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Reactive Power Control in Electrical Power Transmission System

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Abstract
In this paper, an understanding of reactive power associated with power transmission networks is developed. To make transmission networks operate within desired voltage limits, methods of making up or taking away reactive power—hereafter called reactive-power control—are discussed. Before proceeding further, however, a thorough understanding of the reactive power in ac systems is necessary.
This paper is not intended to provide a comprehensive analysis of transmission lines. Rather, its objective is to examine those aspects that enhance the understanding of the interplay between voltages on the line and the resulting reactive-power flows.

Keywords: **Transmission Line, Facts controller**

1. Introduction

Upon energization, the ac networks and the devices connected to them create associated time-varying electrical fields related to the applied voltage, as well as magnetic fields dependent on the current flow. As they build up, these fields store energy that is released when they collapse. Apart from the energy dissipation in resistive components, all energy-coupling devices, including transformers and energy-conversion devices (e.g., motors and generators), operate based on their capacity to store and release energy.

For the ac circuit shown in Fig.1(a), instantaneous power from the voltage source to the load $Z\angle\phi$, in terms of the instantaneous voltage v and current i, is given as

$$p = vi \qquad 1.1$$

In the steady state, where $V = V_{max}\cos(\omega t)$ and $I = I_{max}\cos(\omega t - \varphi)$:

$$P_c = \frac{V_{max}\, I_{max}}{2}\, [\cos\phi + \cos(2\omega t - \phi)]\ V$$

$$= V\, I \cos\phi\,(1 + \cos 2\omega t) + V\, I \sin\phi \sin 2\omega t \qquad 1.2$$

where V and I are the respective root mean square (rms) values of *v* and *i*.
Equations (1.1) and (1.2) are pictorially represented in Fig.1(b). Equation (1.2) comprises two double-frequency (2q) components. The first term has an average value as well as a peak magnitude of VI cos f. This average value is the active power, P, flowing from the source to the load. The second term has a zero average value, but its peak value is VI sinϕ. Written in phasor domain, the complex power in the network in Fig.1(a) is given by

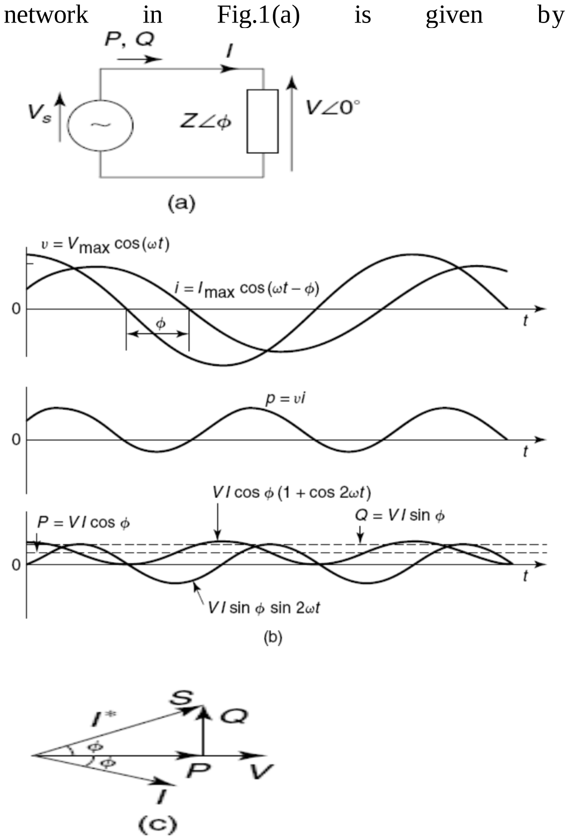

Figure .1 The electrical parameters in an ac network.

$$S = \bar{V}\,.\,\bar{I}^*$$

$$= P + jQ = V\, I \cos\phi + j\, VI \sin\phi \qquad 1.3$$

where P is called the active power, which is measured in watts (W), and Q is called the reactive power, which is measured in volt–ampere reactives (var). Comparing Eqs. (1.3) and (1.2), the peak value of the second component of instantaneous power in Eq. (1.2) is identified as the reactive power.

The reactive power is essential for creating the needed coupling fields for energy devices. It constitutes voltage and current loading of circuits but does not result in an average (active) power consumption and is, in fact, an important component in all ac power networks. In high-power networks, active and reactive powers are measured in megawatts (MW) and MVAR, respectively. Figure1(c) shows a commonly used power triangle.

Electromagnetic devices store energy in their magnetic fields. These devices draw lagging currents, thereby resulting in positive values of Q; therefore, they are frequently referred to as the absorbers of reactive power. Electrostatic devices, on the other hand, store electric energy in fields. These devices draw leading currents and result in a negative value of Q; thus they are seen to be suppliers of reactive power. The convention for assigning signs to reactive power is different for sources and loads, for which reason readers are urged to use a consistent notation of voltage and current, to rely on the resulting sign of Q, and to not be confused by absorbers or suppliers of reactive power.

2. UNCOMPENSATED TRANSMISSION LINES - A Simple Case.

To develop a good, qualitative understanding of the need for reactive-power control, let us consider a simple case of a lossless short-transmission line connecting a source Vs to a load Z∠ϕ. (For simplicity, the line is represented only by its inductive reactance X*l*.) Fig.1 shows such a network with its parameters, as well as a phasor diagram showing the relationship between voltages and currents. From Fig.1(b), it is clear that between the sending- and the

receiving-end voltages, a magnitude variation, as well as a phase difference, is created. The most significant part of the voltage drop in the line reactance ($\Delta V1 = jIxXl$) is due to the reactive component of the load current, Ix. To keep the voltages in the network at nearly the rated value, two control actions seem possible:

1. load compensation, and
2. system compensation.

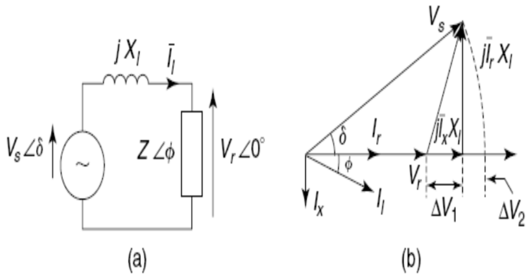

Figure. 2 A short, lossless transmission line feeding a load.

3. Load Compensation

It is possible to compensate for the reactive current Ix of the load by adding a parallel capacitive load so that Ic = − Ix. Doing so causes the effective power factor of the combination to become unity. The absence of Ix eliminates the voltage drop ΔV_1, bringing Vr closer in magnitude to Vs; this condition is called load compensation. Actually, by charging extra for supplying the reactive power, a power utility company makes it advantageous for customers to use load compensation on their premises.

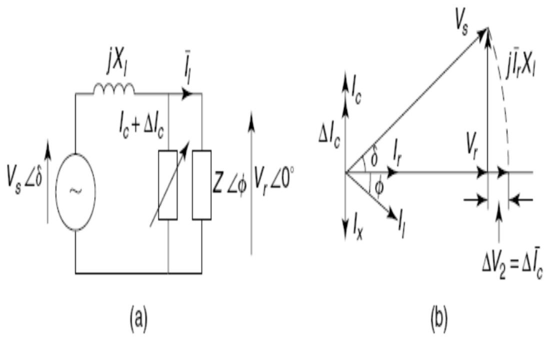

Figure. 3 The reactive-power control for voltage regulations.

Loads compensated to the unity power factor reduce the line drop but do not eliminate it; they still experience a drop of ΔV_2 from $j\bar{I}rXl$.

4. System Compensation

To regulate the receiving-end voltage at the rated value, a power utility may install a reactive-power compensator as shown in Fig.3. This compensator draws a reactive current to overcome both components of the voltage drop ΔV_1 and ΔV_2 as a consequence of the load current Il through the line reactance X*l*. To compensate for ΔV_2, an additional capacitive current, ΔIc, over and above Ic that compensates for Ix, is drawn by the compensator. When $\Delta IcXl = \Delta V_2$, the receiving-end voltage, Vr, equals the sending-end voltage, Vs. Such compensators are employed by power utilities to ensure the quality of supply to their customers [1].

5. Lossless Distributed Parameter Lines

Most power-transmission lines are characterized by distributed parameters: series resistance, r; series inductance, l; shunt conductance, g; and shunt capacitance, c; all per-unit (pu) length. These parameters all depend on the conductors' size, spacing, clearance above the ground, and frequency and temperature of operation. In addition, these parameters depend on the bundling arrangement of the line conductors and the nearness to other parallel lines.

The characteristic behavior of a transmission line is dominated by its l and c parameters. Parameters r and g account for the transmission losses. The fundamental equations governing the propagation of energy along a line are the following wave equations:

$$\frac{d^2 \bar{V}}{dx^2} = zy \ \bar{V} \qquad 1.4a$$

$$\frac{d^2 \bar{I}}{dx^2} = zy \ \bar{I} \qquad 1.4b$$

where zy=(r + jωl)(g + jωc).

For a lossless line, the general solutions are given as

$$\bar{V}(x) = \bar{V}s \cos \beta x - jZ0 \ \bar{I}s \sin \beta x \qquad 1.5a$$

$$\bar{I}(x) = \bar{I}s \cos \beta x - j\frac{\bar{V}s}{Zo} \sin \beta x \qquad 1.5b$$

These equations are used to calculate voltage and current anywhere on line, at a distance x from the sending end, in terms of the sending-end voltage and current and the line parameters. In Eqs. (1.4) and (1.5),

$Zo = \sqrt{\frac{l}{c}}\ \Omega$ = the surge impedance or characteristic impedance

$\beta = \omega\sqrt{lc}$ rad / km = the wave number

$\beta a = \omega\sqrt{lca}$ rad = the electrical length of an a-km line

where l is the line inductance in henries per kilometer (H / km), c is the line shunt capacitance in farads per kilometer (F / km), and $1\sqrt{lc}$ is the propagation velocity of electromagnetic effects on the transmission line. (It is less than the velocity of light.)

From Eq. (1.5), we get

$$\bar{I}s = \frac{\bar{V}s \cos \beta a - \bar{V}r}{jZo \sin \beta a}$$

If $\bar{V}s$ = Vs∠0° and $\bar{V}s$ = Vr∠-δ (cos δ - j sin δ), then

$$Is = \frac{Vr \sin \delta + j(\ Vr \cos \delta - Vs \cos \beta a\ )}{jZo \sin \beta a}$$

1.6

Therefore, the power at the sending end is given as

Ss = Ps + jQs = $\bar{V}s.\ \bar{I}s^*$

$$= \frac{Vs\ Vr\ \sin\ \delta}{Zo \sin\ \beta a} + \frac{V^2 s \cos \beta a - Vs\,Vr \cos\ \delta}{Zo \sin\ \beta a} \qquad 1.7$$

Likewise, power at the receiving end is given as

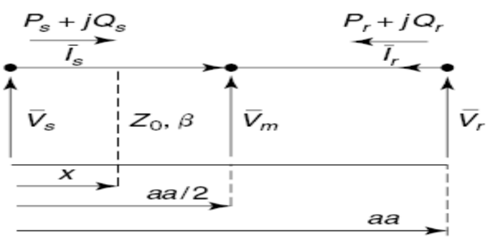

Figure. 4 The power on a lossless distributed line.

$Sr = Pr + jQr$

$$= -\frac{Vs\ Vr\ \sin\ \delta}{Zo \sin\ \beta a} + j\frac{V^2 s \cos \beta a - Vs\,Vr \cos\ \delta}{Zo \sin\ \beta a} \qquad 1.8$$

Comparing Eqs. (1.7) and (1.8) and taking the directional notation of Fig. 1.4 into account, it is concluded that for a lossless line, Ps = −Pr , as expected.

However, Qs ≠ Qr because of the reactive-power absorption / generation in the line.

From Eqs. (1.7) and (1.8), the power flow from the sending end to the receiving end is expressed as

$$P = \frac{Vs\ Vr\ \sin\ \delta}{Zo \sin\ \beta a}$$

In electrically short power lines, where ba is very small, it is possible to make a simplifying assumption that sin βa = βa or Z_0 sin βa=Z_0βa= ωla, where ωla =X*l* is the total series reactance of a line. This substitution results in the following well-recognized power equation:

$$P = \frac{Vs\ Vr}{Xl} \sin \delta \qquad 1.9$$

Accordingly, the maximum power transfer is seen to depend on the line length. When the power-transfer requirement for a given length of a line increases, higher transmission voltages of Vs and Vr must be selected.

6. Symmetrical Lines

When the voltage magnitudes at the two ends of a line are equal, that is, Vs =Vr = V, the line is said to be symmetrical. Because power networks operate as voltage sources, attempts are made to hold almost all node voltages at nearly rated values. A symmetrical line, therefore, presents a realistic situation. From

Eqs. (1.7) and (1.8) the following relationships are derived:

$$Ps - Pr = \frac{V^2}{Zo \sin \beta a} \sin \delta \qquad 1.10$$

And

$$Qs - Qr = \frac{V^2 \cos \beta a - V^2 \cos \delta}{Zo \sin \beta a} \qquad 1.11$$

Active and reactive powers of a transmission line are frequently normalized by choosing the surge-impedance load (SIL) as the base. The SIL is defined as

$P_0 = V^2nom / Z_0$, where Vnom is the rated voltage. When Vs = Vr = Vnom,

$$\frac{Ps}{Po} = -\frac{Pr}{Po} = \frac{\sin \delta}{\sin \beta l}$$

1.12

and

$$\frac{Qs}{Qo} = -\frac{Qr}{Qo} = \frac{\cos \beta a}{\sin \beta a} = \frac{\cos \delta}{\sin \beta a} \qquad 1.13$$

7. Midpoint Conditions of a Symmetrical Line

The magnitude of the midpoint voltage depends on the power transfer. This voltage influences the line insulation and therefore needs to be well understood. For a symmetrical line where the end voltages are held at nominal values, the midpoint voltage shows the highest magnitude variation. In terms of the midpoint voltage $\bar{V}m$, the receiving-end voltage of a symmetrical line, from Eq. (1.4), is given as

$$\bar{V}r = Vm \cos \frac{\beta a}{2} - jZo\ \bar{I}m \sin \frac{\beta a}{2} \qquad 1.14$$

For simplification, define Vm = Vm∠0° as the reference phasor. Because the line is symmetrical and lossless, that is, Ps = − Pr = Pm = P and Qm = 0, the midpoint current Im is given by Im = P / Vm. Under these conditions, Eq. (1.14) can be rewritten as

$$\bar{V}r = Vm \cos \frac{\beta a}{2} - jZo \frac{P}{Vm} \sin \frac{\beta a}{2}$$

or

$$V^2r = V^2m \cos^2 \frac{\beta a}{2} + Z^2o \frac{p^2}{V^2m} \sin^2 \frac{\beta a}{2}$$

Setting Vr = Vnom and V² nom / Z_0 = P_0, we get

$$\frac{V^2r}{V^2nom} = \left(\frac{Vm}{Vnom}\right)^2 \cos^2 \frac{\beta a}{2} + \left(\frac{Zo}{V^2nom}\right)^2 P^2$$

$$\times \left(\frac{Vnom}{Vm}\right)^2 \sin^2 \frac{\beta a}{2}$$

If we let Vm / Vnom = $\tilde{V}m$ (per-unit voltage at the midpoint), then considerng that (Vr / Vnom) =1, we have

$$\tilde{V}^4m - \frac{\tilde{V}^2m}{\cos^2 \frac{\beta a}{2}} + \left(\frac{p}{p^0}\right) \tan^2 \frac{\beta a}{2} = 0$$

Therefore

$$\tilde{V} = \left[\frac{\tilde{V}^2m}{2 \cos^2 \frac{\beta a}{2}} \sqrt{\frac{1}{4 \cos^2 \frac{\beta a}{2}} + \left(\frac{p}{p^0}\right)^2 \tan^2 \frac{\beta a}{2}}\right]^{½} \qquad 1.15$$

Equation (1.15) determines the midpoint voltage of a symmetrical line as a function of the power flow P on it.

Practical Considerations In general, the values of line parameters l and c remain reasonably independent of the transmission voltage. For example, typical values of l and c may lie in the following ranges:

l = the line inductance / km = 0.78–0.98 mH / km

c = the line capacitance / km = 12.1–15.3 nF / km

On the basis of these parameters, the surge impedance, Z_0 $\sqrt{lc}$, lies in the range of 225 to 285.

8. Case Study

To illustrate a number of important considerations, let us choose a 735-kV symmetrical lossless transmission line with l = 0.932 mH / km, c =12.2 nF / km, and a line length of 800 km. From the foregoing Parameters

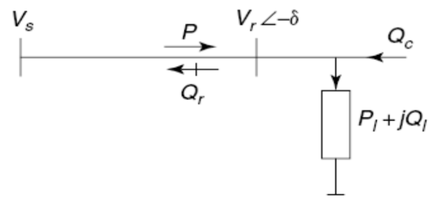

Figure. 5 The reactive-power balance at the receiving end.

$$Zo = \sqrt{\frac{l}{c}} = \sqrt{\frac{0.932}{12.2}}\ 10^3 = 276.4\ \Omega$$

Therefore, the SIL is

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

For this line to operate as a symmetrical line, that is,

Vs = Vr = 735 kV, we have from Eq. (1.10):

$$Ps = \frac{V^2}{Zo \sin \beta a} \sin \delta = \frac{735^2}{276.4 \sin \lfloor (\omega\sqrt{lc})\ 800 \rfloor} \sin \delta$$

$$= 2298.5 \sin \delta = \text{MW} = 1.176 Po \sin \delta\ \text{MW} \qquad 1.16$$

It is important to calculate the required additional reactive power to hold the receiving-end voltage to 1 pu (735 kV). Let us assume that connected at the receiving end is a load of fixed power factor 0.9 lagging. For any load condition, the reactive power balance at receiving end bus shown in Fig.5 Qc =Qr +Qi, where Qr is the reactive power flow from the receiving end into the line, Q_1 is the reactive-power component of the load, and Qc is the reactive power needed from the system to hold Vr to the rated value (1 pu).

Figure.6 shows Qr / P_0, Ql / P_0 and Qc / P_0 as functions of P / P_0. It should be observed that at no load (P = 0), nearly 1090-MVAR or 0.557-pu reactive power must be absorbed to hold the receiving-end voltage to 1 pu. To avoid over insulating the line so that it might withstand over voltages under no-load or light conditions, a common practice is to permanently connect shunt reactors at both ends to allow line energization from either end. Unfortunately, this natural

protection becomes a liability under increased load conditions, for extra reactive power, Qc, is needed to hold the terminal bus voltages at the desired level. The midpoint voltage of this line is calculated using Eq. (1.15), and typical voltage distribution on a distributed line is shown in Fig.7.

Alternatively, consider the receiving half of the line. From Eq. (1.7), the power flow on the line is given as

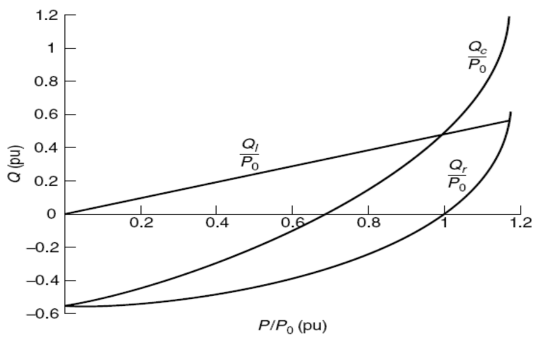

Figure. 6 The reactive-power flows at the receiving end.

$$Po = \frac{VmVr}{Zo\sin\frac{\beta a}{2}} \sin\frac{\delta}{2} = \frac{V^2nom}{Zo\sin\ \beta a} \sin\delta$$

Because Vr = Vs = Vnom,

$$\tilde{V}m = \frac{Vm}{Vnom}\ \frac{\sin\frac{\beta a}{2}}{\sin\ \beta a}\ \frac{\sin\ \delta}{\sin\ \delta/2}$$

$$= 0.5724\,\frac{\sin\ \delta}{\sin\ \delta/2} \qquad 1.17$$

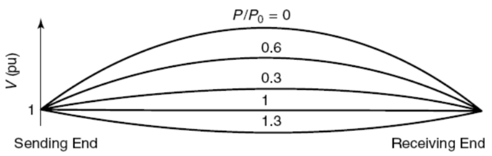

Figure. 7 The typical voltage distribution on a distributed line.

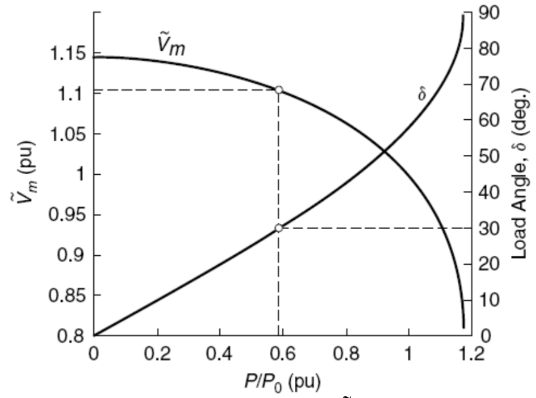

Figure. 8 The midpoint voltage, Ṽ, and load angle, d, as functions of P / P_0.

Fig.8 shows the load angle d and the midpoint-normalized per-unit voltage (Ṽ m) as functions of P / P_0 per-unit power transfer on the line. For this line, it is observed that for light loading below the surge-impedance load, the midpoint voltage exceeds Vnom and reaches its highest value at no load. Furthermore, for stability considerations should an operating load angle of, say, 30° be chosen to define the full-load rating of the line (0.588P_0), the midpoint voltage of the line will be 1.1058 pu. These expected over voltages in the range 0.1–0.2 pu from full load to no load are not within acceptable limits. Therefore, special techniques must be used to control these over voltages.

It is possible to control the overall voltage profile of such a line as the one described in this case study by creating a midpoint voltage bus and connecting a controllable reactive-power source, called a var compensator, to it so that below the surge-impedance loading P_0, the var compensator absorbs reactive power, and above P_0, it supplies reactive power.

Fig.9 shows a midpoint var compensator employed as a voltage controller and the expected voltage profile along the line. Of course, it is not important to hold the midpoint voltage Vmc at 1-pu voltage, especially if there is no load connected to it. Also, it is not necessary to have a controllable var source at the midpoint; instead, an adequately sized fixed- or switched-shunt reactor could be used to keep the overvoltage within limits.

To continue this discussion with the aid of the case study, let us hold the midpoint voltage to Vmc under all load conditions by employing a continuous var controller of unlimited capacity. Using Eq. (1.7), we have control: Vmc = 1 pu.

$$Qm = \frac{V^2mc\ \cos\ \frac{\beta a}{2} - Vs\,Vcm\,\frac{\delta}{2}}{Zo\sin\ \frac{\beta a}{2}} \qquad 1.18$$

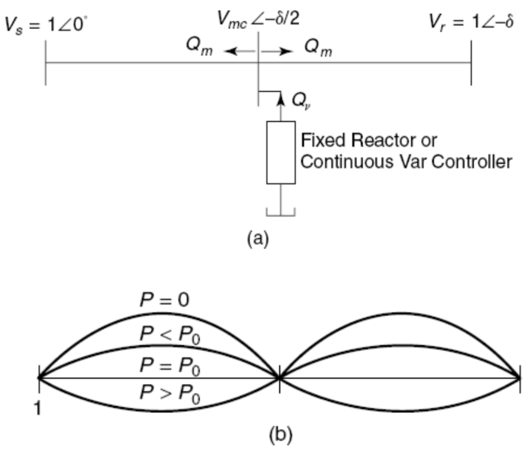

Figure. 9 The midpoint-overvoltage

Therefore, the var requirement from the midpoint var controller is

Qv = 2Qm 1.19

In terms of the midpoint voltage, we can rewrite the power transfer of the line given by Eq. (1.7) as

$$Pcomp = \frac{Vs\,Vmc}{Zo\sin\ \beta a/2}\sin\frac{\delta}{2} \qquad 1.20$$

For the 735-kV, 800-km line with $\beta = 1.27 \times 10^{-3}$ rad / km, and assuming Vs = Vr = 1 pu and Vmc = 1.05 pu, we get

$$\beta\frac{a}{2} = \beta \times 400 = 0.508 \text{ rad}$$

$$Pcomp = \frac{735^2 \times 1.05}{276.4\sin(0.508)}\sin\frac{\delta}{2}$$

$$= 4215.28\sin\frac{\delta}{2} = 2.157Po\sin\frac{\delta}{2}$$

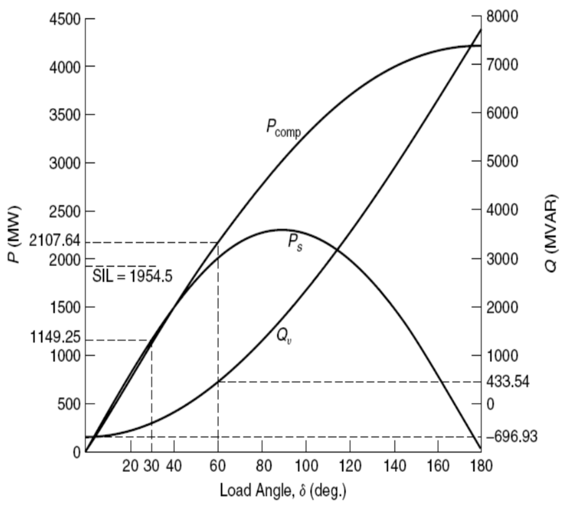

Figure. 10 The relationship between active power, P, and reactive power, Q, with load angle δ in the 735-kV midpoint-compensated line.

Qv = 2Qm

$$= 2 \times \frac{(1.05 \times 735)^2\cos(0.508) - 735^2 \times 1.05\cos\frac{\delta}{2}}{276.4\sin(0.508)}$$

$$= 7740.98 - 8437.91\cos\frac{\delta}{2} = (3.96 - 4.32\cos\frac{\delta}{2})\ Po$$

Fig.10 depicts the following relations:

Ps = 2298.5 sin δ MW = the uncompensated line.

Pcomp = 4215.28 sin (δ / 2) MW = the unlimited midpoint compensation to hold Vmc = 1.05 pu.

Qv = 7740.98 − 8437.91 cos (d / 2) MVAR = the reactive power injected by the compensator SIL of the line.

P_0 = 1954 . 5 MW.

The results of Fig.10 need careful interpretation. Note the following:

1⟹ If the nominal rating of a line might correspond to δ = 30°, the 735-kV, 800-km symmetric line in this case study will be rated at Pnom = 22985 sin(30°) = 1149.25 MW, which is only 58.8% of the SIL.

2⟹ If the preceding 735-kV symmetric line is provided with unlimited midpoint reactive-power compensation, Qv, to hold the midpoint voltage, Vmc, at 1.05 pu, then the maximum transferable power increases from 2298.5 MW (Ps in the uncompensated case) to 4215.28 MW (Pcomp in the compensated case), implying a ±83.39% increase. The nominal rating for this line could be 2107.64 MW (or 108% of SIL) for δ = 60°

3⟹ To maintain the midpoint voltage, Vmc, of the 735-kV symmetric line at 1.05 pu, the midpoint compensator's var supply would range from −696.93 MVAR to 7740.98 MVAR. This is a very large operating range for a line with 1954.5 MW SIL.

Therefore, let us search for a workable solution.

1⟹ Assume that the midpoint-compensated line is rated at δ = 60° for stable operation, that is, Pcomp = 2107.64 MW, with a nominal rating ($1.08P_0$).

2⟹ The midpoint-compensator power for d = 60° is Qv = 433.54 MVAR.

3⟹ On the basis of entries 1 and 2, select a realistic midpoint var compensator rated to operate from −600 to +400 MVAR.

The performance of the 735-kV, 800-km symmetric line, with a midpoint var compensator designed to operate at 1.05 pu terminal voltage in a controllable range, can be analyzed as follows: Beyond the limit Qv > 400 MVAR, the var compensator behaves like a fixed capacitor of rating .

$$Xc = \frac{V^2m}{Qv} = \frac{(1.05 \times 735)^2}{400} = 1489\ \Omega$$

In the uncontrollable range, from Eq. (1.18) the corresponding value of Qm in each half of the line is

$$Qm = \frac{V^2m}{2Xc} = \frac{V^2 \cos\frac{\beta a}{2} - VsVm \cos\frac{\delta}{2}}{Zo \sin \frac{\beta a}{2}}$$

or

$$Vm = \frac{Vs \ \cos\frac{\delta}{2}}{\cos\frac{\beta a}{2} - \frac{Zo}{2Xc} \sin\frac{\beta a}{2}}$$

$$= \frac{735 \ \cos\frac{\delta}{2}}{\cos(0.508) - \frac{276.4}{2 \times 1489}\sin(0.508)}$$

$$= 886.778 \cos\frac{\delta}{2} = 1.2065\text{Vnom} \cos\frac{\delta}{2}$$

From this value of Vm (beyond the controllable capacitor range), the power flow on the line is given as

$$P = \frac{Vs\, Vm \sin \delta/2}{Zo \sin \beta a/2}$$

$$= \frac{735 \times 886.778 \sin\frac{\delta}{2} \cos\frac{\delta}{2}}{276.4 \sin(0.508)}$$

= 2423.9 sin δ

The start of uncontrollable range on the capacitive side of the var compensator corresponds to Qv > 400 MVAR at a value of d calculated from

$$Qv = 400 = 7740.98 - 8437.91 \cos\frac{\delta}{2}$$

or

δ = 59°

Likewise, below *Qv* < - 600 MVAR, the inductive limit of the var compensator is reached at a value of δ calculated from

$$Qv = 400 = 7740.98 - 8437.91 \cos\frac{\delta}{2}$$

or

δ = 17.38°

Thus

P = 4215.28sin(8.69)° = 637.1 MW

The value of the fixed inductor below δ = 17.38° is calculated as

$$Xl = \frac{V^2m}{Qv} = \frac{(735 \times 1.05)^2}{600} = 992.66\ \Omega$$

Since

$$Qm = \frac{-V^2m}{2Xl} = \frac{V^2m \cos\frac{\beta a}{2} - Vs\, Vm \cos\frac{\delta}{2}}{Zo \sin\frac{\beta a}{2}}$$

or

$$Vm = \frac{Vs \cos\frac{\delta}{2}}{\cos\frac{\beta a}{2} - \frac{Zo}{2Xc}\sin\frac{\beta a}{2}}$$

$$= \frac{735 \cos\frac{\delta}{2}}{\cos(0.508) + \frac{276.4}{2 \times 992.66}\sin(0.508)}$$

$$= 780.72 \cos\frac{\delta}{2} = 1.0622\text{Vnom} \cos\frac{\delta}{2}$$

Using the foregoing value of Vm, power in the inductive uncontrollable range of the midpoint var compensator is given as

$$P = \frac{Vs\, Vm \cos\frac{\delta}{2}}{Zo \sin\frac{\beta a}{2}}$$

$$= \frac{735 \times 780.72 \sin\frac{\delta}{2} \cos\frac{\delta}{2}}{276.4 \sin(0.508)}$$

= 2134 sin δ

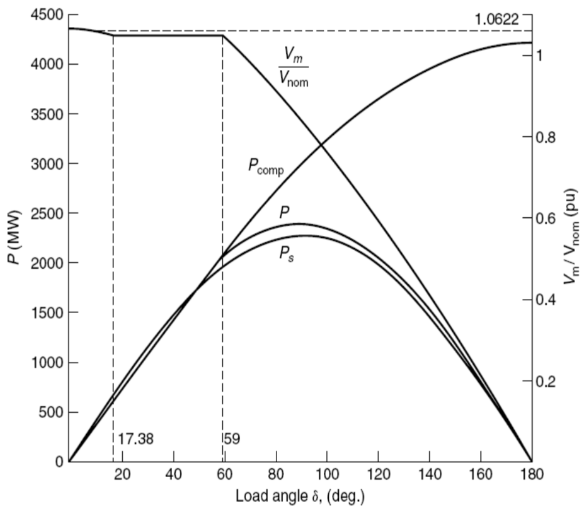

Figure. 11 The relationship between power P, midpoint voltage Vm, and load angle δ of a 735-kV symmetric line compensated by a −600+400 MVAR range–controlled var compensator.

Fig.11 depicts following relations:

Ps = 2298.5 sin d MW = the uncompensated line

Pcomp = 4215.28 sin (δ / 2) MW = the unlimited midpoint compensation to hold Vmc = 1.05 pu
Vm = 1.0622Vnom cos(δ / 2) pu, for 0 < δ ≤ 17.38°
P = 2134 sin δ MW
Vm = 1.05Vnom pu, for 17.38° ≤ δ ≤ 59°
P = 4215.28 sin(≤ / 2) MW
Vm = 1.2065Vnom cos(≤ / 2) pu, for 59° ≤ δ ≤ 180°
P = 2423.9 sin ≤ MW

Fig.11 shows the results of a symmetric 735-kV, 800-km lossless line where, at its midpoint, a controllable var compensator is installed that holds the midpoint voltage at 1.05-pu value. The var compensator has a fully controllable range of −600 MVAR to +400 MVAR. Beyond the +400-MVAR limit, the compensator behaves like a fixed capacitor (Xc = 1489 Ω); below − 600 MVAR, it acts like a fixed inductor (X_l =992.66 Ω). It should be observed that under these circumstances, the maximum power transfer of the line is modified to 2423.9 MW, and the maximum overvoltage of the midpoint is limited to 1.062 pu.

9. The conclusions are as follows:

1⇒ As the length of the line increases on account of the line-charging capacitances, the line experiences significant overvoltages at light-load conditions.

2⇒ Over voltages can be limited by using fixed- or switched-shunt reactors at the line ends as well as at intermediate buses where needed.

3⇒ The application of midpoint or intermediate bus-voltage controllers (var compensators) enhances the power-transmission capacity of a long line.

4⇒ In practical cases, var controllers are sized by carefully selecting their continuous-operating range to hold the connecting-bus voltage within an acceptable range of values in the normal line-loading range.

Active and Passive Var Control When fixed inductors and/ or capacitors are employed to absorb or generate reactive power, they constitute passive control. An active var control, on the other hand, is produced when its reactive power is changed irrespective of the terminal voltage to which the var controller is connected.

10. PASSIVE COMPENSATION

In the foregoing discussion, a lossless line was analyzed, and the case study presented in Section 2 provided many numerical results and highlighted the problems of voltage control and the need to exercise reactive-power control to make a system workable. Reactive-power control for a line is often called reactive-power compensation. External devices or subsystems that control reactive power on transmission lines are known as compensators. Truly speaking, a compensator mitigates the undesirable effects of the circuit parameters of a given line. The objectives of line compensation are invariably

1⇒ To increase the power-transmission capacity of the line, and **/** or

2⇒ To keep the voltage profile of the line along its length within acceptable bounds to ensure the quality of supply to the connected customers as well as to minimize the line-insulation costs.

Because reactive-power compensation influences the power-transmission capacity of the connected line, controlled compensation can be used to improve the system stability (by changing the maximum power-transmission capacity), as well as to provide it with positive damping. Like other system components, reactive-power compensators are dimensioned, and their types are selected on the basis of both their technical and cost effectiveness.

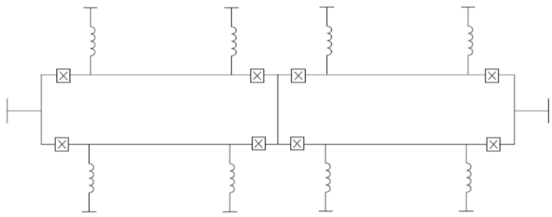

Figure. 12 The two sections of a double-circuit high-voltage ac line for long-distance Transmission.

11. Effect on Power-Transfer Capacity

The consideration of series compensation invariably raises the issue of its comparison with shunt compensation. A simple system analysis can be performed to develop a basic understanding of the effect of shunt and series compensation on power-transmission capacity.

Consider a short, symmetrical electrical line as shown in Fig.13. For an uncompensated line, and assuming Vs = Vr = V, the power equation (1.9) becomes

$$P = \frac{V^2}{Xl}\sin\delta = \frac{V^2}{Xl}\,2\sin\frac{\delta}{2}\cos\frac{\delta}{2} \qquad 1.21$$

From the voltage-phasor equations and the phasor diagram in Fig.13(a),

$$Il = \frac{2V}{Xl}\sin\frac{\delta}{2} \qquad 1.22$$

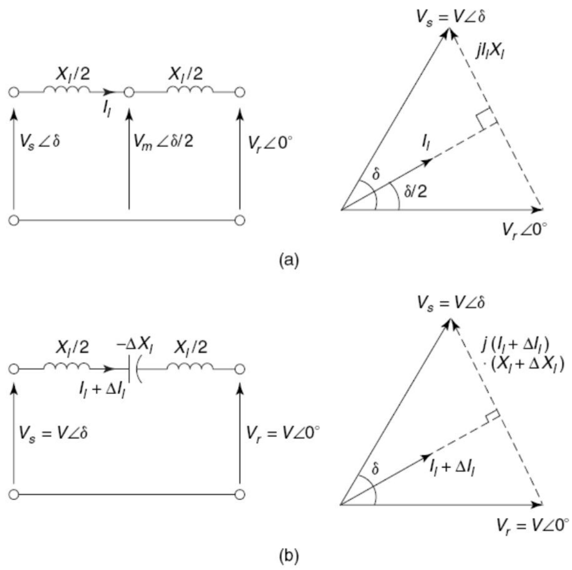

Figure. 13 The series compensation of a short, symmetrical transmission line.

12. Series Compensation

If the effective reactance of a line is controlled by inserting a series capacitor, and if the line terminal voltages are held unchanged, then a ΔX_l change in the line reactance will result in a ΔI_l change in the current, where

$$\Delta I_l = -\frac{2V}{X^2 l}\sin\frac{\delta}{2}\, X_l = -I_l\,\frac{\Delta Xl}{Xl} \qquad 1.23$$

Therefore, from Eq. (1.21), the corresponding change in the power transfer will be

$$\Delta P = -\frac{V^2}{X^2 l}\, 2\sin\frac{\delta}{2}\cos\frac{\delta}{2}\Delta X_l \qquad 1.24$$

Using Eqs. (1.22) and (1.23), Eq. (1.24) may be written as

$$\Delta P = \frac{1}{2\tan\frac{\delta}{2}}\left(-\Delta X_l I^2 l\right)$$

As$-\Delta$Xl is the reactance added by series capacitors, $\Delta X_l I^2 l$ = ΔQse represents the incremental var rating of the series capacitor. Therefore

$$\frac{\Delta P}{\Delta Qse} = \frac{1}{2\tan\frac{\delta}{2}} \qquad 1.25$$

13. Shunt Compensation

Reconsider the short, symmetrical line described in Fig.13(a). Apply a shunt capacitor at the midpoint of the line so that a shunt susceptance is incrementally added (ΔBc), as shown in Fig.14. For the system in this figure, the power transfer in terms of the midpoint voltage on the line is

$$P = \frac{V\,Vm}{\frac{Xl}{2}}\sin\frac{\delta}{2} \qquad 1.26$$

The differential change in power, ΔP, as a result of a differential change, ΔVm, is given as

$$\Delta P = \frac{2}{Xl}\sin\frac{\delta}{2}\,\Delta Vm \qquad 1.27$$

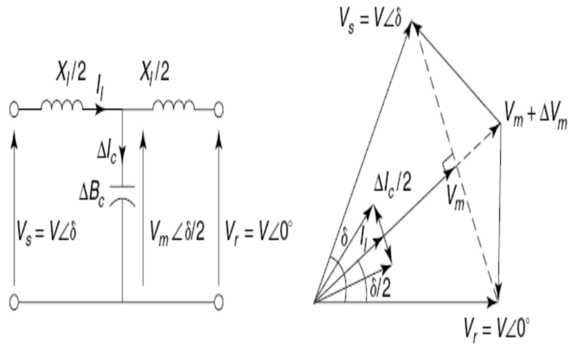

Figure. 14 The midpoint-capacitor compensation of a short, symmetrical line.

Also as shown in Fig.14, ΔIc = Vm ΔBc

The current ΔIc in the midline shunt capacitor modifies the line currents in the sending and receiving ends of the line to the following:

$$Ils = Il - \frac{\Delta Ic}{2} \text{ and } Ilr = Il = + \frac{\Delta Ic}{2}$$

As $Vm = Vr + j\,IlrXl\ /\ 2$,

$$\Delta Vm = \frac{\Delta Ic Xl}{4} = \frac{\Delta Vm Xl}{4}\,\Delta Bc \qquad 1.28$$

Substituting the results of Eq. (1.28) in Eq. (1.27), we get

$$\Delta P = \frac{VVm}{2}\sin\frac{\delta}{2}\,\Delta Bc$$

If the midpoint voltage of the line is approximately equal to V cos δ / 2, then the incremental rating of the shunt-capacitor compensation will be ΔQsh = $V^2 m\Delta Bc$,

or

$$\frac{\Delta P}{\Delta Qsh} = \frac{1}{2}\tan\frac{\delta}{2} \qquad 1.29$$

By comparing Eqs. (1.25) and Eqs. (1.29), we deduce that for an equivalent power transfer on a short electrical line,

$$\frac{\Delta Qse}{\Delta Qsh} = \left(\tan\frac{\delta}{2}\right)^2 \qquad 1.30$$

Assuming an operating load angle δ = 30°, we get the ratio of the ratings of series (ΔQse) to shunt (ΔQsh) compensators to be 0.072, or 7.2%.

From the foregoing discussion, it is clear that the var net rating of the series compensator is only 7.2% of that required of a shunt compensator for the same change in power transfer. Therefore, one concludes that the series-capacitive compensation is not only achieved with a smaller MVAR rating, but also that it is automatically adjusted for the entire range of the line loading. However, the cost of the compensator is not directly related only to the MVAR-rating series capacitor costs increase because they carry full line current and also both their
ends must be insulated for the line voltage.
Practical application of series capacitors requires isolation and bypass arrangements as well as protection and monitoring arrangements. For a com plete discussion of series compensation, it is recommended that readers consult in given references.

14. SUMMARY

This paper elucidated the concepts of reactive power and presented the theoretical bases of reactive-power compensation in electrical transmission systems. A detailed case study was presented in which the principles of shunt-reactive power compensation were illustrated, and a comparative analysis of both series and shunt compensation was included as well.

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