Modeling and Investigating Lightning Wave Transfer through Distribution Transformer to Watercraft Power System

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ABSTRACT:
This paper deals with modeling and investigating transient overvoltage resulting from lightning in medium voltage grid and transferring it to low-voltage grid inside watercraft during berthing and connection of the grid in the coast. Lightning wave transfer through distribution transformer has been considered taking high-frequency model of transformer into account for passage of impulse wave. The effect of high-frequency model obtained from the transformer has been compared and validated using capacitive π model using previous measurements. The effect of different quantities of the system for connecting coast power to the watercraft including length of the connection cable, the loads on the watercraft network, type of loads, and effect of transformers' secondary on the watercraft was examined on the level of transient overvoltage on low-voltage loads. Determining the primary and secondary overvoltage levels of transformers allows for specifying the protective level of arrestors for insulator protection coordination. This protective level, which has been obtained from IEEE lightning arrestor selection guideline, has been employed to determine the suitable values of the lightning arrestor for coast to watercraft power connection system.

KEYWORDS: transient overvoltage, transformer high-frequency model, coast to watercraft power connection, lightning wave transfer in transformer.

1. INTRODUCTION

During berthing, many watercrafts in the coast are connected to the power grid on the coast to supply their low-voltage loads. Such a low-voltage system may experience transient state phenomena including ferroresonance, different types of error, direct lightning onto the watercraft, lightning close to low-voltage grid, and lightning wave transfer from the upstream network through distribution transformer [1]. This study specifically deals with transient overvoltage resulting from lightning wave transfer through distribution transformer.

The most important factor in high-frequency wave transfer in transformer is primary and secondary coupling capacitator [2]. In an ideal transformer, the value of this capacitive coupling is zero, and since the inductance impedance of coupling at high frequencies grows considerably, the extent of impulse wave transfer in an ideal transformer is trivial. However, in a real transformer, due to adjacency of primary and secondary coils, coupling capacitator always exists between them, and impulse wave transferred to the secondary is considerable.

In previous studies, various methods have been proposed to calculate the voltage transfer from primary to secondary side.

In [3] the main results of an investigation conducted with the aim of reducing to an acceptable level the lightning-caused distribution transformer failure rate in a region in the South of Brazil is presented. In [4] modelling is conducted to finding correlation between transient voltage that injected on bushing and electric field that occur.

As a new work in [5], the influence of repeated lightning impulses on the oil paper insulation, especially the mechanism behind this phenomenon, is experimentally investigated. Simulation and measurement of lightning impulse voltage distributions over transformer windings is investigated in [6]. This study presents a method for fast and accurate transient solution of the circuit differential equations that describe the voltage distribution over the winding system. In [7], the internal voltage stress is studied during very fast transients generated during transformer energization.

In [8], the extent of the wave transferred from the primary to transformer secondary has been calculated in terms of natural impedance of the line in the primary and secondary side. However, in most applied studies, impulse wave transfer has been conducted using high-frequency transformer modeling. A complex model has been modeled from distribution transformer using 20 impedance elements in [9], and impedance values have been obtained using frequency spectrometry.

Some study such as [10-12] are focused on lightning protection of distributed transformers.

One of the most common high-frequency transformer models is impedance π model. It is obtained using three branches of RLC in π arrangement and using frequency spectrometer at both ends of each individual coil [13]. Since the most important impedance element at high frequency is capacitor, in some high-frequency modelings, two parallel π models are used, one of which has solely a frequency variable capacitor, while the other model is transformer RL model, which can be considered as constant at high frequencies [14]. A numerical method for calculating resistance, inductance and capacitance matrices of transformer windings is presented in [15]. In [1], the two methods of capacitor π and full impedance π models have been compared in a distribution transformer. According to the results, the performance of both models is close to each other in most cases, whereas usage of capacitor π model is far simpler and needs less calculation.

In this study, the effect of direct strike on transmission lines has been modeled through lightning simulation in EMTP software, and the transient overvoltage resulting from it in the secondary side is examined using transformer capacitor π model. Sensitivity of the transient overvoltage to different quantities in the transformer secondary side is the main subject of interest in this study.

2. MODELING HIGH-FREQUENCY TRANSFORMER

Part of the wave resulting from lightning strike to transmission lines in the upstream network can be transferred to distribution grids through transformer. The extent of transference of this wave is dependent on frequency response of transformer and specifically coupling capacitor between the transformer primary and secondary. Various models have been obtained for high-frequency wave transfer, many of which are based on complex measurements in the internal parts of the transformer or use of frequency spectrometer. Comparison of a complex model and paralleled capacitor π model which is obtained using short circuit and open circuit test values of transformer, indicates that the capacitor π model offers acceptable responses at high frequencies thanks to its simplicity.

Therefore, in this paper, the transformer has been modeled as parallel capacitor π model (which can be implemented in EMTP software through BCTRAN model). Fig. 1 demonstrates simulation of this model in the software. BCTRAN model values are obtained through short-circuit and open circuit test measurements of the transformer. These values are constant in relation to frequency and have been extracted from a similar transformer in [16]. The frequency-dependent capacitator value of this transformer at frequencies above 100 kHz is as follows: *CM*=0.350nF, *CLM*=0.695nF, and *CL*=0.410nF.

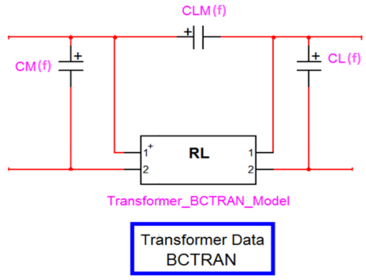

Fig. 1. π model of transformer at high-frequency in EMTP software.

To investigate the accuracy of this modeling, a similar impulse test [17] has been used to analyze the response of a 13.8kV/220V transformer, and the results have been compared. For this purpose, an impulse pulse voltage with an amplitude of 8kV and wave front of 2µs was injected into the transformer primary. Fig. 2 compares typical model and high-frequency π model response with the response obtained from [17] for a distribution transformer. Considering the different voltage of transformers, the voltage fluctuation range in the transient state is different in them. However, the similarity of the shape of π model waves with the shape of waves measured in both states can confirm the arrangement accuracy of the modeling.

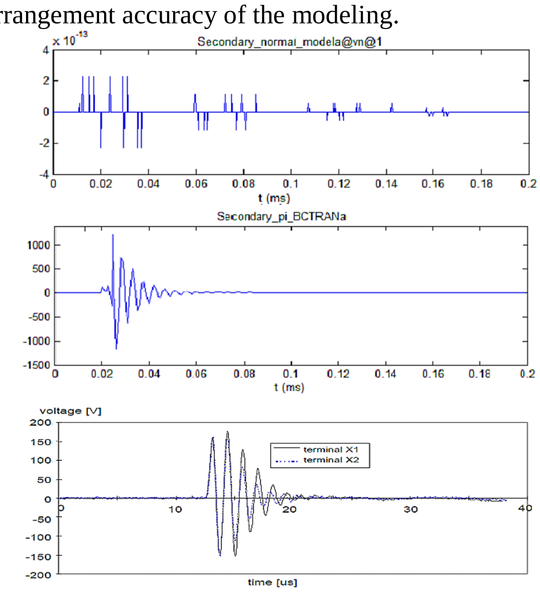

Fig. 2. Comparing impulse response of high-frequency model for the studied transformer with a) typical transformer model b) high-frequency π model c) transformer similar to the one in [17].

3. THE STUDIED SYSTEM

Watercraft power systems can be considered an island system connectable to the power grid. According to Fig. 3, this system is connected to aerial lines using a 33.6 kV transformer. The distribution transformer can feed the watercraft during berthing through a connection cable. When the watercraft is in the sea, feeding the loads and its engines is performed by two generator diesels, which are turned off during ship berthing.

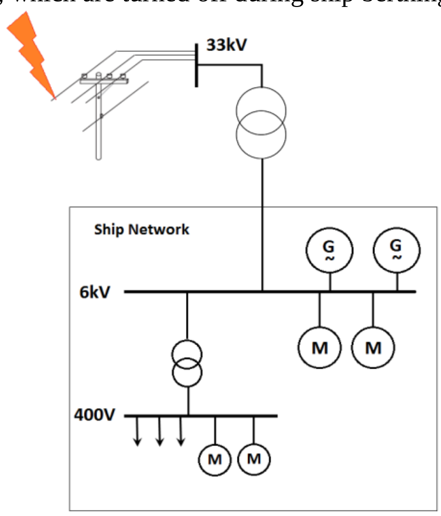

Fig. 3. The single-line diagram of connecting the watercraft power system to the coast.

In the studied network, a 33kV aerial line has been connected to the primary side of the distribution transformer, with the specifications provided in Table 1. Further, the secondary side of the transformer has been connected to the watercraft by cable. The arrangement of conductors of the mentioned airline is demonstrated in Fig. 4.

Table 1. The specifications of the single circuit 33 kV transmission line connected to the distribution transformer primary.

Line specifications	Value
Line length	2.5 km
Line type	Single circuit with four conductors
The post height	8.4 m
The resistance DC lines	0.1 Ω/km
Space between the lines	1.5 m, 0.7 m

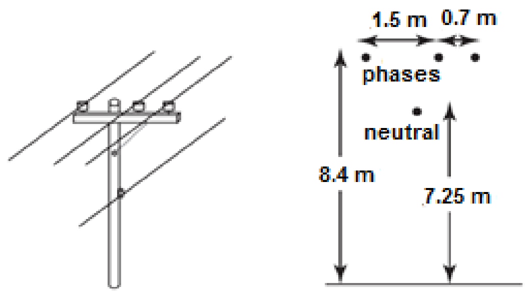

Fig. 4. A schema of the 33kV aerial line in the primary of distribution transformer.

4. SIMULATION RESULTS

The aerial line mentioned in the previous section has been modeled using frequency-dependent model J-Marti in EMTP software. To simulate lightning strike, a generator with medium lightning values has been used. The peak range of the lightning current is 31 kA on average, and the medium slope of its current is 24kA/µs [18]. For the modeled lightning wave shape, standard lightning test (with wave front of 1.2 µs and the range 50% drop time of 50 µs) has been used. The lightning strikes at 250 m away from the distribution transformer directly to a phase of the aerial line. Fig. 5 reveals the effect of incidence of such a lightning in the distribution transformer primary and secondary. Existence of three RLC branches in the transformer π model, all of which have capacitive and inductive elements causes development of fluctuations with natural frequency of the system in the trans-impulse response.

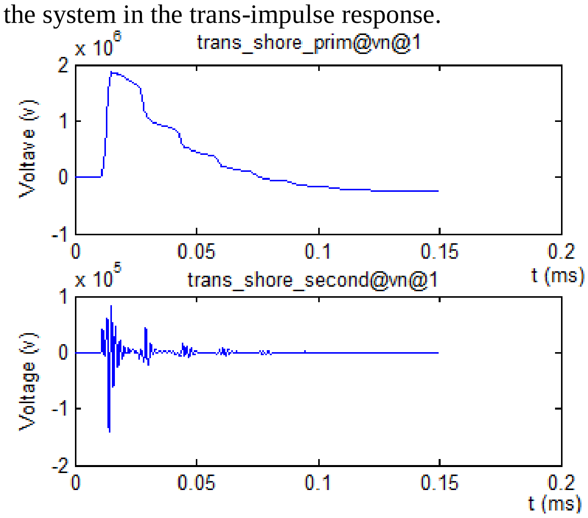

Fig. 5. Voltages resulting from direct lightning to the aerial lines in a) primary and b) secondary of the open circuit distribution transformer.

Figs. 6-12 represent the effect of connection of the cable between the coast and watercraft, the effect of enhancing the cable length, the effect of reducing the cable capacitator, the effect of adding 100 kW at 6.6 kV, the effect of adding 1 MW at 6.6 kV, the effect of adding 1MVar at 6.6 kV, the effect of electrification of transformer secondary, and low-voltage loads, respectively. As parallel capacitators find great importance at high frequencies, in Fig 8, the effect of reducing capacitator on the voltage of induced lightning has been investigated.

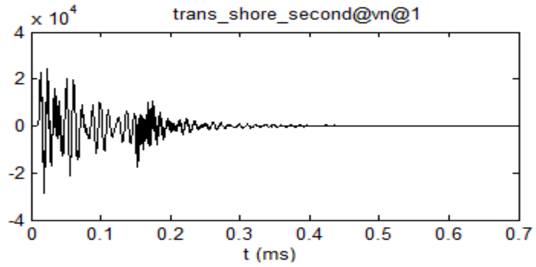

Fig. 6. The voltage resulting from lightning in the distribution transformer secondary connected to the 500 m cable.

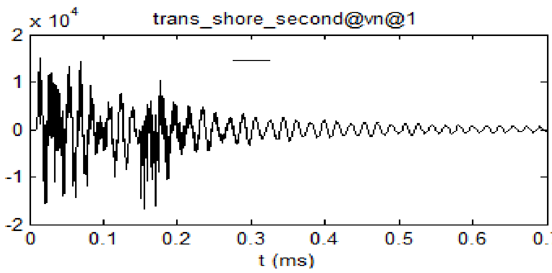

Fig. 7. The voltage resulting from lightning in the distribution transformer secondary connected to the 1000 m cable.

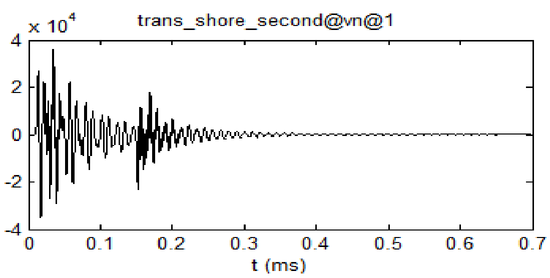

Fig. 8. The effect of reducing the cable capacitator to 2/3 of the underground cable length.

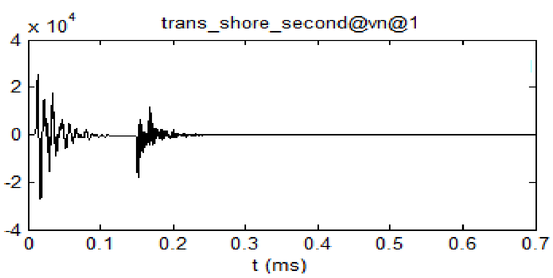

Fig. 9. The transformer secondary voltage when connected to the coast and with 100 kW load on the watercraft.

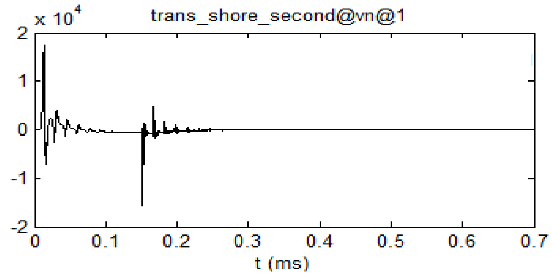

Fig. 10. The transformer secondary voltage when connected to the coast and with 1000 kW load on the watercraft.

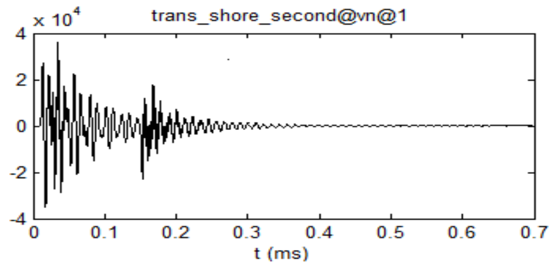

Fig. 11. The transformer secondary voltage when connected to the coast and with 1000 kVar load on the watercraft.

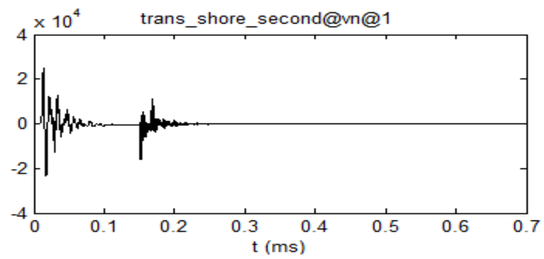

Fig. 12. The transformer secondary voltage in the case of transformer connection onto the ship and connection of all loads.

According to the obtained results, the maximum overvoltage resulting from the lightning pulse in the transformer secondary occurs when the secondary is open circuit. This phenomenon can be justified in two ways. Physically, in an open circuit transformer, there is no instrument to absorb the lightning wave energy transferred to the secondary, where the potential level at this terminal will be maximum. In terms of circuit, as a resistance load becomes parallel to the branch off the transformer π model, it causes decreased output impedance, thus reducing the output voltage level. According to Figs. 6 and 7, elevation of the cable length has resulted in lowered range of fluctuations.

For more accurate and comprehensive analysis of the results, the effect of cable length, active loads connected to the transformer, and installing lightning arrestor at transient overvoltages has been examined.

4.1. The Effect of Cable Length

The maximum overvoltage developed in the transformer secondary in terms of the cable length connected to it has been demonstrated in Fig. 13. Elevation of the cable length connected to the transformer by up to 1 km reduces the overvoltages developed in the transformer from 25 to 15 kV with a dramatic rate. Further elevation of the cable length decreases overvoltages more mildly, as in π model of power transmission line, elongation signifies serialization of a larger number of π branches, enhancing the input impedance of these branches exactly in this exponential form.

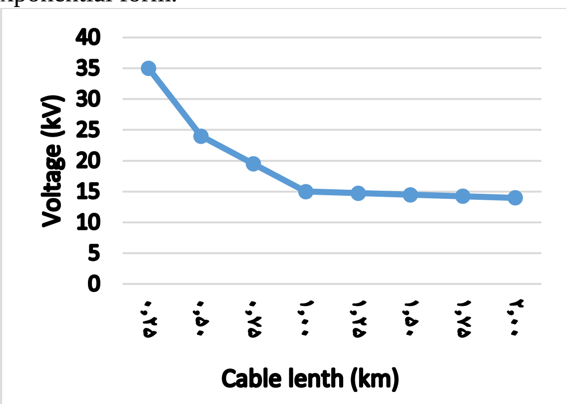

Fig. 13. The overvoltages resulting from lightning in the distribution transformer secondary across different cable lengths.

4.2. The Effect of Active Loads

Existence of active load and the actual power in the transformer secondary results in a significant reduction in the fluctuations and the overvoltage resulting from the impulse wave. This is due to the parallelization of the load equivalent resistance with the transformer output impedance, which both reduces this impedance and attenuates the fluctuations resulting from the output LC branch. Variations of the overvoltage of the transformer secondary with the actual charge in the secondary are demonstrated in Diagram 14. According to this figure, the secondary load value has also an effect similar to the impact of cable length on the impulse voltage value transferred to the transformer secondary.

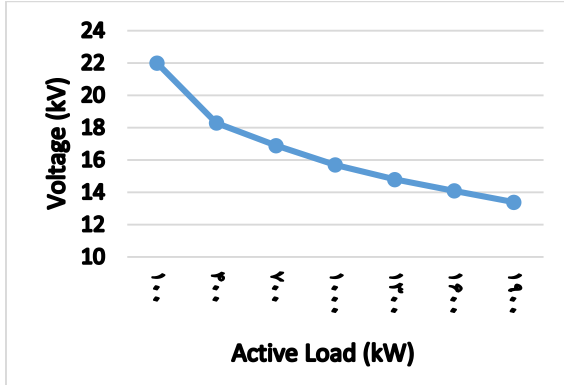

Fig. 14. The overvoltages resulting from lightning in the distribution transformer secondary across different active loads.

4.3. The Effect of Installing Lightning Arrestor

The most effective method to reduce transient overvoltages resulting from lightning is usage of arrestor in the transformer terminals. Fig. 15 shows the effect of use of lightning arrestor in the transformer primary of the coast. According to this figure, addition of lightning arrestor in the transformer primary side causes reduction of overvoltage to a level below the installation tolerance at voltages of 33 kV and 6.6 kV. However, if the lighting strikes a point close to the transformer, in addition to medium voltage lines, it can also induce voltage onto low-voltage cables and lines. Calculation of numerical values of field integrals [19] for a lightning occurring several meters away from the distribution transformer indicates that the voltage levels induced as low-voltage grow to over 25 kV, which adds on the overvoltage transformed from the transformer, turning into a threatening value for the transformer insulator. In any case, usage of lightning arrestor in the transformer secondary is necessary to protect a low-voltage network. Furthermore, due to existence of a connecting cable between the coast and watercraft and the possibility of incidence of unpredictable overvoltages in this path, application of lightning arrestor in the main Busbar of the watercraft is again necessary.

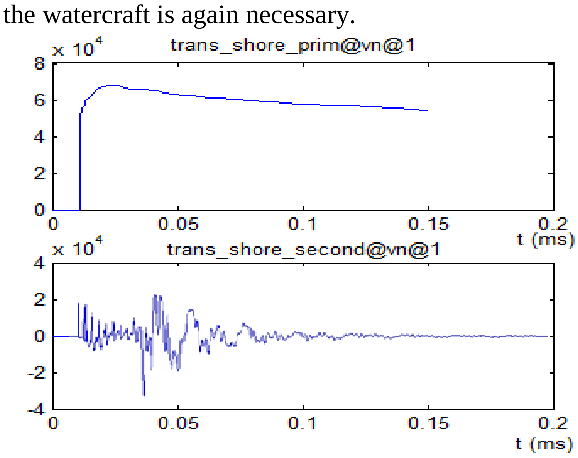

Fig. 15. The effect of installing lightning arrestor in

a) primary and b) secondary of the distribution transformer at open circuit transformer state.

5. CONCLUSION

Lightning strike to medium voltage aerial lines causes transient overvoltages in distribution systems connected to transformer by transferring lightning wave through it.

Lightning strike in a 33kV system results in development of transient overvoltages, which are dangerous for insulations of both sides of the transformer. The lightning field can directly induce voltage on the secondary side. To protect the equipment, lightening arrestor is used on both sides of the transformer.

The length and specifications of the cable connecting coast and watercraft have a direct impact on the overvoltage developed in the transformer secondary. The longer the cable and the lower its leakage capacitator, the better it is able to reduce the generated overvoltages.

Furthermore, the type of the load connected to the network on the watercraft has an inverse relationship with the developed voltages. If the resistance load is large enough, it can attenuate overvoltages up to a risk-free level for the system. However, reactive loads do not have a significant effect on reducing transient overvoltages.

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