Loading Effects on the Attenuation of the Transferred Transients Through Cable Winding Transformer (Dryformer).

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Abstract – **Recently, dry power transformer (Dryformer) that performs one step transformation from transmission to distribution voltage levels, has been introduced [1]. The Dryformer (dry power transformer) combines the features of power transformer with that of station distribution transformer, by utilising XLPE insulated round conductor cable for winding construction. The parameters of the cable winding can be determined in the same way as for single core transmission cable, however, the influence of mutual inductance in the windings makes the transient propagation slower in the windings, than in corresponding transmission cable of the same size and length. Therefore it is important to have a better understanding of Dryformer behaviour with respect to transient surge voltage transfer under various loading conditions.**

The model for the Dryformer is derived earlier [2] based on the frequency characteristics of the transformer admittance functions measured (in frequency domain) at its terminals over the frequency bandwidth of up to 3MHz. The validity of formulated model has been verified in this paper by comparing the model predictions with experimentally obtained responses under resistive, capacitive, and inductive loads. The model is then applied to investigate the influence of the load characteristics on the transfer of surges due to lightning strike caused transient etc, across the Dryformer circuits. Surges that have various steepness, amplitude and duration characteristics are used in the simulations.

Experimental and simulation results of the transferred transient voltage through unloaded Dryformer [3] have shown that there are considerable differences in the characteristics of the transferred surge voltages when compared to the transient transferred through the unloaded conventional transformers. Even though the types of loads that can be connected to the Dryformer terminals are naturally variable, attempt is made in this paper to evaluate resistive, inductive and capacitive elements, which represents certain major loading conditions encountered in practice. We have found that various loading conditions at Dryformer terminals influence the peak amplitude, shape of waveform and the duration of the transferred transient.

I. INTRODUCTION

Power transformers provides an important link between the remotely located generating power station and associated long span transmission lines to customers at load centres. The connected loads (equipment) at consumer premises, whether it is in industrial, commercial or dwelling premises are of inherently low impulse withstand capability. Transformers are expected to provide essential isolation between the two circuits that operate at different voltage levels i.e. supply side and load side circuits. The loads that are supplied by electrical power system network are variable in nature, can be resistive, inductive, capacitive or a combination of these different load types. It is anticipated that the various types of load that can be connected at the transformer terminals will have a profound influence on the nature of transient transfer through the transformer windings or between the transformer terminals. It is the purpose of this paper to study the influence of the various principal loads that are expected in practice, on the transient transfer between the transformer terminals. Recently, a number of transformer models [4 -7] have been formulated for studying the transient surge transfer between the conventional transformer terminals. However, majority of these studies have been carried out on unloaded transformer with a view of establishing the worst case of transient transfer through the transformer windings and thereafter appearing at the transformer terminals. Various loading conditions at transformer terminals will not only influence the peak amplitude of the transferred surge but may also have an influence on the duration and resulting oscillations of the transferred surge. Model formulation methods implied in some of these models [6,7] are not well-suited for the study of transient surge transfer, of transformer that have loads connected at its terminals. These developed models have shown to reproduce significantly the transferred transient surge characteristics on unloaded transformer, but the predictions shows significant deviations when the transformer is loaded at its terminals. However, linear transformer models that are formulated from the experimentally measured short circuit admittance functions are capable of predicting the transferred surge transfer due to any type of load connected at transformer terminals. The model that has been used in this work is developed in [2] and is based on the experimentally derived short circuit admittance functions. Although, it is a tradition that surge arresters are installed at transformer terminals, in this work the presence of surge arresters at either side of transformer terminals has not been taken into account.

Since the Dryformer will be connected directly to transmission lines, the high voltage (HV) circuit breakers and associated surge arresters will be within short reach of Dryformer terminals. Therefore, the operation of these circuit breakers, for example, in gas insulated switchgear (GIS), will generate steeper and higher voltage surges, which will travel a short distance before reaching the Dryformer terminals. Similarly, lightning strike to a phase or shield conductor of a transmission line tower, at a point close to Dryformer location can cause insulation flashover, and hence induce transient overvoltage of high magnitude and steepness. Traditionally, the primary (high voltage) side of power transformers is protected against transient overvoltages by installing surge arresters. The tradition has been practised for many years simply because the high-voltage networks (primary) were believed to be more exposed to lightning and switching perturbations than the low-voltage (secondary) networks. Despite this fact, transients can be transferred through the transformer windings to secondary connected network, which is often not protected with an arrester. This may be caused by the transient surge voltages that are well below the protector's threshold value, but their rise-times are sufficient enough to excite winding resonance, producing significant voltage amplification in the windings which will cause insulation degradation. Same behaviour applies for surges that enter through unprotected secondary terminals; the resulting voltage amplifications of the surge as it propagates through, poses threat to the Dryformer itself and to the connected equipment. Switching transients that are generated in LV installations have lower magnitudes (depending on the voltage magnitude being interrupted) compared to those generated in HV networks. However, as pointed out earlier, that the magnitudes of the excitation surge as well as the steepness i.e. frequency contents of the transient surge, can have some influences on the magnitude and duration of the transferred surge.

This paper presents the advanced understanding of transient overvoltage transferred from the more exposed transmission lines to distribution power network and vice versa through the Dryformer by considering the various terminal-loading conditions. The Dryformer studied in this work is a single-phase prototype unit rated at 10MVA, 54/17 kV. The transferred transient voltages in this work have been calculated with the help of the transformer model developed in [2]. The suitability of the model in simulating the transient transfer through the Dryformer due to surge voltage excitation at either side (primary or secondary) and load application at the corresponding unsurged terminals is verified by comparing the experimental and model predictions. Dryformer is a new technological design that has not enjoyed the benefit of years of service operation in power network that are exposed to variety of transient overvoltage levels. This study provides an estimation of transient voltage levels that will appear at the loaded transformer terminals due to surges that are encountered in practice. By the fact that Dryformer converts transmission voltage to medium voltage in one step, it introduces new interaction and behaviour of transient transfer between the network system that were initially indirectly linked to transmission line system. Section 2 of the paper describes the validation of the model that has been used in this work in predicting the transferred surges through a loaded transformer. Experimentally obtained surge transfer from primary to secondary and secondary to primary are compared with model (used in this work) predictions with consideration of various principal loading at the Dryformer terminals. Section 3 describes the effect of load on the transferred surges from primary to secondary and vice versa of a loaded transformer, with consideration of the influences of excitation rise-time (steepness) and magnitude on the transferred surges.

In this paper however, no comparison with loaded conventional transformer is made, because no similar study of transient response characteristics of conventional transformer that have similar rating and voltage ratio to that of Dryformer studied in this work has been carried out. Over the decades there have been several achievements on studies of conventional transformer response to transient transfer between its circuits. Due to computation equipment limitation, the studies carried in early years have been experimental based [8] with emphasis on the transient voltage transfer from HV circuit to loaded LV circuits. The threat posed by transient over-voltage that enters through unprotected LV circuits and hence, propagating to HV circuits were not taken into account.

II. MODEL VALIDATION

To verify the derived model for its suitability in the study of surge transfer through a loaded transformer, the experimentally obtained transferred surge with pre-defined resistive, inductive, or capacitive load is compared with corresponding transferred surge predicted by the model (simulated transient transfer characteristic).

Excitation impulse is obtained from Schaffner NSG-650, a combination waveform impulse source, which provides a standard lightning voltage waveform (1.2/50 μs), and a standard current waveform (8/20 μs). Excitation and transferred voltage waveforms are simultaneously recorded using a digital storage Oscilloscope (Lecroy LC574A) with the help of 6 kV Lecroy probes. As it has been difficult to obtain a portable impulse source that is capable of generating high impulse voltages, we have carried out our studies at fairly low impulse voltage levels (4 kV peak). However, since transformers are behaving linearly at high frequencies (above 1 kHz) i.e. frequency spectra contained in the impulse waveforms used in this study, testing at either low voltage or high voltage levels will not make any difference in the shape of transferred waveform.

A. Dryformer loaded at secondary terminals

In practice, transformers are loaded at their secondary terminals (low voltage side). The varied nature of equipment that is connected at transformer terminals, makes it difficult to evaluate all the possible combinations. However, the model used in this study is verified by comparing its predictions with that of experimentally obtained responses, when secondary terminals are loaded with resistive, inductive and capacitive loads respectively, as shown in Figure 1 through Figure 4.

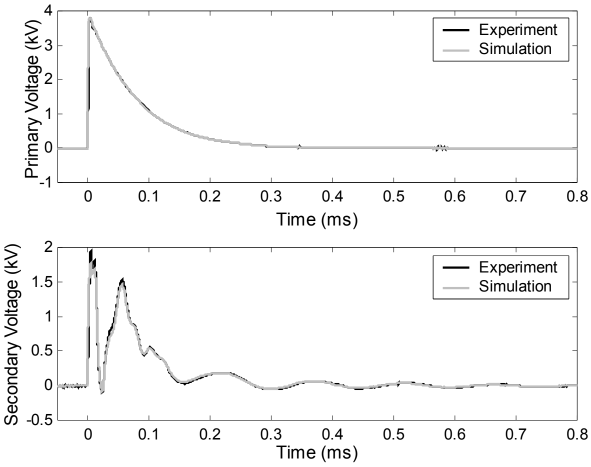

Fig. 1 Comparison of surge voltage transfer from primary to secondary with resistive load (390 ohms) on secondary terminals.

Figure 1 shows that the model reproduces accurately the experimentally obtained surge transfer characteristics of resistive loading at secondary terminals. A load of 390 Ω has been considered to represent an approximation of the characteristic impedance of an overhead line.

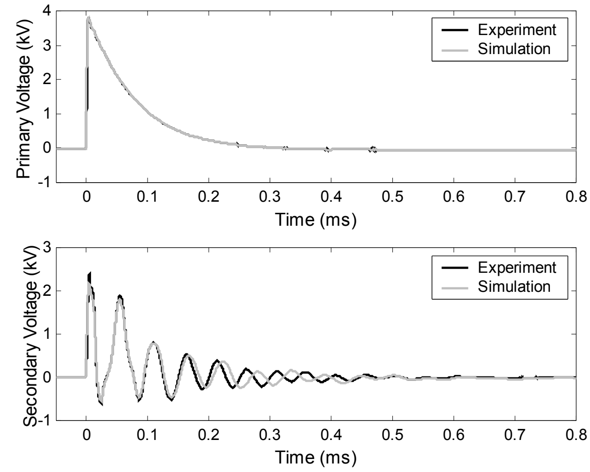

Fig. 2 Comparison of surge voltage transfer from primary to secondary with inductive load (5 mH) on secondary terminals.

With the inductive load, even though the model appears to predict sufficiently the general features of experimentally obtained results (Figure 2), some small discrepancies appear on the tail oscillations of transferred surge to inductive loaded secondary terminals. Assumption made on simulation that the inductive load is purely inductive, is not realistic because the presence of small resistive component is inevitably part of it and may have contributed to this discrepancy. For resistive and inductive loading (Figure 1 and 2), the transferred surge voltage from primary to secondary decays at about the same time to that of excitation voltage.

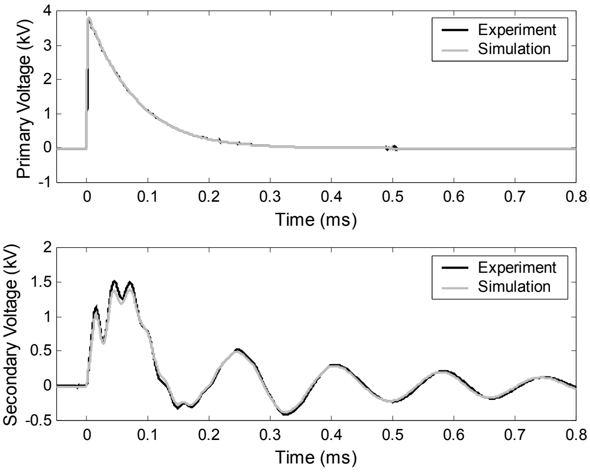

Fig. 3 Comparison of surge voltage transfer from primary to secondary with capacitive load (150 nF) on secondary terminals.

Figure 3 shows that the model predicts exemplarily the experimental results for capacitive load at the secondary terminals. Further, we note that the duration of the transferred surge to secondary is longer than the duration of excitation surge on the primary.

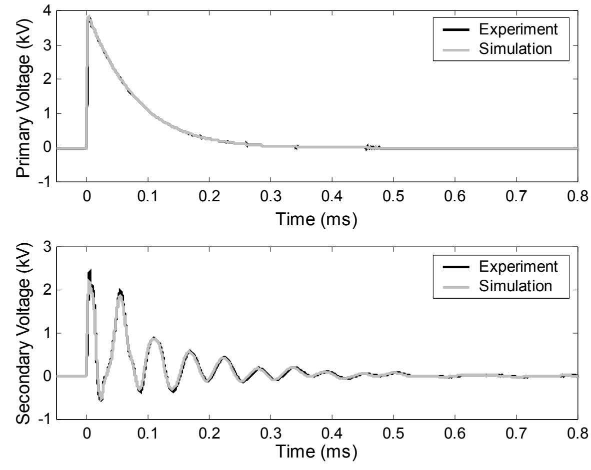

Fig. 4 Comparison of surge voltage transfer from primary to secondary with resistive and inductive loads (39 ohm in series with 5 mH) on secondary terminals.

Figure 4 shows the surge voltage transfer when the secondary connected load consists of a series combination of resistor and inductor. The excellent agreement between experiment and simulation in this case has confirmed our previous reasoning for the cause of small discrepancy on comparing the simulation and experimental results of inductive loaded surge transfer characteristics in Figure 3. The good agreement achieved on comparisons made between experimental results and model predictions (Figure 1 through Figure 4) validates that the model can be used for studies of transient transfer characteristics of various loads that are encountered in practice, over the frequency range at which the model is valid.

B. Dryformer loaded at primary terminals

In practice the load that has to be considered as the terminal load at the primary terminals is the characteristic impedance of the lines and impedance of the equipment supplying power to the Dryformer. The power network that conveys power to Dryformer primary, consists of various interconnections of power equipment such as transformers, aerial lines, shunt reactors, arresters etc, which results to an equivalent complex impedance of varying nature. However, in this study we are considering that the primary terminals are terminated with the line impedance (assumed as 390 Ω load), and Figure 5 shows the comparison of experimental with that of simulation prediction of surge transfer characteristic.

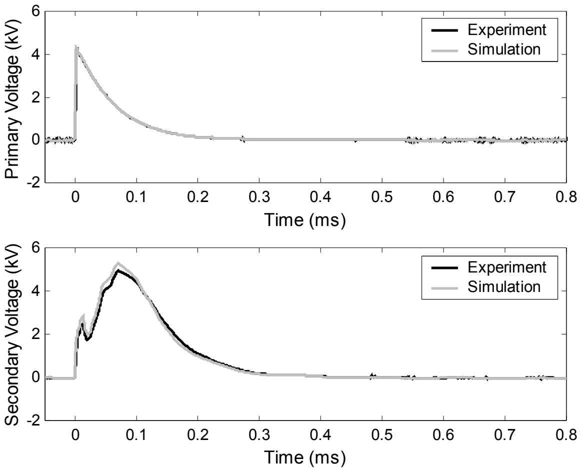

Fig. 5 Comparison of surge voltage transfer from secondary to primary with resistive load (390 ohm) on primary terminals.

Similarities that have been realised in the comparison of experimental and simulation surge transfer characteristics (Figure 5), shows that the model can be used to predict satisfactorily the surge transfer from secondary to loaded primary circuit.

III. EFFECT OF LOAD CHARACTERISTIC ON THE TRANSFERRED SURGES

The transformer transient response studies by computer simulation is preferred over experimental studies due to the possibility of generating by computer, a variety of excitation waveforms (standard and non-standard), which may be difficult to be realised experimentally. The excitation surge used in all the simulated cases in this section is a non-standard impulse 0.4/50 μs, which has sufficiently high frequency spectra covering the highest frequency bandwidth of the Dryformer model. Therefore the obtained surge transfer characteristic results reflects the transient transfer levels under loading conditions that will be encountered when transient over-voltage is induced in power network, such as during lightning strikes.

Figure 6 through Figure 8 shows the effect of varying the resistive, inductive and capacitive load respectively, connected on secondary terminals on the surge transfer through the Dryformer.

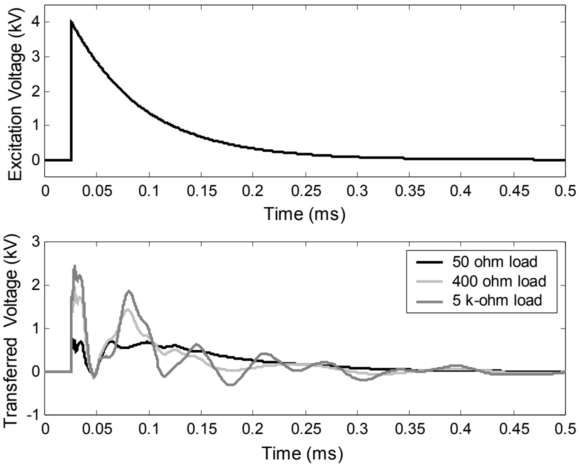

Fig. 6 Effect of varying resistive loads on the transferred surge voltage from primary to secondary Dryformer terminals.

It can be noted from Figure 6 that the duration of transferred transient voltage from primary to secondary is about the same as that of the excitation surge for all three resistive loading conditions, 50 Ω, 400 Ω, and 5 kΩ. We further note that when the Dryformer is supplying resistive equipment both the peak magnitude and oscillations of the transferred surge decreases with decreasing impedance of resistive load.

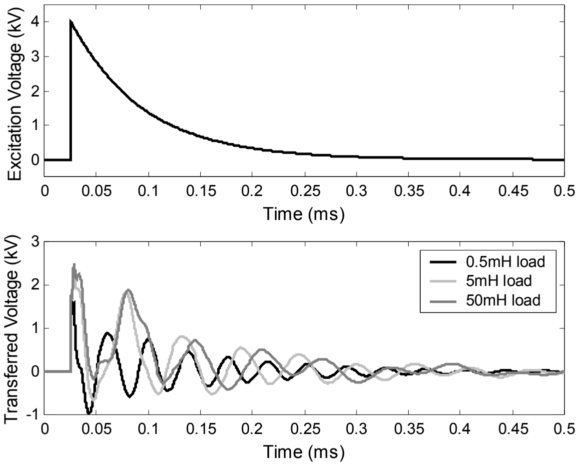

Fig. 7 Effect of varying inductive loads on the transferred surge voltage from primary to secondary Dryformer terminals.

With inductive loading (Figure 7) the duration of the transferred surge to secondary is about the same as that of excitation, and the peak magnitude of the transferred surge decreases with decreasing inductance of inductive load, while the oscillations frequency increases with decreasing inductance. It appears that for inductive load with inductance above 5 mH there is no significant change in the peak amplitudes, but the reduction in oscillations frequency is significant.

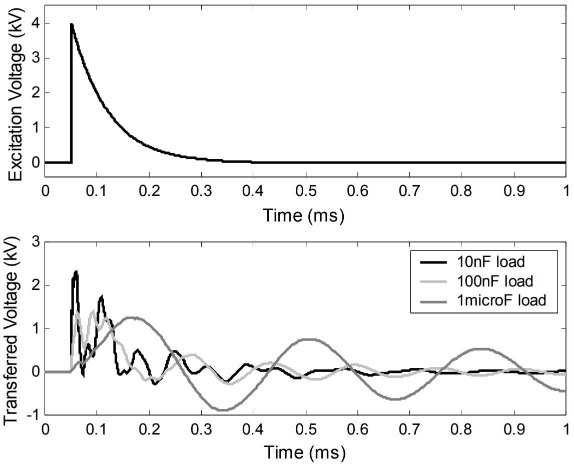

Fig. 8 Effect of varying capacitive loads on the transferred surge voltage from primary to secondary Dryformer terminals.

When the Dryformer supplies a capacitive load (Figure 8) the duration (period) of the transferred surge increases with an increase in the capacitance of the load. The initial peak magnitude, the rise time to peak and oscillatory frequency of the transferred surge decreases with increasing capacitance of the load.

Figure 9 and Figure 10 shows the effect of varying the resistive and inductive load respectively connected on primary terminals on the surge transfer through the Dryformer from secondary to primary terminals.

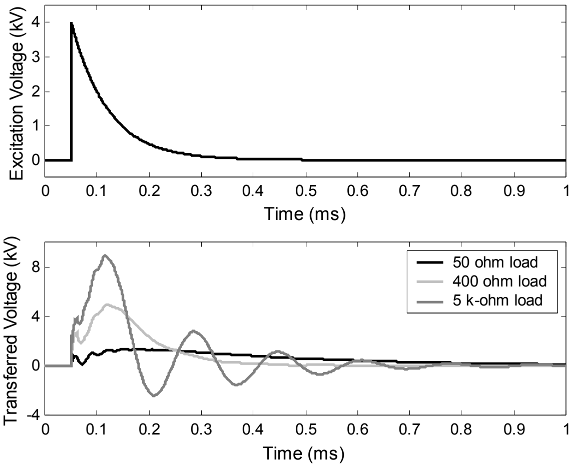

Fig. 9 Effect of varying resistive load on the transferred surge voltage from secondary to primary Dryformer terminals

Figure 9 shows the duration of transferred transient voltage from secondary to primary is longer than that of excitation surge for all resistive loading conditions taken into consideration i.e. 50 Ω, 400 Ω, and 5 kΩ. It is further noted that with resistive loading at primary terminals the peak magnitude and oscillations of the transferred surge increases with increasing resistance of resistive load.

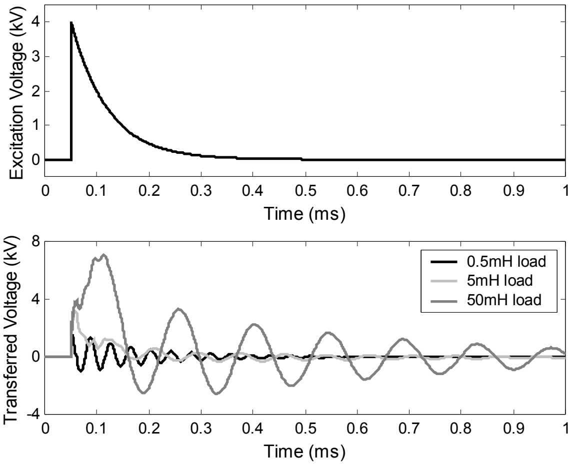

Fig. 10 Effect of varying inductive loads on the transferred surge voltage from secondary to primary Dryformer terminals.

When an inductive load (Figure 10) is terminated at primary terminals, the duration of the transferred surge to primary is longer than that of excitation. The peak magnitude of the transferred surge decreases with decreasing inductance of inductive load, while the oscillations frequency increases with decreasing inductance.

IV. CONCLUSIONS

The high frequency model used in this work has shown to be suitable for predicting the surge transfer through the Dryformer on application of various loading conditions on either circuit terminals. The model used in ATP/EMTP reproduces exemplary the experimentally obtained surge transfer characteristics between the Dryformer circuits, for open circuit (unloaded) studies [2] as well as loading studies carried out in this work.

In all the studied cases, it appears that the variation of loading at Dryformer terminals produces significant change in the peak magnitude and the shape of the transferred surge voltage. Variation of resistive and inductive loads has been found to produce decreased peak magnitude of the transferred surge from primary to secondary for decreased value of resistance and inductance of the load respectively, even though the duration of the transferred surge is about the same as that of excitation waveform. On the other hand, increase in capacitive loading has an effect of decreasing the initial peak magnitude, increasing rise time to peak, and increase in the duration of the transferred surge from primary to secondary terminals. In all the three loading conditions that have been treated, there are limiting values of resistance, inductance and capacitance, below or above which value, the peak amplitude and duration of the transferred surge from primary to secondary remains practically unchanged.

Terminating the primary terminals with variable resistive and inductive loads, has been found to produce decreased peak magnitude of the transferred surge from secondary to primary for decreased value of resistance and inductance of the load respectively. The duration of the transferred surge from secondary to primary is longer than the duration of excitation waveform. An increase in resistance and inductance values of the load has an effect of increasing the duration of the transferred surge to primary with more pronounced oscillation peaks and decreased oscillatory frequency of the transferred surge.

Having validated the surge transfer characteristic through the Dryformer on resistive, inductive and capacitive loading, it is evident that surge transfer characteristic for practical loading condition that can be represented as a combination of the studied components (i.e. RLC) can adequately be predicted. This work substantiates that the high frequency model formulated from short circuit admittance function [2] can be used for unloaded as well as loaded surge voltage transfer through transformers.

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