

Evaluation of excessive transmission line losses caused by unbalanced and nonlinear three-phase loads

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1. Introduction

This work evaluates excessive transmission line losses in the three-phase systems caused by unbalanced and nonlinear loads. In the single-phase systems, where currents and voltages contain exclusively fundamental harmonic components, energy transmission and reciprocal energy exchange between source and load can be adequately treated by the concept of active and reactive power [1]. However, this approach fails when currents and voltages contain higher order harmonic components or when unbalanced and nonlinear three-phase loads are analyzed. In such cases mathematical tools like orthogonal decompositions of currents in the time or frequency domains [2] - [8] can be applied. Using these tools, it is possible to determine current components indispensable for energy transmission and those current components that do not contribute to the energy transmission and cause excessive transmission losses which can be avoided.

The ratio between RMS (root mean square) value of current component indispensable for energy transmission and the RMS value of the original three-phase current is applied to introduce generalized power factor in the three-phase system. The generalized power factor is used to characterize the load unbalance and effects of nonlinear load. Excessive transmission losses in a low voltage distribution line are evaluated by case studies performed for different operating conditions.

Key words: transmission line losses, orthogonal current decomposition, asymmetrical and nonlinear three-phase loads

2. Orthogonal decomposition of currents

Let $i_1(t)$, $i_2(t)$, $i_3(t)$ and $u_1(t)$, $u_2(t)$, $u_3(t)$ be the line currents and voltages of a three-phase system observed inside a selected time window $[0, T]$. The inner product of current and voltage vectors is defined by (1):

$$\begin{aligned} (\mathbf{u}, \mathbf{i}) &= \frac{1}{t_2 - t_1} \int_{t_1}^{t_2} \mathbf{u}^T \mathbf{i} d\tau = \frac{1}{t_2 - t_1} \int_{t_1}^{t_2} \begin{bmatrix} u_1(\tau) \\ u_2(\tau) \\ u_3(\tau) \end{bmatrix}^T \begin{bmatrix} i_1(\tau) \\ i_2(\tau) \\ i_3(\tau) \end{bmatrix} d\tau = \\ &= \frac{1}{t_2 - t_1} \int_{t_1}^{t_2} p_1(\tau) + p_2(\tau) + p_3(\tau) d\tau = P_1 + P_2 + P_3 = P \end{aligned} \quad (1)$$

where p_1 , p_2 and p_3 denote instantaneous values of power in all three phases. From (2) it is obvious that the inner product of current and voltage vectors equals the average active power P of the three-phase system.

Let us introduce RMS values of the current vector I and voltage vector U by Euclidean norms of these vectors (2) and (3). Squares of both norms equal the sums of squared current or voltage RMS values in individual phases.

$$I^2 = \|\mathbf{i}\|^2 = I_1^2 + I_2^2 + I_3^2 = \frac{1}{t_2 - t_1} \int_{t_1}^{t_2} \mathbf{i}^T \mathbf{i} d\tau \quad (2)$$

$$U^2 = \|\mathbf{u}\|^2 = U_1^2 + U_2^2 + U_3^2 = \frac{1}{t_2 - t_1} \int_{t_1}^{t_2} \mathbf{u}^T \mathbf{u} d\tau \quad (3)$$

In (2) and (3) I_1 , I_2 , I_3 , and U_1 , U_2 , U_3 denote the RMS values of currents and voltages in all three phases. The equivalent conductivity of entire three-phase system G is defined by (4). The equivalent conductivity G is required to introduce current vector \mathbf{i}_u (4) which is collinear with applied voltage vector \mathbf{u} and is the only current vector indispensable for energy transmission.

$$G = \frac{P}{U^2} = \frac{P}{\|\mathbf{u}\|^2} \Rightarrow \mathbf{i}_u = G\mathbf{u} \quad (4)$$

In the first approximation the transmission line losses are proportional to the $\|\mathbf{i}\|^2$ while only current vector \mathbf{i}_u contributes to the energy transmission. Thus (5) can be used as a measure for excessive transmission losses.

$$1/PF^2 = \frac{\|\mathbf{i}\|^2}{\|\mathbf{i}_u\|^2} \quad (5)$$

where PF' is generalized power factor of the three-phase system.

3. Evaluation of excessive transmission losses

In order to evaluate excessive transmission losses in a low voltage distribution line a system with nonlinear and unbalanced load schematically shown in Figure 1 was applied. The feeder network is denoted by Q while C1 and C2 denote two measurement points.

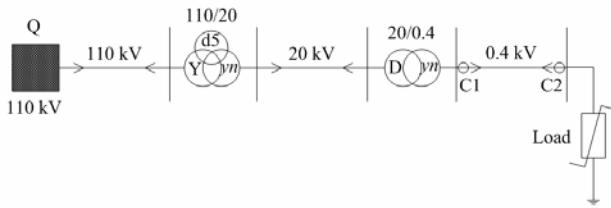


Figure 1: Schematic presentation of discussed system

Transmission losses were evaluated for the balanced linear, unbalanced linear, balanced nonlinear and unbalanced nonlinear load. The load power was 72.53 kW and 131.26 kW while the generalized power factor was between 0.73 and 1. The expression “unbalanced” load means that the RMS value of one line current is 20% higher than the RMS values of the other two line currents.

Table I shows the relative transmission losses P_{LOSS} calculated as a ratio $\frac{||i||^2}{||i_a||^2}$ (5) for balanced and unbalanced linear loads and balanced and unbalanced nonlinear loads. They are given for different values of the load active power P_{LOAD} and different values of generalized power factor PF' .

4. Conclusion

This paper evaluates excessive transmission line losses caused by unbalanced and nonlinear loads. It is shown that the excessive transmission losses increase with the inverse ratio of squared generalized power factor. According to the presented results, in the case of unbalanced nonlinear loads the excessive transmission

losses can reach almost the same value as the transmission losses due to the linear and balanced loads, which means that the total transmission losses are almost doubled.

References

- [1] S. Svensson, “Power measurement uncertainties in a non-sinusoidal power system,” in *International Symposium on Electric Power Engineering, Proceedings: Power systems*, (Stockholm, Sweden), pp. 617-622, IEEE 1995.
- [2] L. S. Czarnecki, “Orthogonal Decomposition of the Currents in a 3-Phase Nonlinear Asymmetrical Circuit with a Nonsinusoidal Voltage Source,” *IEEE Transactions on Instrumentation and Measurement*, vol 37, pp 30-34, March 1988.
- [3] L. S. Czarnecki, T. Swietlicki, “Powers in nonsinusoidal networks: Their interpretation, analysis, and measurement,” *IEEE Transactions on Instrumentation and Measurement*, vol 39, pp 340-345, April 1990.
- [4] L. S. Czarnecki, “Scattered and reactive current, voltage, and power in circuits with nonsinusoidal waveforms and their compensation,” *IEEE Trans. on Instr. and Meas.*, vol. 40, no. 3, pp. 563–567, 1991.
- [5] R. Sasdelli, G. C. Montanari, “Compesable power for electrical systems in nonsinusoidal conditions ,” *IEEE Transactions on Instrumentation and Measurement*, vol 43, pp 592-598, April 1994.
- [6] L. S. Czarnecki, “Minimisation of unbalanced and reactive currents in three-phase asymmetrical circuits with nonsinusoidal voltage,” *IEEE Proceedings-B*, vol. 139, no. 4, pp. 347–354, 1992.
- [7] A. Ferrero, “A new approach to the definition of power components in three-phase systems under nonsinusoidal conditions,” *IEEE Transactions on Instrumentation and Measurement*, vol 40, pp 568-577, Jun 1991.
- [8] L. S. Czarnecki, S. M. Hsu, G. Chen “Adaptive balancing compensator,” *IEEE Transactions on Power Delivery*, vol. 10, no. 3, pp. 1244–1250, 1996.
- [9] 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 2006.

Table I: Relative transmission losses P_{LOSS} given as a function of active load power P_{LOAD} and load generalized power factor PF' .

| P_{LOAD} (kW) | Linear load | | | | Nonlinear load | | | |
|--------------------|-------------|-----------------|------------|-----------------|----------------|-----------------|------------|-----------------|
| | balanced | | unbalanced | | balanced | | unbalanced | |
| | PF' | P_{LOSS} (pu) | PF' | P_{LOSS} (pu) | PF' | P_{LOSS} (pu) | PF' | P_{LOSS} (pu) |
| 72.53 | 1.000 | 1.000 | 0.979 | 1.042 | 0.754 | 1.757 | 0.728 | 1.888 |
| 72.53 | 1.000 | 1.000 | 0.979 | 1.042 | 0.956 | 1.094 | 0.936 | 1.141 |
| 131.26 | 1.000 | 1.000 | 0.972 | 1.058 | 0.803 | 1.551 | 0.779 | 1.648 |