MULTI-PHASE (6-PHASE & 12-PHASE) POWER TRANSMISSION SYSTEMS WITH THYRISTOR CONTROLLED SERIES CAPACITOR

ZAKIR HUSAIN
Department of Electrical Engineering,
N.I.T. Hamirpur (H.P), India

R.K. SINGH and S.N. TIWARI
Department of Electrical Engineering,
M.N.N.I.T. Allahabad (U.P), India

Abstract: - Multi-phase (employing phases more than three) power transmission systems have been investigated as a potential alternative to conventional three-phase systems for bulk power transmission at EHV and UHV levels in the past. The technology has been found to be effective to remove some of the limitations of three-phase system arising out of the use of extremely high voltages to increase power capability of lines, excessive rights-of-way (ROW) requirement and several environmental problems.

A recently conducted survey reveals that the integration of flexible A.C. transmission system (FACTS) devices into conventional three-phase transmission system for enhancement and control of power flow is well established, however, this aspect has not been investigated for multi-phase power transmission systems. This paper therefore attempts to study: a FACTS device i.e. thyristor controlled series capacitor (TCSC), its model and effect on power flow and load ability of multi-phase EHV transmission lines. Sample systems are employed to study quantitative benefits of six-phase and twelve-phase lines over their three-phase counter parts.

Key-Words: - Multi-phase, Power-transmission, Rights-of-way, Flexible A.C. transmission system, Thyristor controlled series capacitor, Loadability.

1 Introduction

The deregulation and competitive environment in the contemporary power system network are poised to a new scenario in terms of load and power flow conditions leading to problems of line capacity. In this regard multi-phase power transmission systems [1-8] have been investigated as potential alternative to increase transmission capacity with out increasing system voltages which have already reached extremely high level i.e. EHV & UHV. Further constraints on land availability and several environmental problems have renewed interests in techniques and technologies for power carrying capacity of existing ROW and multi-phase systems (especially 6-phase & 12-phase) has been found to be quite promising.

The application of flexible ac transmission system (FACT) controllers for power flow control and transmission capacity enhancement over and existing transmission corridor has rapidly met with favor with conventional three-phase system [9-11]. This paper makes an attempt to study power flow and loadability of EHV transmission line equipped with TCSC.

2 Modeling of TCSC

A thyristor controlled series capacitor (TCSC) is connected in series with a transmission line, used basically, to decrease the impedance of transmission line carrying power over a long distance. The circuit diagram of TCSC for one of the phases of a high phase order transmission line is shown in Fig.1. Thyristor T_1 is fired in positive half cycle and T_2 in negative half cycle of the line current. It is to be noted that the firing is symmetrical in positive and negative cycles.
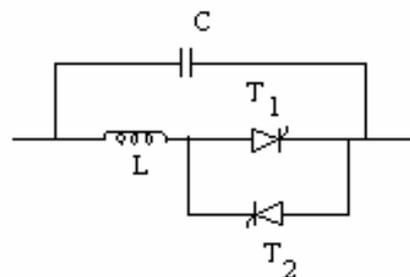

Fig.1 Basic TCSC Scheme

The TCSC offers equivalent capacitive or inductive reactance depending on the firing angle of the TCSC thyristors. The TCSC shown in Fig.1 has a fixed capacitor in parallel with series connected thyristor and inductor, also known as TCR. The inductive reactance of a TCR at a firing angle ψ is given by

$$X_{L(\Psi)} = X_L \frac{\pi}{\pi - 2\Psi - Sin\psi} \tag{1}$$

$$X_{L(\Psi)} = \frac{X_L(\psi) X_C}{X_L(\psi) - X_C} \tag{2}$$

Where, $X_C = \dfrac{1}{2\pi f C}$, C being capacitance of TCSC.

2.1 DESIGN OF TCSC

The design of TCSC involves determining values of L (or X_L), C (or X_C) and the firing angle ψ of the thyristors T_1 and T_2 in order to obtain a desired values of compensation, (hence $X_{TCSC(\psi)} = \alpha X_{TL}$, α being the % value of compensation). This is achieved firstly noting that at $\psi = \pi/2$, the TCSC yields maximum capacitance. Therefore as a constraint, it is to be insured that at $\psi = \pi/2$, the TCSC gives minimum compensation $\alpha_{\lim it}$ (say 10 %) desired and achievable as;

$$X_{TCSC}(\frac{\pi}{2}) = \alpha_{mim} X_{TL} \tag{3}$$

Where, X_{TL} = inductive reactance of transmission line

Or $\dfrac{X_L(\pi/2) X_C}{X_L(\pi/2) - X_C} = \dfrac{\pi X_L X_C}{\pi X_L + X_C} = \alpha_{mim} X_{TL}$ (4)

Further, utilizing the constraints of internal circuit resonance which may be assumed to occur at $\psi = \psi_R$ (say $\pi/6$), the following equation may be written as,

$$X_L(\psi) = X_C$$

$$X_L \frac{\pi}{\pi - 2\psi - Sin\psi} = X_C \tag{5}$$

and specially for $\psi_R = \pi/6$, this gives

$$X_L = (\frac{2\pi}{3} - \frac{1}{2}) \frac{X_C}{\pi} \tag{6}$$

Solving equations (3) and (6) yields the values X_L or L and X_C or C. The value of ψ for a given

degree of compensation (say a) then will be determined making use of:

$$X_{TCSC}(\psi) = \alpha X_{TL}, \text{ and equations (1) and (2)}$$

The Table 1 gives design parameter for different degree of compensation, as desired by the designer

Table 1

Deg. Of Compensa-tion	3-phase		6-phase		12-phase	
	ψ (deg)	$X_{TCSC}(\psi)$	ψ (deg.)	$X_{TCSC}(\psi)$	ψ (deg.)	$X_{TCSC}(\psi)$
25%	51.60	0.0995002	51.60	0.118151502	51.60	0.141500426
50%	40.56	0.1990024	40.56	0.2363019	40.56	0.28002441
75%	36.99	0.298516	36.99	0.354485	36.99	0.42449714

3 Line Model with Compensation

Power Flow Equations for Test System
A series compensation of TCSC is proposed at receiving end of a transmission line and its equivalent circuit is represented in Fig. 2
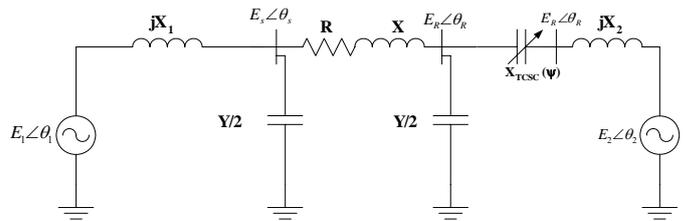

Fig. 2 A circuit model for power and loadability study.

With reference to the system described in Fig.2, voltage E_R is derived and computed as

$$E_R = \frac{2Z E_2 + jZ_3 E_1}{Z_2 + Z_4} \tag{7}$$

and E_S is also computed as

$$E_S = (2Z E_1 - 2 j E_R (X_1 - X_{TCSC(\psi)}))/Z_1 \tag{8}$$

where,

$$Z = R + jX_{TL}$$
$$Z_1 = 2Z + j(X_1 - X_{TCSC(\psi)})(2 + YZ)$$
$$Z_2 = 2Z + jX_2(2 + YZ)$$
$$Z_3 = j4XZ_2/Z_1$$
$$Z_4 = 4X_2(X_1 - X_{TCSC(\psi)})$$

ψ = firing angle of thyristors

By substituting equation (7) and (8) in power flow equation take the form of equation (9).

$$P_S = |E_S||E_R| Cos(\beta + \delta)/|B| + |A||E_S|^2 Sin(\beta - \alpha)/|B|$$
$$= P_A \tag{9}$$

where,

$$A = (1 + YZ/2) - (X_{TCSC(\psi)}))Y(1 + YZ/4)$$

$$B = Z - (X_{TCSC(\psi)})(1 + \frac{YZ}{2})$$

δ is the angle between E_S and E_R

ψ degree of compensation is shown in Table 1

4 LINE LOADABILITY ANALYSES

In model shown in Fig. 2 the transmission line as represented by an equivalent π with the terminal systems as Thevinian equivalent [12,13] and FACTS device model as TCSC in series with resistance and reactance of the line. The transmission line is consisted of positive sequence inductive and capacitive parameters. The Thevinian equivalent impedances are determined from short circuit strengths of the systems the voltages $|E_1|$ and $|E_2|$ are specified as 1.0 and 9.7 p.u. respectively based on a.c. load flow. The power flow and load ability analysis are carried out on three transmission alternatives namely 3-phase, 6-phase and 12-phase for which system voltage is 462KV, L-G. The specification of 3-phase, 6-phase and 12-phase used as sample system are given in Table2

Table2: Test system specification & line parameters

3-Phase System 462 kV (L-G)	6-Phase System 462 kV (L-G)	12-Phase System 462 kV (L-G)
SIL = 3275 MW Z=(0.0063+j0.398) Ω /mi Y=j10. 638μS	SIL = 4494 MW Z= (0.0126+j0.4726) Ω /mi Y=j8.9606μS	SIL = 5485 MW Z=(0.025+j0.5667) Ω /mi Y=j7.483μS

5 Power Flow and Loadability Curves

The power flow and loadability analyses are carried out on three alternatives as described in Table2. Initially power flow for uncompensated line (250 km length) and employing various degree of compensation for three transmission alternatives (3-phase, 6-phase and 12-phase) are computed, recorded and plotted as shown in Fig. 3 (a-d).

Next, with all known voltages and other parameters mentioned in the above sections, the ratio P_A/SIL for uncompensated and various degree of compensation for the three alternatives, for 5% voltage drop and 30% stability margin criteria, have been plotted against line length between 100 and 600 miles as shown in Fig. 4 (a-d). The loadability characteristics depicted in Fig. 4 (a-d) are used to study qualitative and quantitative benefits in each case.
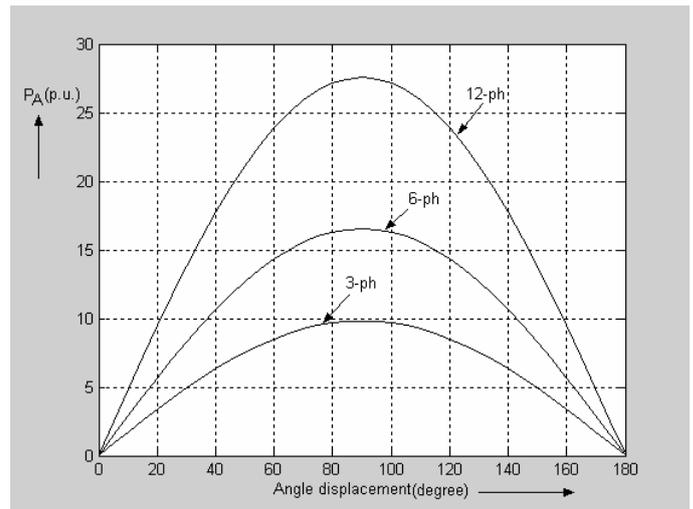

Fig. (a) power-angle curves for line length 250 Km. with no compensation
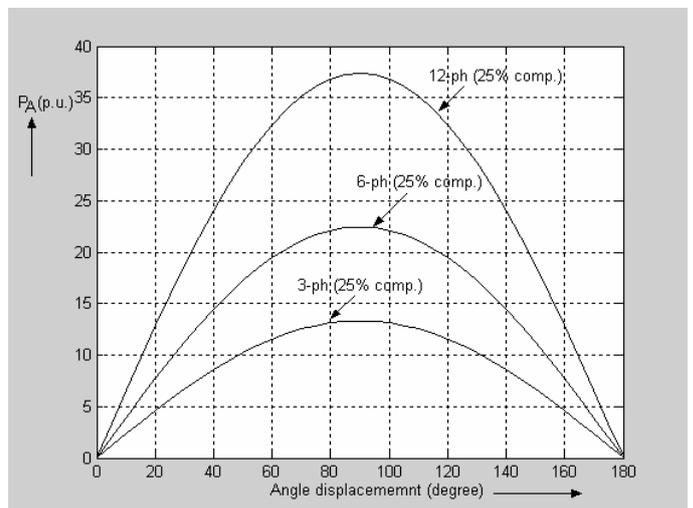

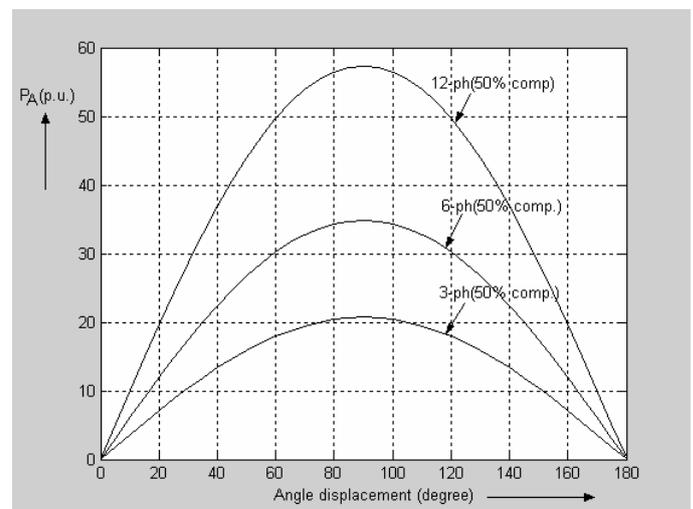Fig. 3 (b) power-angle curves for 250 Km line with 25% compensation.

Fig. 3.13 (c) power-angle curves for 250 km line with 50% compensation
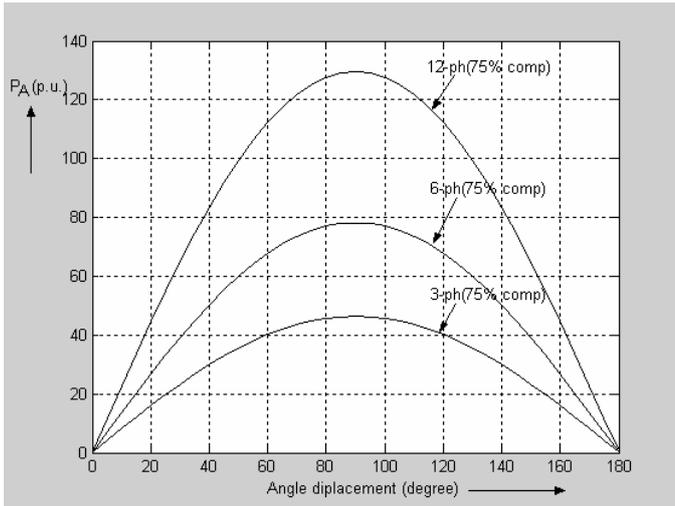
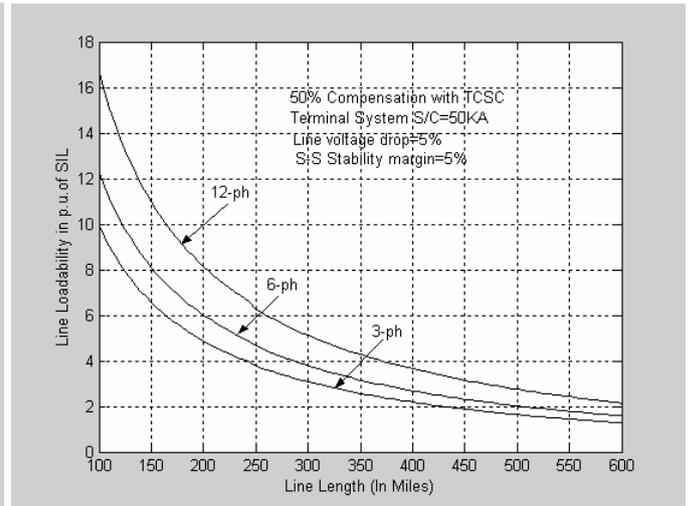Fig. 3 (d) power-angle curves for 250 km line with 75% compensation.

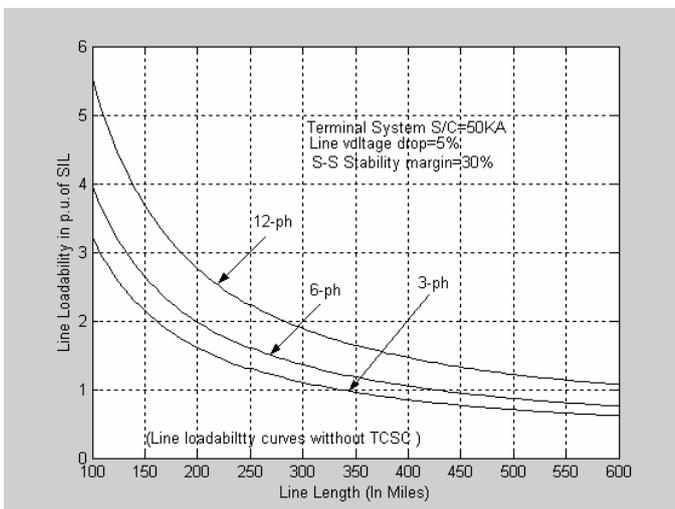Fig.4 (c) Loadability curves for 462 kV three alternatives lines with 50% compensation.

Fig. 4 (a) Loadability curves for 462 kV three alternatives lines (3-phase, 6-phase and 12-phase) with out compensation.
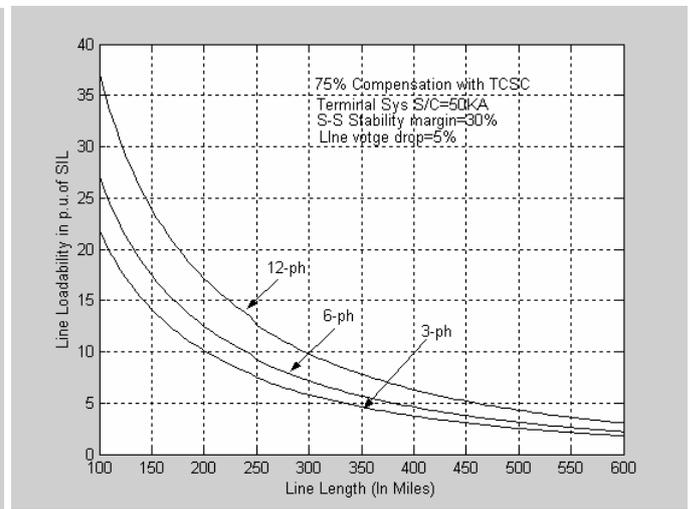

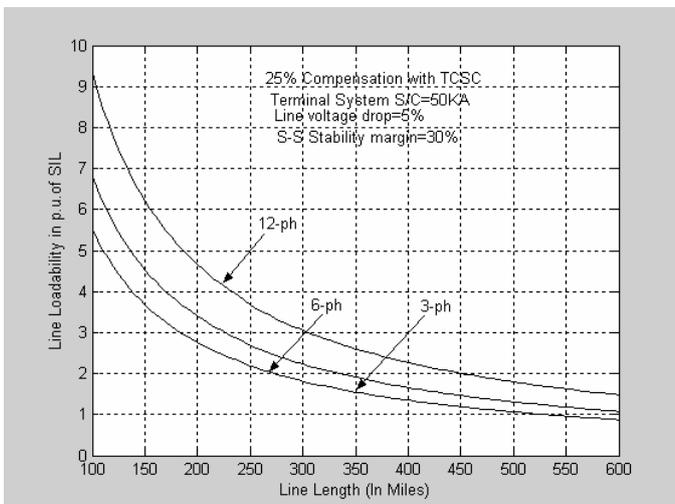Fig.3.14 (d) Loadability curves for 462 KV three alternatives lines with 75% compensation.

6 Results and conclusions

The power flow and loadability analyses are carried out on three transmission alternatives described in Table 2. The power flow for the case of uncompensated line (250 km length) and employing various degree of compensation are calculated and plotted as in Fig.3 (a-d). It is evident from Fig. 3 (a-d) that higher steady–state stability limit (P_{max} (Fig. 3 (a-d)) called steady state limit is associated with multi-phase lines as compared to its 3-phase counterpart. The loadability studied for uncompensated line as well as compensated line with several degree of compensation (by varying $X_{TCSC(\psi)}$) revealed remarkable benefits (Fig. 4 (a-d)) in line loadability of multi-phase lines than its lower phase counterpart. This aspect of multi-phase lines may be very attractive and beneficial to the electric transmission utilities.

Fig. 4 (b) Loadability curves for 462 KV three alternatives lines with 25%compensation

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