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ANALYSIS OF THE OPPOSITE REACTIVE POWER DIRECTION PHENOMENON ON TWO PARALLEL OVERHEAD TRANSMISSION LINES

ANALIZA POJAVA NASPROTNE JALOVE MOČI NA DVEH VZPOREDNIH NADZEMNIH VODIH

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Abstract

This paper presents an analysis of the opposite reactive power direction phenomenon on two parallel overhead transmission lines. Measurements are performed on transmission lines, recorded using energy meters. Superficial reasoning leads to the conclusion that the measurement system is not trustworthy. In addition, more detailed theoretical analysis shows that the phenomenon is possible and it is not the result of the incorrect measurement, but it is the result of reactive power distribution along the respective transmission lines.

Povzetek

V članku je predstavljena analiza pojava nasprotne jalove moč na dveh vzporednih nadzemnih vodih. Najprej so meritve opravljene na realnem daljnovodu in pojav je posnete z merilniki električne energije. Površno razmišljanje nas pripelje do zaključka, da je sistem merjenja dvomljiva.

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Podrobnejša teoretična analiza pa pokaže, da je ta pojav mogoč in ni posledica nepravilnega merjenja. Vendar je rezultat porazdelitve jalove moči vzdolž posameznih prenosnih vodov.

1 INTRODUCTION

In current power systems, transmission system operators (TSO) are associated with larger organizations in order to satisfy increasing requirements for energy exchange in the competitive market environment. TSOs in Europe are joined to the *European Network of Transmission System Operators for electricity* (ENTSO-E), *[1]*, where the rights and obligations are defined according to REGULATION (EC) No 714/2009 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL, *[2]*. Transmission lines are one of the key unique components of electricity transmission, *[3]*. The rapidly increasing needs for technical and economic compromises in the competitive market environment emphasizes the importance of accurate energy measurements. Therefore, metering points are equipped with modern equipment (accuracy class 0.2) in order to meet all requirements for reliable and accurate measurement, which is the fundamental requirement for the functioning of the TSO in the above-mentioned market environment, *[4].*

2 THE DESCRIPTION OF OPPOSITE REACTIVE POWER DIRECTION PHENOMENON

2.1 The architecture of metering point

Current metering points in the high voltage power system consist of instrument transformers (voltage and current), an energy meter, and connection equipment (see Fig. 1.). The purpose of the metering point is to provide information about the measurand (measured value, i.e. the quantity of interest), *[5, 6]*.

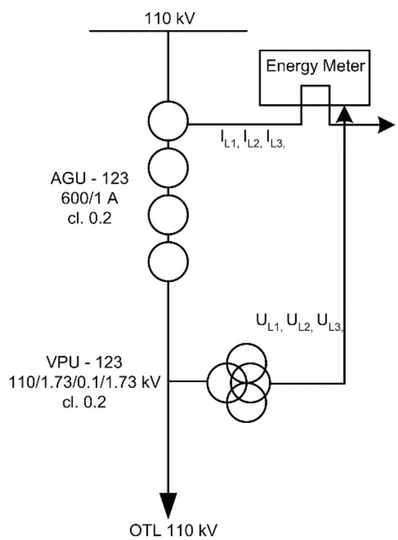

Figure 1: *The principal scheme of metering point*

For more details about the requirements for the instrument transformers and energy meters, the reader is referred to *[7–10]*.

In this paper, two parallel 110 kV overhead transmission lines (OTL) are observed (see Fig. 2). Both lines have their own independent metering point, as presented in Fig. 1.

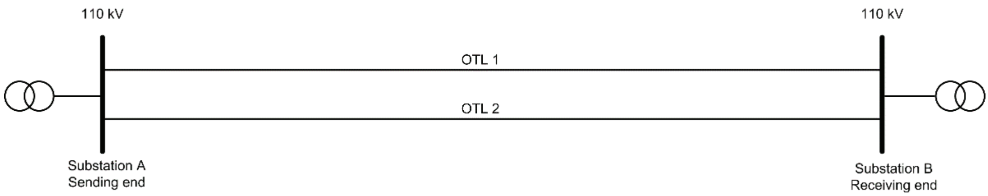

Figure 2: *Two parallel 110 kV overhead transmission lines*

Energy meters, such those as described in *[11, 12]*, measure active and reactive power and energy in two directions. In some measuring periods, the opposite reactive power direction is measured. At first glance, this phenomenon sounds ambiguous. Superficial reasoning leads to the conclusion that the quality of the measurement system is doubtful. However, more detailed analysis is necessary. Additional testing shows the correctness of the measuring system components, and the efforts are directed to an analysis of the electrical conditions on the OTL.

2.2 Measurement results

The measurement was performed on a real transmission line under the jurisdiction of the Croatian Transmission System Operator in the period of 2016/10/20 from 00:00–24:00 h. Owing to confidentiality, we are not able to publish the name of the transmission line.

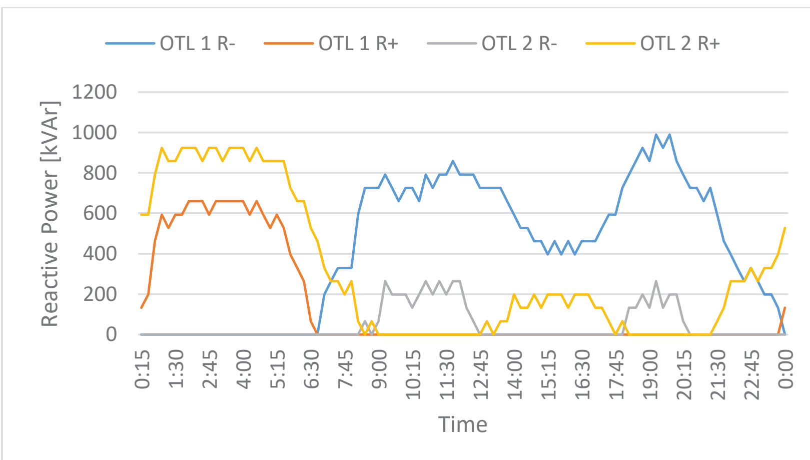

Figure 3: *Measurement results*

Fig. 3 shows the measurement results with the resolution of 15 minutes. In the periods of 6:45–8:00 h and 12:45–18:00 h the reactive powers on OTL 1 and OTL 2 are of the opposite directions, i.e. the opposite reactive power phenomenon is present. In addition, the latter phenomenon would be theoretically analysed and proofed.

3 MATHEMATICAL ANALYSIS OF THE OPPOSITE REACTIVE POWER PHENOMENON

3.1 Theoretical analysis of parallel transmission line electrical conditions

The short transmission line model, as recommended in *[14]*, is used (see Fig 4). OTL parameters are substituted using direct impedance, i.e. using its resistance *R*, inductance *L* and capacitance *C*, *[15]*.

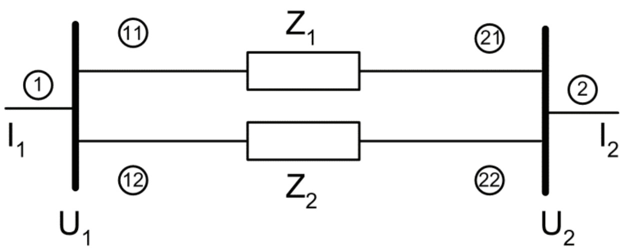

Figure 4: *Equivalent circuit of two parallel 110 kV overhead transmission lines*

Primary OTL parameters are: l_1, l_2 – line length, Z_1, Z_2 – impedances, Y_1, Y_2 – admittances, R_1, R_2 – resistances, L_1, L_2 – inductances and C_1, C_2 – capacitances. Electrical conditions are described using the following quantities: *U* – voltage, *I* – current, *S* – apparent power, *P* – active power and *Q* – reactive power. The indices that would be associated with the respective quantities are: 1 – sending end, 2 – receiving end, i.e. 11 – sending end of the first line, 21 – receiving end of the first line, 12 – sending end of the second line and 22 – receiving end of the second line (see. Fig. 4).

Owing to the calculation correctness, very small (almost negligible) capacitances to the ground should be considered in the calculation procedure. Equivalent impedances in phasor expression are calculated as (3.1) an (3.2)

$$\overline{Z_1} = R_{11}l_1 + j\omega L_{11}l_1, \tag{3.1}$$

$$\overline{Z_2} = R_{12}l_2 + j\omega L_{12}l_2. \tag{3.2}$$

Equivalent admittances are calculated as (3.3) and (3.4)

$$\overline{Y_1} = j\omega C_1, \tag{3.3}$$

$$\overline{Y_2} = j\omega C_2. \tag{3.4}$$

The total equivalent impedance is (3.5)

$$\bar{Z} = \frac{\overline{Z_1 Z_2}}{\overline{Z_1}+\overline{Z_2}}. \tag{3.5}$$

The total equivalent admittance is (3.6)

$$\bar{Y} = \bar{Y_1} + \bar{Y_2}. \tag{3.6}$$

Characteristic impedance of the OTL is (3.7)

$$\bar{Z_C} = \sqrt{\frac{\bar{Z}}{\bar{Y}}}. \tag{3.7}$$

Propagation equation for the entire line length is (3.8)

$$\bar{\Theta} = \bar{\gamma} * l = \alpha + j\beta, \tag{3.8}$$

where α is the attenuation (loss) factor, β is the phase (velocity) factor and $\bar{\gamma}$ is propagation constant, *[13]*. Transmission equations in hyperbolic form, *[16]*, with known conditions at the receiving end of the line (current, voltage) are (3.9) and (3.10)

$$\bar{V_1} = \bar{V_2} * \mathrm{ch}(\bar{\gamma} * l) + \overline{Z_C} * \bar{I_2} * \mathrm{sh}(\bar{\gamma} * l), \tag{3.9}$$

$$\bar{I_1} = \bar{I_2} * \mathrm{ch}(\bar{\gamma} * l) + \frac{\bar{V_2}}{\bar{Z_C}} * \bar{I_2} * \mathrm{sh}(\bar{\gamma} * l). \tag{3.10}$$

With the aim of calculating voltage $\bar{V_1}$ and current $\bar{I_1}$ at the sending end of the line, $sh(\bar{\gamma} \cdot l)$ and $ch(\bar{\gamma} \cdot l)$ components are calculated using (3.11) an (3.12)

$$\mathrm{sh}(\bar{\gamma} \cdot l) = \mathrm{sh}\alpha * \cos\beta + j\ \mathrm{ch}\,\alpha * \sin\beta, \tag{3.11}$$

$$\mathrm{ch}(\bar{\gamma} \cdot l) = \mathrm{ch}\alpha * \cos\beta + j\ \mathrm{sh}\,\alpha * \sin\beta, \tag{3.12}$$

and current $\bar{I_2}$ at the receiving end of the line is calculated considering the respective conditions (power and voltage) (3.13)

$$\bar{I_2} = \frac{P_2{}^{\angle-\varphi}}{\sqrt{3}U_2 cos^{\varphi}}. \tag{3.13}$$

The above-mentioned values describe the conditions at the ends of the line for two parallel lines together. Hence, the respective conditions for both lines individually are to be calculated. From Kirchhoff currents law applied at the sending end of the line follows by (3.14)

$$\bar{I_1} = \overline{I_{11}} + \overline{I_{12}} \xrightarrow{yields} \overline{I_{12}} = \bar{I_1} - \overline{I_{11}}. \tag{3.14}$$

The lines are connected in parallel, and thus the voltages are equal (3.15) and (3.16)

$$\overline{I_{11}} * \overline{Z_1} = \overline{I_{12}} * \overline{Z_2}, \tag{3.15}$$

$$\overline{I_{11}} * \overline{Z_1} = (\bar{I_1} - \overline{I_{11}}) * \overline{Z_2}. \tag{3.16}$$

From (3.16) follows the current $\overline{I_{11}}$ at the sending end of the first line by (3.17)

$$\overline{I_{11}} = \frac{\bar{I_1}\overline{Z_2}}{\overline{Z_1}+\overline{Z_2}}. \tag{3.17}$$

From (3.14) and (3.17) follows the current $\overline{I_{12}}$ at the sending end of the second line. The apparent powers $\overline{S_{11}}$ and $\overline{S_{12}}$ at the sending ends of the lines are calculated as (3.19)

$$\overline{S_{11}} = 3\bar{V_1}\overline{I_{11}}, \tag{3.18}$$

and (3.19)

$$\overline{S_{12}} = 3\bar{V_1}\overline{I_{12}}. \tag{3.19}$$

From Kirchhoff currents law applied at the receiving end of the line, follows (3.20)

$$\overline{I_2} = \overline{I_{21}} + \overline{I_{22}} \xrightarrow{yields} \overline{I_{22}} = \overline{I_2} - \overline{I_{21}}. \tag{3.20}$$

The lines are connected parallel, and thus the voltages are equal by (3.21) and (3.22)

$$\overline{I_{21}} * \overline{Z_1} = \overline{I_{22}} * \overline{Z_2}, \tag{3.21}$$

$$\overline{I_{21}} * \overline{Z_1} = (\overline{I_2} - \overline{I_{21}}) * \overline{Z_2}. \tag{3.22}$$

From (3.22) follows the current $\overline{I_{21}}$ at the receiving end of the first line (3.23)

$$\overline{I_{21}} = \frac{\overline{I_2}\,\overline{Z_2}}{\overline{Z_1}+\overline{Z_2}}. \tag{3.23}$$

From (3.20) and (3.23) follows the current $\overline{I_{22}}$ at the receiving end of the second line. The apparent powers $\overline{S_{21}}$ and $\overline{S_{22}}$ at the sending ends of the lines are calculated as (3.24)

$$\overline{S_{21}} = 3\overline{V_2}\,\overline{I_{21}}, \tag{3.24}$$

and (3.25)

$$\overline{S_{22}} = 3\overline{V_2}\,\overline{I_{22}}. \tag{3.25}$$

3.2 Numerical proof of the opposite reactive power phenomenon

Owing to confidentiality, we are not able to publish the names of the OTLs, but the measurement results are from a real transmission system. Primary parameters of the OTLs are presented in Table 1.

Table 1: *Primary parameters of OTLs*

Parameter	OTL 1	OTL 2
Line length *l*, [km]	4.95	5.64
Resistance *R*, [Ω/km]	0.1388	0.1946
Inductance *L*, [mH/km]	1.3111	1.3528
Capacitance *C*, [nF/km]	8.8872	8.5944

The electrical conditions considered for the purposes of a numerical example are at the moment the opposite reactive powers measured using energy meters. The calculation procedure is started for measured quantities at the receiving end of the OTL: $\overline{U_2} = 110^{\angle 0^\circ}$ kV (line voltage) and $\overline{S_2} = P_2 + jQ_2 = 30 + j2$ MVA.
Other needed OTL parameters are calculated using equations (3.1) – (3.12), and the results are presented in Table 2.

Table 2: *Calculated parameters of OTLs*

Parameter	OTL 1	OTL 2
Equivalent impedance [Ω]	$2.150^{\angle 71.38^\circ}$	$2.630^{\angle 65.33^\circ}$
Total impedance $\bar{Z}$ [Ω]	$1.180^{\angle 68.6^\circ}$	
Equivalent admittance [S]	$j1.382*10^{-5}$	$j1.523*10^{-5}$
Total admittance $\bar{Y}$ [S]	$j2.905*10^{-5}$	
Characteristic impedance $\bar{Z}_C$ [Ω]	$201.543^{\angle -10.47^\circ}$	
Propagation constant $\bar{\Theta}$	$1.087*10^{-3} + j5.753*10^{-3}$	
Attenuation (loss) factor α	$1.087*10^{-3}$	
Phase (velocity) factor β	$5.753*10^{-3}$	
$\mathrm{sh}(\bar{\gamma} \cdot l)$	$5.855 * 10^{-3\angle 72.3^\circ}$	
$\mathrm{ch}(\bar{\gamma} \cdot l)$	$0.999^{\angle 0^\circ}$	

Calculation results for the electrical parameters for both OTLs together are presented in Table 3.

Table 3: *Electrical parameters of both OTLs together*

Parameter	Sending end	Receiving end
Line voltage *U*, [kV]	$110.161^{\angle 0.14^\circ}$	$110^{\angle 0^\circ}$
Current *I*, [A]	$157.900^{\angle -3.1^\circ}$	$157.810^{\angle -3.81^\circ}$
cosφ	0.9984	0.9978
Apparent power $\bar{S}$, [MVA]	$30.128^{\angle 3.24^\circ}$	$30.066^{\angle 3.81^\circ}$

Calculation results for the electrical parameters for both OTLs separately are presented in Table 4.

Table 4: *Electrical parameters of both OTLs separately*

Parameter	Sending end		Receiving end	
	OTL 1	**OTL2**	**OTL 1**	**OTL2**
Current *I*, [A]	$87.060^{\angle -5.87^\circ}$	$71.061^{\angle 0.29^\circ}$	$87.01^{\angle -6.58^\circ}$	$71.02^{\angle -0.42^\circ}$
Apparent power $\bar{S}$, [MVA]	$16.610^{\angle 6.00^\circ}$	$13.560^{\angle -0.148^\circ}$	$16.578^{\angle 6.58^\circ}$	$13.530^{\angle -0.42^\circ}$
Active power *P*, [MW]	16.520	13.560	16.468	13.530
Reactive power *Q*, [MVAr]	**1.736**	**-0.035**	1.899	0.099

From the results, it can be observed that the reactive powers $Q_{11} = 1.736\ \mathrm{MVAr}$ (sending end of a first OTL) and $Q_{12} = -0.035\ \mathrm{MVAr}$ (receiving end of a second OTL) are of the opposite signs. Therefore, the mathematical calculation shows that opposite directions of the reactive power on two parallel OTLs is theoretically possible.

3.3 Physical interpretation of the results

From the point of view of the transmission network, receiving end acts as a consumer of inductive reactive power. Let us consider the sending end to be a referent point for the calculation of energy directions. In this case, the direction of reactive power "R-" means that the sending end sends inductive reactive power while direction "R+" conversely means that the sending end receives inductive reactive power. In the described phenomenon that occurs in certain periods, the sending end in one OTL receives and the second OTL gives the reactive power. Therefore, the reactive powers are in mutually opposite directions. Since the OTLs are relatively short (ca. 5 km) and their capacity against the ground is very small (the contribution of reactive power is about 100 kVAr per OTL), it is to be assumed that the cause of the phenomenon is not in the capacity of the OTLs. This is what makes the phenomenon confused, and at the first moment, the validity of measurements was doubtful. The detailed analysis of the phenomenon leads to an entirely different result. Fig. 5. shows the phasors of the voltage and currents at the sending end of the OTL.

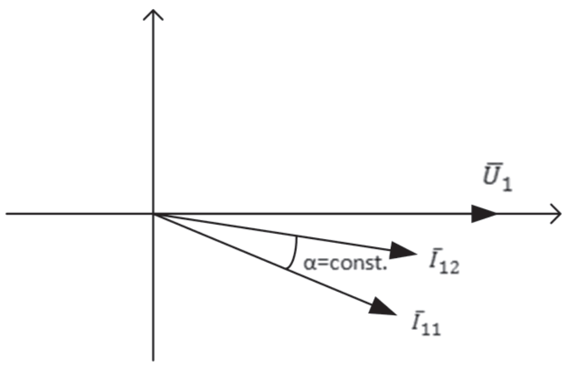

Figure 5: *Currents and voltage at the sending end of the OTL*

It is worth noting that the angle between the currents is independent of load. By changing the load, the angle of current to voltage is proportionally changed. By increasing the load, the angle increases, i.e. approaching the voltage and in the respective moment will cross over. Such an operating condition is shown in Fig. 6.

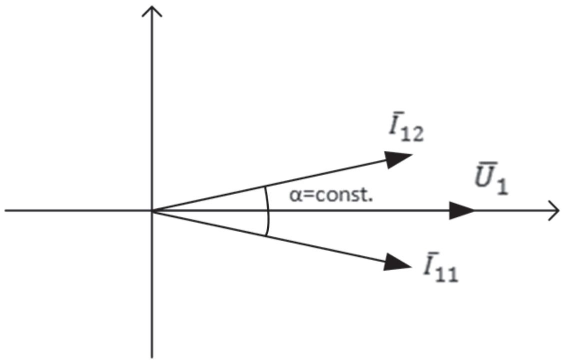

Figure 6: *Currents and voltage at the sending end of the OTL during the opposite reactive power phenomenon*

It is clear that the reactive powers are in the opposite directions. Energy meters register this as the sending end while simultaneously receiving reactive power on one OTL and sending reactive power on the other OTL. From the physical and mathematical point of view, it is obvious that the presented operating condition can be explained independently of the capacity against the ground. This confirms that the reason for the presented phenomenon is not the distribution of capacitive currents along the lines nor incorrect measurement, but this phenomenon comes only due to the distribution of reactive powers along the impedances of the respective OTLs.

4 CONCLUSION

This paper presents an analysis of the opposite reactive power direction on two parallel overhead transmission lines. At the first, the latter phenomenon was measured on the real transmission line using energy meters and seemed ambiguous, i.e. superficial reasoning leads to the conclusion that the quality of the measurement system is doubtful. Additional theoretical analysis was performed. The results show that the phenomenon is theoretically possible and it is independent of the capacities against the ground. Moreover, it is not the result of the incorrect measurement, but it originates only due to the distribution of the reactive powers along the impedances of the transmission lines.

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