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Original Article

Investigation of Resonance Condition in OFF Shore Wind Park during Energization Events

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Abstract *- Transformer energisation in offshore High-Voltage Alternating Current (HVAC) transmission systems can result in significant transient and temporary overvoltages due to the interaction between transformer magnetising inrush currents and network resonances. A detailed Electromagnetic Transient (EMT) model comprising a Thevenin-equivalent grid, frequency-dependent cable representation, and a saturable transformer model was developed to analyse the switching behaviour of the system. Wind Turbine Transformers (WTTs) are experiencing high dielectric stress due to transients induced during energization and de-energization events in offshore wind parks. This paper investigates the energisation of WTT connected to an onshore grid through a HVAC export cable under weak-grid conditions, the resonance potential on the terminal of WTT is assessed. A black box model of a 300 kVA transformer is derived by measurement and implemented in ATP. Vector fitting is used in establishing the frequency domain model and lumped parameter RLC description of the transformer is introduced in ATP as a user specified component. More Emphasis is given on the accurate modeling of cable-transformer energization as well as cable ground fault. Finally, transients induced during switching in an array of Wind Park are simulated in ATP to identify resonance situations and transformer terminal voltages.*

Keywords *- Black box modeling, Energization transients, Induced over voltages, Offshore wind farm, Resonant frequency.*

1. Introduction

The integration of offshore wind generation into existing power systems presents significant technical challenges, particularly during switching and energisation operations. HVAC transmission systems are widely used to connect offshore wind farms to onshore grids over moderate distances. These systems typically comprise long submarine cables, power transformers, and reactive compensation equipment whose electrical characteristics may interact during transient conditions [1].

Transformer energization produces magnetizing inrush currents due to core saturation. These currents contain low-order harmonic components that can interact with the inductive and capacitive elements of the HVAC network [2].

In offshore transmission systems, the high capacitance of long submarine cables and relatively low network damping increase the likelihood of harmonic resonance [8]. Such interactions can lead to transient overvoltages and Temporary Overvoltages (TOVs), imposing additional electrical stress on transformers, cables, switchgear, and other network components. Previous studies have shown that offshore HVAC transmission systems incorporating long export cables are particularly susceptible to resonance-driven over voltages during transformer energisation.

The interaction between cable capacitance and network inductance may create resonant conditions at low-order harmonic frequencies, including the second and third harmonics, resulting in sustained voltage amplification and increased equipment stress [1].

Furthermore, transformer inrush currents contain dominant low-order harmonics that can excite these resonant modes and contribute to significant TOVs, highlighting the need for detailed EMT studies when assessing offshore transmission systems [2].

Several mitigation techniques have been proposed, including controlled switching, pre-insertion resistors, and harmonic filtering. Among these methods, C-type filters are particularly attractive because they provide effective damping of low-order resonances while maintaining minimal losses at the fundamental frequency [4].

Resonances close to 100 Hz can significantly increase voltage magnitudes during transformer energisation, especially under weak-grid conditions, and increasing cable length may further increase the likelihood of interaction with transformer inrush harmonics [5]. To connect OFF shore wind farm to the on-shore substation long export cables is used and each wind turbine is associated with step-up wind turbine transformer and array cable.

In [3], examined the grid integrated OFF Shore Wind Farms and Medium Voltage underground cable systems are differed and aligned. Though the switching of both the systems deals with similar equipment, e.g.MV transformers, MV cables and Vacuum Circuit Breakers (VCBs), many parameters need to be considered during energization of OFF Shore Wind Farm as its maintenance cost is high, repair and physical accessibility are major issues for OWFs. Wind turbine transformers installed in any wind farm can be subjected to insulation failures due to over voltages, e.g. Temporary over voltages during energization and de-energization events, Load rejection, WTT failure.

Several studies have examined these effects and analyzed how these factors can lead to dielectric failures in transformers [4-9]. Experiment based results on 11.4 kV/235 V distribution transformer demonstrate that the application of a step voltage through a 27 m length cable can result in over voltages as high as 24 per unit on the open low-voltage side [4].

These findings highlight the critical importance of analysing resonance effects both at transformer terminals and within winding structures. Most of the researchers only focused on simulation process of transformer inrush currents transient over voltages and temporary over voltages produced during energisation of Transformers.

The objective of this study is to derive transformer model in ATP from the measured data, with this model dominant resonance frequencies are identified after performing impedance based and induced voltage frequency scan, during the energisation of an offshore Wind turbine transformer connected to the onshore network via a HVAC cable when the travelling wave frequency (depends on cable length) matches with resonance frequency resulting highest Peak transient and temporary over voltages.

The assessment also focuses on identifying worst-case Transient Overvoltage (TOV) conditions by performing several studies. In the proposed work, over voltages along a cable in a wind turbine string are simulated and analysed using ATP. The occurrence of resonance over voltages at transformer terminals is evaluated under two conditions energization of the cable–transformer system and the presence of an earth fault at the cable input. Additionally, the influence of cable length on the resulting over voltage characteristics is systematically investigated.

2. Network Modelling and Resonance Assessment

The components of Off shore wind farm considered for investigating switching transients are Wind Turbine Transformers, long submarine cables, Vacuum Circuit Breakers (VCB).

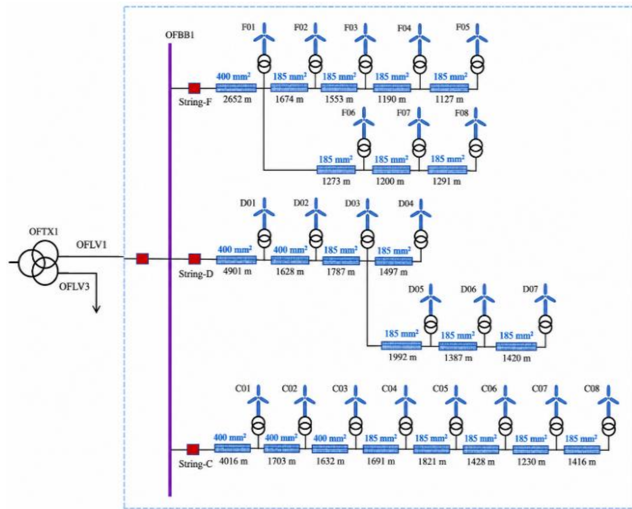


Fig. 1 Single line diagram of OFF Shore wind farm

The OFF Shore wind farm considered for the study is shown in Figure 1, which consists of array cables connected with wind turbine transformer in each row there is a separate VCB to energize each WTT and one VCB for energizing the entire array. For mathematical modelling of 11.4kV/235V Transformers in ATP, below procedure is adopted:

1. 6×6 admittance matrix for 11.4kV/235V rating transformer is computed from experimental measurements over the frequency range of 10 Hz to 100 MHz. The effects of connected coaxial measurement cables are compensated to ensure accurate results.

2. A black-box representation of the transformer is developed based on the measured data using the vector fitting technique [5, 10]. This method utilizes the “Matrix Fitting Toolbox,” which provides an improved representation of the open-circuit response. The toolbox is available online and is widely used for frequency-domain modeling.

3. The derived model is implemented in ATP by representing the transformer as an equivalent lumped RLC network using elements from the User Specified Library.

The vector fitting method which is well-described in [5, 10] is based on the rational approximation of each element of the admittance matrix in frequency domain,

$$Y(i,j) \approx \sum_{k=1}^{n} \frac{c_{ij,k}}{s-a_k} + d_{ij} \qquad (1)$$

Where a are the common poles for fitting all Y matrix elements and c_{ij} are the residues for each ij element and they can be real or come in complex conjugated pairs. For cable modeling, the JMarti model is employed due to its suitability for transient analysis in distributed parameter systems. In this model, the transformation matrix is assumed to be frequency-independent and is computed at a selected reference frequency.

The frequency matrix parameter is selected based on the dominant traveling-wave frequency of the underground cable. This frequency is primarily determined by the cable length and the wave propagation velocity, and can be approximated from the cable's propagation characteristics. Therefore, an appropriate frequency-dependent matrix is required to accurately represent the cable behavior during electromagnetic transient simulations.

3. Results and Discussions

The onshore grid is represented using a Thevenin equivalent corresponding to the minimum short-circuit level, representing the weakest credible network condition. To identify potential resonance conditions, a frequency scan of the combined network (1A current source + array cable + transformer) is performed at the wind turbine transformer busbar.

The results indicate a pronounced resonance in the vicinity of the second harmonic frequency. This resonance condition aligns with transformer energisation behaviour, where significant second-harmonic magnetising currents are generated due to core saturation, leading to excitation of the identified network resonance [5].

In this section, the resonance frequency for the studied transformer is obtained and the impact of cable length on resonance over voltages due to switching transient is assessed. The circuit for frequency scan to compute first column of Z matrix is shown in Figure 2.

3.1. Resonance in Impedance Matrix Elements

According to Equation (2), in order to simulate the first column of Z matrix, a current source with 1 A magnitude is connected to the phase A of High Voltage (HV) side and the induced voltage for all nodes are obtained. In addition, the other nodes should be open circuited. The induced voltage for HV nodes and LV nodes is illustrated in Figure 3 and Figure 4, respectively.

The first dominant resonance frequency of the studied transformer is approximately 2 kHz. There are other resonance frequencies such as 6.3, 75, 240, 457 and 800 kHz. For the LV impedances, there is also an important resonance frequency at 2 MHz. The sensitivity of the transformer due to over voltages for these resonance frequencies will be investigated later.

$$\begin{bmatrix} V_1 \\ V_2 \\ V_3 \\ V_4 \\ V_5 \\ V_6 \end{bmatrix} = \begin{bmatrix} Z_{11} & & \\ Z_{21} & & \\ Z_{31} & & \\ Z_{41} & Z_{ij} & \\ Z_{51} & & \\ Z_{61} & & \end{bmatrix} \begin{bmatrix} 1 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} \quad (2)$$

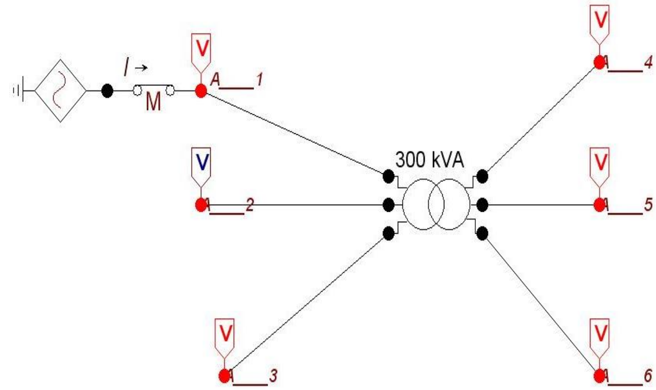


Fig. 2 Transformer impedance evaluation circuit

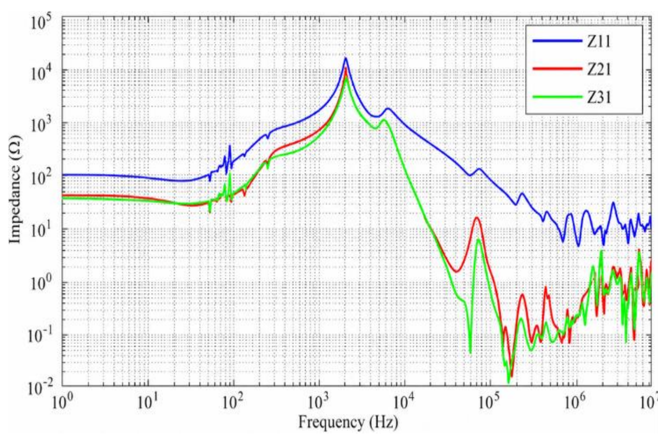


Fig. 3 Impedances of HV winding

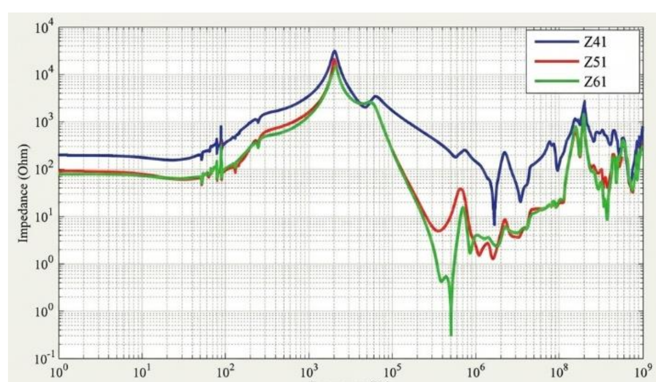


Fig. 4 Impedances of LV winding

3.2. Resonance for Induced Voltage

Investigating the voltage ratio for various phases, we achieve more information about resonance behavior of transformer. Considering the circuit in Figure 5 for voltage ratio simulation, the frequency response of phase B and C in HV side while applying one per unit voltage to phase A is depicted in Figure 6. Besides, voltage induced in secondary side of transformer is shown in Figure 7 in per unit.

The base voltage for HV side is 11.4 kV and for LV side is 235 V. From the Figures 6 & 7 the following observations were made:

- At 2 kHz, phase B has a peak in both HV and LV side and phase C has a valley in both HV and LV side which is similar to impedance characteristics in this frequency.
- At 4.8 kHz, induce voltages on phase B and C in both HV and LV side have a peak. This peak is more than 1 p.u.

There are two peak values for induced voltage in LV side at frequencies 214 and 710 kHz which are quite close to resonance frequencies in impedance characteristics (240 and 800 kHz). At 2 MHz, the induced voltage in LV side reaches to 10 p.u. considering the rated low voltage side as base voltage (n_{HV}=11kV/235V=48.51).

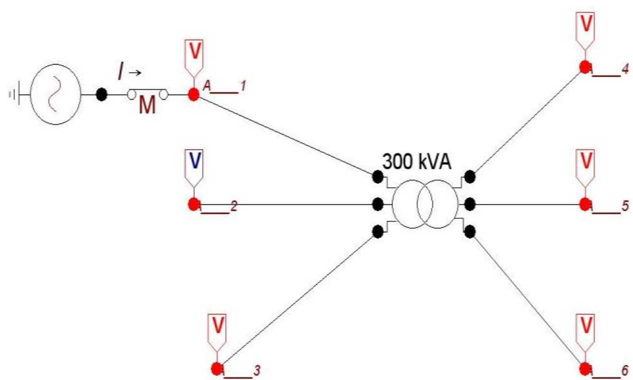


Fig. 5 Voltage ratio evaluation circuit

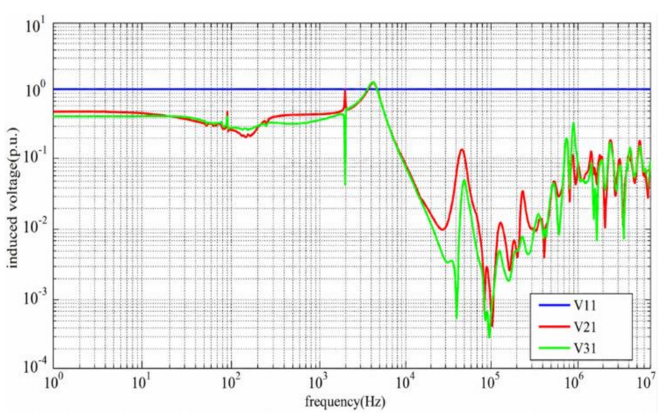


Fig. 6 Induced voltage for HV terminals

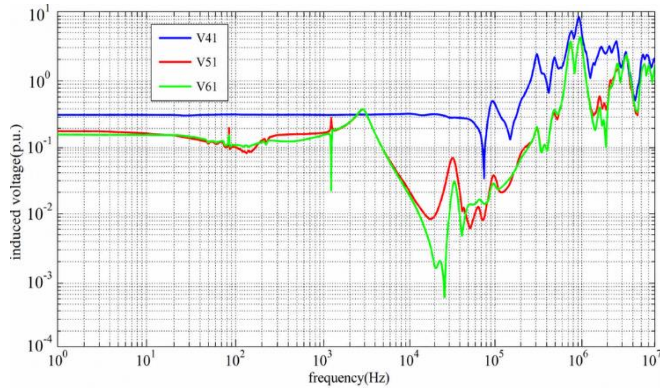


Fig. 7 Induced voltage for LV terminals

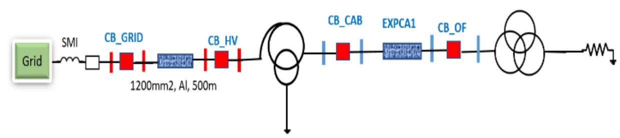


Fig. 8 Cable-transformer energization circuit

3.3. Transformer Energization

The over voltages on transformer terminal due to energization are assessed according to Figure 8. the transformer energisation is performed when the voltage of phase A is at its peak value.

The cable length is set to 500m.The switching transients in Primary and secondary side of transformer are illustrated in Figure 9 (a) and Figure 9 (b), respectively. More detailed waveform of LV side of transformer is illustrated in Figure 10.

As shown in Figure 10 (b), the 2 MHz transient waveform occurred just after energization is due to resonance phenomenon which corresponds to resonance frequency of induced voltage on V_{41} in Figure 7. In addition, the traveling wave phenomenon in cable is observed in Figure 10 (a), which its frequency is 92.6 kHz. The frequency is obtained via (3),

$$f = \frac{1}{4\tau} = \frac{V_{cable}}{4l} \tag{3}$$

In the above Equation (1) is representing the length of the cable and V_{cable} is representing the velocity of travelling wave in underground cable from simulation travelling wave propagation time is achieved and is set to 2.7µs, *frequency* and *Velocity* are 92.6 kHz and 1.85×10^{8} m/s are evaluated using above equation. Equation (3) can give accurate results only when the input impedance of the transformer is higher when compared to the cable impedance.

Variation of Peak voltage on secondary side for various cable lengths is depicted in Figure 11. For various cable lengths the frequency is estimated using Equation (3) the frequency matrix is updated for these cable lengths in Jmarti model.

The blue dots are the result of a series of simulation which cable length is varied 50 meter in each step. Observing abrupt changes in V_{4max} from 50 to 150 meter, to observe variation of phase voltages more accurately, the cable length is adjusted in smaller steps in this range. Therefore, the cable length is varied by 10-meter steps and the simulation results are shown with red dots. Besides, the simulation is also made for 105-m cable.

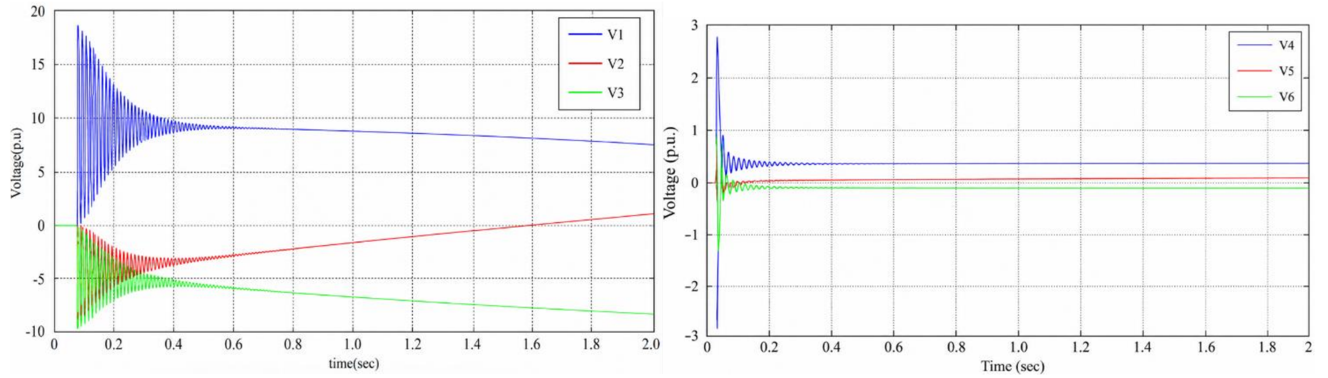


Fig. 9 Transient over voltage waveform (p.u) during cable-transformer energization, (a) HV side, and (b) LV side, cable length=500m.

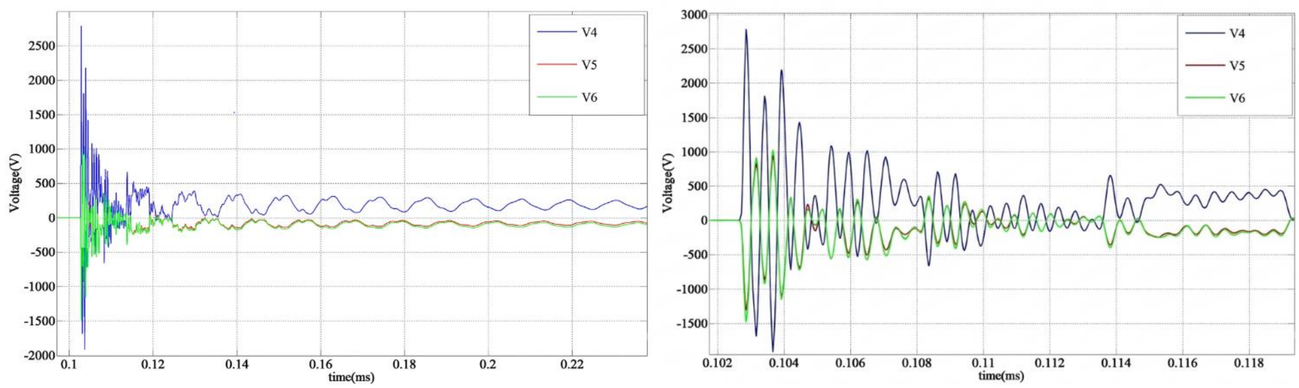


Fig. 10 The transformed voltage (V) on secondary side during energization of transformer connected with cable of 500 m length. (a) The appearance of 92.6 kHz traveling wave, and (b) The appearance of 2 MHz transients at the beginning of switching.

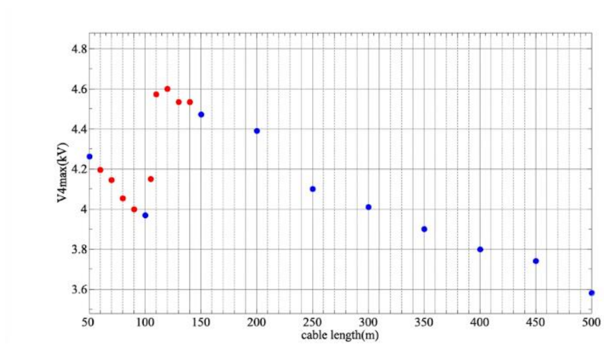


Fig. 11 Highest peaks observed for various cable lengths

It should be noted that energizing transformer with a 23-m cable, corresponding with traveling frequency equal to 2 MHz, results in resonance phenomena (Figure 12). Because traveling frequency is equal to transformer resonance frequency (2 MHz) and highest peak over voltages are observed during this condition.If the induced voltages on LV side of transformer are transformed into frequency domain, the frequency spectrum of the waveform can be analyzed and the effect of cable length on the dominant resonance frequency, any other resonance frequency as well as traveling frequency can be investigated.

In addition, the analysis of the induced voltages in modal domain is required. In modal domain, the comparison of 3-phase and 1-phase energization may give us the effect of induced voltage from other phases.

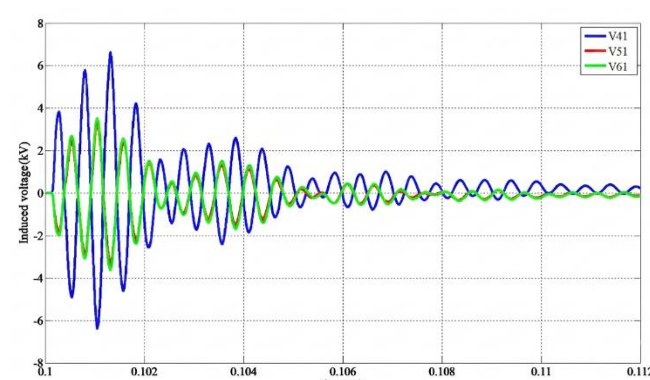


Fig. 12 Voltage waveform on LV side during energization of transformer connected with cable length 23 m (f $_{trav}$ =2MHz)

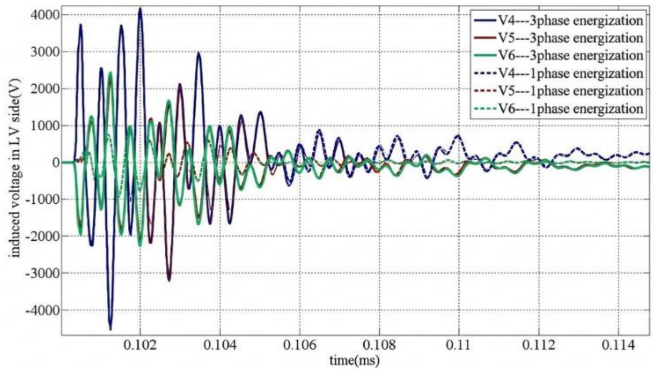


Fig. 13 Voltage waveform on 235V side for 3 and 1 phase energization, cable length=65 m ($F_{traveling}$=710 kHz)

The LV side voltages are simulated for one phase energization as well and the results are compared with three phase energizations in Figure 13. The cable length is set equal to 65 meter which corresponds to 710 kHz. This cable length is considered critical due to frequency response of 235V side in Figure 7. The first peak in V_4 is not changed in one phase energization compared to 3 phase one, while the second and third peaks are influenced. Furthermore, in one phase energization, voltages in phase B and C are decreased drastically and rapidly damped .23m and 65m cable lengths are considered for simulation as these lengths corresponds to travelling frequencies of 2MHz and 710 kHz matching with transformer resonance frequencies estimated from impedance frequency scan.

3.4. Cable Ground Fault

The other phenomenon which can lead to resonance over voltages is ground fault in cable connected to the transformer. To investigate the ground fault, the following circuit is employed for ATP simulation and the system is considered to be in steady state initially. The network equivalent circuit consists of resistance and inductance equal to 0.1 Ω and 5 mH.

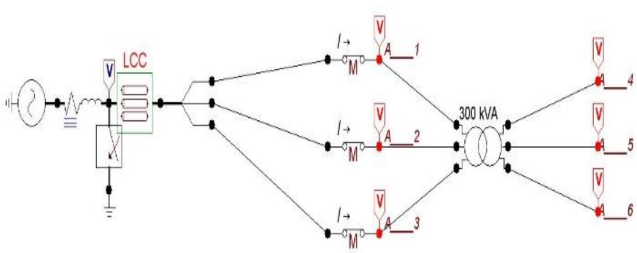


Fig. 14 Earth fault initiation circuit

The cable length is considered to be 500 meters. The earth fault occurs when phase A is at its negative peak. The over voltages produced due to earth fault in 11.4kV and 235V sides are presented in Figure 15 and Figure 16. Since earth fault occurred in negative peak, a positive surge in the cable travels and the resonance over voltages produced in LV side of transformer is similar to energization of transformer at peak voltage (Figure 17). The occurrence of 2 MHz resonance phenomenon in both cases can be observed in the first microseconds of initiation.

The amplitudes of overvoltages are different due to the happening of earth fault at negative peak and cable energization at positive peak. Besides, the energization happened simultaneously for three phases while earth fault happened just for phase A.

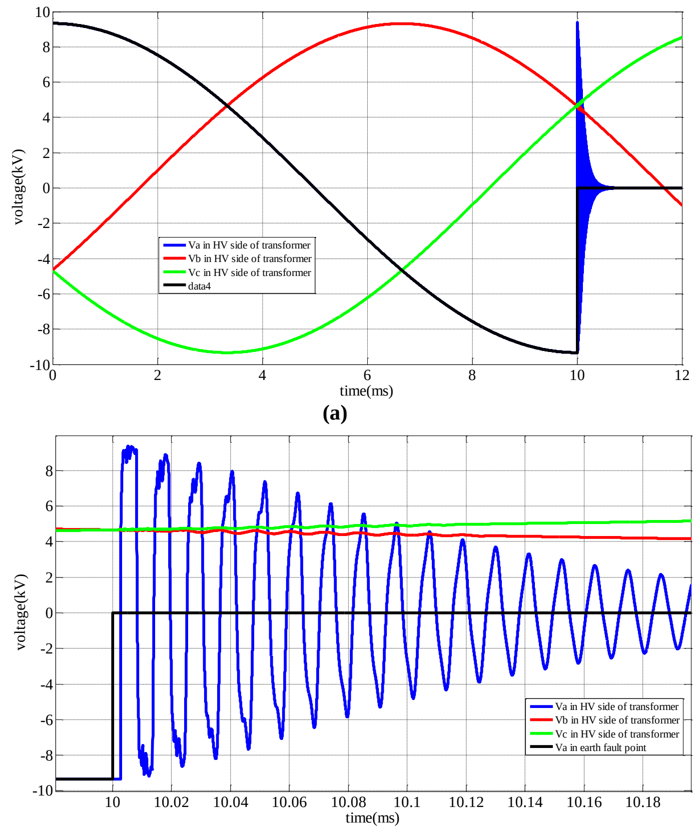
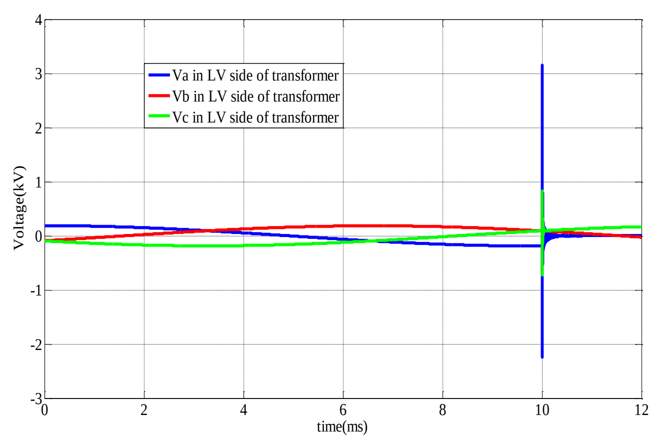
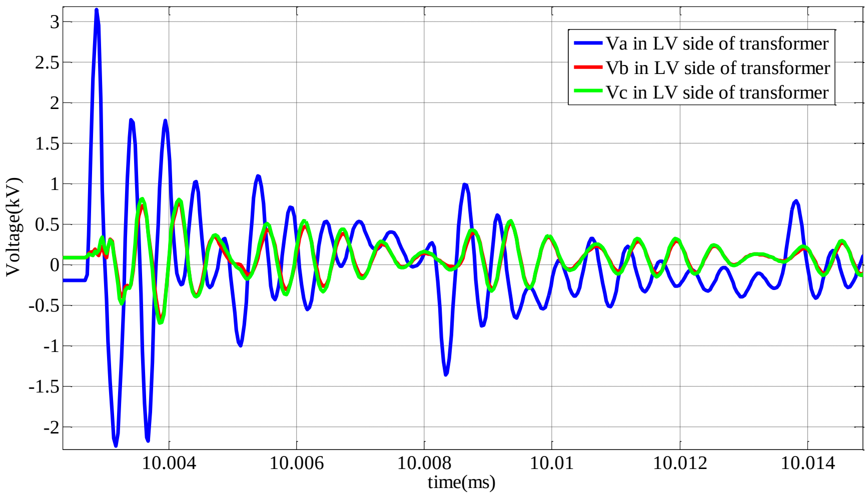


Fig. 15 Earth fault initiation circuit, HV side of transformer. (a) Occurrence of earth fault at phase A in HV side of transformer while the system is in steady state, and (b) Traveling waves in HV side of the transformer.



(a)



(b)

Fig. 16 Earth fault initiation circuit, LV side of transformer. (a) Phase voltages in LV side of the transformer, before and after earth fault, and (b) Resonance overvoltage (2MHz) and traveling waves in LV side of the transformer.

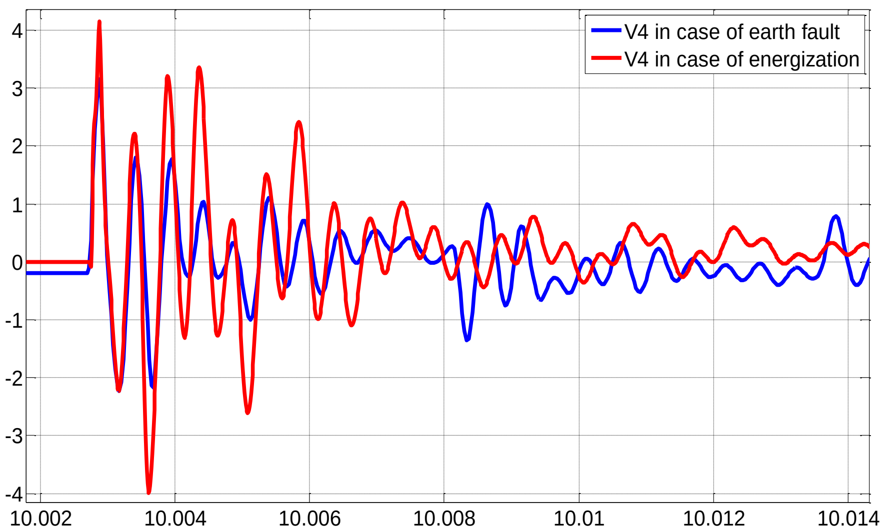


Fig. 17 Comparison between resonances due to earth fault and energization for phase A on 235V side of transformer, cable length is 500 m

3.5. Wind Mill Energization

The transient's analysis presented so far has focused on a single cable-transformer configuration. The third objective is to examine the transient over voltages when an array of wind turbine string is energized through 500m cable.

The Off Shore Wind turbine array with transformers shown in Figure 1 is designed in ATP according to Figure 18 where multiple cable–transformer units are connected in series. The transient over voltages and inrush currents in A phase of 11.4 kV and 235 V transformer windings are depicted in Figure 19 and Figure 20 (a) and (b) respectively.

The transient nature due to transformer energization at the instant of voltage peak and the super impostion of the Transient over voltages at the 11kV side of wind turbine transformer can be seen in Figure 19. In addition, oscillations produced with 2MHz resonant frequency are also added the voltages on 11kV side. Figure 20 (a), presents over voltage wave form with similar resonance phenomenon observed on 235V winding of transformers.

Amplitudes of transient over voltages produced during Cable-Transformer enrgisation are reduced due to the presence of cable, energy associated with travelling wave is dissipated in cable it was observed form Figure 20 (a) and Figure 20 (b) The inrush currents produced during energisation of Cable and transformer at any end is proportional to the induced voltage at the same end. Therefore, the magnitude of transient current is reduced from the first transformer to last one.3

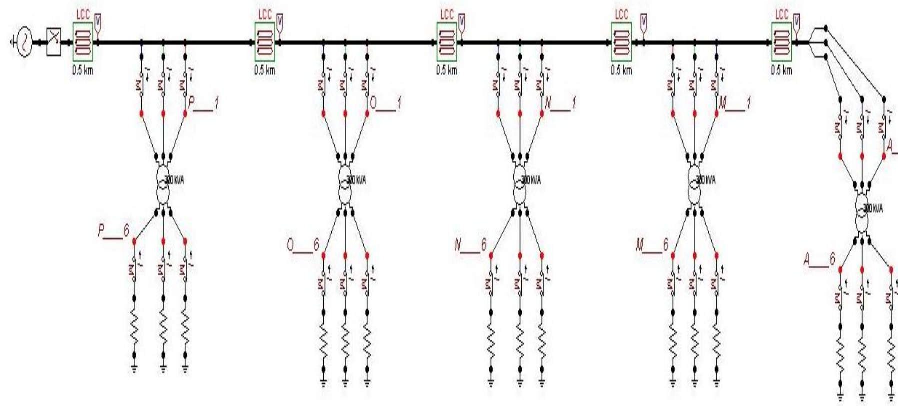


Fig. 18 Energisation circuit for five wind turbine transformers

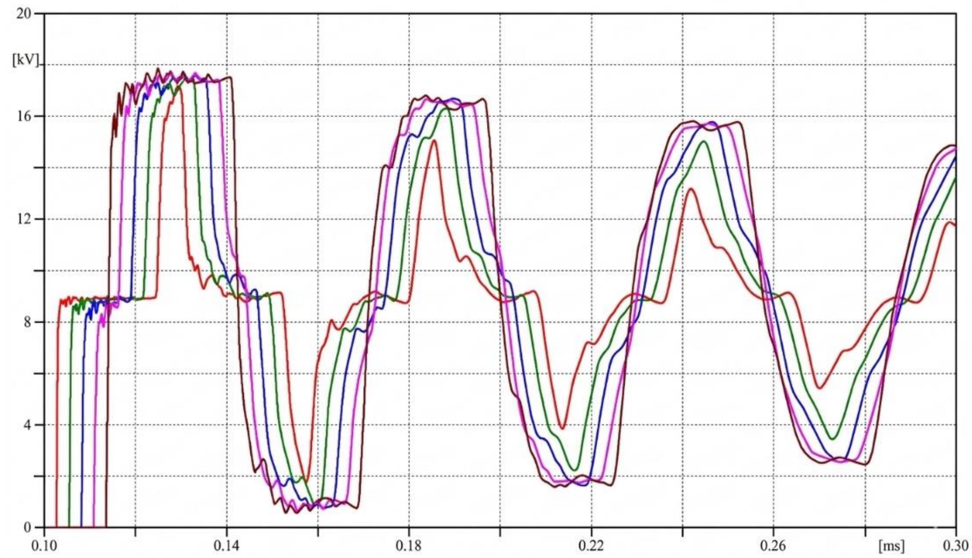
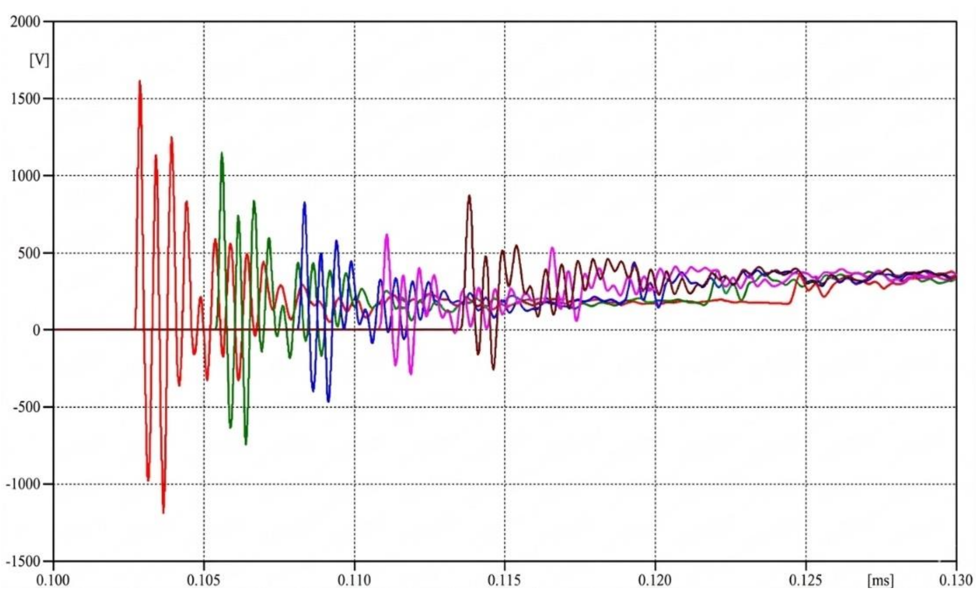
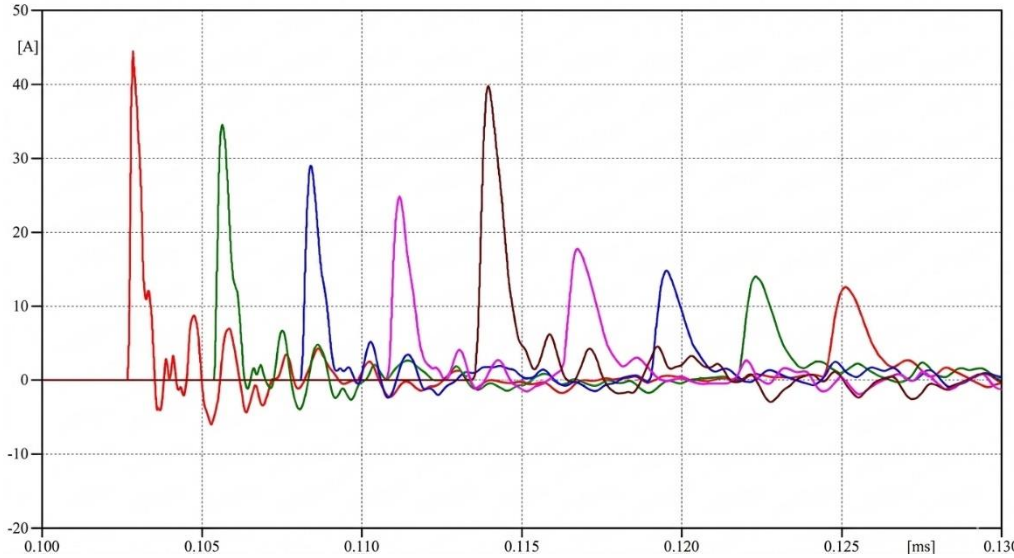


Fig. 19 Transient overvoltage waveforms of 11.4 kV side of five wind turbine transformers



(a)



(b)

Fig. 20 (a) Transient overvoltage wave form of 235V winding of all transformers, and (b) Transient Currents of 11.4 kV windings of transformers.

4. Conclusion

In this paper, transformer modeling was performed in frequency domain by means of black box modeling in ATP. The impedance-based frequency scan and induced voltage frequency scan were used to study the resonance frequency behavior of transformer. Two cases were investigated for observing over voltages with resonance phenomenon. Earth fault and cable energisation. Cable energisation was carried out in the case of 3 phase and single phase energisation when the power frequency voltage is at its peak value. Also, the earth fault was established at the negative peak of phase A. So, in both cases a positive surge goes inside the cable and similar situations happen. Both the test cases exhibit the dominant resonance frequency of 2 MHz. The other characteristic frequency in these two cases is the travelling wave frequency, that scales inversely with the cable length.

Assessment of Peak transient overvoltage on phase A for 235V side of the transformer shows that increasing the cable length generally results in the decreasing of the maximum overvoltage, while for cable length <120 meter, the effect of cable length is complicated and the analysis of the overvoltage waveform in frequency domain is required. The transient over voltages in 11.4kV and 235V sides of transformers in wind mill row are also comprising the dominant resonance and travelling frequency. To estimate the contribution of dominant and other resonance frequency on over voltages, transformation of overvoltage waveforms to frequency domain is required. Additionally, the analysis in modal domain is required to determine the impact of the other phases on induced voltage in one phase.

Conflicts of Interest

The authors declares that there is no conflict of interest regarding the publication of this paper.

Funding Statement

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