATION

FACTS for series compensation modify line impedance: X is decreased so as to increase the transmittable active power. However, more reactive power must be provided.

$$P = \frac{V^2}{X - X_C}\sin(\delta)\ ;Q = \frac{V^2}{X - X_C}[1-\cos(\delta)]$$

13. CLASSIFICATION

FACTS-devices are classified into shunt-compensating and series compensating devices shows below in figure 6 and 7.

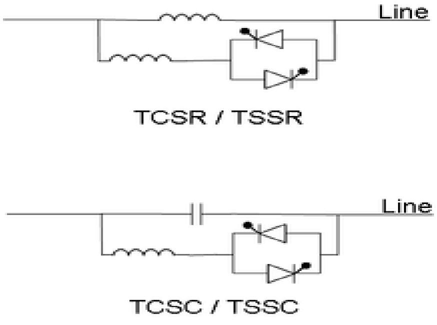

Fig.6: **Series compensation (schematic)**

- Static synchronous series compensator (SSSC)
- Thyristor-controlled series capacitor (TCSC): a series capacitor bank is shunted by a thyristor-controlled reactor
- Thyristor-controlled series reactor (TCSR): a series reactor bank is shunted by a thyristor-controlled reactor
- Thyristor-switched series capacitor (TSSC): a series capacitor bank is shunted by a thyristor-switched reactor
- Thyristor-switched series reactor (TSSR): a series reactor bank is shunted by a thyristor-switched reactor

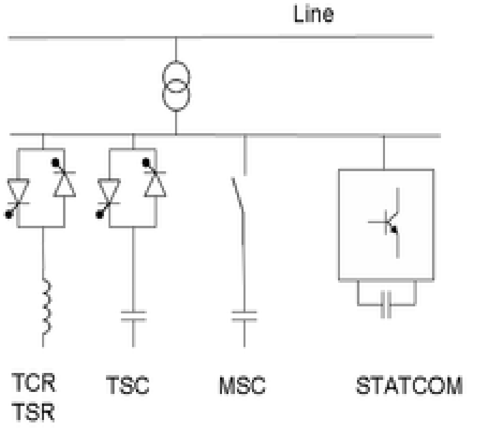

Fig.7: shunt compensation

Static synchronous compensator (STATCOM); previously known as a static condenser (STATCON)

- Static VAR compensator (SVC). Most common SVCs are:
- Thyristor-controlled reactor (TCR): reactor is connected in series with a bidirectional thyristor valve. The thyristor valve is phase-controlled. Equivalent reactance is varied continuously.
- Thyristor-switched reactor (TSR): Same as TCR but thyristor is either in zero- or full- conduction. Equivalent reactance is varied in stepwise manner.
- Thyristor-switched capacitor (TSC): capacitor is connected in series with a bidirectional thyristor valve. Thyristor is either in zero- or full- conduction. Equivalent reactance is varied in stepwise manner.
- Mechanically-switched capacitor (MSC): capacitor is switched by circuit-breaker. It aims at compensating steady state reactive power. It is switched only a few times a day.

APPLICATIONS

FACT-devices are being extensively used now-a-days for improving the performance of HVAC systems and for enhancing their economic efficiency. In most of the applications static VAR compensators are made use of they are made of power electronic devices.

The compensation, if properly made, improves the performance level as well as improves the voltage stability. STATCOM (or STATCON) are better as compensating devices. Made of IGBT, their response is faster. Their reactive power capability does not depend on the voltage. But they are more expensive. Therefore, the application of SVCs is more common.

14. CONCLUSIONS

The transmission lines have two storage parameters- the inductance and the capacitance and two dissipative parameters- the resistance and the leakance. The effect of leakance is small and is very often neglected in mathematical modeling. For short transmission lines, the capacitive effect is so small that it is neglected. Then the transmission line behaves as series impedance with relatively low value of inductance. Such lines are only subject to voltage drop as the load is generally lagging. For medium lines, the capacitive effect is considerable and cannot be neglected. Perhaps some problems of voltage regulation may arise during the lean hours of night due to Ferranti effect.

The effect of distributed parameters is dominant in long lines; the distribution effect considerably influences the performance variables. With this effect included, the performance equations are in terms of hyper geometric functions. For convenience, we convert the equations into equivalent-T or equivalent-π representation. The maximum power transfer capability of such a line is limited by the line parameters. FACT-system can do a marvel in this area by properly compensating the power lines.

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