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The Assessment of Overvoltage protection Within Energization of Offshore Wind Farms

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Abstract

The beneficiary of Offshore Wind Farms (OWF) to land wind farms in the sense of more power productivity and land view disturbance leads to more investment and consideration. Nevertheless, the maintenance of OWFs is a significant issue due to accessibility and repair costs. Thus, the protection of OWFs electrical components should be investigated in various operation conditions such as energization, deenergization as well as lightning strikes to the blade of wind turbines. In this paper, the overvoltages due to energization are simulated and the impact of surge arresters and capacitive filters to protect wind turbine components is analyzed. Modeling of the components in OWF is considered based upon their frequency behavior. The significant components for energization studies are interconnecting cables, Wind Turbine Transformers (WTTs), surge arresters, vacuum circuit breakers as well. For modeling the cables, JMarti model is applied and model frequency is modified based on cable length. WTTs as the heart of wind farms are modeled based on vector fitting and transformer terminal measurements. Surge arresters as the main overvoltage protector is modeled considering stray lead inductances which degrade the efficiency of the surges arresters in reality. Simulation results indicate that energizing a row of OWF is actually similar to a ladder cables-transformers energization which LV terminal of transformers should be considered no load. The overvoltages in LV can reach up to 10-15 p.u. if surge arresters and capacitive filters are not installed. By the application of surge arresters and capacitive filters, the overvoltage peak and rate of rise of overvoltage (dU/dt) can be respectively controlled.

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1. Introduction

Number of Offshore Wind Farm (OWF) installations in Europe has grown significantly in the last decade. Although the first OWF was installed in Vindeby- Denmark in 1991, the development of OWF was not significant during 1990-2000. However the share of OWF in wind power market has later been drastically increased from 0.12% to 9.5% during 2000-2010 [1]. By installing OWFs at more distance from the shore, more power can be harnessed from the OWFs.

Due to the increased distance of OWFs from shore and adverse weather conditions in oceans, a main criterion in OWF design and operation is high reliability, with little maintenance. There have been studies on switching transients in land wind farms and OWFs [2]-[8]. Though, there has been less focus on energization or switching transients which lead to resonance overvoltages. Furthermore, overvoltages due to short circuit can also emerge resonance overvoltages in Low Voltage (LV) side of WTTs.

Since OWF consists of a series of cable-transformer connections, the energization of OWFs can lead to resonance overvoltages when the travelling wave frequency of energized cable equals with dominant resonance frequency of WTTs. In [9], the general criterion for resonance overvoltages in cable-transformer connection is studied and various connections are surveyed.

The appropriate modeling of OWF row for energization is introduced in next section. Main energization topologies are introduced and the modeling of overvoltage protection devices such as surge arrester and capacitive filter is analyzed. Finally the simulation results of row energization and the role of protective devices are investigated. These analysis and observations will lead to better OWF designs and help operating companies to prevent damages due to energization overvoltages in general and specifically resonance overvoltages.

2. Modeling

Modeling of OWFs depends on the aim of analysis. In [10], it is shown that for analyzing the 3-phase to ground fault in grid connected to OWF, the aggregated model of OWF can give good results for Point of Common Coupling (PCC) voltage, active and reactive power. Whilst such a model, which consider the whole OWF as a generator with a power equal to the sum of wind turbines power, is not sufficient to model the transient overvoltages in disconnection of OWF from grid [7].

Also the modeling of OWF components should be performed based on the frequency range of the phenomena and times interval of study. For instance, modeling of WTTs for first 0.5 ms after energization should be based on available high frequency models of transformer which core does not play significant role for voltage induction on transformer terminals. While just after this time interval, the core should be considered in transformer model for inrush current analysis.

The main components in OWFs for the switching transient investigations are WTTs, cables, Vacuum Circuit Breakers (VCB), surge arresters and capacitive filters. It should be mentioned that during the OWF energization, the power converters are not initiated. Thus, the wind turbine generators are not connected to WTTs.

The OWF row considered for simulation in this paper is illustrated in figure 1. It consists of three WTTs which are connected in a row with three cables for interconnection. There are three VCBs to switch the WTTs and one VCB for switching the row. This row is simulated and analyzed in Alternative Transient Program (ATP).

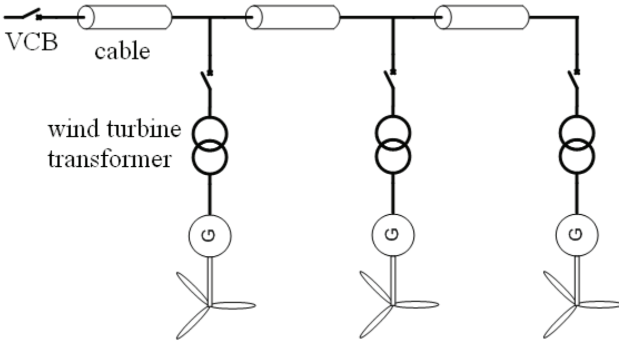

Fig. 1. Offshore wind farm system

VCBs have multiple prestrike and multiple reignitions in energization and de-energization respectively, which can mainly affect the amplitude and the waveform of overvoltages in OWF [3]. Since the focus of this paper is on resonance overvoltages during OWF energization, VCBs are modeled as ideal switches. The modeling of other components is brought in the following subsections:

2.1. Wind Turbine Transformers (WTT)

For representing the WTTs in ATP, we used a wide-band model of a 300 kVA 11/0.230 kV transformer developed in [9]. This model was obtained by terminal frequency sweep measurements and black box model extraction. Here, the following steps were taken.

1. The 6×6 admittance matrix of 11.4kV/0.230 kV, 300 kVA transformer was established by measurements as functions of frequency from 10 Hz to 10 MHz. The coaxial measurement cables were compensated for.
2. The black box model of the transformer was obtained based on vector fitting [11]-[12] followed by passivity enforcement by residue perturbation.
3. An equivalent RLC lumped parameter network was generated from the rational model and implemented in ATP-EMTP.

2.2. Cable Modeling

For cable modeling, the JMarti model [13] is used. The JMarti model considers the transformation matrix frequency independent and computes it for a fixed, single frequency, which is chosen in the vicinity of the dominant frequency in the simulation. The frequency is established according to the cable traveling frequency which is related to the cable length,

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

V_{cable} is the surge velocity inside lossless cable which is inversely proportional to relative permittivity (ε_r) and relative permeability (μ_r) of the cable. l and τ are cable length and traveling time constant respectively.

In order to verify the cable model, the one phase energization of 11/0.230 kV 300 kVA transformer with a 27 m cable, examined in [9], is simulated here with the same cable and transformer parameters (figure 2). It should be emphasized that same 300 kVA transformer with the same black box modeling as [9] is employed here. Cable modeling in [9] is based on terminal measurement of cable and vector fitting, while here cable model is based on geometrical parameters and JMarti model. Cable parameters for this simulation are listed in table 1.

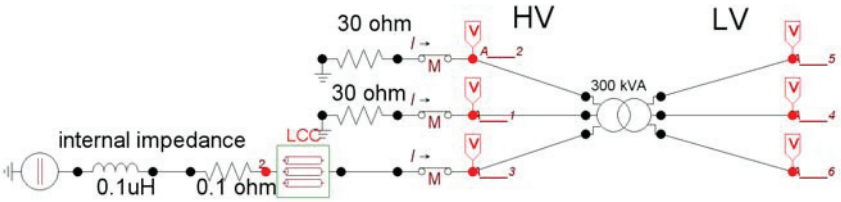

Fig. 2. 300 kVA transformer one phase energization with 27 m cable [9]

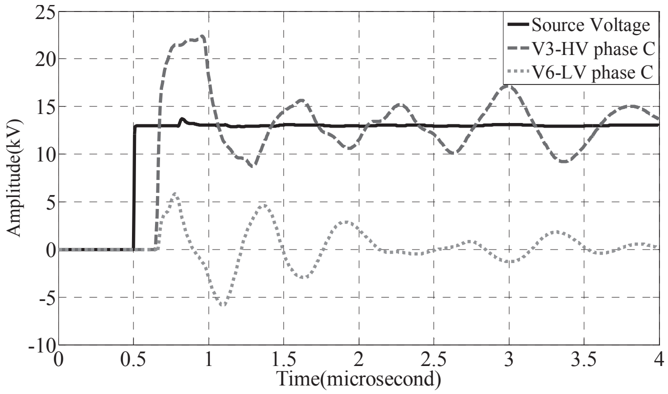

Fig. 3. Verification of cable modeling according to fig. 2. Source voltage (solid line), Voltage on phase C HV terminal (dashed line), Voltage on phase C LV terminal (dotted line).

Table 1. Cable parameters for fig. 2

Cable parameters	Values
Core radius (mm)	8.7
Sheath internal radius (mm)	23.6
Sheath external radius (mm)	30
Total radius(mm)	35
Insulation Permittivity (ε_r)	3.4
Permittivity of jacket	3.4
Core resistivity(Ω.m)	1.72×10^{-8}
sheath resistivity(Ω.m)	2.2×10^{-7}

As it can be observed, the voltage on LV terminal of transformers reaches about half of the excited voltage. Since the turn ratio of transformer is 11/0.230 (48:1), it concludes that the induced voltage on LV is about 24 p.u. and this excitation resulted in resonance overvoltage.

It should be mentioned that, the cable parameters which are applied for OWF in figure 1 is different from table I which used for verification of modeling. The cable used for simulation in fig 1 has the parameters which are shown in table 2.

Table 2. Cable parameters for fig. 1

Cable parameters	Values
surge velocity in XLPE cable (m/s)	8.7
core outer radius (m)	23.6
core resistivity (ohm×m)	30
core permeability (H/m)	35
core-sheath insulation permittivity (F/m)	3.4
sheath inner radius (m)	3.4
sheath outer radius (m)	$1.72\times10^{`-8}$
sheath resistivity (ohm×m)	$2.2\times10^{`-7}$
sheath insulation permittivity (F/m)	2.3

2.3. LV Load Capacitance or filters

Depending on the wind turbine configuration [14], soft start or full-scale frequency converters can be on LV side of transformers. Besides, there can be a cable between Power Electronic (PE) elements and transformer which is placed in the wind turbine base. In the energization of OWF, the soft-start or frequency converter is initiated after the energization of transformer. Thus, they are off. In the most of OWF designs, there is circuit breakers in LV side of transformer and are energized after the HV circuit breakers. Therefore, capacitance filters for controlling dU/dt can be introduced in transformer LV terminal if needed.

In two cases the LV load should be considered for energization transient analysis;

1. If the power electronic elements are connected to transformer without circuit breaker
2. LV circuit breaker is connected prior to the HV one

In these cases, the first elements connected to LV transformer terminal are playing dominant role in transient overvoltages. If the transformer is in the base, the first element will be the LV cable which has uninitiated PE elements at the end. If transformer is on top, just the PE elements will be the load.

2.4. Surge Arrester

Generally, surge arresters are installed on WTT terminals in order to protect them from lightning surges which hit the wind turbine blades or nacelle [15]. In [16], the absorbed energy of surge arrester during earth fault in OWF is also investigated and grounding transformer or fast grounding switch are suggested for diminishing overvoltages in OWF and protecting surge arrester from blowups.

The characteristics of surge arrester applied in LV and HV terminals of transformer are based on ABB POLIM-R-2N [17] and POLIM-C..N [18]. In the datasheet of the surge arresters, V-I characteristic for segment I>1 kA is given. For I<1 kA , V-I data is considered in a way that the log-log plot of V-I characteristic become as linear as possible. It is due to the mathematic modeling of different segments of surge arrester to fit the following equation [19],

$$i = p\left(\frac{v}{V_{ref}}\right)^{q} \qquad (2)$$

where p is the exponent, q is the multiplier for that segment, and V_{ref} is an arbitrary reference voltage that normalizes the equation and prevents numerical overflow during exponentiation. It should be mentioned that an inductance of 1 μH per meter should be considered for ground lead of surge arrester. Stray inductances degrade the effectively of surge arresters.

3. Simulation results

The application of surge arrester and capacitive filter in the LV side of WTTS in figure 1 is simulated here. It is assumed that the row is already energized and WTTs, which are in the base of wind turbine, are planned to be energized one by one. The results are depicted in figure 8 for phase A LV side of first WTT. The capacitance of the capacitive filter is 100nF.

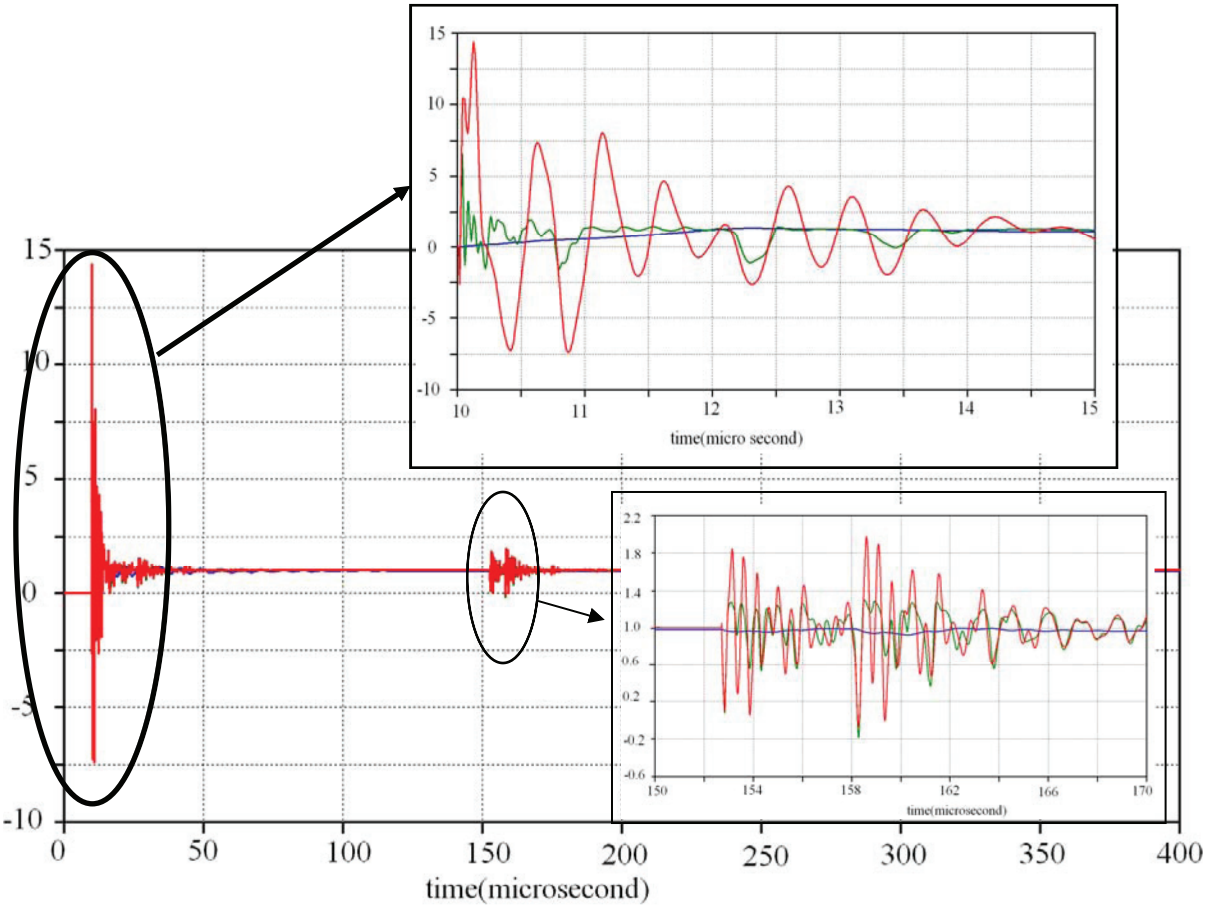

Fig. 4. Voltage on phase A LV side of first WTT in row without surge arrester (red curve), with just surge arrester (green curve) and with both surge arrester and capacitive filter (blue curve) in LV p.u.

From figure 4, it can be studied that;

1. Surger arresters really help the extreme overvoltages, but they are not sufficient. Since in this case maximum peak (U_{max}) is still high even with surge arrester. Besides, dU/dt is the same as case without surge arrester (upper figure in figure4) with value in the order of 100 kV/µs theoretically.
2. Introducing capacitive filters with reasonable value can lead to decreasing the dU/dt in the level which is safe for transformer LV insulators (upper part in figure 8). Here dU/dt is decreased to 0.022 kV/ µs.
3. Even during energization of second WTT, the induced overvoltages in LV side of first WTT can be relatively high with U_{max} near to 2 p.u. and du/dt near 2 kV/ µs. (lower part in figure 4).

4. Conclusion

The energization overvoltages of Offshore Wind Farms (OWF) are investigated in this paper in time domain. Since energization of OWF can result in resonance phenomena, detailed wind turbine transformer model is applied based on measurement and black box modelling. When feeding cable length is in the way that travelling wave frequency matches the dominant resonance frequency of transformer, resonance overvoltages on the LV terminal of transformer can be observed which their amplitude may be 24-26 pu in no load condition. This phenomenon was validated with experiments in reference.

To observe the effect of surge arresters, the inductance of stray lead in surge arresters should be included; first because it degrades the efficiency of surge arrester to some extent, second it changes the waveform of overvoltages to cos(θ)-1 form due to second order circuit which introduces in this way and it basically leads in low initial dU/dt. It is of great interest for next step of the research.

The introduction of capacitive filter became necessary, since surge arrester could not decrease the dU/dt, precisely speaking surge arrester control average dU/dt due to controlling U_{max}. Selection of appropriate capacitive filter can decrease the harmful dU/dt by a factor of 100. It should though be mentioned that taking capacitive filters more than 1 µF interferes with harmonic filters design or reactive power compensators and should be noticed if the capacitive filter can be analyzed with those studies. It may either be beneficial, e.g. in filtering high harmonics and consequently can be connected always or should be disconnected since it interrupted the harmonic filter or compensators function.

The simulation of OWF energization in various situation, considering the HF model of wind turbine transformer, assists on industrial design, appropriate component selection, reliability as well as maintenance cost and time savings.

Acknowledgements

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