JET Journal of Energy Technology

JET Volume 7 (2014) p.p. 11-26
Issue 1, February 2014

www.fe.um.si/en/jet.html

ANALYSIS OF VOLTAGE SAG PROPAGATION THROUGH THE DISTRIBUTION NETWORK

ANALIZA ŠIRJENJA UPADOV NAPETOSTI V DISTRIBUCIJSKEM OMREŽJU

Zvonimir Klaić, Krešimir Fekete[ℜ], Goran Knežević

Keywords: power quality, voltage sag, transformer winding, computer simulation

Abstract

Power quality is a hugely important aspect of power delivery. This paper deals with voltage sags, which are reflected in the aspect of power quality. During a voltage sag, the voltage at the customer terminal is reduced and can cause undesirable equipment trips. The main causes of voltage sags are short-circuit faults. Most short-circuits in a power system are either single line-to-ground or two phase short circuits. The causes of voltage sags in the power system are not the subject of this paper. This paper analyses the propagation of single-phase voltage sags caused by a line-to-ground short circuit in a transmission network, from the high voltage level to the distribution level through various types of transformers. The influence of the transformer winding connection on the propagation of voltage sag is investigated from the theoretical aspect, the practical aspect and the computer simulation aspect. One example of voltage sag propagation from the transmission network to the distribution network that is captured with the power quality measurements is analysed. Theoretical calculations of voltage sag propagation through the various types of transformer windings connections are presented and compared to the measurement result. Furthermore, a computer model of the observed distribution network is modelled in DigSILENT Power Factory software. This model is used for the simulation of voltage sag propagation. The results of the computer simulation are presented and compared to the measurements. Conclusions and comments on the results are presented at the end of the paper.

[ℜ] Corresponding author: Krešimir Fekete, PhD, University of Osijek, Faculty of Electrical Engineering, Tel.: +385 91 224 6097, Fax: +385 31 224605, Mailing address: Kneza Trpimira 2b, 31000 Osijek, Croatia, E-mail address: kresimir.fekete@etfos.hr

Povzetek

Kakovost električne energije je zelo pomemben vidik pri razdeljevanju električne energije. Ta članek se ukvarja z upadi napetosti, ki predstavljajo en vidik kakovosti električne energije. Med upadom napetosti je napetost na uporabniškem priključku znižana in lahko povzroča neželene napake opreme. Glavni vzrok upadov napetosti so kratkostične okvare. Večina kratkih stikov v omrežju je enofaznih zemeljskih ali dvofaznih. Vzroki upadov napetosti v elektroenergetskem sistemu niso predmet tega članka. Članek predstavlja analize širjenja enofaznih upadov napetosti zaradi enofaznih zemeljskih kratkih stikov v prenosnem omrežju, od nivoja visoke napetosti do nivoja napetosti distribucije preko različnih tipov transformatorjev. Vpliv vezave transformatorskega navitja na širjenje upada napetosti je raziskan iz teoretičnega vidika, praktičnega vidika in vidika računalniške simulacije. Analiziran je en primer širjenja upada napetosti iz prenosnega omrežja na distribucijsko omrežje, ki je zajeto z merjenjem kakovosti električne energije. Teoretični izračuni širjenja upada napetosti preko različnih tipov vezav navitij transformatorja so predstavljene in primerjane z rezultati meritev. Prav tako je računalniški model opazovanega distribucijskega omrežja modeliran v DigSILENT Power Factory programski opremi. Računalniški model je uporabljen za simulacijo širjenja upada napetosti. Rezultati računalniške simulacije so predstavljeni in primerjani z meritvami. Zaključki in komentarji rezultatov so predstavljeni na koncu članka.

1 INTRODUCTION

Voltage sags are short duration reductions in the rms (root-mean-square) value, [1], and are the most frequent cause of power quality problems, [2]. They can cause interruptions of industrial processes, which could result in a malfunction of equipment and considerable economic losses. The interest in voltage sags is mainly due to the problems they cause on several types of equipment: adjustable-speed drivers, process-control equipment, computers, etc., [1]. Voltage sags are caused by short circuits, overloads or by starting of large motors, [3]. A large number of customer buses in the distribution network may experience voltage sags when faults occur in the transmission systems. Even though some of these buses are distant from the original fault locations, they still encounter voltage sags, [4]. The faults in the distribution systems normally cause voltage sags only at the local customer buses, [5]. Most short circuits in power systems are unsymmetrical (line-to-ground, line-to-line, double-line-to-ground). In that case, calculations must be done in all three phases, or the symmetrical component theory must be used.

The numbers and characteristics of voltage sags (known as ‘the performance of voltage sags’) at the customer buses may differ from each other and from that at the original fault locations, [1]. The difference in voltage sag performance, i.e. magnitude and phase angle relationships in particular, is a result of the propagation of voltage sags from the original fault locations to different customer buses. The propagation of voltage sags through different types of transformer connections results in a different performance of voltage sags on the secondary side of the transformers, [4]. Voltage sag propagation normally occurs from a higher voltage to a lower voltage level. Due to impedance of the transformer, the reverse direction of the voltage sag propagation is less significant, [4].

This paper analyses the propagation of single-phase voltage sag caused by a line-to-ground short circuit in a transmission network, from the high voltage level to the distribution level through various types of transformers (regarding winding connections). One example of voltage sag propagation from the transmission to the distribution level that is recorded with the power quality measurements is presented. In the literature, [6], a detailed analysis of voltage sag as well as similar cases of voltage sag propagation that is measured at another time is performed. The innovation of this paper, in comparison to, [6], is the construction of computer model of the observed distribution system and the simulation of voltage sag propagation. The results of the calculation and simulation are presented and compared to measurements.

The structure of this paper is as follows: first, a brief theoretical explanation of voltage sags is made in Section 2. In Section 3, the influence of transformer winding connections on the voltage sag propagation is presented. Section 4 deals with the example of measured voltage sag propagation from the transmission to the distribution level. A computer simulation of voltage sag propagation is presented in Section 5. The conclusion and suggestions for further work are discussed in the last section.

2 VOLTAGE SAGS

2.1 Description and Definition

Voltage sags are two-dimensional electromagnetic disturbances determined according to voltage magnitude and duration time, [1]. Voltage sags are defined as a decrease in the rms value of an AC voltage between 0.1 p.u. and 0.9 p.u. at the power frequency for durations from 0.5 cycles to 1 min, [7], [8]. According to [9], the duration of the voltage sag is defined as the time between the rms of voltage dropping below the threshold and when the rms of voltage returns to the threshold. An example of voltage sag is shown in Figure 1, [10]. It can be seen that the rms voltage drops to a value of about 70% of the pre-event voltage for about 140 mos. Afterwards, the voltage recovers to about the pre-sag value. The threshold is 90% of rated voltage. The magnitude and duration are the main characteristics of voltage sags. The voltage during sag can also contain a rather large number of higher frequency components.

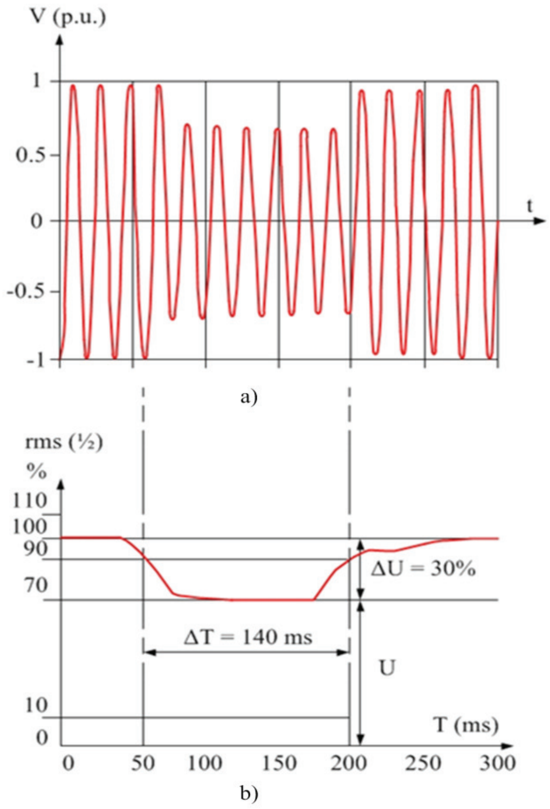

Figure 1: *Example of a voltage sag: a) time domain and b) rms value [10]*

Magnitude and duration are the main characteristics of voltage sags, and they have been used for the development of compatibility charts and indices for equipment. In addition to these, the other characteristics, such as unbalanced voltage sags, phase angle shifts, the point on the wave of initiation and recovery, and waveform distortion, have been found to significantly influence the equipment's sensitivity to the voltage sags, [1].

2.2 Model for Theoretical Calculations

To quantify voltage sag magnitude in radial systems, the voltage divider model, [1], shown in Figure 2, can be used. This is a simplified model, especially for transmission systems (which are meshed), but it can be a useful model to predict some of the properties of sags, [1].

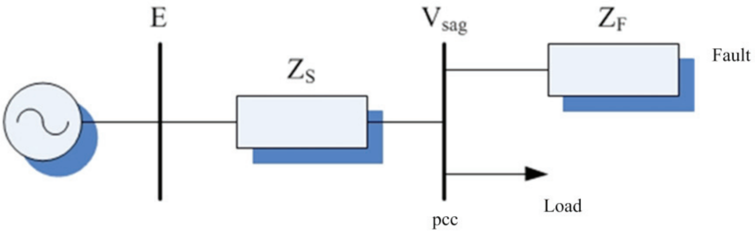

Figure 2: *Voltage divider model [2]*

Z_S is the source impedance seen from the point-of-common coupling (PCC) and Z_F is the impedance between the PCC and the fault location. The PCC coupling is the point from which both the fault and the load are fed, [1]. E is the source voltage. The voltage at the pcc (V_{sag}) can be found using Equation (2.1), [1]:

$$V_{sag} = \frac{Z_F}{Z_S + Z_F} \cdot E \tag{2.1}$$

If it is assumed that the pre-event voltage E is 1 p.u., then Equation (2.1) results in Equation (2.2):

$$V_{sag} = \frac{Z_F}{Z_S + Z_F} \tag{2.2}$$

It can be seen from Equation 2.2 that the sag becomes deeper for faults electrically closer to the customer (Z_F becomes smaller), and for systems with a smaller fault level (Z_S becomes larger), [1].

2.3 Single Line-to-Ground Fault

This type of fault is non-symmetrical, and the symmetrical component theory will be used for calculation. The voltage divider model presented in the previous subsection has to be split into its three components: a positive-sequence network, a negative-sequence network and a zero-sequence network. The three component networks have to be connected into one equivalent circuit at the fault position depending on the fault type. For a single line-to-ground fault, the three networks should be connected in a series at the fault position, as shown in Figure 3, [1]. Index 1 denotes positive-sequence quantities; Index 2 denotes negative-sequence quantities; and Index 0 denotes zero-sequence quantities.

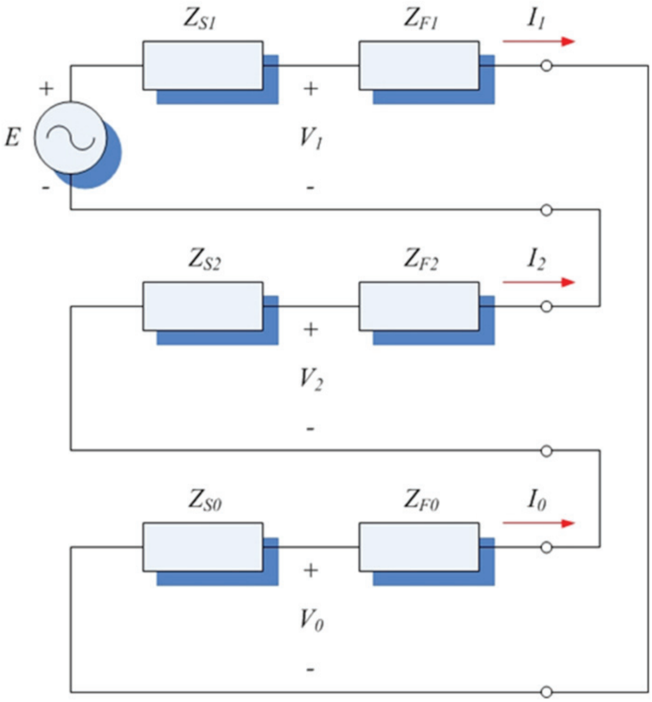

***Figure 3:** Equivalent circuit for a single line-to-ground fault, [1]*

The following expressions are obtained for the component voltages at the PCC, [1]:

$$V_1 = \frac{Z_{F1} + Z_{S2} + Z_{F2} + Z_{S0} + Z_{F0}}{(Z_{F1} + Z_{F2} + Z_{F0}) + (Z_{S1} + Z_{S2} + Z_{S0})} \tag{2.3}$$

$$V_2 = \frac{Z_{S2}}{(Z_{F1} + Z_{F2} + Z_{F0}) + (Z_{S1} + Z_{S2} + Z_{S0})} \tag{2.4}$$

$$V_0 = \frac{Z_{S0}}{(Z_{F1} + Z_{F2} + Z_{F0}) + (Z_{S1} + Z_{S2} + Z_{S0})} \tag{2.5}$$

The voltages in the three phases at the PCC during the fault are, [1],:

$$V_a = V_1 + V_2 + V_0 \tag{2.6}$$

$$V_b = a^2 V_1 + a V_2 + V_0 \tag{2.7}$$

$$V_c = a V_1 + a^2 V_2 + V_0 \tag{2.8}$$

Indices *a*, *b* and *c* denotes original phases and operator *a* is equal to, [1],:

$$a = 1^{\angle 120^\circ} \tag{2.9}$$

Substituting $Z_F = Z_{F1}+Z_{F2}+Z_{F0}$and $Z_S = Z_{S1}+Z_{S2}+Z_{S0}$, the voltages in the three phases are, [1],:

$$V_a = 1 - \frac{Z_{S1}+Z_{S2}+Z_{S0}}{\left(Z_{F1}+Z_{F2}+Z_{F0}\right)+\left(Z_{S1}+Z_{S2}+Z_{S0}\right)} \tag{2.10}$$

$$V_b = a^2 - \frac{a^2 Z_{S1}+aZ_{S2}+Z_{S0}}{\left(Z_{F1}+Z_{F2}+Z_{F0}\right)+\left(Z_{S1}+Z_{S2}+Z_{S0}\right)} \tag{2.11}$$

$$V_c = a - \frac{aZ_{S1}+a^2 Z_{S2}+Z_{S0}}{\left(Z_{F1}+Z_{F2}+Z_{F0}\right)+\left(Z_{S1}+Z_{S2}+Z_{S0}\right)} \tag{2.12}$$

In a solidly-grounded system, the source impedances in the three sequence components are often about equal, [1]. The voltages during the single line-to-ground fault in solidly-grounded systems regarding the mentioned assumption are:

$$V_a = -\frac{Z_{S1}}{\frac{1}{3}\left(Z_{F1}+Z_{F2}+Z_{F0}\right)+Z_{S1}} \tag{2.13}$$

$$V_b = a^2 \tag{2.14}$$

$$V_c = a \tag{2.15}$$

In a resistance or high-impedance grounded system, the zero-sequence source impedance differs from the positive and negative sequence. The assumption that the positive- and negative-sequence impedances are equal can be used. The voltages during single line-to-ground fault in impedance-grounded systems at PCC are, [1],:

$$V_a = 1 - \frac{3Z_{S1}}{\left(2Z_{F1}+Z_{F0}\right)+\left(2Z_{S1}+Z_{S0}\right)} \tag{2.16}$$

$$V_b = a^2 \tag{2.17}$$

$$V_c = a \tag{2.18}$$

3 INFLUENCE OF THE TRANSFORMER WINDING CONNECTIONS ON THE VOLTAGE SAG PROPAGATION

Transformers can be divided into three groups regarding their influence on the propagation of voltage sag, [1], [4],:

- transformers that do not affect voltage sag performance: the only type of the transformer into this group is the star-star connection with both star points grounded.
- transformers that remove the zero-sequence voltage: examples are the star-star connected transformer with one or both sides not grounded, and the delta-delta connected transformer.
- transformers that swap line and phase voltages: for these transformers, each secondary-side voltage equals the difference between two primary-side voltages. Examples are the delta-star (Dy) and the star-delta (Yd) transformer as well as the star-zigzag (Yz) transformer.

The transformers from the first (Ynyn) and from the second group (Yd) will be analysed in this paper. A detailed theoretical analysis of influence of different types of transformer winding connections on voltage sag propagation can be found in the available literature on power quality, [1], [4], [11] and [12]. In the aforementioned literature, the influence of the clock number is further explained.

If voltage sag caused by a single line-to-ground fault comes to the Yd transformer, the voltage at the secondary side can be calculated, [1]:

$$V_a = 1 \tag{3.1}$$

$$V_b = -\frac{1}{2} - \left(\frac{1}{6} + \frac{1}{3}V\right) j\sqrt{3} \tag{3.2}$$

$$V_c = -\frac{1}{2} + \left(\frac{1}{6} + \frac{1}{3}V\right) j\sqrt{3} \tag{3.3}$$

The voltage sag that is present only in one phase on the primary side of the transformer is present in two phases on the secondary side, as shown in Figure 4, [4].

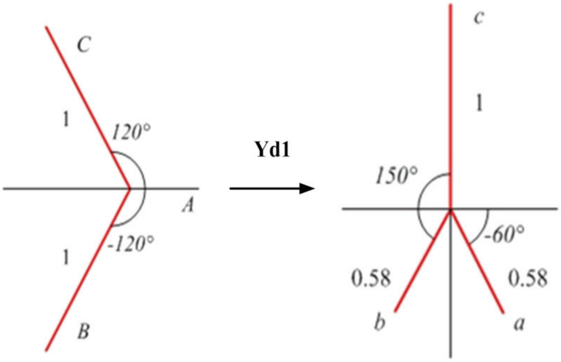

Figure 4: *The propagation of single phase voltage sag through Yd1 transformer*

4 ANALYSIS OF THE MEASURED VOLTAGE SAG PROPAGATION

During a power quality measurement campaign in the transmission and distribution transformer stations in Croatia that was performed by the authors of the paper, the propagation of single phase voltage sags was recorded on 30th June 2007. The values obtained from measurements are presented and compared with those obtained using Equations (3.1)-(3.3). Figure 5 presents the single-line diagram of the analysed system. 'MT' indicates the points where power quality analysers were connected.

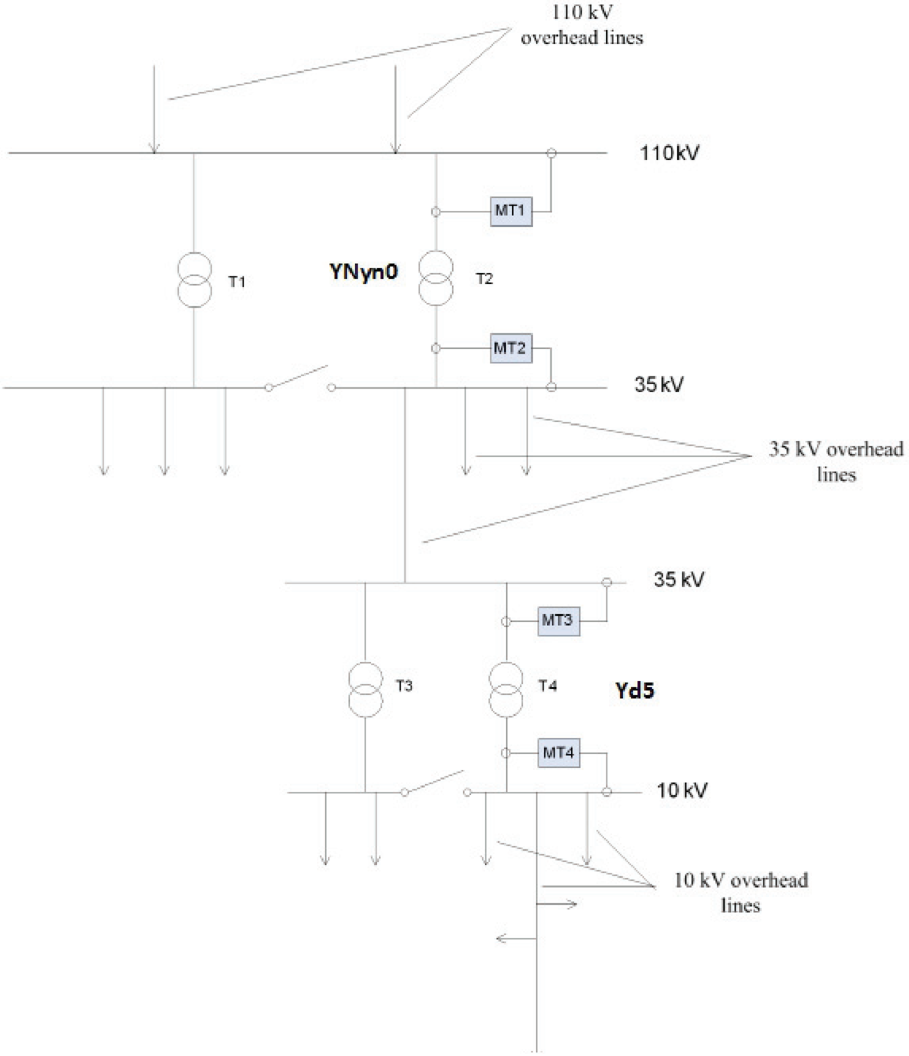

__Figure 5:__ The single-line diagram of the analysed system

The voltage sag that was recorded on 30th June was a single-line voltage sag that was caused by the single line-to-ground short circuit in the transmission network. The measured data of the voltage sag propagation through the 110/35 kV and 35/10 kV transformers are shown in Table 1, in which only the voltages of affected phases are presented.

Table 1: *Data for the measured example of voltage sag propagation*

Transformer 110/35 kV (YNyn0)			
	Primary winding	Secondary winding	
Date	30/06/2007	30/06/2007	
Phase	V_a	V_a	
Duration [ms]	80.004	80	
Phase Voltage [V]	44100	14563.18	
Relative voltage [%]	69.439	72.07	
Transformer 35/10 kV (Yd5)			
Date	30/06/2007	30/06/2007	
Phase	V_a	V_a	V_c
Duration [s]	80	80.022	70.0019
Phase voltage [V]	14630.64	4776	4937
Relative voltage [%]	72.4	82.72	85.51

The single line voltage sag does not change after the first transformer (110/35 kV, connection YNyn). After the second transformer, the voltage sag is present in two phases. This case is similar to those presented in Figure 4, and the difference is only in clock number. The voltage sag that is presented in phase *a* at the primary side of Yd5 transformer, at the secondary side is presented in phases *a* and *c*. The magnitude of the voltages after the Yd5 transformer can be calculated using Equations (3.1)-(3.3).

$$V_a = -\frac{1}{2} - \left(\frac{1}{6} + \frac{1}{3}V\right) j\sqrt{3} = 0.8657 \;\; pu \tag{4.1}$$

$$V_b = 1 \tag{4.2}$$

$$V_c = -\frac{1}{2} + \left(\frac{1}{6} + \frac{1}{3}V\right) j\sqrt{3} = 0.8657 \;\; pu \tag{4.3}$$

V is the pu value of the phase voltage magnitude on the primary side of the affected phase, i.e. *V* = 0.724pu. Equations (3.1) to (3.3) are adopted for Yd5 transformer according to literature [4] i.e. voltage sag at the secondary side of the transformer is present in phase *a* and *c* and voltage in phase b remains unchanged. It can be concluded that measurement results and results that are obtained using Equations (3.1)-(3.3) are close to each other. The differences between measured and calculated values are 3.84% for phase *a* and 1.06% for phase *c* respectively.

5 SIMULATION OF THE VOLTAGE SAG PROPAGATION

In order to make a simulation of the measured example of the voltage sag propagation that is discussed in Section 4, a computer model of the observed distribution network is created in DIGSilent Power Factory software [13]. Figure 6 shows the single line diagram of distribution network that is modelled in DIGSilent and that corresponds to the single line diagram presented in Figure 5.

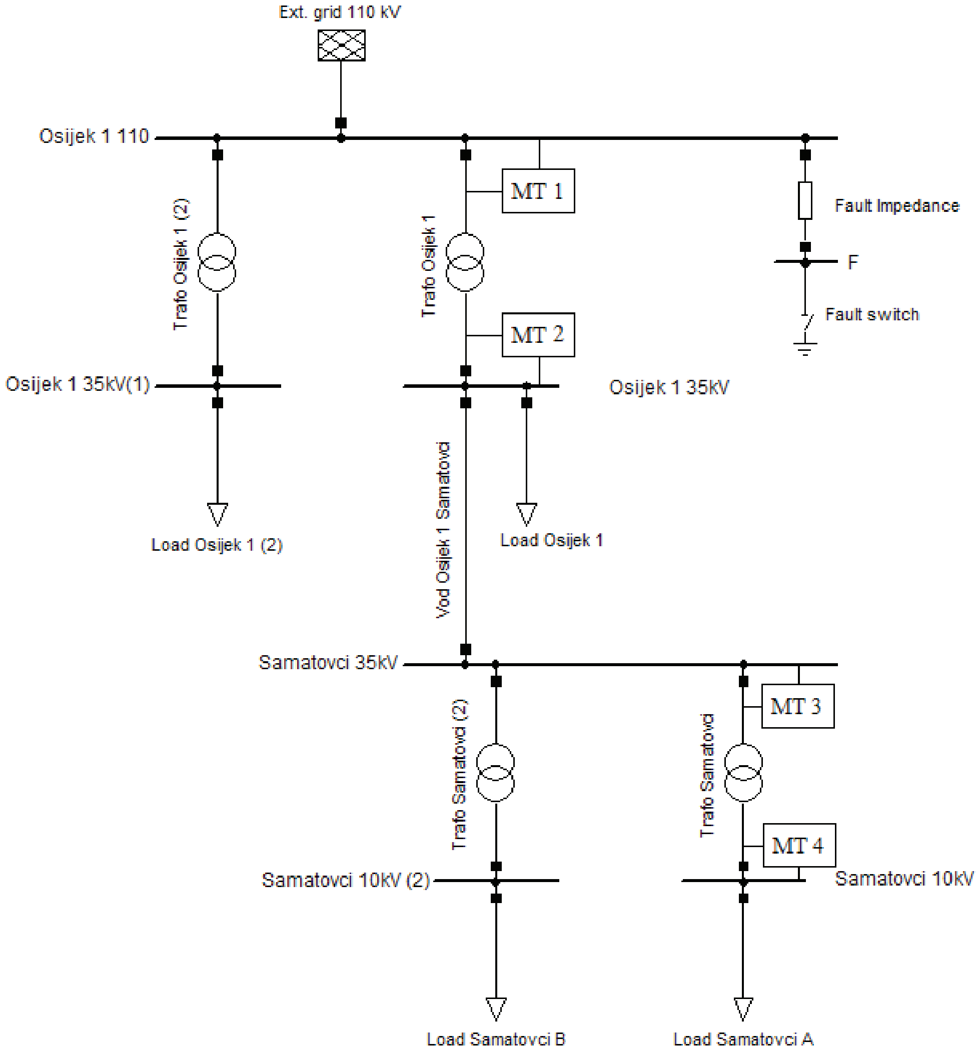

Figure 6: *DIGSilent single line diagram of the modelled distribution network*

Figure 7 presents the simulated voltage sag in phase *a* at the primary side of the YNyn0 transformer (MT1). In order to obtain such a voltage sag, the single line-to-ground short circuit is simulated at the Osijek 1 110 bus. The fault impedance is necessary in order to simulate the same value of voltage sag as is measured. The duration of voltage sag is 80 ms according to Table 1.

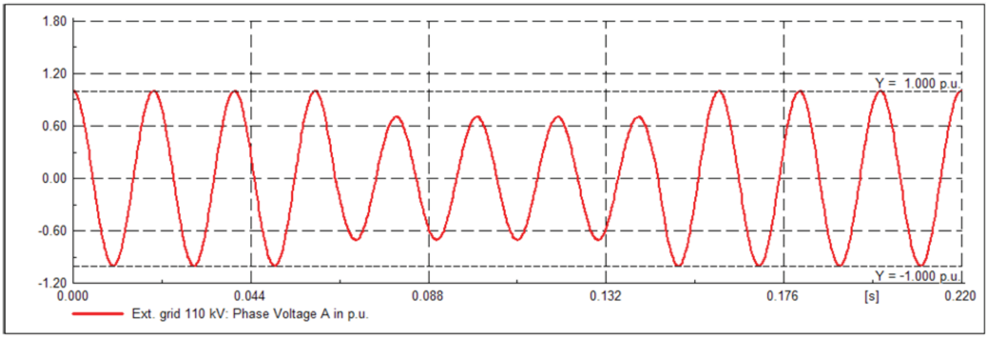

Figure 7: *Simulated voltage sag at the location MT1*

The RMS value of simulated voltage sag can be found in Table 2, where it is compared to the measured and calculated values that are presented in Table 1 and Equations (4.1)-(4.3). Simulated voltage sag propagation through the 110/35 kV transformer is presented in Figure 8. The type of the transformer is YNyn0 and it belongs to the first group of transformers, as explained in Section 3. As can be seen from Figure 8, voltage sag is present in phase *A* at the primary side of the transformer (MT 1) and also in the phase *a* at the secondary side (MT 2), i.e. voltage sag is almost unchanged.

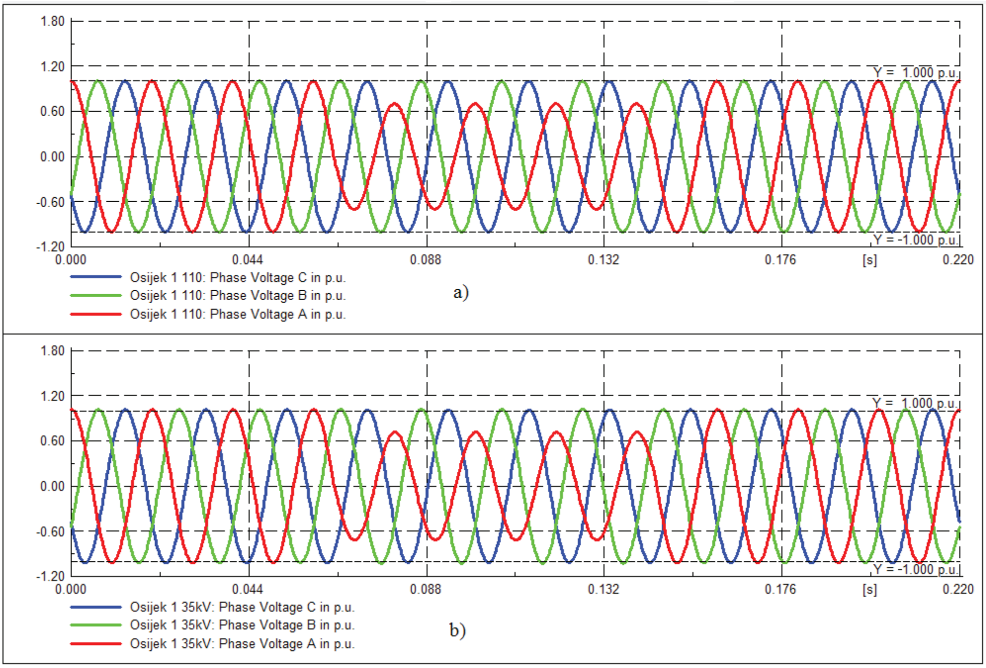

Figure 8: *Simulated voltage sag a) at the location MT 1 and b) at the location MT 2*

Transformer Dy5 (35/10 kV) is more appealing for analysis because it belongs to the second group of transformers, according to classification in Section 3. Transformers from that group remove the zero-sequence voltage and change the performance of voltage sag. The impact of the transformer is reflected in the fact that the voltage sag at the primary side is present only in one phase, while on the secondary side it is present in two phases. Figure 9 shows simulated voltage sag propagation through the 35/10 kV Dy5 transformer, i.e. at the locations MT 3 and MT 4.

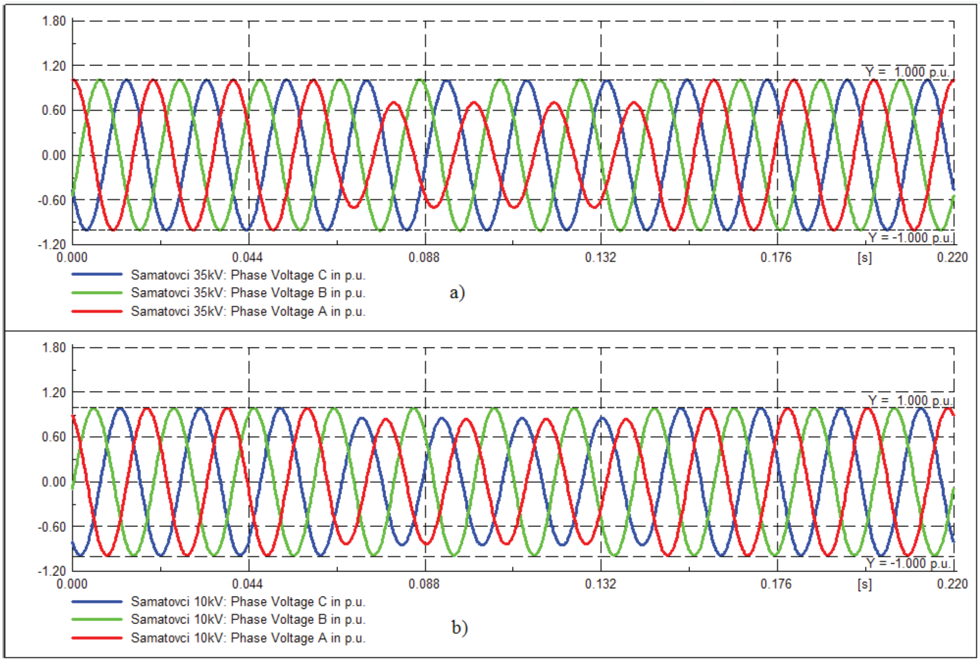

Figure 9: *Simulated voltage sag a) at the location MT 3 and b) at the location MT 4*

The comparison of simulated results with measurement data is presented in Table 2. Good agreement between simulated and measured values is obvious, verifying the computer model

Table 2: *Results of the simulation compared to the measurement data*

<table>
<tr><th colspan="4">Transformer 110/35 kV (YNyn0)</th></tr>
<tr><td></td><td>Primary winding</td><td colspan="2">Secondary winding</td></tr>
<tr><td>Date</td><td>30/06/2007</td><td colspan="2">30/06/2007</td></tr>
<tr><td>Phase</td><td>V_a</td><td colspan="2">V_a</td></tr>
<tr><td>Duration [ms]</td><td>80.004</td><td colspan="2">80</td></tr>
<tr><td>Phase Voltage [V]</td><td>44100</td><td colspan="2">14563.18</td></tr>
<tr><td>Relative voltage [%]</td><td>69.439</td><td colspan="2">72.07</td></tr>
<tr><td>Simulation obtained voltage [%]</td><td>70.09</td><td colspan="2">72.1</td></tr>
<tr><th colspan="4">Transformer 35/10 kV (Yd5)</th></tr>
<tr><td>Date</td><td>30/06/2007</td><td colspan="2">30/06/2007</td></tr>
<tr><td>Phase</td><td>V_a</td><td>V_a</td><td>V_c</td></tr>
<tr><td>Duration [s]</td><td>80</td><td>80.022</td><td>70.0019</td></tr>
<tr><td>Phase voltage [V]</td><td>14630.64</td><td>4776</td><td>4937</td></tr>
<tr><td>Relative voltage [%]</td><td>72.4</td><td>82.72</td><td>85.51</td></tr>
<tr><td>Simulation obtained relative voltage [%]</td><td>71.7</td><td>83.6</td><td>85.2</td></tr>
</table>

6 CONCLUSION

This paper analyses the propagation of a single-phase voltage sag caused by line-to-ground short circuits in the transmission network, from the high voltage level to the distribution level through various types of transformers. It provides an example how a transformer winding connection influences voltage sag propagation in a real power system. One example of voltage sag propagation from the transmission to the distribution level captured with the power quality measurements is presented. Calculations of voltage sag performance based on the theory explained in Section 3 are made, and the results are compared to measurements. A computer model of the observed distribution network is created and used for simulation of voltage sag propagation. Simulation results match those obtained by measurements. The created computer model can be used for detail analysis of voltage sag propagation and its influence on the distribution network. Further work on this topic will include more types of voltage sags (not only single line) and more combinations of transformer winding connections.

References

[1] **M.H.J. Bollen**: *Understanding Power Quality Problems: Voltage Sags and interruptions*, IEEE Press Series on Power Engineering, Piscataway, New York 2000

[2] **Z. Klaić, D. Šljivac and Z. Baus**: *Probability Density Functions of Voltage Sags Measured Indices*, Journal of Electrical Engineering, Vol.62 (No. 5) 2011, pp. 335–341.

[3] **Z. Klaić, D. Sipl and S. Nikolovski**: *Economic Impact of Power Quality Disturbances,* Proceedings of 22nd International Conference & Exhibition on Electricity Distribution, Stockholm 10-13 June 2013

[4] **M.T. Aung, and J.V. Milanovic:**, *The influence of transformer winding connections on the propagation of voltage sags*, IEEE Trans. Power Delivery, Vol. 21 (No. 1) 2006, pp. 262-269

[5] **M. McGranaghan, D.R. Mueller, and M. Samotyj**: *Voltage sag in industrial systems*, IEEE Trans. Ind. Appl., Vol. 29 (No. 2) 1993, pp. 397–403

[6] **Z. Klaić, K. Fekete, S. Nikolovski and Z. Prekratić**: *Propagation of the Voltage Sags Through Different Winding Connections of the Transformers,* Proceedings of 11thInternational Conference on Electrical Power Quality and Utilisation, Lisbon 17-19 October2011

[7] IEEE Recommended Practice for Design of Reliable Industrial and Commercial Power Systems, 1997

[8] IEEE Recommended Practice for Evaluating Electric Power System Compatibility with Electronic Process Equipment, 1998

[9] **EURELECTRIC**: *Power Quality in European Electricity Supply Networks*, Brussels, 2002

[10] **Ph. Feracci**: *Cahier Technique no. 199 – Power Quality*, Schneider Electric, 2001

[11] **J. Pedra, L. Sainz, F. Corcoles and L. Guasch:** Symmetrical and Unsymmetrical Voltage Sag Effects on Three-Phase Transformer, IEEE Trans. Power Delivery, Vol. 20 (No. 2) 2005, pp. 1683-1691

[12] **N.R. Patne and K.L. Thakre:** Effect of transformer on stochastic estimation of voltage sag due to faults in the power system: a PSCAD/EMTDC simulation, Turkish Journal of Electrical Engineering & Computer Sciences, Vol. 18 (No.1) 2010, pp. 43-58

[13] http:// www.digsilent.de