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Analysis of Cable-Transformer Resonant Interactions due to CB Prestriking Transients

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***Abstract*—Power transformer energization involves a significant electromagnetic energy exchange among system components, which periodically oscillates with the natural frequencies of the system. As a result, weakly damped resonating overvoltages (OVs) may prevail, overstressing the system and thus leading to potential insulation failure. This phenomenon is particularly notable in cable-transformer systems, where the coinciding of natural frequencies is more likely to occur. The prestriking phenomenon during circuit breaker (CB) closing plays an important role in the excitation of the resonance frequencies. Specifically, repeated prestrikes can create high-frequency resonances during switching-on operations. This paper deals primarily with the mutual interactions between cable and transformer during transformer energization. Furthermore, by using a suitable model, the impact of CB prestrikes on the resultant resonance excitation is analyzed. Results demonstrate that cable-transformer interactions can lead to high-frequency oscillatory OVs with extreme magnitudes.**

***Index Terms*—Cable, circuit breaker (CB), overvoltage (OV), prestrike, resonance, transformer.**

I. Introduction

Circuit breakers (CBs) are mechanical switches that are used to connect and disconnect relevant parts of the power system securely. During CB closing upon transformer energization, multiple prestrikes take place between CB contacts, producing repeated fast surges [1]. Prestrikes occur due to electric arc ignition as the CB contacts close, and the gap withstand capability decreases. The resultant arcing current through the CB exhibits high-frequency behavior. Due to the arc instability, the arc extinguishes just before reaching the current zero, depending on the rate of current variation. Shortly after the prestrike is interrupted, a transient recovery voltage (TRV) is developed across the CB, which will cause the arc to re-ignite as soon as the contact gap withstand voltage becomes lower than the TRV. This process may be repeated multiple times until CB contacts physically touch each other [2].

Moreover, the transition of the CB state between close and open is accompanied by the transient redistribution of electromagnetic energy between the system components. This process does not occur instantly but rather through the oscillating transformation of energy from a magnetic field to an electric field and vice versa. The frequencies of these oscillations are characteristics of the circuit, referred to as the natural resonance frequencies [3].

Power transformers, as costly and critical equipment, are particularly vulnerable to such resonances. Considering their bulkiness, resonance frequencies are formed in transformers due to the mutual capacitances and inductances between transformer windings, core, and tank. The situation can even intensify for transformers connected to cables in two ways. Primarily, the connection of insulated cables can cause additional resonance frequencies apart from those of the transformer. In addition, increased overvoltages (OVs) can occur by continuous superposition of resonating waveforms on transformer windings with new incoming surges, not only due to prestrike surges resulting from the CB but also due to wave propagation and reflection in the cable. As a consequence, excessive overvoltages with complex waveforms can be imposed on transformer windings, causing deterioration of the insulating material, resulting in transformer lifetime degradation and even failure [4]. Moreover, due to the nonlinear distribution of the voltages along transformer windings, high interturn and interwinding voltage stresses may be generated [5]. This effect may accelerate the failure process.

Resonances due to cable-transformer interactions have been widely studied in the literature. A case of severe OVs observed on the secondary side of a transformer energized through a long cable was analyzed in [6], attributed to the matching of resonance frequencies for both cable and transformer. In [4], an experimental analysis was performed to investigate the prestrike effect in a vacuum circuit breaker (VCB) on a power transformer with and without a cable on the primary side. In this research work, a simulated model of the laboratory test setup was also developed to study the distribution of resonating voltage components along the transformer winding. The results in [4] demonstrated the significant role of the cable on the frequency and duration of the occurred voltage resonances. By using a transformer model with available internal nodes, several energization cases were studied in [7] to investigate the distribution of voltages along the transformer windings, considering various cable lengths on the primary side and different terminations on the secondary side. In [8], high-frequency interactions between cable and transformer were investigated, analyzing several topologies susceptible to resonances due to energizations and ground faults. Similar to [6], the results in [8] stressed that severe oscillating OVs

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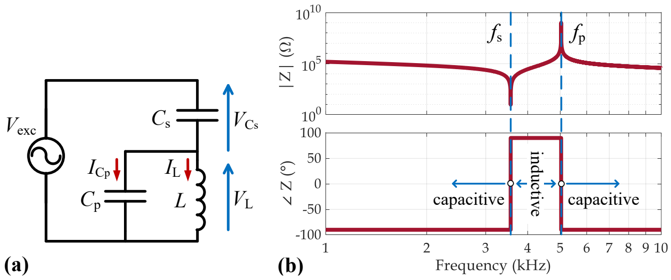

Fig. 1. (a) Series-parallel resonant circuit, (b) Impedance characteristic of series-parallel circuit.

might arise when the resonance frequencies of the cable and transformer coincide. The study in [9] provides a theoretical analysis of the formation of cable resonances as quarter-wave-length standing waves. It is shown that the voltage resonances in quarter-wave-length cables, when transferred to the secondary side, can impose severe OVs on the LV winding, exceeding its insulation withstand level.

Although earlier research has been conducted on the mutual interactions between cables and transformers [4], [6]–[9], the characteristics of the oscillatory components excited in a cable-transformer system after a transient occurrence are not well understood. On the other hand, the characteristics of the re-ignited arc in CB, and hence, the number and duration of restrikes are influenced by the frequency and magnitude of TRVs from the cable-transformer system [4]. Understanding mutual interactions between cable and transformer can be advantageous in twofold: i) Proper protection against fast transients can be applied based on insight over the severity and frequency of expected resonances [11]–[13]; ii) Magnification of resonances can be avoided by preventing the matching of cable-transformer natural frequencies [6], [8]. Consequently, an in-depth study on the CB prestrike effect on components due to transformer energization via a cable is necessary.

This paper lays out the resonant cable-transformer interactions excited by CB prestrikes during the energization process. To this end, firstly, the phenomenon of resonance in electrical circuits is analyzed theoretically. Thereafter, the prestrike effect during the energization of a transformer through a cable is investigated by using a refined CB model and a test system simulated in the EMTP-RV environment. In this regard, voltage waveforms across the CB and on transformer terminals, along with the CB arcing current, are analyzed in detail. It is shown that the presence of the cable may affect both the excited resonance frequencies and also their amplification factors, potentially leading to high-frequency OVs of excessive magnitudes.

The rest of this article is organized as follows: Theoretical analysis of resonance phenomenon is presented in Section II. Section III introduces the studied test system and CB model implemented in EMTP-RV. In Section IV, cable-transformer interactions are studied through simulations and results are discussed. Concluding remarks are given in Section V.

II. Theoretical Analysis

The resonance phenomenon is an oscillatory behaviour in physical systems that occurs when the system is excited by a periodic external force with the same frequency as its natural oscillation frequency [3]. A system resonates when it possesses the capability to interchange energy between

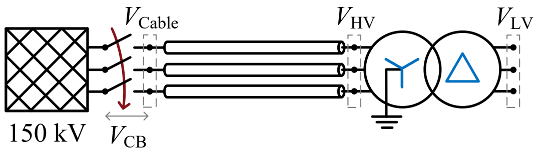

Fig. 2. Adopted test system.

two or more distinct storage modes, such as the electric field in capacitances and the magnetic field in inductances of electric systems. At the resonance frequency, the capacitive and inductive energy requirements become equal, and hence, the total impedance will be purely resistive.

The resonance phenomenon can be analyzed according to Fig. 1. The simple circuit in Fig. 1a demonstrates a series-parallel structure of capacitive and inductive energy storage units, which can form two distinct resonance modes, series, and parallel. Under series resonance, the impedance of the circuit becomes minimum, prevailing as a short circuit from the source's point of view:

$$V_{\text{L}} + V_{\text{C}_\text{s}} = 0 \tag{1}$$

Although in this condition, the voltages of the inductor L and the series capacitor C_s cancel each other, they undergo extreme values, and thus, an OV condition is imposed on the circuit components.

In the case of parallel resonance, the total impedance becomes maximum, and the current through the circuit approaches zero as:

$$I_{\text{L}} + I_{\text{C}_\text{p}} = 0 \tag{2}$$

Similarly, while the currents in the inductor L and the parallel capacitor C_p cancel, they take high values, causing severe currents in the circuit components.

Yielding $V_\text{L} = -V_{\text{C}_\text{s}}$ for series and $I_\text{L} = -I_{\text{C}_\text{p}}$ for parallel resonances, the frequencies f_s and f_p respectively for series and parallel resonances can be obtained as:

$$f_\text{s} = \frac{1}{2\pi\sqrt{L \cdot (C_\text{s} + C_\text{p})}} \tag{3}$$

$$f_\text{p} = \frac{1}{2\pi\sqrt{L \cdot C_\text{p}}} \tag{4}$$

Considering $L = 1\,\text{H}$, $C_\text{s} = 1\,\text{nF}$ and $C_\text{p} = 1\,\text{nF}$, the harmonic impedance characteristic of the series-parallel circuit is obtained according to Fig. 1b. As it can be seen, the circuit's behavior abruptly changes at resonance frequencies, shifting between dominant capacitive and inductive.

III. Test System Description

A test system, according to Fig. 2, is simulated to investigate the severity of the cable-transformer resonances and their excitation upon CB restrikes. This section introduces the details of the simulation model.

A. Power Transformer Model

The transformer is simulated based on the well-known BCTRAN model [13]. In this method, the multi-phase multi-winding transformer is described through the admittance matrix corresponding to the coupled resistances and inductances of the transformer, calculated based on the no-load excitation and short-circuit test data. To account for the capacitive couplings, the winding-to-ground and cross-over capacitances are divided in half and stacked at the ends of relevant windings

TABLE I
SPECIFICATIONS OF TEST TRANSFORMER

Parameter	Value
Ratio	$150/11.2\,\mathrm{kV}$
Vector Group	Ynd5
Rated Power	$48\,\mathrm{MVA}$
Rated Frequency	$50\,\mathrm{Hz}$
No-Load Loss	$26.4\,\mathrm{kW}$

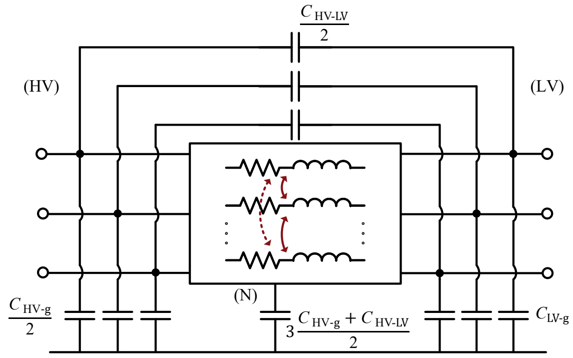

Fig. 3. Implemented BCTRAN transformer model.

[14], as illustrated in Fig. 3 with $C_{\mathrm{HV-g}} = 1.186\,\mathrm{nF}$, $C_{\mathrm{LV-g}} = 3.286\,\mathrm{nF}$ and $C_{\mathrm{HV-LV}} = 1.263\,\mathrm{nF}$. It is important to note that this type of transformer model is selected since it satisfies the necessary requirements for the focus of this study, i.e., analyzing cable-transformer resonant interactions due to CB prestrikes, while also maintaining simplicity. Table I presents the specifications of the test transformer.

B. Cable System Model

Accurate methods have been proposed for the transient modeling of cable systems based on their geometrical and physical characteristics [15]. The main focus of this study is on the wave propagation characteristics and the free oscillation frequencies of cable systems. In this regard, cables are simulated by constant-parameter distributed models in EMTP-RV. The wave propagation velocity v' in a medium with a permeability μ and permittivity ε is given by [16]:

$$v' = \frac{c}{\sqrt{\mu\varepsilon}} \tag{5}$$

where $c = 3 \times 10^8\,\mathrm{m/sec}$ is the speed of light. This corresponds to the time $\tau = l/v'$ required for an electromagnetic wave to travel across a line/cable of length l. Considering that traveling waves are constituted of different frequency components, it can be asserted that a distributed line/cable will resonate for an oscillating component completing a quarter of a full cycle or its odd multiples over the time τ [9], expressed as:

$$f_{n,\mathrm{C}} = n\frac{v'}{4l} \tag{6}$$

where $f_{n,\mathrm{C}}$ denotes the resonance frequencies of the line/cable, and n is a natural number. While odd values of n mark the series resonance points, the even values correspond to parallel resonances. According to (6), resonance frequencies in cables depend on their physical characteristics reflected by propagation velocity v' and the length l. In this analysis, the cable is considered based on the specifications in Table II, while the frequency characteristics are reproduced by varying the length, according to (6).

TABLE II
SPECIFICATIONS OF CABLE

Parameter	Value
Core Diameter	$21.60\,\mathrm{mm}$
Total Diameter	$83.00\,\mathrm{mm}$
Resistance	$0.0778\,\Omega/\mathrm{km}$
Capacitance	$0.13\,\mu\mathrm{F/km}$
Characteristic Impedance	$50\,\Omega$

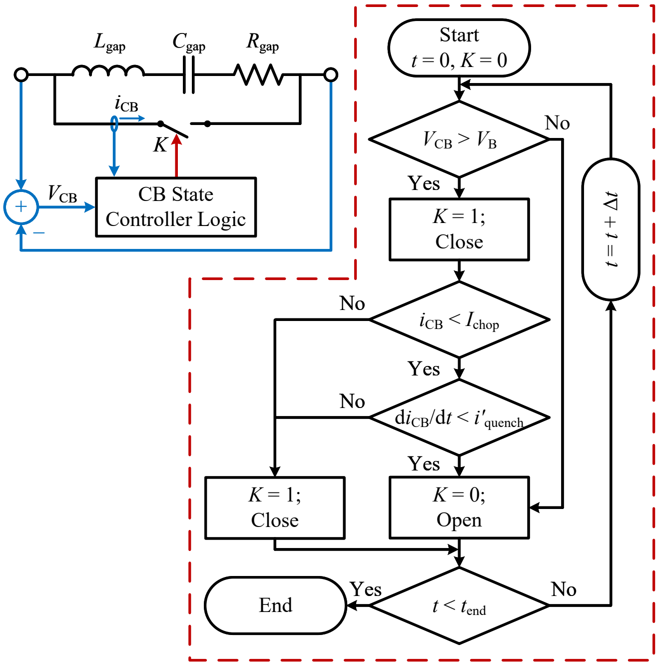

Fig. 4. Implemented CB model.

C. Circuit Breaker Model

The CB is represented by a model shown in Fig. 4. As can be seen, the model is composed of a controlled ideal switch K connected in parallel to an RLC branch representing the parasitic parameters of the gap. According to the flowchart in Fig. 4, prestriking transients have been modeled by controlling the ideal switch state considering the contact gap withstand voltage V_{B}, the chopping current I_{chop}, and the high-frequency current quenching capability i'_{quench}, yielded by [17]:

$$V_{\mathrm{B}} = A(t - t_0) + B \tag{7}$$

$$i'_{\mathrm{quench}} = C(t - t_0) + D \tag{8}$$

where t_0 is the contact closing time, and the parameters of CB have been considered according to [17], with $I_{\mathrm{chop}} = 3\,\mathrm{A}$, $A = -0.02\,\mathrm{kV}/\mu\mathrm{s}$, $B = 0\,\mathrm{kV}$, $C = 0\,\mathrm{A/s^2}$, and $D = 350\,\mathrm{A}/\mu\mathrm{s}$. Arc parameters R_{gap}, L_{gap}, C_{gap} are equal to $100\,\Omega$, $0.05\,\mu\mathrm{H}$, and $0.1\,\mathrm{nF}$, respectively.

IV. SIMULATION RESULTS AND DISCUSSION

In this section, the cable-transformer interactions have been analyzed in the adopted test system. To this aim, simulations have been performed in the frequency- and time domain.

A. Energization of Transformer Without Cable

The frequency response of the test transformer can be observed by the harmonic terminal impedance as shown in Fig. 5, where Fig. 5a shows the HV-side terminal impedance when the LV-side is open, and Fig. 5b shows the LV-side terminal impedance with the HV-side open, both with the solidly

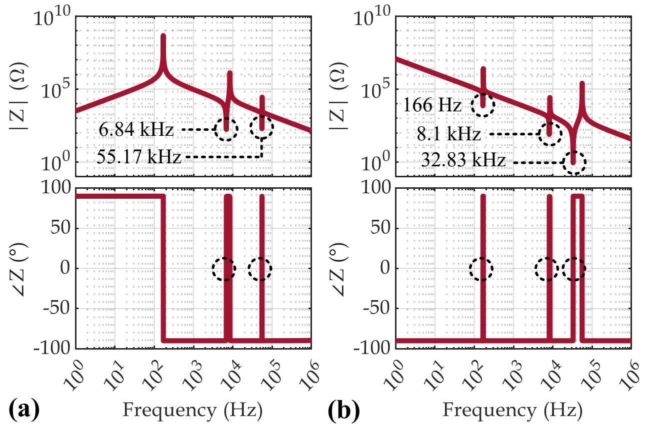

Fig. 5. Terminal impedance of test transformer: (a) HV-side, (b) LV-side.

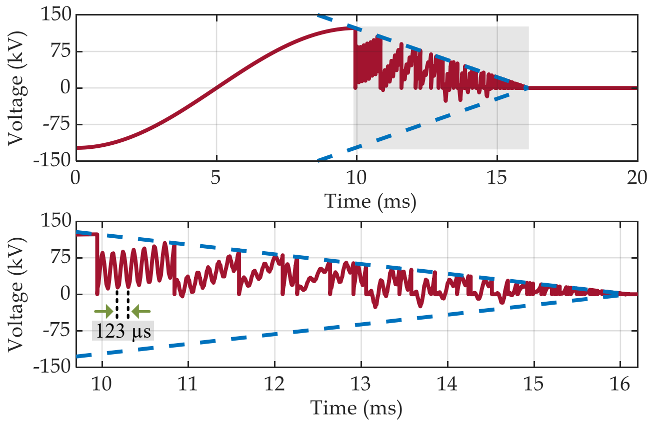

Fig. 6. CB voltage during transformer energization.

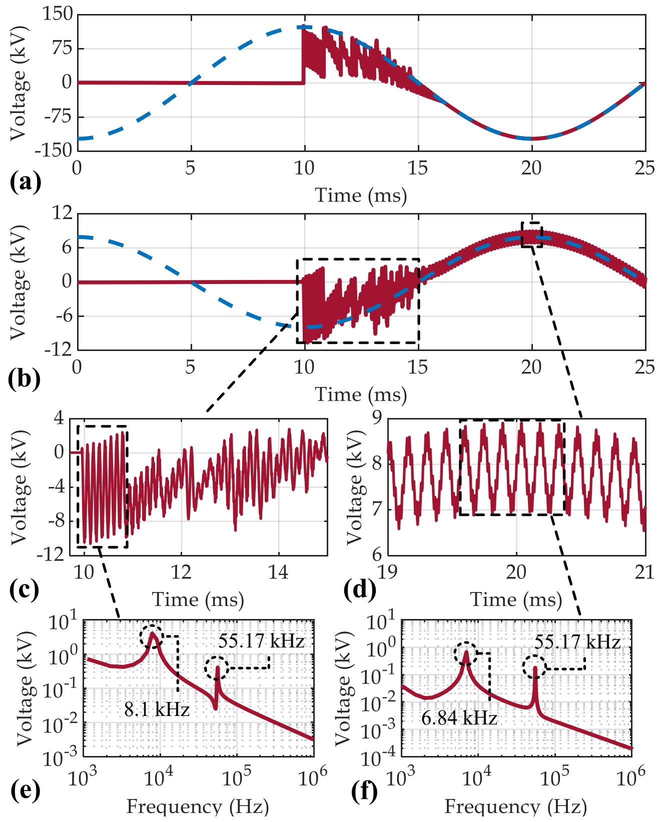

Fig. 7. Transformer terminal voltages during energization without cable: (a) HV terminal, (b) LV terminal, (c) LV-side voltage during CB closing, (d) LV-side voltage after CB is fully closed, (e) Frequency components of LV-side voltage during CB closing, (f) Frequency components of LV-side voltage after CB is fully closed.

grounded neutral point. As it can be seen, the transformer exhibits a resonance at specified frequencies.

It is assumed that phase "a" of the CB closes with a contact closing time set for the first prestrike to occur at the peak of the excitation voltage. Fig. 6 demonstrates the voltage across CB where the blue dashed lines represent the dropping contact gap withstand voltage. As seen in this figure, the arc is unstable and extinguishes promptly, imposing a fast TRV on the CB. The period of the main component in the TRV is observed to be around $123\,\mu$s, corresponding to $8.1\,$kHz resonance frequency marked in Fig. 5b. As it is evident from Fig. 6, the arc between contacts does not sustain, and numerous prestrikes take place until the contacts are completely closed.

Transformer terminal voltages in this condition are shown in Fig. 7. The blue dashed lines in Figs. 7a and 7b represent the corresponding voltages under the condition when CB is normally closed. As can be seen from the obtained results, high-frequency resonances have been excited. The waveform of the transformer's LV-side voltage is zoomed in Figs. 7c and 7d, corresponding to intervals during and after contacts are (being) closed. The fast Fourier transform (FFT) analysis for these waveforms is shown in Figs. 7e and 7f, respectively. According to Fig. 7e, after arc extincts, resonance frequencies of $8.1\,$kHz and $55.17\,$kHz occur, where the former is dominant. The dominant $8.1\,$kHz is also apparent in the TRV as marked in Fig. 6. After CB contacts are fully closed, resonance frequencies $8.1\,$kHz and $55.17\,$kHz are excited, as shown in Fig. 7f. These frequencies are marked in transformer's HV terminal impedance response, as shown in Fig. 5a.

B. Transformer Energization through Cable

The effect of cable on the transformer energization transients is analyzed for the case where cable length is set to $897.2\,$m. According to equation (6), at this length, the fundamental cable resonance frequency is equal to $f_{1,\mathrm{C}} = 55.17\,$kHz, matching the second resonance frequency of transformer's HV terminal impedance, marked in Fig. 5a.

Figure 8 shows the impedance characteristic of the cable-transformer system depending on the frequency. The part corresponding to frequency matching is zoomed on the right. As can be seen, the matching of cable and transformer resonance frequencies has caused a split in the impedance characteristic, forming two close resonance frequencies at $54.16\,$kHz and $55.51\,$kHz. Since these two newly formed resonance frequencies are close to each other, they may not have a noticeably distinct impact on the excited components.

Due to the matching of resonance frequencies, significant OVs at the resonance frequency are expected to occur, as the transients at this frequency are subjected to two stages of amplification, i.e., primarily by the cable and subsequently by the transformer.

Figure 9 represents the voltage across CB, assuming phase "a" of CB closes with a similar contact closing time as the previous condition for the first prestrike to take place at the exciting voltage amplitude. In this case, after the arc extinguishes for the first time, the TRV does not exceed the withstand voltage of the contact gap (blue dashed lines) for a longer period. As seen from the zoomed graphs in Fig. 9, two voltage components are evident, namely with periods equal to

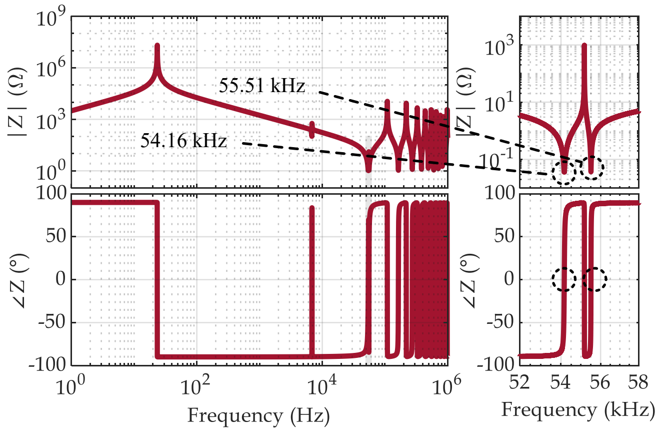

Fig. 8. Impedance response of cable-transformer system.

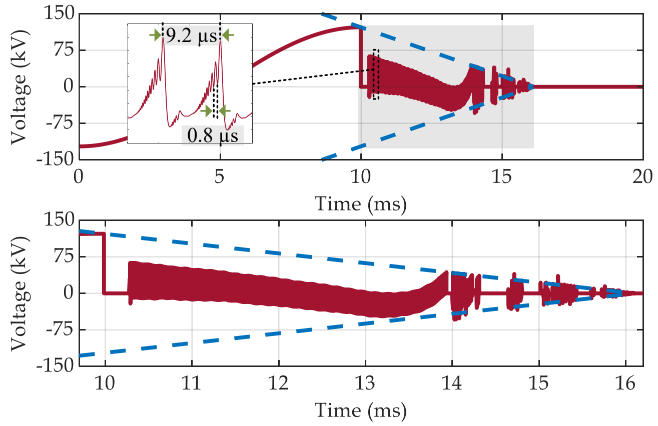

Fig. 9. CB voltage during transformer energization via cable.

$0.8\,\mu$s and $9.2\,\mu$s, where latter is equal to two times the wave traveling time in the cable ($\tau = 4.6\,\mu$s).

Transformer terminal voltages are shown in Fig. 10. Likewise, blue dashed lines in Figs. 10a and 10b show the corresponding voltages under the condition when CB is normally closed. Fig 10a shows transformer HV-side terminal voltage for which two sections are zoomed, corresponding to the first closing upon prestrike and shortly after the arc is extinguished for the first time. In the first interval when CB closes, a square-shape voltage waveform due to wave reflection and refraction is formed, with the full-cycle period of $18.4\,\mu$s equal to 4τ, and voltage spikes up to around $300\,$kV. In the second interval where the arc extinguishes, a similar waveform as of Fig. 9 can be observed, with periods equal to $0.8\,\mu$s and $9.2\,\mu$s, where latter is equal to 2τ.

The voltage at the LV terminal is shown in Fig. 10, where the two intervals during and after the CB is (being) closed have been zoomed in Figs. 10c and 10d. As characterized in the FFT of these waveforms presented in Figs. 10e and 10f, respectively, during the CB closing, the two dominant frequency components of $7\,$kHz and $55\,$kHz are excited. Once the CB contacts are fully closed, no more prestrikes occur, and as a result, no further high-frequency contents are generated. Consequently, resonances are no longer excited. In this condition, oscillations at $55\,$kHz damp faster, while $7\,$kHz oscillations remain the dominant resonance frequency. By comparing the transformer voltages with and without cables, as shown in Figs. 10 and 7, it is evident how the presence of cable has led to the amplification of excited resonances and

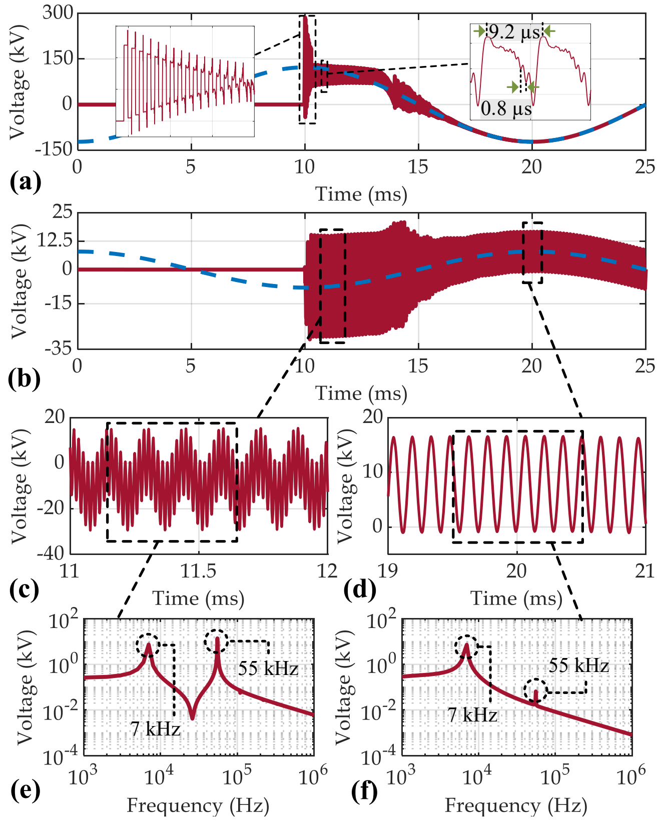

Fig. 10. Transformer terminal voltages during energization via cable: (a) HV terminal, (b) LV terminal, (c) LV-side voltage during CB closing, (d) LV-side voltage after CB is fully closed, (e) Frequency components of LV-side voltage during CB closing, (f) Frequency components of LV-side voltage after CB is fully closed.

the significant intensification of OVs.

C. Discussion

Resonant oscillations generated by transformer energization were analyzed for the cases with and without a cable for the resonance frequency matching the resonance frequency of the transformer. One of the main observations is related to the characteristics of the TRV after the arc extinction for the two cases. For the first case, when the arc is extinguished, the transformer is isolated from the rest of the circuit, and therefore, the obtained energy during the prestrike effect resonates inside the transformer. For this condition, the dominant oscillation frequency in the TRV is $8.1\,$kHz, characterized by the transformer's impedance response observed from the LV-side when the neutral point at the HV-side is solidly grounded. In the second case, the transient waveforms are affected by the mutual interactions of the cable-transformer system. As a result, when the arc ceases, traveling wave reflections take place between the transformer and the open-circuited sending end of the cable. Therefore, TRV is affected by traveling wave reflections, and its period is equal to 2τ.

It was also observed that the connected cable leads to the escalation of OVs, particularly for the resonance condition at $55\,$kHz. The voltage ratio from the transformer's LV to its HV-side and to the cable's sending end corresponding to the cases of energization without and with cable are shown in Fig. 11. In this figure, the blue dashed line represents the unit ratio, where the components related to the parts of the graphs above the line will be amplified. It is important to note that in a step-down transformer, an amplification of equal to

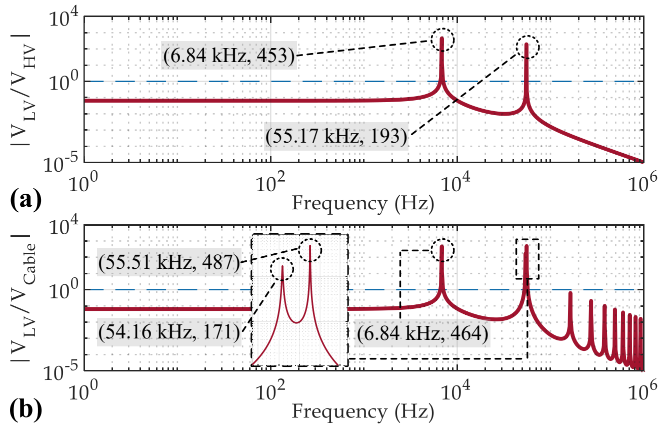

Fig. 11. Voltage amplification ratio: (a) Transformer LV-side to Transformer HV-side, (b) Transformer LV-side to Cable sending end.

one still marks OV on the LV side. The results show that the presence of the cable results in a severe amplification of resonance oscillations compared to the case without cable. In this regard, even though the resonance frequency amplification factor at $6.84\,\mathrm{kHz}$ has slightly increased from 453 to 464, the oscillations around $55\,\mathrm{kHz}$ will be highly amplified with the ratio increased from 193 to 487. This effect is observed by comparing the transformer's LV-side voltages in the two cases in Figs. 7 and 10, where the resonance components have significantly escalated as a result of the cable.

V. Conclusion

The excitation of natural resonance frequencies in electrical power systems can lead to severe OVs that may cause insulation failure of power equipment. These resonance effects can be more severe for a cable-transformer system. Understanding these effects is essential to avoid the occurrence of these unwanted phenomena and protect transformers. In this paper, transients due to CB prestriking phenomenon during transformer energization are investigated. For this purpose, suitable models for the cable, transformer, and CB are developed, taking into account the prestriking phenomenon.

Mutual cable-transformer interactions were analyzed by considering a cable between the CB and transformer, with a resonance frequency matching the transformer resonance frequency. It was primarily observed that the TRV upon arc extinction during contact closing is significantly affected by the presence of the cable. Namely, when the cable is present, due to traveling wave reflections, a recurring impulse waveform is formed over the CB with a period equal to two times the cable time constant. On the other hand, in the case without a cable, the TRV is influenced only by the transformer's inherent resonance characteristics.

Furthermore, through analysis of the transformer terminal voltages, it was observed that the cable contributes to the escalation of OVs in two ways: by consecutive traveling wave reflections and through the amplification of resonant oscillations, where the former is prominent for the HV-side, and the latter for the LV-side. The matching of cable and transformer resonance frequencies contributes to the abrupt amplification of resonating components, imposing severe high-frequency OVs on the transformer.

Simulation results represented that the total impedance characteristic of the cable-transformer system is split around the matched resonance frequency. Although in the case studied in this paper, the two newly formed resonance frequencies are close to each other; distinct oscillation frequencies may prevail for similar conditions due to the matching of cable and transformer resonance frequencies. Moreover, an important difference between the two cases with and without cable is noted regarding the number of prestrikes. Since the arc inception occurs when the TRV exceeds the gap withstand voltage, and it extinguishes when its current magnitude and rate of variation ($\mathrm{d}i/\mathrm{d}t$) are below CB's corresponding current chopping and critical $\mathrm{d}i/\mathrm{d}t$ values, the number of prestrikes is also dependent on the resonances excited thereupon. Future analyses will be conducted to further investigate these effects. In this regard, the formation of resonance frequencies in a cable-transformer system will be analyzed. Additionally, investigations will be carried out using more detailed wideband models for the transformer and cable.

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