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Original scientific paper

Influence of Cables on Power Transmission Network Frequency Response

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Abstract: Harmonic resonance is an important factor to be considered in a power transmission networks during connection of remote generation units with high-voltage cables (e.g. wind or solar power plants etc.). It is known that cable characteristics differ from characteristics of conventional overhead lines. Cable capacitance is far higher than capacitance of an equivalent overhead line, what can potentially lead to the low resonant frequencies which may be triggered by various switching events, such as transformer or shunt reactor energization etc. In this paper, possible consequences of power plant connection to transmission network with long HVAC cable are analysed, with regard to harmonic resonance and frequency response of the network. The research has been conducted on developed model of the power transmission network in the software for calculation of electro-magnetic transients EMTP-RV.

Keywords: cables; frequency response of power transmission network; harmonic resonance; resonant frequencies; wind power plants

1 INTRODUCTION

Today's power systems are designed for efficiency, reliability, ease of operation, and for meeting consumer needs at minimum costs. Gradual, but steady increase of electrical energy consumption, transit, and integration of new distributive renewable energy sources requires adjustment of the power system in regard to the new circumstances. Accordingly, an expansion of transmission network capacities, application of new technological solutions and installation of new elements into the system, such as underground cables, requires special attention when investigating possible interaction between the existing network and such system elements.

The use of cable circuits (underground or submarine cables) at high voltage transmission levels is steadily increasing, especially in urban areas, big cities, and rural locations in order to reduce the environmental impact and to enable the remote offshore or onshore wind farms connections to transmission network.

Due to high cable capacitance, current can start to flow even if the cable is unloaded. This current is called capacitive charging current and its value depending on the voltage level can be 50-60 times higher than the one of an overhead line. Consequently, an installation of cables increases system capacitance that shifts network natural resonant frequencies closer to the power frequency (50 Hz).

The harmonic resonance at low frequencies can be triggered by various switching events in the network. This points out the necessity for transmission system operators to perform required technical analysis, especially the calculations in time and frequency domain.

The resonance phenomenon and the most often used method for the determination of the frequency response are described in sections 2 and 3. Section 4 presents the developed model for frequency domain simulations in the software for calculation of electro-magnetic transients EMTP-RV. Section 5 analyses case scenario of long cable connection to the power transmission network. To examine the possibility of exciting low resonant frequencies, time-domain simulation of transformer energization is performed and presented in section 6.

2 RESONANCE PHENOMENON

Majority of AC power system elements, such as overhead transmission lines and underground cables, can be represented with resistance, capacitance and inductance. It is generally known that change of inductive or capacitive reactance in the circuit affects its impedance, which is frequency dependent. Analysis of frequency response can become very complex when the real power systems are studied. Topology changes in power system may in some cases lead to unusual electromechanical and electromagnetic phenomena.

The phenomenon of resonance [1] exists in various physical systems and occurs when a frequency of external oscillations corresponds with a natural frequency of self-oscillations, whereby maximum energy is transferred from one oscillating system (transmitter) to another (receiver), if their oscillation frequencies are similar.

Various network configurations, either planned or unplanned, such as some critical configurations during restoration or energization of unloaded transformers, shunt reactors, transmission lines and cables, may result with resonance [2-4]. In some cases, resonance can cause high harmonic temporary overvoltages, which may lead to failure of high voltage equipment such as surge arresters [2, 3, 5]. The resonance in electrical systems occurs when the capacitive reactance equals the inductive reactance at the driving frequency. This frequency is also called natural resonant frequency [1], and it can be calculated by the following equation:

$$f_{\mathrm{r}} = \frac{1}{2\pi\sqrt{LC}} \tag{1}$$

Resonance may occur at one or more frequencies, depending on the number of capacitive and inductive elements in the circuit. If the observed circuit has such n elements, then it has $n/2$ resonant frequencies. In very complex circuits such as transmission networks, depending on their configuration, two types of resonance may occur: serial and parallel [1, 6, 7].

Parallel resonance is characterized by high impedance at the resonance frequency. Ideally, the resultant susceptance of resonance circuit is zero. The frequency response of a parallel resonant circuit shows that the magnitude of the current is a function of frequency and it reaches minimum value at the resonant frequency. Consequently, the magnitude of the current flowing through the inductive and capacitive elements can become many times larger than the supply current, even at resonance, but as they are equal and they have opposing phase angles, they effectively cancel each other out. Increased voltage distortion with increased losses may be caused by parallel resonance conditions, which can be achieved for example with a capacitor banks for improving system's reactive power, connected in parallel with non-linear loads and network inductances.

On the other hand, serial resonance is characterized by a low impedance at the resonant frequency. The resultant reactance of the resonance circuit is zero. If this type of resonance occurs, voltages at inductive and capacitive elements in the power system reach high values in magnitude, but they have opposing phase angles and cancel each other out.

Several methods for determination of system's frequency response already exist in literature [8, 9]. Section 3 gives an overview of the commonly used methods.

3 METHODS FOR DETERMINATION OF POWER TRANSMISSION NETWORK FREQUENCY RESPONSE

The main purpose of system's frequency scan is to determine high impedance frequencies within the selected frequency range, which indicates possible resonance issues in the studied network.

The commonly used method for determination of the frequency response is frequency scan with calculations in the frequency domain, by use of a various software tools. Frequency scans are used to identify resonant points and corresponding resonant frequencies. This method is based on the nodal impedance matrix, whereby impedance/ admittance frequency response of the observed system needs to be determined.

The method is effective for detection of harmonic resonance and also for filter design. The frequency scan can be applied on both one phase and three phase systems. Fig. 1 illustrates concept of frequency scan method.

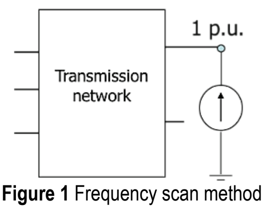

Figure 1 Frequency scan method

By injecting a one per unit current to the bus *i*, while all the other buses are left open-circuited, the measured voltage magnitude and phase angle at bus *i* corresponds to the impedance Z_{ii} at frequency *f*:

$$\begin{bmatrix} V_1 \\ V_2 \\ .. \\ .. \\ V_N \end{bmatrix} = \begin{bmatrix} Z_{11} & . & . & . & Z_{1N} \\ Z_{21} & . & . & . & Z_{2N} \\ .. & .. & .. & .. & .. \\ .. & & .... & & .. \\ Z_{N1} & .. & .. & .. & Z_{NN} \end{bmatrix} \cdot \begin{bmatrix} 1 \\ 0 \\ .. \\ .. \\ 0 \end{bmatrix} \quad (2)$$

This process can be repeated at discrete frequencies throughout the range of interest in order to obtain the impedance frequency response. Mathematically, this corresponds to calculating the diagonal elements of the impedance matrix. Using the same methodology, it is possible to determine the admittance frequency response as well. The result of frequency scan is impedance amplitude $Z = f(f)$ and phase angle $\varphi = f(f)$ versus frequency [1, 10]. When the impedance $Z = f(f)$ is equal to the global or local maximum, and the impedance phase angle is close to 0°, frequency is equal to the parallel resonance frequency of the system. When the impedance $Z = f(f)$ is equal to the global or local minimal, and at the same time the impedance phase angle is close to 0°, frequency is equal to the series resonant frequency of the system.

Another well-known method used for determination of frequency response is the harmonic resonance mode analysis (HRMA), or simply called modal analysis [9]. The harmonic resonance occurs when the nodal voltages are very high, which is associated with the admittance matrix approaching singularity.

Generally, both the frequency scan method and the HRMA are forms of resonance analysis strongly related to the impedance/admittance matrix and its variation with frequency for the power system of interest. The frequency scan method is very illustrative, as it clearly shows the points of resonance, but it does not indicate which of the systems components cause the resonance and where is the best location to control the resonance [8, 9]. So, HRMA can be used for more detailed harmonic analysis.

4 MODEL OF THE POWER TRANSMISSION NETWORK UNDER STUDY

For the main purpose of calculations in frequency domain, the model of one "medium-sized" power transmission network is developed in the software EMTP-RV (Fig. 2). The model comprises three voltage levels (400 kV, 220 kV and 110 kV) and consists of 202 nodes, 311 transmission lines, 36 power transformers (400/220 kV, 400/110 kV and 220/110 kV), 77 generator step-up transformers (400/x kV, 220/x kV and 110/x kV) and 77 generator units.

The developed model is suitable for performing the following types of study:

- Load-flow and short-circuit calculations,
- Low-frequency transient phenomena studies,
- Frequency domain studies etc.

Such network models allow investigating of possible challenges related to undergrounding of transmission power system, as well as connection of remote power plants with cables, what is investigated in the scope of case scenario in section 5.

Network data for developed EMTP-RV model is imported from the SCADA/EMS system. The same data can be used in other power system software (e.g. PSS/E), what allows verification of developed EMTP-RV model.

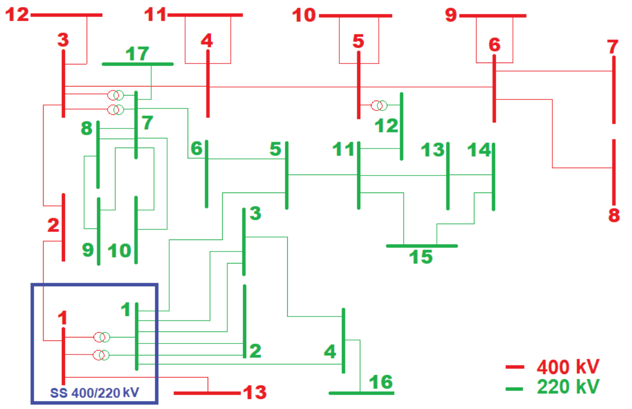

Figure 2 Single-line diagram of developed transmission network model (only 220 kV and 400 kV voltage levels are shown). The substation marked with blue colour presents point of power plant connection via cable, what is analysed in case scenario in section 5.

4.1 Transmission Line and Cable Modelling

Transmission lines and cables can be modelled as: Constant Parameter (CP) model and Frequency Dependent (FD) model [12, 13]. Frequency scan comparison of both models shows that CP line model is less precise than frequency dependent line and cable model in analysis of high frequency problems (frequencies above few kHz), but CP models can be used in frequency scan analysis of transmission networks associated with lower frequency phenomena. Also, CP line model requires less computational time, which is important when dealing with large network models [13].

Accordingly, transmission lines and cables are modelled as CP model with included propagation. For frequency scan simulations, pi-circuit parameters of CP line model from Fig. 3 (*R* - resistance, *L* - inductance, *G* - conductance, *C* - capacitance) are calculated at each frequency per unit length.

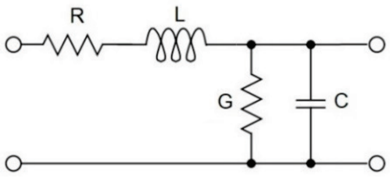

Figure 3 Circuit representation of constant parameter line model

4.2 Generator Modelling

The generator units are modelled by use of constant reactance model [12]. This model consists of a simple AC voltage source connected in series with sequence impedance (positive and zero sequence) which presents generator's sub-transient reactance. Also, this generator model neglects magnetic saliency, assumes that the operating reactance of the generator is the transient reactance, and considers the voltage behind transient reactance to be constant. Simple generator model is presented in Fig. 4.

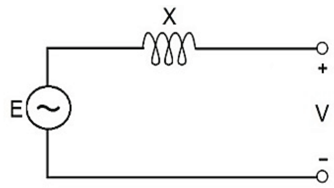

Figure 4 Representation of a generator as a constant voltage source behind transient reactance

4.3 Transformer Modelling

For the purpose of simplification, all transformers are modelled as standard two winding T-model transformers. Similar approach has been used in the power system studies for many decades. An equivalent circuit of the T-model is presented in Fig. 5 [12, 15], where R_H and R_X present series resistances including cooper losses of each winding (skin effect and Joules losses), L_H and L_X present leakage inductance, R_m and L_m present core behaviour (including nonlinearity, saturation, hysteresis and other iron losses) and N_H / N_X is transformer ratio.

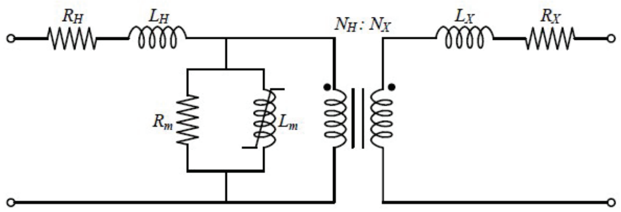

Figure 5 Equivalent circuit of a power transformer (T-model)

The T-model of transformer is suitable for low frequency analysis (up to few kHz), while for analysis at higher frequencies more detailed transformer models should be used (such as Black Box, White Box and Grey Box) [14].

4.4 Load Modelling

The loads are modelled as parallel combination of equivalent *R*, *L* and C branches [12]. The resistance value in parallel combination is given by:

$$R = \frac{V_{\text{load}}^2}{P} \quad (3)$$

When $Q > 0$, the inductance value in parallel combination is given by:

$$L = \frac{V_{\text{load}}^2}{\omega Q} \quad (4)$$

When $Q < 0$, the capacitance value in parallel combination is given by:

$$C = \frac{|Q|}{\omega V_{\text{load}}^2} \quad (5)$$

During frequency scan, the equivalent load impedance is calculated at each frequency of interest.

5 CASE SCENARIO OF POWER PLANT CONNECTION TO THE TRANSMISSION NETWORK WITH LONG HVAC CABLE

In order to identify possible risks related to the low-frequency resonance phenomena, this case scenario shows analysis of resonances that can occur when long (HVAC) cable is connected to the transmission network [6, 16-18]. Introduction of long cables to transmission networks also requires more detailed analysis (steady state load flow calculations) in order to determine optimal reactive power compensation.

Table 1 Different connection scenarios

Scenario	Overhead line length / km	Cable length / km
A	0	0
B	80	0
C	60	20
D	40	40
E	20	60
F	0	80

For the purposes of this study, it is assumed that 80 km remote wind power plant will be connected to the existing network on the observed point of connection at 220 kV level (according to the marked point of connection from Fig. 2). Initial frequency scans, performed on 220 kV voltage level show that the harmonic impedance has low-order resonant frequencies at the given point of the network. In order to investigate the influence of different cable and overhead line lengths on the resonance behaviour of the transmission network, the analysis considering different connection scenarios was performed and presented in Tab. 1.

Scenario A indicates that there is no connection of wind power plant to the existing network, while scenarios B-F represent the wind power plant connection to the existing network with different overhead line and cable lengths.

It is most interesting to check the resonant frequencies at low-order ranges. Fig. 6 shows positive-sequence frequency scan at 220 kV voltage level. It can be seen that the first resonance peak for scenarios A and B is similar (343 Hz). For scenarios C-F the first resonance peak varies from 298 Hz to 203 Hz, for the case of 80 km cable length. It is also important to check zero-sequence resonant peaks.

Zero-sequence frequency scan at 220 kV voltage level is presented in Fig. 7. It shows that the first resonant peak varies from 275 Hz to 160 Hz (the worst case) with higher impedance magnitudes.

Frequency scans from Figs. 6 and 7 indicate that increase of cable capacitance considerably contributes to the shifting of the resonant frequencies, whereby low-order frequencies (up to 7th harmonic) could be reached.

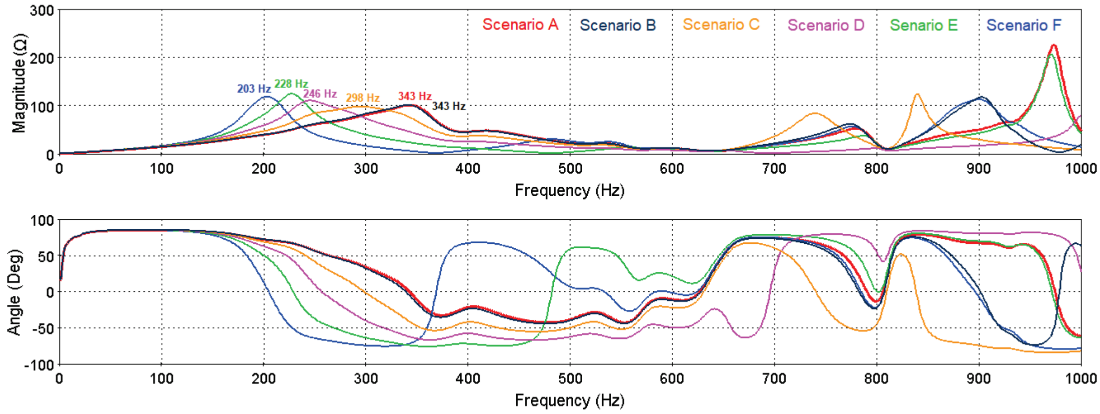

Figure 6 Magnitude and angle (positive sequence) of the power transmission network frequency response at 220 kV voltage level of the observed substation for different connection scenarios

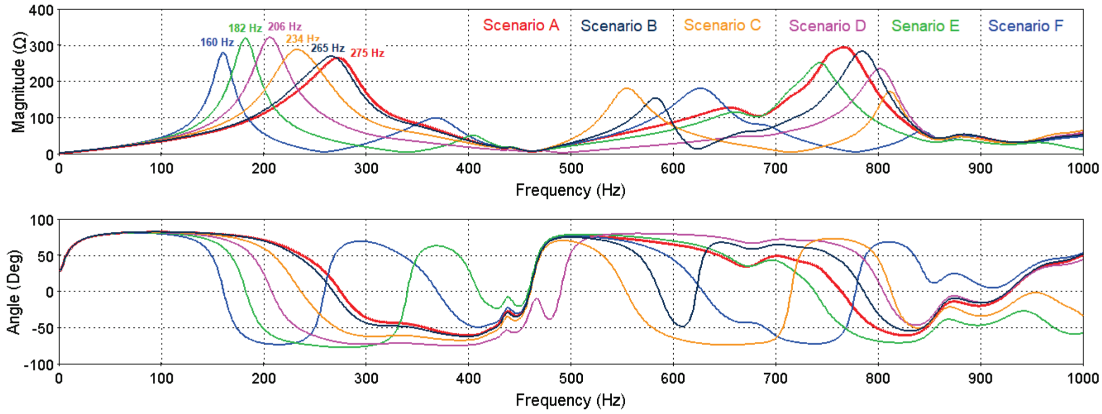

Figure 7 Magnitude and angle (zero sequence) of the power transmission network frequency response at 220 kV voltage level of the observed substation for different connection scenarios

Changing of network topology is another factor that can contribute to the change of the resonant frequencies, what is shown in Figs. 8 and 9, whereby impedance frequency scan was performed for different network topologies of surrounding network for the case with the lowest resonant frequency (scenario F). Therefore, the following network topologies (according to the single-line diagram from Fig. 2) are considered to show their impact on resonant frequencies:

- Network topology 1: wind power plant is connected to the existing network via 80 km cable; all (220 kV and 400 kV) transmission lines connected to the observed substation are energized.
- Network topology 2: wind power plant is connected to the existing network via 80 km cable; 101 km long 400 kV overhead line from substation 1 – 2 is switched off.
- Network topology 3: wind power plant is connected to the existing network via 80 km cable; 113 km long 400 kV overhead line from substation 1 – 13 is switched off.
- Network topology 4: wind power plant is connected to the existing network via 80 km cable; 210 km long 220 kV overhead line from substation 1 – 5 is switched off.
- Network topology 5: wind power plant is connected to the existing network via 80 km cable; 25 km long 220 kV overhead line from substation 1 – 4 is switched off.

Frequency scan of positive sequence impedance from Fig. 8 shows impact of the network topology change on the resonant frequencies. For the network topology 1 (connection scenario F), assumed as a base case, the resonant frequency is 203 Hz. For different network topologies of surrounding network, the first resonant peak varies from 192 Hz to 206 Hz. The increase of network impedance magnitude is mostly affected by the network topology 2 (switching off 101 km long 400 kV overhead line).

The impact of network topology change on resonant frequencies for zero-sequence frequency scan is shown in Fig. 9. Similar to positive-sequence frequency scan, the first resonant peak varies from 153 Hz to 166 Hz, with regard to 160 Hz from the base case. Also, impedance magnitudes are higher comparing to the positive-sequence frequency scan. The frequencies and magnitudes presented in Figs. 6-9 could be excited by various switching operations such as auto-reclosure of transmission lines or transformer energization, as shown in section 6.

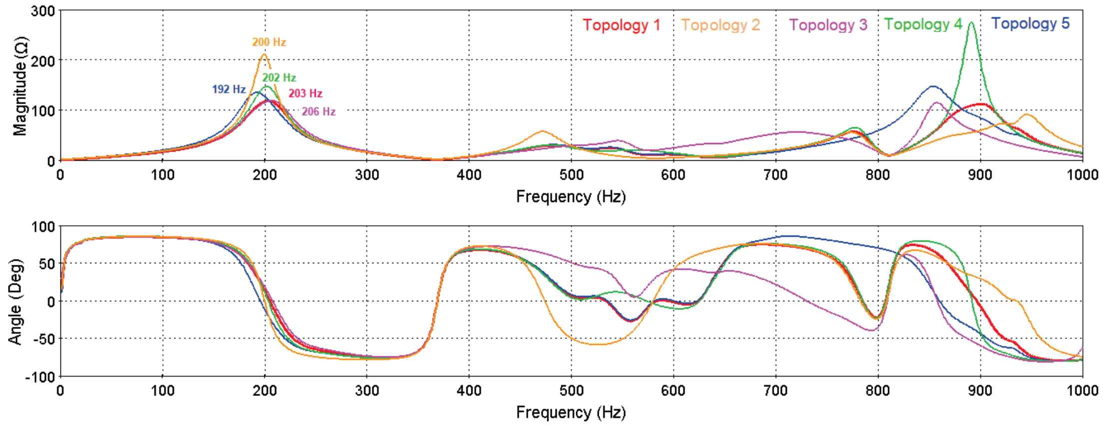

Figure 8 Magnitude and angle (positive-sequence) of the power transmission network frequency response at 220 kV voltage level of the observed substation for different network topologies

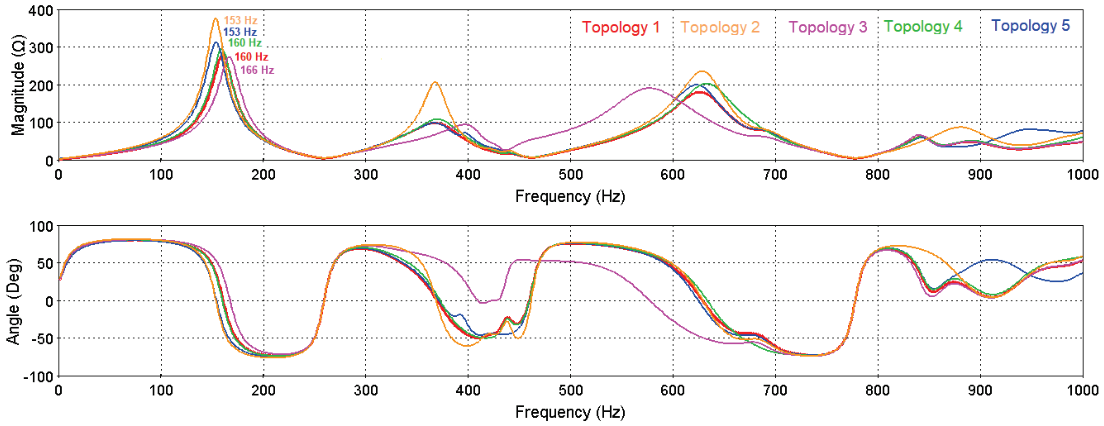

Figure 9 Magnitude and angle (zero-sequence) of the power transmission network frequency response at 220 kV voltage level of the observed substation for different network topologies

6 TIME-DOMAIN STUDIES THAT COULD POSSIBLY EXCITE LOW RESONANT FREQUENCIES

Resonant frequencies may be triggered by various switching operations. One of them is transformer energization [2, 6], which can produce serious issues in power systems. Because of its non-linear behaviour, harmonic currents are generated.

In normal operation, harmonic currents due to transformer core are usually low. During transformer energization, inrush current magnitude is typically 5-10 times higher than the rated current magnitude and the harmonic content can be high. Depending on the energization instant and residual magnetic flux the transformer core may be highly saturated. This leads to the highly distorted current wave shape that contains significant harmonics.

If one of the harmonic components of the inrush current is close to the resonant frequency of the power system, a sustained overvoltage can be produced.

This section analyses possibility of exciting the low resonances shown in Figs. 6-9 in previous section. An example of the wind power plant 220/15,75 kV transformer energization is analysed. A wind power plant connection diagram is shown in Fig. 10.

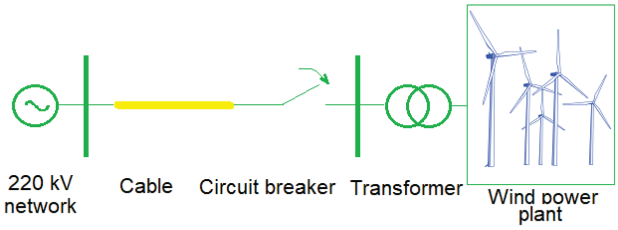

Figure 10 Wind power plant connection diagram

The equivalent 220 kV network was represented with positive (R_1 = 2,15 Ω, L_1 = 34,35 mH) and zero (R_0 = 2,00 Ω, L_0 = 31,95 mH) sequence impedances, determined from single-phase and three-phase short circuit currents at the observed point of the wind power plant connection. The connection cable (80 km long) is modelled using a CP model, with positive (R_1 = 0,04 Ω, L_1 = 0,41 mH, C_1 = 0,18 μF) and zero (R_0 = 0,12 Ω, L_0 = 1,24 mH, C_0 = 0,11 μF) sequence impedances. The circuit breaker is considered as an ideal switch with closing time of all three phases at 15 ms. The wind power plant 220/15,75 kV transformer is represented as 3 phase unit with data obtained from nameplate data (connection type YNd5, rated power: 190 MVA) and magnetization curve obtained from the transformer test report (no-load losses test).

Table 2 Transformer no-load losses test

Voltage / pu	Current / %
80,0	0,039
89,5	0,049
95,0	0,057
100,1	0,070
105,2	0,094
109,9	0,148

Inrush currents and subsequent harmonic overvoltages are highly dependent on two initial conditions: residual fluxes of the energized transformer and switching times [19].

Uncontrolled energization of large power transformers may result in deep saturation of one or more cores of the transformer [20]. The saturation results in a higher amplitude of magnetizing inrush currents that are rich in harmonics and have also a high direct current component.

The simulation of transformer energization is performed with the software EMTP-RV, when the transformer is energized from high voltage side, although energizing of the low voltage winding generates higher inrush currents. The simulation is performed without residual flux in the core. Fig. 11 shows the phase-to-ground voltages at HV side of transformer during energization, with maximum amplitude of 1,39 pu in the phase A.

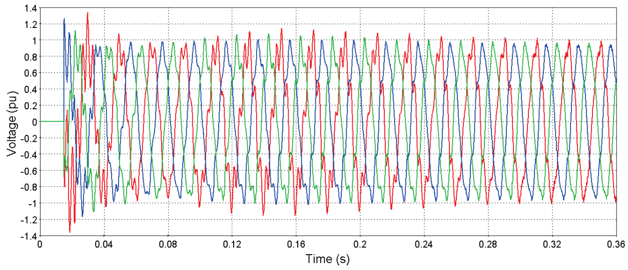

Figure 11 Transformer voltages at HV side during energization (U_{max} = 1,39 pu)

Fig. 12 shows transformer inrush currents. Maximum amplitude of the inrush current is obtained in the phase A (4,85 pu).

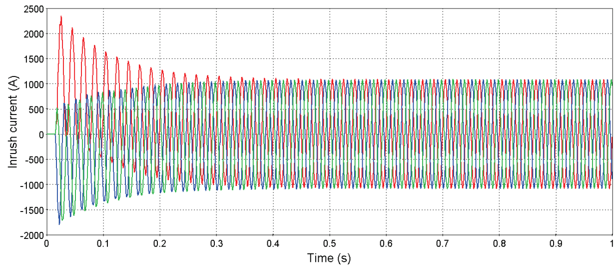

Figure 12 Transformer inrush currents (I_{max} = 4,85 pu)

Frequency spectrum of the transformer inrush current (phase A) is presented in Fig. 13, where significant occurrence of odd harmonics is evident.

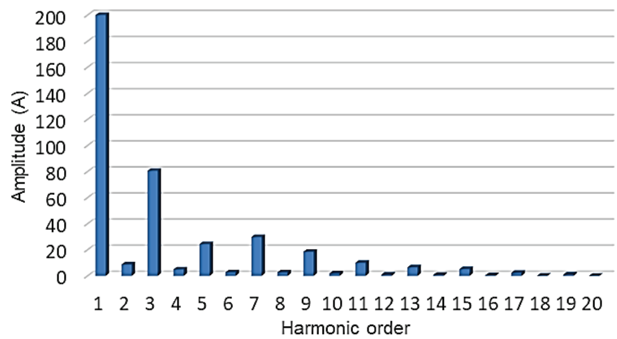

Figure 13 Frequency spectrum of the transformer inrush current in the phase A

Normally, all triplen harmonics are absorbed in delta windings, so the harmonics being generated are of orders 5, 7, 11, 13, 17, 19 etc. With the supplied voltage free of any DC component, a hysteresis loop of the transformer core is symmetrical to the B-H coordinate system origin, what implies the existence of the odd harmonics of an AC excitation current waveform exclusively. The appearance of a DC component of inrush current can result with the occurrence of the even harmonics [21].

The harmonic analysis in Fig. 13 shows that the dominant harmonics of the inrush current waveform are in the frequency range of 150-350 Hz, what corresponds to the resonant frequencies of the transmission network shown in section 5, when long HVAC cable has been introduced to the network. To avoid harmonic resonance overvoltages, different mitigation measures can be implemented. The best way to avoid harmonic resonance is to assure that series and parallel combinations of system's capacitance and inductance do not match the harmonic frequency. This requires special system analysis and design of harmonic filters with the main objective of reducing harmonics.

System equipment is designed to withstand temporary overvoltages according to the IEC 60071-1 [22]. Surge arresters will normally be activated before the harmonic resonance overvoltage reaches the equipment's standard short-duration power-frequency withstand voltage. But, sustained resonance overvoltages, even if they are below the specified withstand voltage may damage the system equipment such as surge arresters, due to high energy stress.

7 CONCLUSION

In this paper, developed model of the power transmission network for calculations in frequency domain has been presented. The frequency scan method has been used to determine the resonant frequencies in the case of a wind power plant connection to the transmission network via cable. Introduction of cables to power transmission system contributes to the occurrence of high harmonic impedances at low resonant frequencies, which can be excited by various switching events in the network.

At first, a frequency scan at the 220 kV voltage level, performed for different connection scenarios and different network topologies showed the first resonant peaks in the range of 192-343 Hz for positive sequence, and 153-275 Hz for zero sequence.

Then, an example of 220/15,75 kV transformer energization, with included non-linear magnetizing characteristic to represent the occurrence of transformer inrush currents (that contain higher harmonics) showed that the dominant harmonics of the inrush current waveform can be in the range of 150-350 Hz for the particular transformer.

This theoretical study has been performed by use of real data to show possibility of resonance in the real network. It points out importance of conducting the described studies at the early stage of such projects, especially in frequency and time domain in order to predict possible dangerous sustained overvoltages and resonant frequencies. Also, it is important to investigate described phenomena for different connection scenarios as well as for different network topologies.

Acknowledgement

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8 REFERENCES

[1] Emin, Z., et al. (2014). *Resonance and Ferroresonance in Power Networks*. Cigré Technical Brochure 569 - WG C4.307, Paris, France.

[2] Cheng, C. P. & Chen, S. (2003). Simulation of Resonance Over-voltage during Energization of High Voltage Power Network, IPST, New Orleans, USA.

[3] Colla, L., Lauria, S., & Gatta, F. M. (2007). Temporary Overvoltages due to Harmonic Resonance in Long EHV Cables. *International Conference on Power Systems Transients*, Lyon, France, June.

[4] Hammad, A., Boshoff, S., van der Merwe, W. C., van Dyk, C., Otto, W., & Kleyenstüber, U. H. E. (2015). *SVC for Mitigating 50 Hz Resonance of a Long 400 kV AC Interconnection*, ABB library.

[5] Dennetière, S., Parisot, A., Milin, E., & Dalmau Pons, A. (2011). Resonance and insertion studies with EMTP: Working with large scale network models. *International Conference on Power Systems Transients*, Delft, Netherlands.

[6] Jansen, K., van Hulst, B., Engelbrecht, C., Hesen, P., Velitsikakis, K., & Lakenbrink, C. (2015). *Resonances due to Long HVAC Offshore Cable Connections: Studies to verify the Immunity of Dutch Transmission network*. IEEE Eindhoven PowerTech, Netherland. https://doi.org/10.1109/PTC.2015.7232408

[7] Bollen, M. H. J., Mousavi-Gargari, S., & Bahramirad, S. (2014). Harmonic resonances due to transmission-system cables. *International Conference on Renewable Energies and Power Quality*, Cordoba, Spain, April. https://doi.org/10.24084/repqj12.463

[8] Rauma, K. (2012). Electrical Resonances and Harmonics in a Wind Power Plant. Aalto University, *Master Thesis*, Finland.

[9] Brantsæter, H. A. (2015). Harmonic Resonance Mode Analysis and Application for Offshore Wind Power Plants, *Doctoral Thesis*, Norway.

[10] Kowalak, R., Malkowski, R., Czapp, S., Klucznik, J., Lubosny, Z., & Dobrzynski, K. (2016). Computer-aided analysis of resonance risk in power system with Static Var Compensators. *Przegląd Elektrotechniczny*, ISSN 0033-2097, R. 92 NR 3/2016.

[11] Galland, O., Leu, D., Berner, V., & Favre-Perrod, P. (2015). Resonance Analysis of a Transmission Power System and Possible Consequences of its Undergrounding. *Period. Polytech. Elec. Eng. Comp. Sci., 59*(3). https://doi.org/10.3311/PPee.8576

[12] EMTP Theory Book, Portland, USA, 1995.

[13] Gérin-Lajoie, L. & Mahseredjian, J. (2009). Simulation of an extra-large network in EMTP: from electromagnetic to electromechanical transients. *International Conference on Power Systems Transients*, Kyoto, Japan, June.

[14] Jurisic, B., Uglesic, I., Xemard, A., & Paladian, F. (2018). High frequency transformer model derived from limited information about the transformer geometry. *International Journal of Electrical Power & Energy Systems*, 94, 300-310. https://doi.org/10.1016/j.ijepes.2017.07.017

[15] Teshmont consultants LP. (2014). *Transformer modelling guide*, Calgary, Canada, July.

[16] Palone, F., Rebolini, M., Lauria, S., Schembari, M., & Vassallo, J. (2014). *Frequency domain studies for the Malta-Sicily interconnector*, Paris Cigre Session.

[17] Hasan, K. N., Rauma, K., Luna, A., Candela, J. I., & Rodriguez, P. (2012). Harmonic Resonance Study for Wind Power Plant. *International Conference on Renewable Energies and Power Quality*, Santiago de Compostela (Spain). https://doi.org/10.1109/ICIAS.2012.6306230

[18] Vernay, Y., Deschanvres, S., & Fillion, Y. (2014). *RTE experiences with the insertion of long EHVAC insulated cables*, C4-303, Paris Cigre Session.

[19] Chiesa, N., Høidalen, H. K., Lambert, M., & Martınez Duro, M. (2011). Calculation of Inrush Currents – Benchmarking of Transformer Models. *International Conference on Power Systems Transients*, Delft, Netherland, June 14-17.

[20] Moon, R. & Dhatrak, R. K. (2014). A Study of Effect of Magnetizing Inrush Current on Different Ratings of Transformers. *IJAREEIE, 3*(4), 2320-3765.

[21] Hodder, S., Kasztenny, B., Fischer, N., & Xia, Y. (2014). Low second-harmonic content in transformer inrush currents - Analysis and practical solutions for protection security. *67th Annual Conference for Protective Relay Engineers, CPRE 2014.* https://doi.org/10.1109/CPRE.2014.6799037
[22] IEC 60071-1:2006. Insulation co-ordination - Part 1: Definitions, principles and rules.

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