Increase of transmission line losses caused by higher harmonic components evaluated by orthogonal decomposition of three-phase currents in the time domain

[1]Miran Rošer, [2]Gorazd Štumberger, [2]Matej Toman, [2]Drago Dolinar

[1]Elektro Celje d.d.
Vrunčeva 2a, 3000 Celje, Slovenia

[2]University of Maribor, Faculty of Electrical Engineering and Computer Science
Smetanova 17, 2000 Maribor, Slovenia
phone:+386 2 220 7075, fax:+386 2 220 7272, e-mail: **Gorazd.Stumberger.@uni-mb.si**

Abstract. This work analyses transmission line losses in a 35 kV distribution network where currents and voltages contain higher harmonic components. They are caused by a nonlinear load – a rectifier with rated power of 4.7 MVA. In order to evaluate increase of transmission line losses due to the current higher harmonic components, the three-phase current vector is decomposed into two orthogonal components. The first orthogonal component of the three-phase current vector is collinear with the three-phase line voltage vector, while the second one is orthogonal to it. The first one contributes to the active power while the second one does not. It causes additional transmission line losses which could be avoided if the second orthogonal component of the three-phase current vector is minimized. The RMS values of both orthogonal components of the three-phase current vector are used to evaluate the additional transmission line losses.

Key words: transmission line losses, higher harmonic components, orthogonal decomposition, three-phase currents

1. Introduction

One of the very effective tools used for analysis of three-phase currents and voltages [1]-[8] are orthogonal decompositions of three-phase currents in time domain [1]-[5], [8]. In this work, this tool is applied to analyze increase of transmission line losses in a 35 kV distribution network where currents and voltages contain higher harmonics. These higher harmonics are caused by a nonlinear load – a rectifier with rated power of 4.7 MVA.

The aforementioned three-phase line currents and voltages are given in the form of current vector and voltage vector [8]. The current vector is decomposed into two orthogonal components. The first one is collinear with the voltage vector while the second one is orthogonal to it. Only the current vector component collinear with the voltage vector contributes to the energy transmission and to active power while the current vector component orthogonal to the voltage vector causes reciprocal energy exchange between source and load whose average value equals zero. Thus, the current vector component orthogonal to the voltage causes additional transmission line losses which can be avoided. These additional losses can be evaluated by the norm or RMS value of the current vector component orthogonal to the voltage vector.

2. Network with nonlinear load

Figure 1 shows a part of discussed distribution network with a nonlinear load. Our observation focuses on the losses in the 35 kV line, connecting 35 kV bus and nonlinear load.

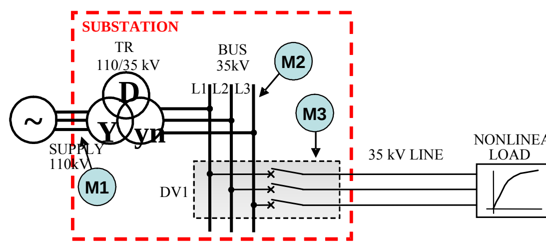

Figure 1: Part of the distribution network with a nonlinear load

The line voltages and currents measured in 35 kV network in points M2 and M3, respectively, are shown in Figure 2, while their amplitude spectra are shown in Figures 3 and 4.

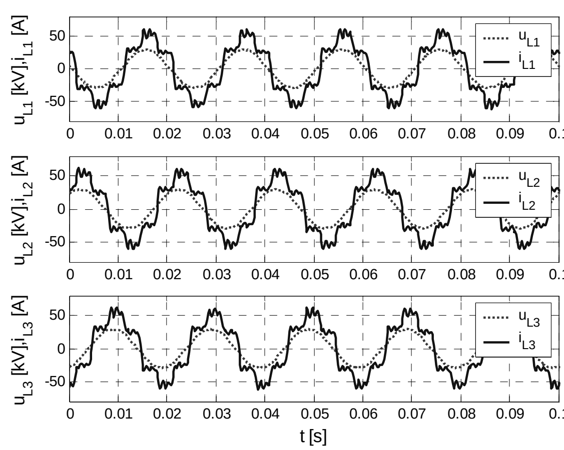

Figure 2: Line currents and voltages measured in a 35 kV network

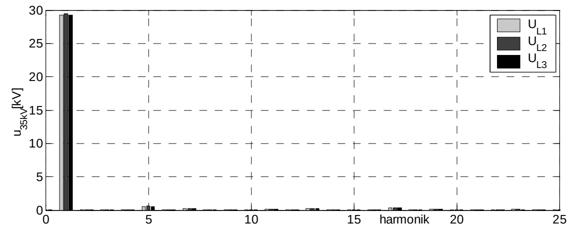

Figure 3: Amplitude spectra of line voltages on 35 kV level

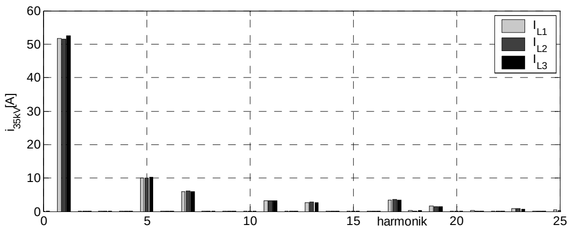

Figure 4: Amplitude spectra of line currents on 35 kV level

The RMS values of individual line currents and voltages are shown in Table I together with active power measured in individual lines.

TABLE I: The RMS values of measured line currents and voltages and active power

	Line L1	Line L2	Line L3
Current [A]	36.64	36.48	37.23
Voltage [kV]	20.69	20.80	20.75
Active Power [kW]	742	749	751

3. Orthogonal decomposition

Orthogonal decomposition in the time domain [8] is performed in order to decompose currents measured at 35 kV level into two orthogonal components. To allow for orthogonal decomposition, current and voltage vectors, **i**(t) and **u**(t), are introduced by (1):

$$\mathbf{i}(t)=\begin{bmatrix} i_{L1}(t) \\ i_{L2}(t) \\ i_{L3}(t) \end{bmatrix},\ \mathbf{u}(t)=\begin{bmatrix} u_{L1}(t) \\ u_{L2}(t) \\ u_{L3}(t) \end{bmatrix}, \tag{1}$$

where $i_{L1}(t)$, $i_{L2}(t)$, $i_{L3}(t)$ and $u_{L1}(t)$, $u_{L2}(t)$, $u_{L3}(t)$ denote measured line currents and voltages. The norms or RMS values of both vectors, $I(t)$ and $U(t)$, are given by (2) and (3):

$$I(t)=\sqrt{\frac{1}{T}\int_{t-T}^{t}\mathbf{i}^{\mathrm{T}}(\tau)\mathbf{i}(\tau)d\tau}=\sqrt{\sum_{k=L1}^{L3}I_k^2} \tag{2}$$

$$U(t)=\sqrt{\frac{1}{T}\int_{t-T}^{t}\mathbf{u}^{\mathrm{T}}(\tau)\mathbf{u}(\tau)d\tau}=\sqrt{\sum_{k=L1}^{L3}U_k^2} \tag{3}$$

where the time interval of interest is given as [t-T, t] while U_k and I_k denote RMS values of individual line currents and voltages. The average active power $P(t)$ is calculated by (4), while (5) introduces the equivalent conductivity of the three-phase system $G_e(t)$:

$$P(t)=\frac{1}{T}\int_{t\text{-}T}^{t}\mathbf{u}^{\mathrm{T}}(\tau)\,\mathbf{i}(\tau)\,d\tau \tag{4}$$

$$G_e(t)=\frac{P(t)}{U^2(t)} \tag{5}$$

Two orthogonal components of the current vector **i**(t), marked with $\mathbf{i}_u(t)$ and $\mathbf{i}_{uo}(t)$, are introduced in (6) and (7).

$$\mathbf{i}_u(t)=G_e(t)\mathbf{u}(t)=\frac{P(t)}{U^2(t)}\mathbf{u}(t) \tag{6}$$

$$\mathbf{i}_{uo}(t)=\mathbf{i}(t)-\mathbf{i}_u(t) \tag{7}$$

The first one is collinear with the voltage vector and is indispensable for energy transmission and active power generation. The second one is orthogonal to the current vector. It is responsible for reciprocal energy exchange between source and load. The average value of this reciprocal energy exchange equals zero.

If the voltage vector **u**(t) is given, the current vector **i**(t) and its orthogonal components $\mathbf{i}_u(t)$ and $\mathbf{i}_{uo}(t)$ produce, together with the voltage vector, instantaneous powers $p(t)$, $p_s(t)$ and $p_q(t)$ (8).

$$\begin{aligned} p_s(t)&=\mathbf{u}^{\mathrm{T}}(t)\mathbf{i}(t) \\ p(t)&=\mathbf{u}^{\mathrm{T}}(t)\mathbf{i}_u(t) \\ p_q(t)&=\mathbf{u}^{\mathrm{T}}(t)\mathbf{i}_{uo}(t) \end{aligned} \tag{8}$$

The instantaneous power losses in the discussed 35 kV line caused by the current vectors **i**(t), $\mathbf{i}_u(t)$ and $\mathbf{i}_{uo}(t)$ are denoted as $p_{si}(t)$, $p_i(t)$ and $p_{qi}(t)$, respectively. They are introduced in (9) to (11):

$$p_{si}(t)=R\,\mathbf{i}^{\mathrm{T}}(t)\,\mathbf{i}(t) \tag{9}$$

$$p_i(t)=R\,\mathbf{i}_u^{\mathrm{T}}(t)\,\mathbf{i}_u(t) \tag{10}$$

$$p_{qi}(t)=R\,\mathbf{i}_{uo}^{\mathrm{T}}(t)\,\mathbf{i}_{uo}(t) \tag{11}$$

where R is the resistance of the 35 kV line. Integrals of instantaneous powers (9) to (11) represent corresponding energy losses in time interval [t-T, t]. These losses are calculated by (12) to (14).

$$W_{si}=\int_{t-T}^{t}p_{si}(\tau)\,d\tau=\int_{t-T}^{t}R\,\mathbf{i}^{\mathrm{T}}(\tau)\,\mathbf{i}\ (\tau)\,d\tau \tag{12}$$

$$W_i=\int_{t-T}^{t}p_i(\tau)\,d\tau=\int_{t-T}^{t}R\,\mathbf{i}_u^{\mathrm{T}}(\tau)\,\mathbf{i}_u(\tau)\,d\tau \tag{13}$$

$$W_{qi}=\int_{t-T}^{t}p_{qi}(\tau)\,d\tau=\int_{t-T}^{t}R\,\mathbf{i}_{uo}^{\mathrm{T}}(\tau)\,\mathbf{i}_{uo}(\tau)\,d\tau \tag{14}$$

The average power losses in the given time interval, are calculated by (15) to (17).

$$P_{si} = R \quad \frac{1}{T}\int_{t-T}^{t} \mathbf{i}^{T}(\tau)\,\mathbf{i}(\tau)\,d\tau \qquad (15)$$

$$P_{i} = R\,\frac{1}{T}\int_{t-T}^{t} \mathbf{i}_{u}^{T}(\tau)\,\mathbf{i}_{u}(\tau)\,d\tau \qquad (16)$$

$$P_{qi} = R\,\frac{1}{T}\int_{t-T}^{t} \mathbf{i}_{uo}^{T}(\tau)\,\mathbf{i}_{uo}(\tau)\,d\tau \qquad (17)$$

where the power losses P_{si} are caused by the current vector $\mathbf{i}(t)$, the power losses P_i are caused by the current vector $\mathbf{i}_u(t)$, while the power losses P_{qi} are caused by the current vector $\mathbf{i}_{uo}(t)$. Only the power losses P_i are unavoidable. They are caused by the current vector $\mathbf{i}_u(t)$ which is indispensable for energy transmission. The current vector $\mathbf{i}_{uo}(t)$ does not contribute to the transmitted energy, therefore, losses caused by this current vector represent additional losses which can be avoided.

4. Results

The results presented in this section are given for currents and voltages presented in Figure 2, section 2. Components of vectors $\mathbf{u}(t)$, $\mathbf{i}(t)$, $\mathbf{i}_u(t)$ and $\mathbf{i}_{uo}(t)$ are shown in Figure 5. They were determined by (1) to (7). Components of the voltage vector $\mathbf{u}(t)$ are line voltages u_{L1}, u_{L2}, u_{L3}, while the line currents i_{L1}, i_{L2}, i_{L3} are components of the current vector $\mathbf{i}(t)$. Components of the current vectors $\mathbf{i}_u(t)$ and $\mathbf{i}_{uo}(t)$ in individual lines are i_{L1u}, i_{L2u}, i_{L3u} and i_{L1uo}, i_{L2uo}, i_{L3uo}.

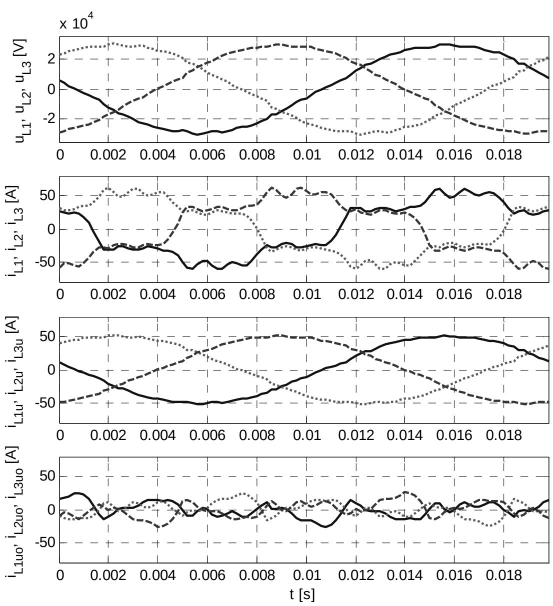

Figure 5: Components of vectors $\mathbf{u}(t)$, $\mathbf{i}(t)$, $\mathbf{i}_u(t)$ in $\mathbf{i}_{uo}(t)$

The results presented in Figure 5 show that components of the current vector $\mathbf{i}_u(t)$ in individual lines (i_{L1u}, i_{L2u}, i_{L3u}) are collinear with the corresponding voltage vector components u_{L1}, u_{L2}, and u_{L3} .

The transmission line instantaneous power losses, given by expressions (9) to (11), are shown in Figure 7 together with their integrals (12), (13) and (14).

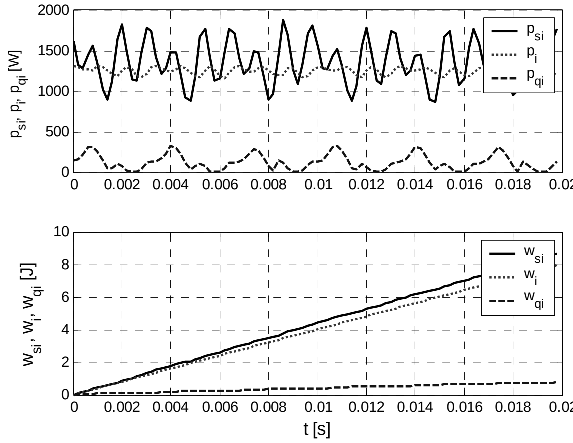

Figure 6: Power and energy losses in 35 kV transmission line

The energy losses (12) to (14) were used to calculate average power losses P_{si}, P_i and P_{qi}, which can be calculated also by (15) to (17). The obtained results are shown in Table II.

TABLE II: Power losses

P_{si} [W]	P_i [W]	P_{qi} [W]
1371.4	1250.7	120.7

A similar ratio between individual losses, as it is show in Table II for one period of fundamental, was confirmed by measurement performed for one day. In order to evaluate monthly loss of energy due to the current vectors $\mathbf{i}(t)$, $\mathbf{i}_u(t)$ and $\mathbf{i}_{uo}(t)$, an average daily energy transmission was analyzed for a period of one month. Considering ratio between individual power losses given in Table II and measured average daily transmission of energy in the discussed 35 kV line, transmission line losses were evaluated.

Figure 7 shows the average daily transmission line losses, due to the current vectors $\mathbf{i}(t)$, $\mathbf{i}_u(t)$ and $\mathbf{i}_{uo}(t)$. The daily losses caused by $\mathbf{i}(t)$ are marked as W_{sid}, the daily losses caused by $\mathbf{i}_u(t)$ are denoted as W_{id} while W_{qid} represents losses due to the current vector $\mathbf{i}_{uo}(t)$.

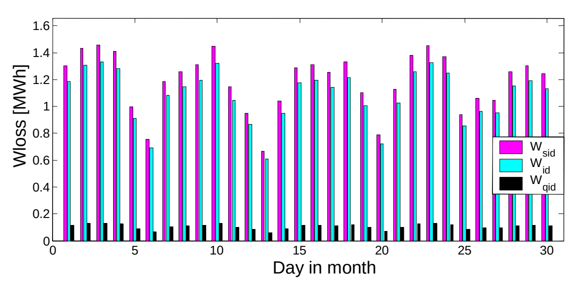

Figure 7: Daily energy losses in 35 kV transmission line

For the given case, the total monthly transmission line losses caused by the current vectors $\mathbf{i}(t)$, $\mathbf{i}_u(t)$ and $\mathbf{i}_{uo}(t)$ are given in Table III.

TABLE III: Total monthly transmission line losses due to $\mathbf{i}(t)$, $\mathbf{i}_u(t)$ and $\mathbf{i}_{uo}(t)$

Total monthly transmission line losses [MWh]		
Due to $\mathbf{i}(t)$	Due to $\mathbf{i}_u(t)$	Due to $\mathbf{i}_{uo}(t)$
35.59	32.45	3.14

The transmission losses due to the current $\mathbf{i}_u(t)$ cannot be avoided, because $\mathbf{i}_u(t)$ is the minimal current vector needed for energy transmission. On the contrary, the current vector $\mathbf{i}_{uo}$(t) represents only a reciprocal energy exchange between the source and load, which must be avoided in order to minimize transmission line losses.

5. Conclusion

This paper discusses transmission line losses in the case of 35 kV network, where currents and voltages contain higher harmonic components caused by a nonlinear load. Measured three phase currents are decomposed into two orthogonal components. Only one of them contributes to the energy transmission, while the other one increases transmission losses. In the given case transmission losses could be decreased for 10 percents by rejection of current component that does not contribute to the energy transmission.

References

[1] L. S. Czarnecki, "On some misinterpretations of the instantaneous reactive power p-q theory," *IEEE Trans. on Power Electronics.*, vol. 19, no. 3, pp. 828-836, 2004.

[2] H. Akagi, Y. Kanazawa, A. Nabae, "Instantaneous reactive power compensators comprising switching devices without energy storage components," *IEEE Trans. on Industry Applications*, vol. 20, no. 3, pp. 625–631, 1984.

[3] A. Nabae, T. Tanaka, "A new definition of instantaneous active- reactive current and power based on instantaneous space vectors on polar coordinates in three-phase circuits," *IEEE Trans. on Power Delivery*, vol. 11, no. 3, pp. 1238–1243, 1996.

[4] J. L. Willems, "A new interpretation of the Akagi-Nabae power components for nonsinusoidal three-phase situations," *IEEE Trans. on Instr. and Meas.*, vol. 41, no. 4, pp. 523–527, 1992.

[5] Gorazd Štumberger, *Treatment of three-phase systems using vector spaces*. Ph.D. Thesis, Faculty of Electrical Engineering and Computer Science, Maribor, 1996.

[6] D. L. Milanez, A. E. Emmanuel, "The instantaneous-space phasor a powerful diagnosis tool," *IEEE Trans. on Instr. and Meas.*, vol. 52, no. 1, pp. 143–148, 2003.

[7] A. E. Emmanuel, "Summary of IEEE Standard 1459: definitions for measurement of electric power quantities under sinusoidal, nonsinusoidal, balanced or unbalanced conditions," *IEEE Trans. on Industry Applications*, vol. 40, no. 3, pp. 869–876, 2004.

[8] G. Štumberger, B. Polajžer, M. Toman, D. Dolinar, Orthogonal decomposition of currents, power definitions and energy transmission in three-phase systems treated in the time domain, Proceedings of the International conference on renewable energies and power quality (ICREPQ'06), Palma de Mallorca, Spain, April 206.