Compensation degree of controllable shunt reactor in EHV/UHV transmission line with series capacitor compensation considered

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Abstract—Based on the compensation degree of shunt reactor and series capacitor under the case of uniform placement, the voltage profile and transmitting power of EHV/ UHV transmission line are analyzed by using π-type equivalent circuit of long transmission line arranged at both ends of controllable shunt reactor. The impact of series capacitor on the compensation degree of controllable shunt reactor are studied deeply by analyzing the compensation degree of sectional placement controllable shunt reactor and then the mathematical expression of compensation degree of controllable reactor with uniform series capacitor compensation is derived carefully. The research results show that the segmented distance of controllable reactor is influenced by compensation degree of series capacitor and with the increase in the degree of series compensation, segmented distance increases.

Keywords-extra high voltage (EHV)/ultra high voltage (UHV); controllable shunt reactor; series capacitor compensation; voltage profile; compensation degree

I. INTRODUCTION

To fulfill the requirement of the increased power transmission over long distance, the power industry in China is developing 1000kV transmission lines, which are characterized by relatively higher distributed capacitance [1]. Two key concerns of an extra high voltage (EHV)/ultra high voltage (UHV) system are restricting power-frequency over–voltage and obtaining the maximum power transfer limit over a long transmission line. It has been proven that series capacitor and shunt reactor compensation are the best available methods because more power can be transferred and voltage profile along the line can be controlled [2]. Many researchers have discussed compensation schemes, load characteristics, sensitivity analysis, law of reactive power control, indexes of compensation performance and so on, for the series capacitor and shunt reactor compensation systems.

Accordingly a number of studies, found in the literature, dealing with compensation degree of controllable shunt reactor has been widely reported. The principle and regulating ranges of UHV controlled shunt reactors are studied in reference [3].The formula for calculating compensation degree of controllable shunt reactor which is applicable to various loads of receiving system is achieved by power flow calculation in reference [4]. The methods to determine the lower limit of compensation degree of HV shunt reactor in the viewpoint of restricting secondary arc current and voltage of no-load line, and to determine the upper limit of compensation degree of HV shunt reactor in the standpoint of evading resonance over voltage are given respectively in references [5,6]. The optimal position at transmission line while the two terminals of long distance transmission line are connected to the power systems is described in reference [7]. However, to the author’s knowledge, until recently, study of compensation degree of controllable shunt reactor with series capacitor compensation considered is still not reported adequately.

This paper can be regarded as an extension of references [3], as the latter laid the analysis foundation for the present study. Analytical expression for compensation degree of controllable shunt reactor is firstly proposed in the case of series capacitor compensation, and then the effect of series capacitor compensation on the spacing between shunt reactors of sectional placement is also analyzed deeply in this paper.

II. COMPENSATION DEGREE OF SHUNT REACTOR AND SERIES CAPACITOR UNDER THE CASE OF UNIFORM PLACEMENT

Consider that the transmission line parameters are uniformly distributed and the line can be modeled by π-type equivalence circuit as shown Fig.1. Controllable shunt reactor X_b is installed at two ends of the line. In order to clarify the most important aspects of transmission line's characteristics, let us assume a line without resistance and conductance. In Fig. 1, total series inductive reactance of the line and shunt capacitive reactance of the line are given respectively by $X_L=Z_c\sin\lambda$, $X_C=Z_c\mathrm{ctg}\lambda/2$.

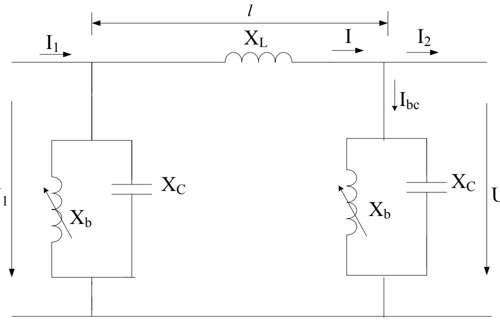

Figure 1. π-type equivalence circuit of long distance lines with controllable shunt reactor installed in two ends

Series and shunt compensation devices are usually placed at both ends of the transmission line or at approximately identical distance along the transmission line. From the point of view of theoretical analysis, it is necessary that basic relations is noted, which is independent of compensation devices and schemes, based on uniform compensation[8].

The compensation degree studies of this paper were applied to existing 1000 kV UHV Nanyang-Jingmen transmission system in China. The parameters of the line were taken from reference [9] and are given in the following $Z=(0.0076+j0.2628)$ Ω/km, C=0.014μF/km. So Z_0 and λ can be calculated as $Z_0\approx 244.5\,\Omega$, $\lambda\approx 0.06°l$.

Parameters of some EHV and UHV transmission line are shown in Table 1.

TABLE I. PARAMETERS OF TRANSMISSION LINE

Voltage level /kV	500	765	1100	1500
Z_0/Ω	270.1	259.9	228.8	228.6
γ/。	0.0605	0.0613	0.0610	0.0610

Surge impedance Z_0 and electrical length of the line λ without compensation can be written as

$$Z_0=\sqrt{\frac{L}{C}}=\sqrt{\frac{\omega L}{\omega C}}=\sqrt{\frac{X_L}{B_C}}$$

$$\lambda = l\omega\sqrt{X_L B_C} \qquad (1)$$

L, C is Unit length inductance and capacitance of line respectively.

It is supposed that series compensation capacitor (C_{se}) is placed uniformly at transmission line, total series inductive reactance of the line after compensation is given by

$$X_L{}' = X_L - \frac{1}{\omega C_{se}} = X_L(1-K_{se}) \qquad (2)$$

Then, the degree of series capacitor compensation is defined by $K_{se}=X_{ces}/X_L$.

Similarly, it is supposed that shunt compensation reactor (X_b) is placed uniformly at transmission line, total shunt capacitive susceptance of the line after compensation is given by

$$B_C{}' = B_C - B_{sh} = B_C(1-K_{sh}) \qquad (3)$$

The degree of shunt capacitor compensation is defined by $K_{sh}=B_{sh}/B_C$.

From (1), (2) and (3) we get surge impedance after compensation

$$Z_0{}' = \sqrt{\frac{X_L'}{B_C{}'}} = \frac{Z_0\sqrt{1-K_{se}}}{\sqrt{1-K_{sh}}} \qquad (4)$$

Also, the corresponding electrical length of the line and natural power after compensation are given by

$$\lambda' = \lambda\sqrt{(1-K_{sh})(1-K_{se})} \qquad (5)$$

$$P_0' = P_0\sqrt{\frac{1-K_{sh}}{1-K_{se}}} \qquad (6)$$

III. VOLTAGE PROFILE AND TRANSMITTING POWER OF THE TRANSMISSION LINE

Assuming there is no loss on the transmission line, the following equations hold true:

$$\mathbf{U_1} = \mathbf{U_2}\cos\lambda + jZ_0\mathbf{I_2}\sin\lambda \qquad (7)$$

$$\mathbf{I_2} = (P - jQ)/3\mathbf{U_2} \qquad (8)$$

Substitute (7) into (8), the result is

$$\mathbf{U_1} = \mathbf{U}_2\cos\lambda + jZ_0\sin\lambda\left(\frac{P-jQ}{3\mathbf{U_2}}\right) \qquad (9)$$

Let $\mathbf{U_2}$ be the reference axis, and let δ be the transmission angle between $\mathbf{U_1}$ and $\mathbf{U_2}$, then $\mathbf{U_1}$ can be expressed as

$$\mathbf{U_1} = U_1 e^{j\delta} = U_1(\cos\delta + j\sin\delta) \qquad (10)$$

The real part of (9) equals the corresponding real part of (10) and so does the imaginary part, we get

$$P = \frac{3U_1U_2}{Z_0\sin\lambda}\sin\delta = \frac{U_1}{U_2}P_0\frac{\sin\delta}{\sin\lambda} \qquad (11)$$

So, the relation between transmitting power, voltage and length of the transmission line and transmission angle are demonstrated as (11).

When the controllable shunt reactors are placed at both ends, voltage profile $\mathbf{U_x}$ can be calculated using the following equations[10]

$$\mathbf{U_x} = \mathbf{U_1}\frac{\sinh\gamma(l-x)}{\sinh\gamma l} + \mathbf{U_2}\frac{\sinh\gamma x}{\sinh\gamma l}$$

$$\mathbf{U_2} = U_1 e^{-j\delta} \qquad (12)$$

where x is used to denote the length from random point to receiving end along the line. According to (12), when $U_1=U_2$, we get the voltage on the mid-point of line

$$U_{\frac{l}{2}} = \dot{U}_1\frac{\sin\frac{\lambda}{2} + e^{-j\delta}\sin\frac{\lambda}{2}}{\sin\lambda} = U_1\frac{\cos\frac{\delta}{2}}{\cos\frac{\lambda}{2}}\cdot e^{-j\frac{\delta}{2}} \qquad (13)$$

It can be noticed from (13) that $U_{l/2}$=U_1, because of cosδ/2 > cosλ/2 when P<P_0.

When P=0, or δ is zero, value of voltage rise on mid-point of the line is the maximum, which is expressed as

$$U_{\frac{l}{2}} = U_1 / \cos\frac{\lambda}{2} \quad (14)$$

In this case, the voltage must be limited by reactive compensation, according to maximum operation limit of voltage rise in transmission line.

IV. COMPENSATION DEGREE OF SECTIONAL PLACEMENT CONTROLLABLE SHUNT REACTOR

A. Compensation degree of controllable shunt reactor ignoring series capacitor compensation

Firstly, compensation degree of controllable shunt reactor is analyzed when series capacitor compensation on the line is taken into account. Shunt reactors can only be fixed at both ends of the line or any intermediate points, and namely shunt reactors compensation is segmented. From Fig. 1, we can obtain

$$\begin{aligned}\mathbf{U_1} &= \mathbf{U_2} + j\mathbf{I_{bc}}X_L + j\mathbf{I_2}X_L \\ &= \mathbf{U_2} + j(\mathbf{I_b} + \mathbf{I_c})X_L + j\mathbf{I_2}X_L\end{aligned} \quad (15)$$

Substitute $K_{sh}=B_{sh}/B_C$, $X_L=Z_0\sin\lambda$, $P0=3U_1U_2/Z_0$ into (15), we get

$$\mathbf{U_1} = \mathbf{U_2}[\cos\lambda + (1-\cos\lambda)K_{sh} + jP\sin\lambda / P_0]$$

Rewriting previous equation yields

$$K_{sh} = \left(\left((\frac{U_1}{U_2})^2 - (\frac{P\sin\lambda}{P_0})^2 \right)^{\frac{1}{2}} - \cos\lambda \right) / (1-\cos\lambda) \quad (16)$$

Controllable reactor is used mainly for controlling the voltage within a stable range by regulating value of K_{sh}.

According to (14), if the voltage rise will be limited to 1.05 times the rated value, we can get $\lambda=36^o$, or l=670 km. Therefore, controllable reactor is placed at both ends of the transmission line of 600km, whose capacity equals to capacitive active power of 300km line. According to (16), the reactor compensation is capable of maintaining a satisfactory voltage level when transmitting power is less than the natural power.

B. Compensation degree of controllable shunt reactor with series capacitor compensation considered

Compensation schemes for series capacitors cannot greatly impact the transmission lines, however compensation schemes for shunt reactors have such significant influence [11]. Therefore schemes for series capacitors compensation can be ignored, which is assumed to be uniform distribution on the line. When series compensation on the line is taken into account, from (4), (5) and (14), the compensation degree of controllable reactor with series compensation considered is given by:

$$K_{sh} = \frac{((\frac{U_S}{U_R})^2 - P\sin(\lambda\sqrt{1-K_{se}})/(P_0\sqrt{\frac{1}{1-K_{se}}})^2)^{1/2} - \cos(\lambda\sqrt{1-K_{se}})}{1-\cos(\lambda\sqrt{1-K_{se}})} \quad (17)$$

The spacing between shunt reactors will be varied when there is series compensation on the transmission line. Substitute (5) (when K_{sh}=0) into (14), we get voltage on the mid-point of line after series compensation

$$U_{\frac{l}{2}} = U_1 / \cos\frac{\lambda\sqrt{(1-K_{se})}}{2} \quad (18)$$

Assuming the voltage rise will be limited to 1.05 times the rated value, from (18), when K_{se} increases from 0.2 to 0.4 and 0.6, λ is 40° , 46° and 56° respectively, also, l is 670 km, 770 km and 930 km respectively. It is clearly demonstrated that the spacing between shunt reactors on the transmission line will be increased when degree of series compensation increases after series compensation.

V. SIMULATION RESULTS

Suppose $U_1=U_2$, when shunt reactor compensation on the line is not taken into account, voltage profile against length of the line for different transmission angle is shown in Fig. 2.

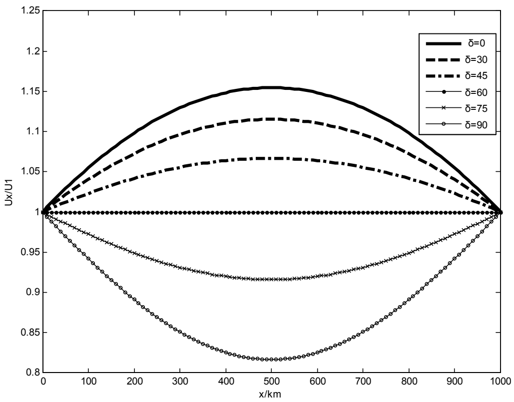

Figure 2. voltage profile against length of the line for different transmission angles

It can be seen that when transmission angle changes from 0° to 60° , namely receiving end active power changes from zero to natural power, voltage profile will be upwardly convex, and the highest voltage occurs on the mid-point of the line. The voltage must be limited by controllable reactor compensation, according to maximum operation limit of voltage rise in transmission line.

Assuming $U_1=U_2$, numerical simulation of the variation in shunt compensation degree against transmitting power（P/P_0） for different length of the line such as 500 km（$\lambda=30^o$）、1000 km（$\lambda=60^o$）、1500 km（$\lambda=90^o$）are shown in Fig. 3 according to Eq.(16)

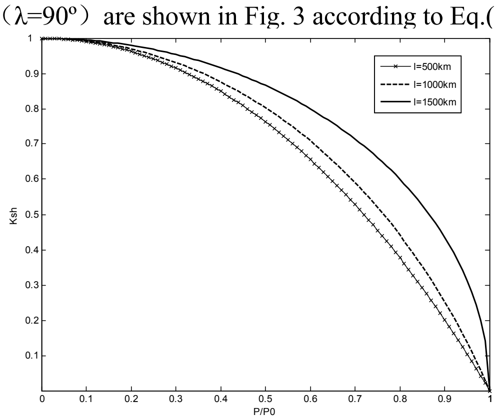

Figure 3. variation in shunt compensation degree against transmitting power for different length of the line

Assuming $U_1=U_2$, when l=500km, the variation in shunt compensation degree against transmitting power（P/P_0） for different degree of series compensation such as K_{se}=0、0.2、0.4、0.6、0.8 are shown in Fig. 4 according to (17). Compared with Fig. 3, the decreasing trend of degree of shunt compensation remains unchanged when transmitting power increases in the case of series compensation. However, the transmitting power corresponding to shunt compensation is no longer less than the natural power as the degree of series compensation increases the transmitting power increases, that is to say series capacitor compensation expands further compensation range of shunt reactors.

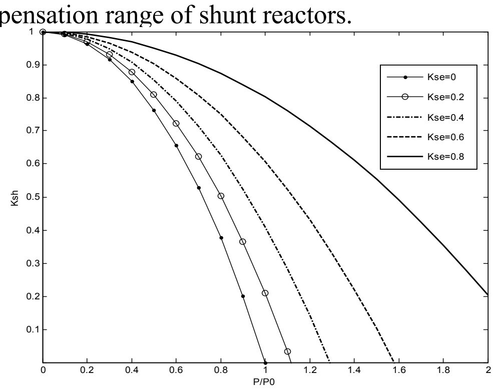

Figure 4. variation in shunt compensation degree against transmitting power for different series compensation degree

Assumin U_1=U_2, variation of shunt compensation degree with series compensation degree for different transmitting power assigned the value P/P_0=50%，P/P_0=75%，P/P_0=100%，P/P_0=125%，P/P_0=150% respectively, are shown in Fig. 5 according to (17). However, because excessive series compensation can lead to resonance, K_{sh} and K_{se} are usually limited to a value below 80%. In order to control the voltage K_{sh} must be increased when transmitting power decreases for given K_{se}. It can be observed in Fig. 5 K_{sh} reaches 0.2 at K_{se} = 0.2 for P/P_0= 100%. A similar pattern for K_{sh} with K_{se} can be observed from Fig. 5 for different transmitting power. This figure can present compensation curves to select suitable degree of shunt and series compensation for different transmitting power in the line, thus the voltage profile are maintained well within the operating limit.

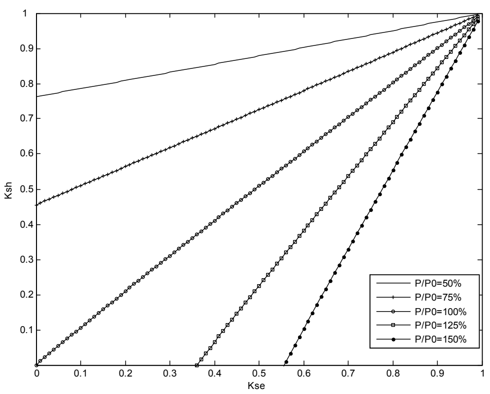

Figure 5. variation in shunt compensation degree against series compensation degree for different transmitting power

VI. CONCLUSIONS

This paper investigates the degree of sectional placement controllable shunt reactor compensation when series compensation is taken into account by analyzing characteristics of uniform placement series-shunt compensation, voltage profile and power transmitting. The following points are noted during the analysis. Analytical expressions for compensation degree of controllable shunt reactor is proposed in the case of series compensation and numerical simulation of compensation degree of controllable reactor are derived. According to the theoretical analysis on controlling voltage the spacing between shunt reactors will be increased as degree of series compensation increases after installing series compensation devices on the transmission line.

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