

PROVIDING OF VOLTAGE STABILIZATION AND STEADY-STATE STABILITY FOR LONG SYNCHRONOUS EAST-WEST INTERCONNECTIONS IN EUROPE

by

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Abstract

By using controllable shunt compensators, distributed along lines it is possible to stabilize the operating voltage in depend on the length of lines. These compensators provide the steady-state stability of electrical energy transmission over such lines.

Key words: reactive, compensation, surge impedance, equivalent characteristics.

Introduction

The main problem for long distance electrical energy transmission by means of alternating current is the providing of a voltage stabilization by variation of a line's loading. As a matter of fact the reactive power of a line is zero only by transmission of the surge impedance loading (the natural power P_n)

$$P_n = \frac{3U_{ph,nom}^2}{Z}, \quad (1)$$

where $U_{ph,nom}$ is the nominal phase to ground voltage, Z is the surge impedance of a line. When a transmission power P is different from surge impedance loading of a line P_n , it generates or consumes reactive power in accordance with approximate relation

$$Q \approx P_n \lambda \left[1 - \left(\frac{P}{P_n} \right)^2 \right], \quad (2)$$

where λ is wave length of a line.

If a transmitted power $P < P_n$ the reactive power of a line Q is positive. That means a line generates reactive power and the bigger the less is the ratio P/P_n . The biggest reactive power of a line corresponds to its idle regime of operation ($P = 0$) and it is equal to

$$Q_{max} = P_n \lambda. \quad (3)$$

For example when $\lambda = 1$ rad $Q_{max} = P_n$; if $\lambda = 2$ rad $Q_{max} = 2P_n$ and so on. That means for a long lines their reactive power is comparable with transmitted power or more.

On the contrary when $P > P_n$ the reactive power of a line is negative ($Q < 0$). That means in this case a line consumes the reactive power or it is similar to a

reactor. And the bigger is the ratio $P/P_n > 1$ the bigger is this reactive power of a line.

The generation or the consumption of a reactive power by a line means that there is additional current in this line. And this additional current induces the instability of the voltage along the line and additional power losses. Both these consequences are negative

Voltage stabilization along the long lines

The voltage distribution along long lines is determined by the wave equation

$$\begin{aligned} \frac{\dot{U}_x}{U_2} = \cos \lambda_x + \frac{\dot{I}_2}{U_2} \frac{R_0 x}{2} \left(\cos \lambda_x + \frac{\sin \lambda_x}{\lambda_x} \right) + \\ + j \left(\frac{R_0 x}{2z} + \frac{\dot{I}_2 z}{U_2} \right), \end{aligned} \quad (4)$$

where U_2 is the voltage at the consuming end of a line, which is combined with the axis of real values, x is the current length of line, λ_x is its current wave length, R_0 is the active resistance of a line per unit of its length. When the line loading is pure active, the current at the consuming end of a line is equal to

$$\dot{I}_2 = \frac{U_2}{z} \frac{P}{P_n}$$

and

$$\begin{aligned} \frac{U_x}{U_2} = \cos \lambda_x + \frac{P}{P_n} \frac{R_0 x}{2z} \left(\cos \lambda_x + \frac{\sin \lambda_x}{\lambda_x} \right) + \\ + j \left(\frac{R_0 x}{2z} + \frac{P}{P_n} \right) \sin \lambda_x. \end{aligned} \quad (5)$$

Respectively the distribution of the absolute values of voltage is determined by the formula

$$\begin{aligned} \frac{U_x}{U_2} = \left\{ 1 + \left[\left(\frac{P}{P_n} \right)^2 - 1 \right] \sin^2 \lambda_x + \right. \\ + \frac{R_0 x}{2z} \frac{P}{P_n} \left(1 + \frac{\sin 2\lambda_x}{2\lambda_x} \right) + \left(\frac{R_0 x}{2z} \right)^2 \times \\ \left. \times \left[\sin^2 \lambda_x + \left(\frac{P}{P_n} \right)^2 \left(\cos^2 \lambda_x + \frac{\sin 2\lambda_x}{\lambda_x} + \frac{\sin^2 \lambda_x}{\lambda_x^2} \right) \right] \right\}^{1/2}. \end{aligned} \quad (6)$$

As it is possible to see by $P/P_n = 1$ the voltage distribution along the line is determined only by active resistance of a line. But if $P/P_n < 1$ the voltage U_x decreases comparing with U_2 and this decrease is the more significant the less is P/P_n and the bigger is λ_x .

On the contrary if $P/P_n > 1$ the voltage U_x increases comparing U_2 and this increase is the bigger the bigger is the ratio P/P_n and the length λ_x .

If x equal to the length of a line ($\lambda_x = \lambda$) formula (6) determines the ratio of voltages at both ends of a line

$$\frac{U_1}{U_2} \approx \sqrt{1 + \left[\left(\frac{P}{P_n} \right)^2 - 1 \right] \sin^2 \lambda + \frac{R}{z} \frac{P}{P_n} \left(1 + \frac{\sin 2\lambda}{2\lambda} \right)}, \quad (7)$$

where U_1 is the voltage at the output end of a line, $R = R_0 \ell$.

Multiplier $\left[\left(\frac{P}{P_n} \right)^2 - 1 \right]$ determines the relative value of a reactive power of a line $Q/P_n \lambda$ (see formula (2)). For this reason the Second member in formulas (6) and (7) determines the reactive component of a voltage deviation and other members determine active component of voltage deviation.

The results of calculations by means of formula (7) are presented in Fig.1.

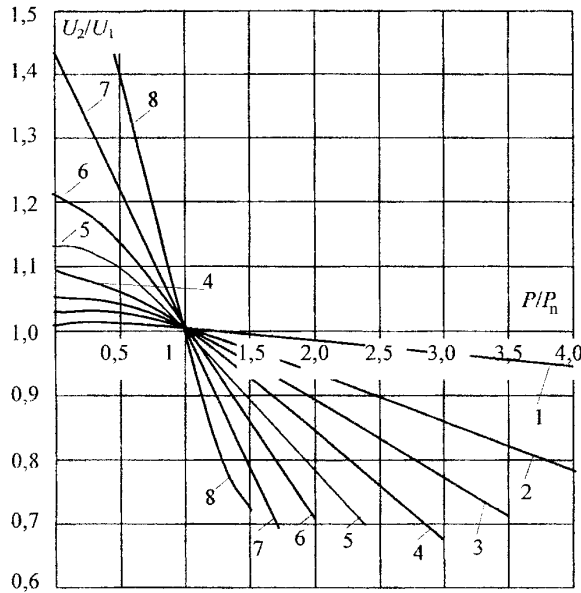


Fig.1. The ratio of voltages at the receiving and output ends of lines versus P/P_n by different wave length of lines $\lambda = 0.1$ rad (1); 0.2 rad (2); 0.3 rad (3); 0.4 rad (4); 0.5 rad (5); 0.6 rad (6); 0.8 rad (7); 1 rad (8).

As it is possible to see the ratio U_2/U_1 can be very big, when $P < P_n$. And the voltage variation by variation of a ratio P/P_n is very big for the long line.

That means it is impossible to operate of long lines without compensation of their reactive power.

In order to exclude such voltage variation by variation of the loading of a line it is necessary to compensate the reactive power of a line. One of the possibility is to provide a compensation of the reactive power of a line in accordance with the relation (2). That means the necessary shunt compensator is to vary its power in accordance with the ratio (2). In this case the reactive component in formulas (6) and (7) will be absent and the voltage distribution along the line will be determined by next relation

$$\frac{U_x}{U_2} \approx \sqrt{1 + \frac{R_0 x}{z} \frac{P}{P_n} \left(1 + \frac{\sin 2\lambda_x}{2\lambda_x} \right)} \quad (8)$$

Respectively the ratio U_1/U_2 will be equal to

$$\frac{U_1}{U_2} \approx \sqrt{1 + \frac{R}{z} \frac{P}{P_n} \left(1 + \frac{\sin 2\lambda}{2\lambda} \right)} \quad (9)$$

For example for 750 kV line the active resistance is equal to

$$R = \frac{\rho \ell}{F_a} = \frac{28.3 \cdot \ell}{5 \times 330} = 0.017 \ell,$$

where active cross section of a phase conductors is equal to $F_a \approx 5 \times 330 \text{ mm}^2$ and the length of a line is in kilometers. Taking into account the value of surge impedance $z = 250 \text{ Ohm}$ we obtain

$$\begin{aligned} \frac{U_1}{U_2} &= \sqrt{1 + 0.069 \cdot 10^{-3} \ell \frac{P}{P_n} \left(1 + \frac{\sin 2\lambda}{2\lambda} \right)} \approx \\ &\approx 1 + 0.034 \cdot 10^{-3} \ell \frac{P}{P_n} \left(1 + \frac{\sin 2\lambda}{2\lambda} \right) \end{aligned}$$

where ℓ is the length of a line in kilometers.

The results of calculations by means of this formula by $P/P_n = 1$ are presented in the next table.

ℓ , km	500	1000	1500	2000	2500	3000
U_1/U_2	1.031	1.048	1.051	1.054	1.071	1.10

As it is possible to see the ratio U_1/U_2 is in the range of 1.05 up to 2000 km by transmission of P_n . These results are significantly different from the data of Fig.1. That means the variable compensation of line's reactive power allows to solve completely the problem of voltage stabilization along the long lines by transmission of SIL. The necessary variable compensation of the line's reactive power can be provide by means of static compensator of transformer type developed in SPSPU [2]. The main scheme of this compensator is presented in Fig.2.

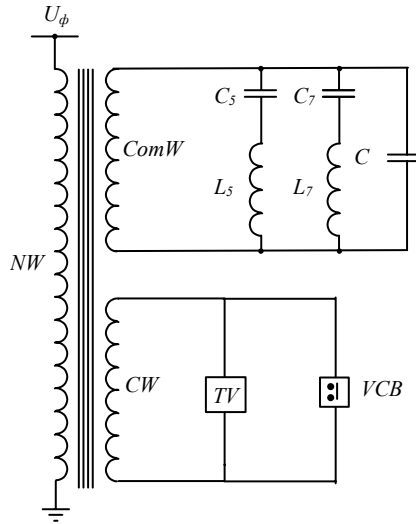


Fig.2. The single line scheme of fast-acting controllable shunt compensator of a transformer type: NW – network winding; CW – control winding; ComW – compensating winding; C_5 - L_5 and C_7 - L_7 – filters of fifth and seventh harmonics; C – capacitive battery, TV – thyristors valve, VCB – vacuum circuit breaker.

Its HV network winding is connected always with a line's conductor. Its control winding is operated by means of thyristor control system. Third compensating winding provides a damping of highest harmonics in the current through NW and the generation of capacitive current in this winding when thyristor's valve is closed (the current in a control winding is equal to zero). On the contrary when thyristor's valve is completely open (the current in a control winding is the maximum) the current through a network winding is the maximum inductive. By intermediate firing angle of a thyristor's valve we can obtain all intermediate values of a current through the network winding of compensator (see Fig.3).

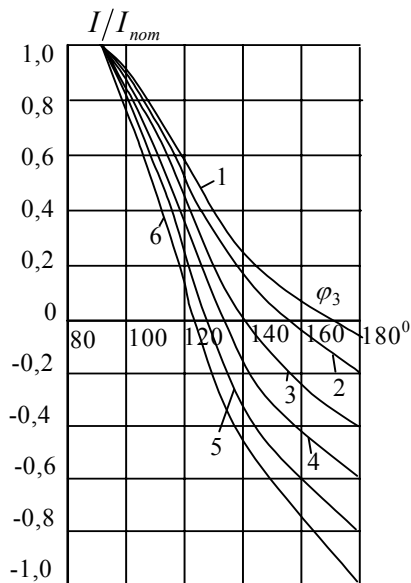


Fig.3. The relative value of current through NW versus firing angle of thyristor's by different value of ratio between maximum capacitive and inductive currents: 1 – 0.043; 2 – 0.2; 3 – 0.4; 4 – 0.6; 5 – 0.8; 6 – 1.0

Using different capacitor's battery, connected with a compensating winding, it is possible to provide different ratio of maximum capacitive and inductive currents in the network winding.

The main peculiarity of a transformer structure, which was developed for such compensator, is its internal inductance, which is near hundred percent. That means the current is nominal when the control winding is short circuited.

The response time of this type of compensator is equal to one half of the power frequencies circle (if it is 50 Hz the response time is equal to 10 mS). Such small response time allows to provide a deep limitation of switching overvoltages, because always during the power circuit-breaker operation this compensator is able to provide any necessary grade of a reactive power compensation up to 100% [3].

The possibility to obtain capacitive current in the network winding provides the possibility of electrical energy transmission above SIL (see Fig.4) [4].

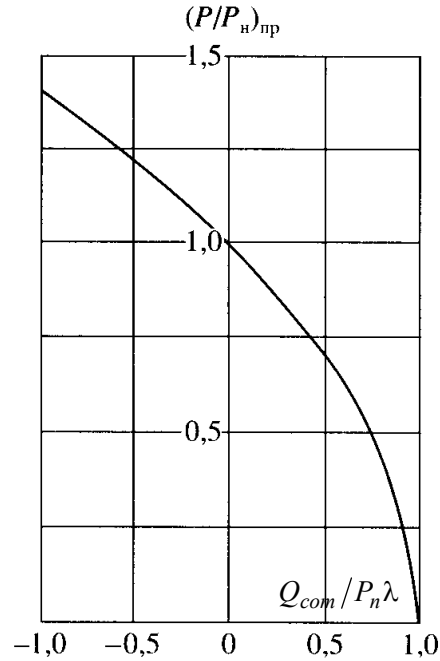


Fig.4. The permissible ratio of a transmitted power to SIL versus the ratio of a compensator capacity Q_{com} and $P_n \lambda$.

In order to limit voltage variation in all points of the line it is necessary to limit the distance between neighboring compensators along the line. The biggest increase of the voltage on the link of a line between two neighboring compensator corresponds to the idle regime of a line operation. The maximum increase of the voltage state place at the middle of a line and it is equal to

$$\frac{U_{\max}}{U_0} = \cos \frac{\lambda_0}{2} \quad (11)$$

where U_0 is the voltage at the place of a compensator installation, λ_0 is the wave length of the link between two compensators

ℓ , km	100	200	300	400
$U_{\max}/U_0$	1.001	1.006	1.012	1.022

ℓ , km	500	600	700	800
$U_{\max}/U_0$	1.035	1.05	1.07	1.095

If the distance between two neighboring compensator is 300-400 km the increase of a voltage at the middle of a link between two compensator is negligible. If the distance between two compensators ℓ_0 is bigger than 400 the ratio $U_{\max}/U_0$ increases very rapidly.

Steady –state stability

The lines with such compensators have perfect characteristics. Really the uncompensated value of a line's capacitance is equal to

$$C_{n.c} = C_{eq} = C \cdot \left(\frac{P}{P_n} \right)^2 \quad (12)$$

That means by transmission of SIL ($P=P_n$) the equivalent capacitance is equal to a physical value C . In idle regime of a line operation ($P=0$) total capacitance of a line is compensated. Because we do not utilize a series compensation of a line's the inductance of a line it is always constant and it is equal to the physical one L .

The surge impedance of a line with compensators is equal to

$$z_{eq} = \sqrt{\frac{L}{C_{eq}}} = \sqrt{\frac{L}{C}} \frac{P_n}{P} = z \frac{P_n}{P}. \quad (13)$$

That means by transmission of SIL the equivalent impedance z_{eq} is equal to physical value. But in idle regime of a line operation it is infinite.

Respectively equivalent SIL of a line

$$P_{n.eq} = \frac{3U_{ph}^2}{z_{eq}} = \frac{3U_{ph}^2}{z} \frac{P}{P_n} = P$$

(14)

That means any values of electrical power transmitted through such line are similar to SIL.

And at last the equivalent value of line's wave length is equal to

$$\begin{aligned} \lambda_{eq} &= \frac{\omega \ell}{v_{eq}} = \omega \ell \sqrt{LC_{eq}} = \omega \ell \sqrt{LC} \frac{P}{P_n} = \\ &= \frac{\omega \ell}{v} \frac{P}{P_n} = \lambda \frac{P}{P_n} \end{aligned} \quad (15)$$

That means if $P=P_n$ the equivalent wave length of a line is equal to its physical value $\lambda_{eq} = \lambda$ and if $P=0$ the value of $\lambda_{eq} = 0$. It is necessary to note that the value of λ_{eq} is equal to the angle between the voltage vectors at both ends of a line $\delta = \lambda_{eq}$. In accordance with (15) the transmitted power

$$P = P_n \frac{\delta}{\lambda}. \quad (16)$$

The derivative of a transmitted power on the angle δ is equal to

$$\frac{dP}{d\delta} = \frac{P_n}{\lambda} \quad (17)$$

This derivative is always positive independ on the length of a line. This is the important sign that the line with controllable compensators is always stable. That means the steady-state stability of the line with controllable compensators is provided automatically.

Reference

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