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Analysis of Cable-Transformer Resonance Interactions Due to Circuit Breaker Prestriking Transients

Behzad Behdani ¹, Member, IEEE, Mohamad Ghaffarian Niasar ², Member, IEEE, and Marjan Popov ³, Fellow, IEEE

Abstract—Power transformer energization involves a significant electromagnetic energy exchange among system components, with periodic oscillations at the system’s natural frequencies. As a result, weakly damped resonance overvoltages may occur, overstressing the system and thereby leading to potential insulation failure. This phenomenon is particularly notable for topologies where a transformer is supplied via cable, as low-damping resonance frequencies are likely to be formed due to mutual interactions between the cable and the transformer. The prestriking phenomenon during circuit breaker closing plays an important role in the excitation of resonance frequencies. Specifically, repeated prestrikes can create high-frequency resonances during switching-on operations. This paper analyzes the mutual interactions between the cable and the transformer, focusing on how the resonances between the cable and the transformer are created. Then, using a suitable modeling approach, the impact of CB prestrikes on the resultant resonance excitation in cable-transformer systems is investigated. Finally, tests are conducted using an experimental test setup to validate the investigations performed. The obtained results demonstrate that resonance frequencies emerging from cable-transformer interactions lead to the excitation of oscillatory overvoltages with extreme magnitudes.

Index Terms—Cable, circuit breaker, overvoltage, prestrike, resonance, transformer.

I. INTRODUCTION

RESONANCE overvoltages (OVs) with high magnitudes can occur in mutual cable-transformer connections and lead to severe failures of crucial pieces of equipment such

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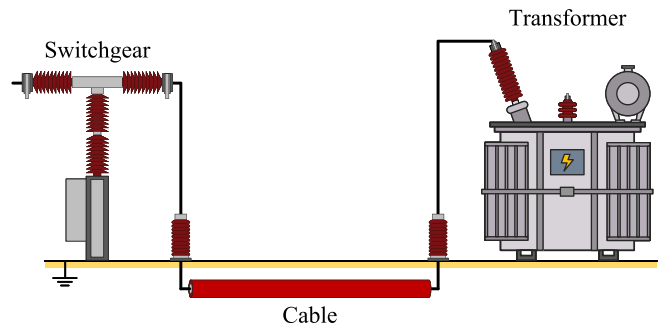


Fig. 1. Schematic of a typical cable-transformer system and switchgear.

as power transformers [1]. In power grids, a resonance phenomenon occurs when the capacitive and inductive energy requirements become equal [2]. At particular frequencies where this condition is met, the capacitive and inductive impedances cancel out, and the resulting voltage and current waveforms may oscillate with a resonance frequency. Resonances in power systems, containing cables and transformers, are also formed similarly due to their inherent capacitances and inductances [3]. However, when the natural resonance frequency of the power transformer matches the natural frequency of the supply cable, severe OVs occur due to their mutual resonant interactions [4].

When power transformers are energized, the grid voltage is suddenly applied to the transformer terminals by closing a circuit breaker (CB). This sudden change generates transient surges that can excite resonance frequencies in the system. Moreover, during CB closure, multiple prestrikes occur between its contacts, generating repeated fast surges [5]. As the CB contacts approach each other, the withstand voltage across the contacts decreases accordingly. As soon as the withstand voltage becomes lower than the voltage across the contacts, electrical breakdown occurs in the gap, leading to arc ignition between the contacts. Depending on the rate of current variation, the arc may become unstable and extinguish before reaching current zero. This leads to a transient recovery voltage (TRV) build-up across the CB, which can re-ignite the arc if it exceeds the gap-withstand voltage. This process repeats multiple times until the CB contacts physically touch each other [6].

The excited resonance state of the system depends on whether an electrical connection is established between the CB contacts.

In other words, the resonance frequencies excited when current flows through the CB (either due to arc ignition or physical connection of CB contacts) are different from those that occur after arc interruption, when no current flows [7]. This effect influences the OV's at the transformer terminals and the number of CB prestrikes. Furthermore, the switchgear is typically connected to the power transformer through an underground cable, as shown in Fig. 1. The repetitive occurrence of prestrikes generates surges that propagate along the cable and reflect from its remote ends. In this way, high OV's are created on transformer windings due to the continuous superposition of resonating waveforms with new incoming surges.

So far, resonance phenomena resulting from mutual cable-transformer interactions and thereby the associated impact on system components have been addressed by several studies. The study in [8] presented that extreme OV's were observed at transformer low-voltage (LV) terminals during energization through a long cable with a resonance frequency that matched the transformer's resonance frequency. An experimental analysis was performed in [7] to investigate the effect of vacuum circuit breaker (VCB) prestrike transients on the occurrence of power transformer resonance during energization with and without a supplying cable. The results of this study showed that the characteristics of the prevailing transients and resonance occurrence depend mainly on the presence of the cable. A transformer model with accessible internal winding nodes was utilized in [9] to investigate how voltage distributions along the windings are influenced by different cable lengths and LV-side terminations. In [4], high-frequency (HF) interactions between cables and transformers were analyzed, highlighting several configurations prone to resonance. Consistent with [7], the results in [4] indicated the occurrence of severe oscillating OV's when the cable and transformer resonance frequencies coincide. According to the theoretical analysis in [10], quarter-wavelength standing waves formed at the cable terminals connected to the high-voltage (HV) side of the transformer were responsible for the severe OV's on its LV side.

Although mutual interactions between cables and transformers have been addressed in previous studies [4], [7], [8], [9], [10], the behavior of the oscillatory components excited in a cable-transformer system following a transient event is still not clearly understood. Moreover, the frequency and magnitude of the re-ignited arc current and the TRV were observed to be influenced by the characteristics of the excited cable-transformer resonance [7]. Gaining a better understanding of these mutual interactions provides multiple advantages. Understanding the severity and frequency of resonance occurrence enables the design of effective protection strategies targeting dangerous resonance frequencies [11], [12], [13]. Moreover, by understanding how mutual cable-transformer resonance is formed, preventive steps can be proposed to avoid and mitigate these effects [14], [4], [9]. Furthermore, this will help ensure that the CB can withstand the expected resonating transients and perform its intended operation safely [7].

This paper analyzes resonant cable-transformer interactions excited by CB prestrikes during energization. First, resonance phenomena in electrical circuits are examined theoretically by

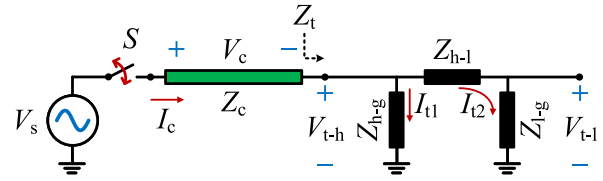


Fig. 2. Simplified circuit model of a cable-transformer system.

analyzing series and parallel resonance modes. Then, an analysis is performed on the formation of resonance frequencies in cable-transformer systems. Afterward, the effect of CB prestriking transients on HF resonances during transformer energization via a cable is studied through simulations in the electromagnetic transient program (EMTP) environment. Finally, the analysis is experimentally validated by tests done on an actual medium-voltage (MV) cable-transformer system. Through the analyses carried out in this study, the following key contributions are achieved:

- It is shown that the excited voltages and currents in a cable-transformer system do not correspond to the resonance frequencies of the cable or transformer individually, but rather to new frequencies that emerge from their mutual interactions.
- The study demonstrates how mutual cable-transformer resonance frequencies are formed and under what conditions the series and parallel resonance modes are excited.
- It is shown that in the case of arc ignition in the CB or full closure of its contacts, series resonance modes are excited, whereas upon arc interruption, parallel resonance modes are excited.
- The effect of cable length on the severity of the resonating OV's in cable-transformer systems is quantified by introducing a simplified two-stage RLC ladder circuit.

Table I provides a summarized comparison between the presented analysis and existing studies on cable-transformer interactions.

The rest of this paper is organized as follows: Section II presents the theoretical analysis of resonance phenomena and the formation of mutual cable-transformer resonance. Section III presents the designed test system and applied CB model. In Section IV, cable-transformer interactions during CB closing are investigated through simulations, and the results are discussed. Section V presents the experimental validation of the analysis. Lastly, Section VI provides the concluding remarks.

II. THEORETICAL ANALYSIS

A. Analysis of Series and Parallel Resonances

The resonance phenomenon in cable-transformer systems can be analyzed by applying a simple circuit model shown in Fig. 2. In this simplified single-phase circuit, the cable is represented by impedance Z_c , and the transformer is modeled as a π -equivalent circuit consisting of Z_{h-g} , Z_{l-g} , and Z_{h-l} , representing the impedances at the HV- and LV terminals to the ground, and the impedance between HV and LV terminals, respectively.

TABLE I
REVIEW AND COMPARISON OF RELATED ANALYSES ON CABLE-TRANSFORMER INTERACTIONS

Reference	Cause of Resonance	Series & Parallel Resonance Modes	Effect of CB Prestrikes	Effect of Cable Length	Performed Analysis
[4]	Not discussed	No	No	Yes	Simulation
[7]	Cable resonance frequencies	Yes	Yes	No	Experimental
[8]	Transformer resonance frequencies	No	No	No	Simulation
[9]	Not discussed	No	No	Yes	Simulation
[10]	Cable resonance frequencies	No	No	Partially	Simulation
This paper	new resonance frequencies formed due to cable-transformer interactions	Yes	Yes	Yes (quantified)	Simulation and Experimental

The system is energized by closing the switch S and applying the voltage source V_s to the circuit. As soon as the switch S is closed, the capacitances and inductances in the circuit are charged in an oscillatory mode, causing a *series resonance*. As outlined in [1], [2], under series resonance, the circuit is seen as a short-circuit (SC) from the source perspective, where:

$$V_c + V_{t-h} = 0. \quad (1)$$

Although in this condition, the voltages V_c and V_{t-h} cancel each other, they undergo extreme values, and thus, an OV condition occurs in the circuit.

As soon as the switch S opens, the current is interrupted, and $I_c = 0$. This way, the energy stored in the capacitances and inductances of the circuit is discharged in an oscillatory mode, resulting in a *parallel resonance* where:

$$I_{t1} + I_{t2} = 0. \quad (2)$$

Similarly, while the currents I_{t1} and I_{t2} cancel, they take high values, causing severe currents in the circuit components. In addition, considering that $V_{t-h} = Z_{h-g} I_{t1}$ and $V_{t-l} = Z_{l-g} I_{t2}$, the voltages over circuit components are also affected by the excited current resonances and vice versa.

This simplified analysis is beneficial for understanding series and parallel resonances in cable-transformer systems. Namely, when an electrical connection is established through the switch (either due to arc ignition or physical connection of CB contacts), series resonance modes are excited, and when this connection is interrupted (i.e., arc extinction), parallel resonance modes are excited. However, to consider the traveling wave behavior of voltages and currents, the cable must be represented by distributed parameters. Therefore, an analysis is conducted on the formation of mutual cable-transformer resonance, considering the wave propagation effects in the cable.

B. Analysis of Mutual Cable-Transformer Resonance Formation

To analyze the formation of mutual cable-transformer resonance frequencies by taking into account wave propagation effects in the cable, the circuit in Fig. 3 is considered. In this circuit, the transformer is represented by its equivalent impedance Z_t , seen from the HV terminal, as indicated in Fig. 2. At the

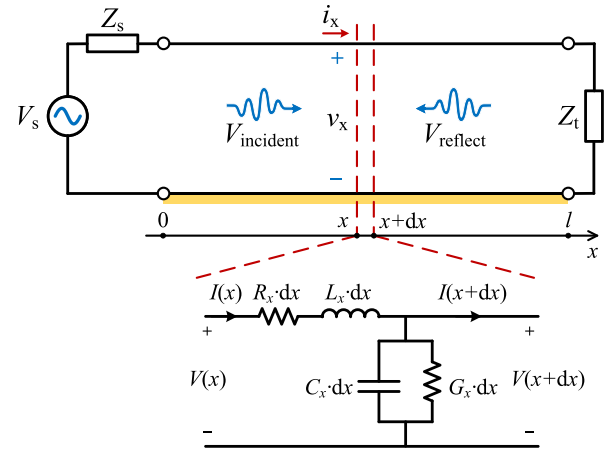


Fig. 3. Cable-transformer circuit model with a distributed parameter cable.

infinitesimal section dx of the distributed cable in Fig. 3, the following frequency domain equations hold [15]:

$$\frac{\partial}{\partial x} V(x, \omega) = -Z_x(\omega) I(x, \omega), \quad (3)$$

$$\frac{\partial}{\partial x} I(x, \omega) = -Y_x(\omega) V(x, \omega), \quad (4)$$

where $Z_x(\omega) = R_x + j\omega L_x$ and $Y_x(\omega) = G_x + j\omega C_x$ are the per unit length impedance and admittance at angular frequency ω , respectively. Considering the propagation function $\gamma(\omega) = \sqrt{Z_x(\omega)Y_x(\omega)}$ and the characteristic impedance $Z_0 = Y_x^{-1}(\omega)\gamma(\omega)$ the general solutions to these equations are expressed by:

$$V(x, \omega) = V_0^+ e^{-\gamma x} + V_0^- e^{\gamma x}, \quad (5)$$

$$I(x, \omega) = Z_0^{-1} (V_0^+ e^{-\gamma x} - V_0^- e^{\gamma x}), \quad (6)$$

where $V_0^\pm$ are the amplitudes of incident and reflected waves.

Defining coefficients $A = V_0^- + V_0^+$ and $B = V_0^- - V_0^+$, (5) and (6) can be rewritten as:

$$V(x) = A \cosh(\gamma x) + B \sinh(\gamma x), \quad (7)$$

$$I(x) = -Z_0^{-1} (A \sinh(\gamma x) + B \cosh(\gamma x)). \quad (8)$$

It should be noted that for simplicity, notations $V(x)$ and $I(x)$ are used instead of $V(x, \omega)$ and $I(x, \omega)$, with the dependence on ω being implicit.

By applying boundary conditions to equations (7) and (8), the cable can be represented based on its terminal voltages and currents as:

$$\begin{bmatrix} V(0) \\ V(l) \end{bmatrix} = \begin{bmatrix} Z_0 \coth(\gamma l) & -Z_0 \operatorname{csch}(\gamma l) \\ Z_0 \operatorname{csch}(\gamma l) & -Z_0 \coth(\gamma l) \end{bmatrix} \times \begin{bmatrix} I(0) \\ I(l) \end{bmatrix}, \quad (9)$$

where l is the length of the cable. According to (9), the SC and open-circuit (OC) impedances of the cable, respectively denoted by Z_{SC} and Z_{OC} , are obtained by:

$$Z_{SC} = \frac{V(0)}{I(0)} \Big|_{V(l)=0} = Z_0 \tanh(\gamma l), \quad (10)$$

$$Z_{OC} = \frac{V(0)}{I(0)} \Big|_{I(l)=0} = Z_0 \coth(\gamma l). \quad (11)$$

Considering that the cable is terminated by the transformer impedance Z_t , the boundary conditions $V(l)/I(l) = Z_t$ must be satisfied. Hence, the total impedance of the cable-transformer system can be calculated as:

$$Z = \frac{V(0)}{I(0)} \Big|_{V(l)/I(l)=Z_t} = \frac{Z_0 Z_t + Z_0^2 \tanh(\gamma l)}{Z_0 + Z_t \tanh(\gamma l)}. \quad (12)$$

As outlined in the previous subsection and [1], [2], for the series/parallel resonance condition, the circuit's impedance becomes minimum/maximum, respectively. Based on (12), the condition of series resonance is met when the numerator becomes zero, while parallel resonance occurs when the denominator approaches zero. The numerator becomes zero under the following condition:

$$Z_t = -Z_0 \tanh(\gamma l), \quad (13)$$

and the denominator tends to zero when the following holds:

$$Z_t = -Z_0 \coth(\gamma l). \quad (14)$$

By comparing equations (13) and (14) with (11) and (12), the conditions for mutual cable-transformer resonance formation can be understood. Specifically, series resonances occur at frequencies where the transformer's terminal impedance characteristic, $Z_t(\omega)$, intersects with the cable's SC impedance characteristic, $Z_{SC}(\omega)$, provided that one exhibits inductive behavior and the other capacitive. Similarly, parallel resonances form at frequencies where $Z_t(\omega)$ intersects with the OC impedance characteristic, $Z_{OC}(\omega)$, again under the condition that one exhibits inductive while the other capacitive behavior.

III. TEST SYSTEM DESCRIPTION

To examine the severity of cable-transformer resonances and their excitation due to CB prestrikes, a test system is simulated as shown in Fig. 4. The simulations are performed in EMTP software environment [16], which is a powerful tool for the analysis of power system transients, developed based on Dommel's method for the digital computer solution of EMTs [17]. This section outlines the details of the simulation model.

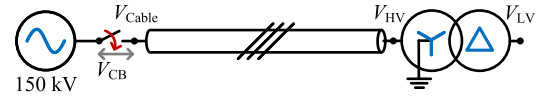


Fig. 4. Adopted test system.

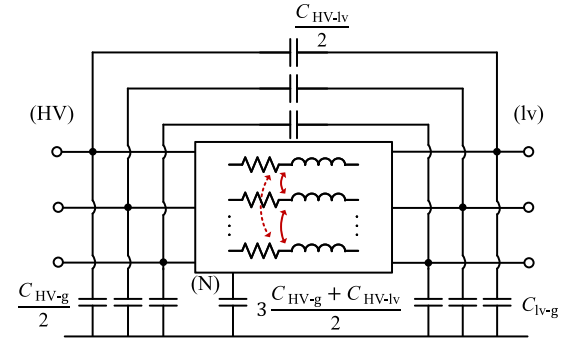


Fig. 5. Implemented BCTRAN transformer model.

TABLE II
SPECIFICATIONS OF TEST TRANSFORMER

Parameter	Value
Nominal Voltage	150/11.2 kV
Vector Group	Ynd5
Rated Power	48 MVA
Rated Frequency	50 Hz
No-Load Loss	26.4 kW

A. Power Transformer Model

The transformer is simulated using the well-known BCTRAN model [18]. In this way, a multi-phase, multi-winding transformer is represented by an admittance matrix that characterizes the coupled resistances and inductances, derived from no-load excitation and SC test data. To incorporate capacitive couplings, the winding-to-ground and cross-over capacitances are halved and placed at the ends of the corresponding windings [15], as illustrated in Fig. 5, with $C_{HV-g} = 1.186$ nF, $C_{LV-g} = 3.286$ nF, and $C_{HV-LV} = 1.263$ nF. As the BCTRAN model may not ideally replicate the exact wideband response of an actual transformer, it sufficiently represents typical transformer behavior over a wide frequency band. This study does not aim to predict the exact OV's that may arise in a specific system but to provide a physical analysis of mutual cable-transformer resonant interactions and their excitation due to CB prestrikes. Given this objective, the applied BCTRAN model meets this requirement while maintaining simplicity. Table II presents the test transformer specifications.

B. Cable System Model

A wideband universal line model (ULM) [19] is applied to represent the cable system with a length of 765 m, and its cross-section is illustrated in Fig. 6. The model specifications are shown in Table III. It is worth mentioning that this cable length is selected because, as will be demonstrated later, its fundamental quarter-wavelength resonance frequency coincides with one of the transformer resonance frequencies.

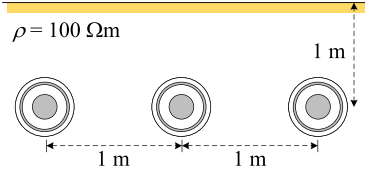


Fig. 6. Cable system arrangement.

TABLE III
CABLE SYSTEM PARAMETERS

Layer	Parameter and Value			
Core Conductor	$r = 21.8 \text{ mm}$	$\rho = 2.65 \times 10^{-8} \Omega \text{ m}$	$\mu_r = 1$	
Core Insulator	$r = 43 \text{ mm}$	$\varepsilon_r = 2.9$	$\mu_r = 1$	
Sheath Conductor	$r = 45.35 \text{ mm}$	$\rho = 2.1 \times 10^{-7} \Omega \text{ m}$	$\mu_r = 1$	
Sheath Insulator	$r = 50.5 \text{ mm}$	$\varepsilon_r = 2.3$	$\mu_r = 1$	

r : radius, ρ : resistivity, ε_r : relative permittivity, μ_r : relative permeability

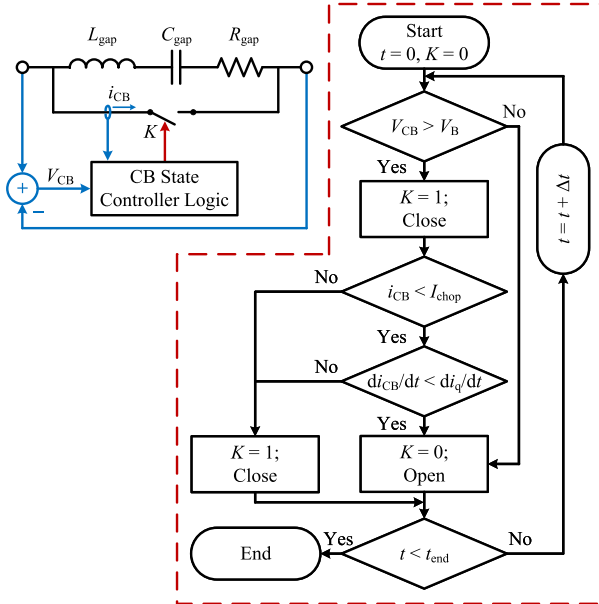


Fig. 7. Implemented CB model.

C. Circuit Breaker Model

The CB is represented as shown in Fig. 7. It is modeled by a controlled ideal switch, K , connected in parallel with an RLC branch that accounts for the parasitic parameters of the gap. According to the flowchart in Fig. 7, prestriking transients are modeled by controlling the switch state based on the contact gap withstand voltage V_B , chopping current I_{chop} , and HF current quenching di_q/dt , as defined in [20]:

$$V_B = A(t - t_0) + B, \quad (15)$$

$$\frac{di_q}{dt} = C(t - t_0) + D, \quad (16)$$

where t_0 represents the contact closing time, and the CB parameters are adopted from [20], with $I_{chop} = 3 \text{ A}$, $A = -0.02 \text{ kV}/\mu\text{s}$, $B = 0 \text{ kV}$, $C = 0 \text{ A}/\text{s}^2$, and $D = 350 \text{ A}/\mu\text{s}$. The gap stray parameters R_{gap} , L_{gap} , and C_{gap} are set to 100Ω , $0.05 \mu\text{H}$, and 0.1 nF , respectively.

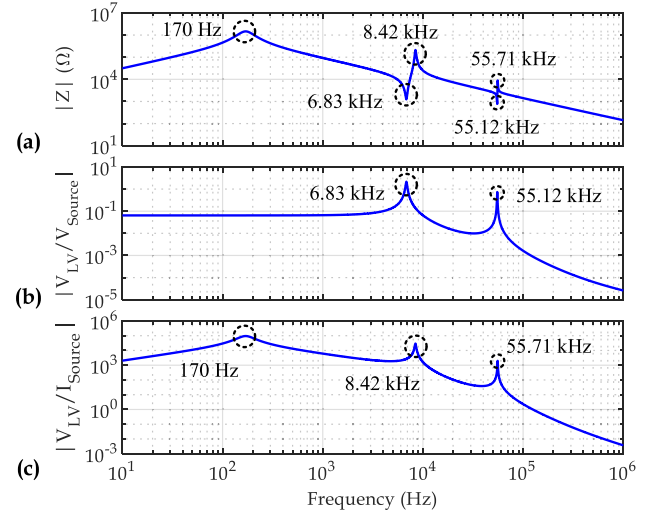


Fig. 8. Power transformer frequency response: (a) HV terminal impedance, (b) Ratio of LV-side voltage to source voltage, (c) Ratio of LV-side voltage to source current.

IV. SIMULATION RESULTS AND DISCUSSION

This section deals with the analysis of cable-transformer interactions in the test system based on simulations conducted in the frequency and time domains.

A. Frequency-Domain Analysis

To understand the resonance frequencies formed within the test system, first, the frequency-domain responses are evaluated. The transformer resonance frequencies are indicated in Fig. 8. As shown, Fig. 8(a) presents the harmonic terminal impedance at the HV side of the system while the LV side is open. Series and parallel resonances are identified by the minima and maxima in the harmonic impedance characteristic, where the transformer series resonance frequencies occur at 6.83 kHz and 55.12 kHz, while its parallel resonance frequencies are 170 Hz, 8.42 kHz, and 55.71 kHz. These resonance frequencies are also observed in Fig. 8(b), which shows the LV-side voltage response to the source voltage, and in Fig. 8(c), which shows the response to the source current.

The effect of the cable on the formation of mutual cable-transformer resonance can be analyzed through the frequency responses in Figs. 9 and 10. Fig. 9 illustrates the series resonance frequencies, while Fig. 10 presents the parallel resonance frequencies in the cable-transformer system. As demonstrated in Section II, series resonances occur where the SC harmonic impedance characteristic of the cable intersects with the harmonic impedance characteristic of the transformer, and parallel resonances emerge when the OC harmonic impedance characteristic of the cable intersects with the harmonic impedance characteristic of the transformer.

As mentioned, for the specific cable length of 765 m, the quarter-wave resonance frequency of the cable coincides with the series resonance frequency of the transformer. Fig. 9(a) shows that the SC harmonic impedance of the cable's intersects with the harmonic impedance characteristic of the transformer

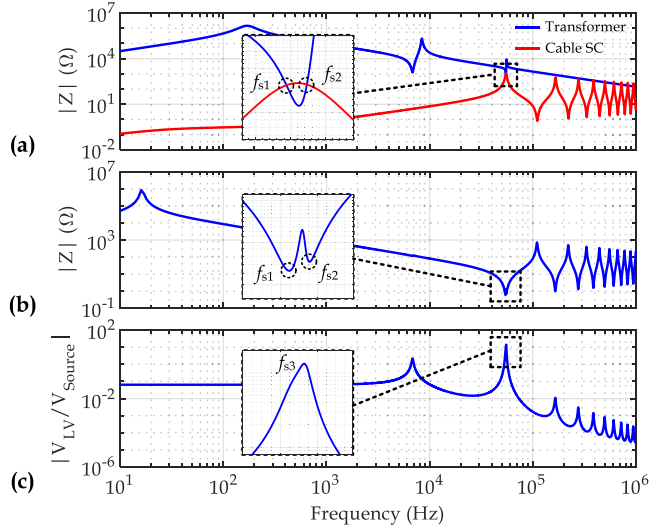


Fig. 9. Series resonance frequencies in the cable-transformer system: (a) the SC harmonic impedance of the cable and terminal harmonic impedance of the transformer, (b) Cable-transformer harmonic impedance, (c) Ratio of LV-side voltage to source voltage.

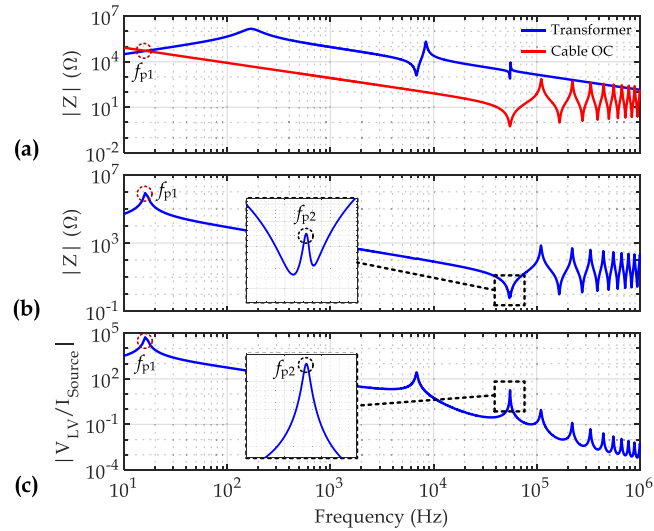


Fig. 10. Parallel resonance frequencies in the cable-transformer system: (a) Intersections of the OC harmonic impedance of the cable and terminal harmonic impedance of the transformer, (b) Cable-transformer harmonic impedance, (c) Ratio of LV-side voltage to source current.

at two points, leading to the formation of two resonance frequencies at $f_{s1} = 54.47$ kHz and $f_{s2} = 55.56$ kHz, as marked in Fig. 9(b). Since these two newly formed resonance frequencies are close to each other, they may not have a noticeably distinct impact on the excited components, resulting in the dominant resonance frequency of $f_{s3} = 55.26$ kHz. This is confirmed by the voltage transfer ratio of the LV side to the source voltage shown in Fig. 9(c).

Fig. 10 presents the parallel resonance frequencies in the cable-transformer system. The intersections between the OC harmonic impedance of the cable and the harmonic impedance of the transformer are shown in Fig. 10(a), while the total harmonic impedance of the cable-transformer system is depicted

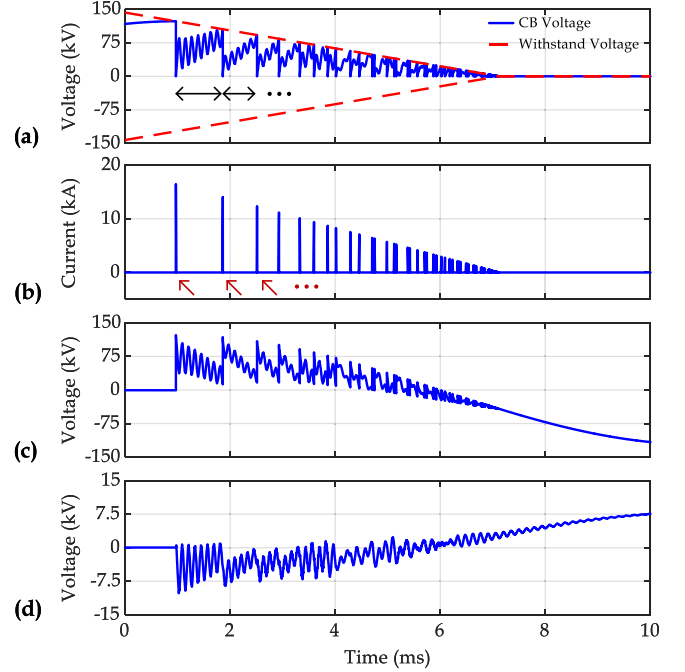


Fig. 11. Transformer energization without cable: (a) Voltage across CB, (b) current through CB, (c) HV terminal voltage, (d) LV terminal voltage.

in Fig. 10(b). Similar to Fig. 8, parallel resonances are identified based on the LV-voltage response to source current. As shown in Fig. 10(a), the intersection of the OC harmonic impedance of the cable with the harmonic impedance of the transformer occurs at $f_{p1} = 16$ Hz, as marked by the red circle in Fig. 10. According to Fig. 10(b) and (c), along with two series resonance frequencies, a parallel resonance frequency is formed at $f_{p2} = 55.17$ kHz as well. In this condition, because the series and parallel resonance frequencies are close to each other, they excite one another upon each arc inception or disconnection during CB prestrikes.

B. Time-Domain Analysis

In this section, the introduced test system is simulated in the time domain to analyze mutual resonance interactions between the cable and the transformer resulting from CB prestriking transients during energization. Energization cases with and without a cable are investigated. It should be mentioned that, in the following cases, the contact closing time is set so that the first prestrike occurs at the excitation voltage amplitude.

1) *Transformer Energization Without Cable:* The first case considers direct transformer energization by the CB without the cable. Fig. 11 presents the simulation results, where the CB TRV and current are shown in Fig. 11(a) and (b), while the transformer's HV and LV terminal voltages are shown in Fig. 11(c) and (d). As can be seen, when the withstand voltage is exceeded, a prestrike takes place, marked by sharp current spikes in Fig. 11(b). However, the arc immediately disappears, as indicated by the intervals marked with black arrows in Fig. 11(a).

For clarity, the TRV waveform is analyzed within the interval following the first arc disconnection in Fig. 12. The frequency content of the TRV waveform is examined using

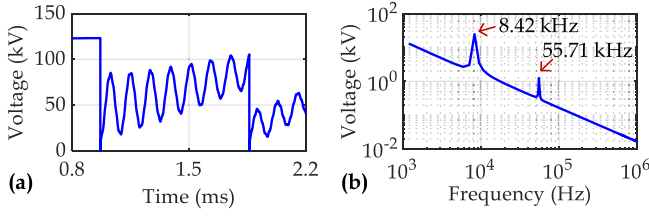


Fig. 12. TRV after first arc disconnection without cable: (a) Time-domain waveform, (b) Frequency-domain waveform.

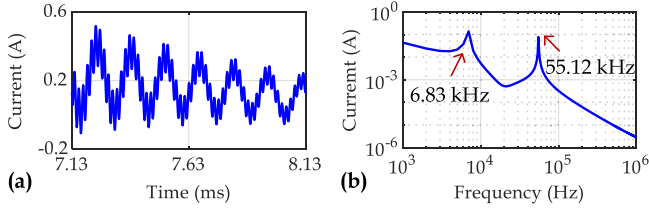


Fig. 13. CB current after the contacts fully close without cable: (a) Time-domain waveform, (b) Frequency-domain waveform.

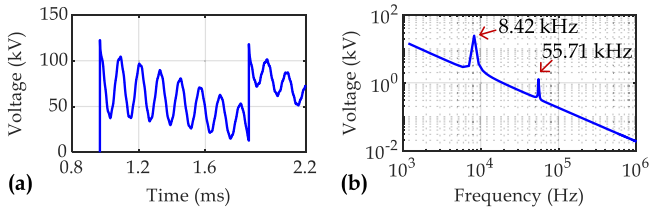


Fig. 14. Transformer HV-side terminal voltage after first arc disconnection without cable: (a) Time-domain waveform, (b) Frequency-domain waveform.

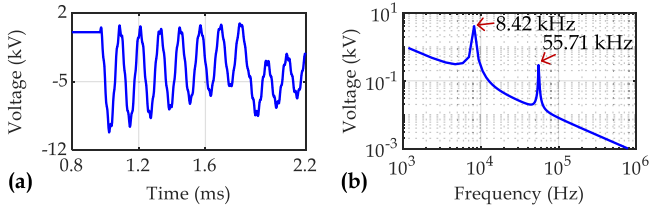


Fig. 15. Transformer LV terminal voltage after first arc disconnection without cable: (a) Time-domain waveform, (b) Frequency-domain waveform.

the Fast Fourier Transform (FFT), as shown in Fig. 12(b). The dominant frequency components of the TRV are 8.42 kHz and 55.71 kHz corresponding to the parallel resonance frequencies of the transformer, as marked in Fig. 8. This is in line with the analysis, which predicted that parallel resonance frequencies are excited when the electrical connection through the CB is interrupted.

The CB current after contact closure and its FFT are shown in Fig. 13(a) and (b). Again, following the analysis in Section II-A, it is confirmed that when the switch is closed, components resonate at series resonance frequencies, that is, 6.83 kHz and 55.12 kHz here.

The transformer terminal voltages and their FFT graphs after the first prestrike ceases are shown in Figs. 14 and 15, respectively, confirming the excitation of the transformer parallel

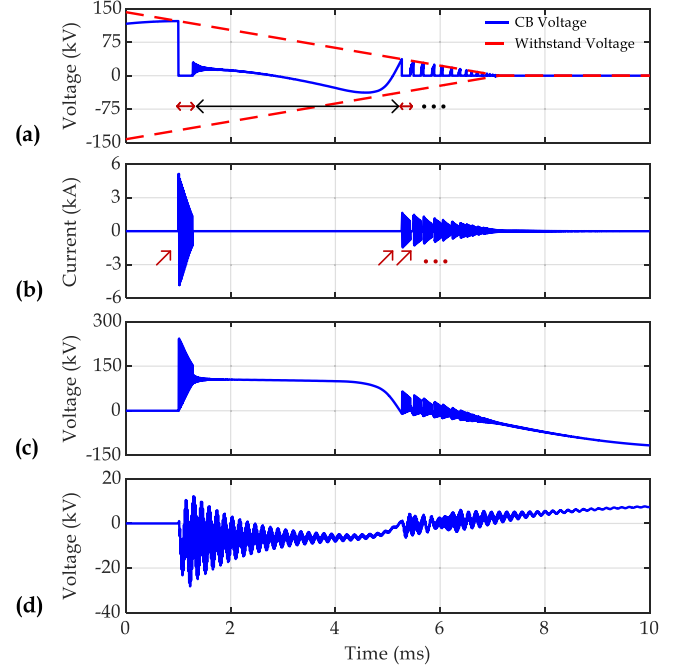


Fig. 16. Transformer energization with a cable: (a) TRV (CB voltage), (b) CB current, (c) HV-side terminal voltage, (d) LV-side terminal voltage.

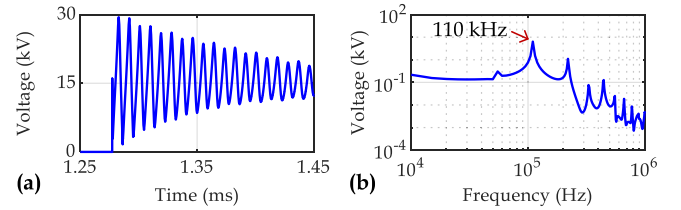


Fig. 17. TRV after first arc disconnection in presence of cable: (a) Time-domain waveform, (b) Frequency-domain waveform.

resonance frequencies at 8.42 kHz and 55.71 kHz, following the analysis in Section II-A.

2) *Transformer Energization Through Cable:* The effect of the cable on the transformer energization transients is shown in Fig. 16, where the voltage and current of the CB are shown in Fig. 16(a) and (b), and the HV- and LV-side transformer terminal voltages are shown in Fig. 16(c) and (d), respectively. Compared to transformer energization without a cable, the arc lasts longer after each prestrike (marked by red arrows in Fig. 16(b)). When the arc extinguishes for the first time, the imposed TRV remains below the CB withstand voltage for a longer period. The intervals when the arc ignites and ceases are indicated by red and black arrows in Fig. 16(a).

The resonance components of the TRV are analyzed in Fig. 17, which presents the initial oscillations of the TRV along with its FFT. In the presence of the cable, the dominant component of the TRV is 110 kHz, corresponding to the first half-wavelength resonance of the cable.

The current components flowing through the CB are analyzed for two intervals: during arcing, as shown in Fig. 18(a) and (b), and after the contacts are fully closed, as shown in Fig. 18(c) and (d). During the arcing phase, the current is initially

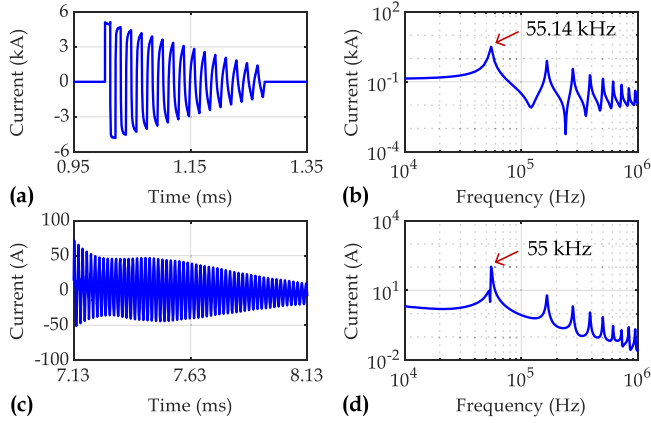


Fig. 18. CB current after contacts fully close in presence of cable: (a) Time-domain waveform and (b) Frequency-domain waveform during first arc occurrence, (c) Time-domain waveform and (d) Frequency-domain waveform.

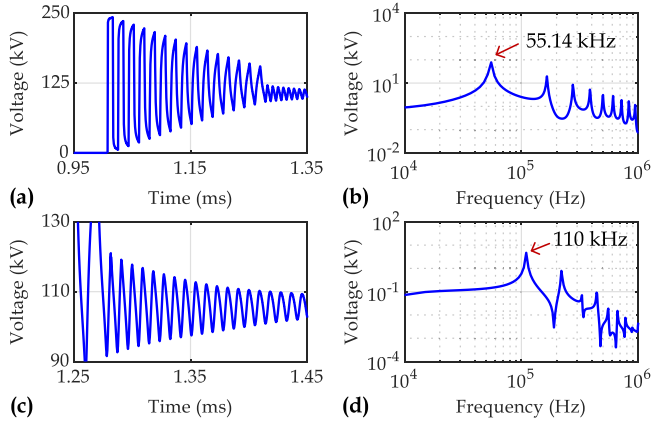


Fig. 19. Transformer HV-side terminal voltage in presence of cable: (a) Time-domain waveform and (b) Frequency-domain waveform during the first prestrike occurrence, (c) Time-domain waveform and (d) Frequency-domain waveform after the first prestrike.

influenced by traveling waves within the cable and gradually shifts to oscillations at the series resonance frequency of the cable-transformer system. Once the contacts are fully closed, the current oscillations are primarily at the series resonance frequency of the cable-transformer system. In particular, the most amplified current oscillation component corresponds to 55 kHz, where the resonance frequencies of the cable and transformer coincide. However, the 6.83 kHz component, previously observed in the CB current during energization without the cable, is no longer present.

The transformer voltage at the HV terminal and its FFT are shown for two intervals: during the first arcing period in Fig. 19(a) and (b), and afterward in Fig. 19(c) and (d). When the arc is present, the transformer HV oscillates with a frequency equal to the quarter-wavelength resonance frequency of the cable, i.e. 55.14 kHz. After the arc is extinguished, the voltage resonance frequency is equal to the first half-wavelength resonance of the cable at 110 kHz.

Transformer LV-side terminal voltage in time and frequency domains is presented in Fig. 20(a) and (b), respectively. As

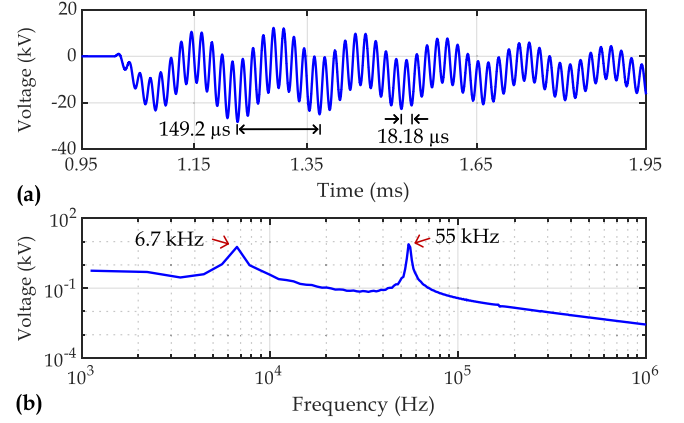


Fig. 20. Transformer LV-side terminal voltage upon energization with a cable: (a) Time-domain waveform (b) Frequency-domain waveform.

shown in Fig. 20(a), an oscillating component with a period of 18.18 μ s is superimposed on another with a period of 149.2 μ s. These components correspond to the series resonance frequencies of 55 kHz and 6.7 kHz, as marked in the FFT graph of transformer LV-side terminal voltage in Fig. 20(b).

The matching of the cable and transformer resonance frequencies resulted in parallel and series resonance conditions around 55 kHz. When a prestrike creates an electrical connection, oscillations occur at the series resonant frequency. Since the cable and transformer experience the same resonance frequency, the amplification factor of the occurring transients is high. After the arc ceases, resonance with the same frequency is still present due to the parallel resonance condition, preventing rapid energy dissipation. Consequently, the next prestrike re-excites the same critical resonance frequency, leading to weakly damped oscillatory OVs.

C. The Effect of the Cable Length

As presented in Section II, cable resonance frequencies depend on the cable length. This can be seen in the expression below [14]:

$$f_{\frac{k}{4}} = k \frac{1}{4\tau} = k \frac{v'}{4l}, \quad (17)$$

where τ and v' correspond to the wave travel time and propagation velocity, and l denotes the cable length. The parameter k is an integer. The cable exhibits quarter-wavelength resonance for odd multiples of k , and half-wavelength resonance for even multiples. This also affects the mutual resonance that occurs between the cable and transformer as seen in Fig. 21, which shows the transformer's maximum terminal OVs upon energization, for various cable lengths ranging from zero (no cable) to 10 km. As can be seen in Fig. 21(a), when a cable is connected, the voltage wave reflections create maximum OV at the HV transformer terminal significantly higher than that in the *no-cable* case. Nevertheless, with the increase of the cable length, damping increases and results in reduced OVs.

In contrast, the maximum OV imposed at the LV terminal as shown in Fig. 21, exhibits magnification for certain lengths, i.e.,

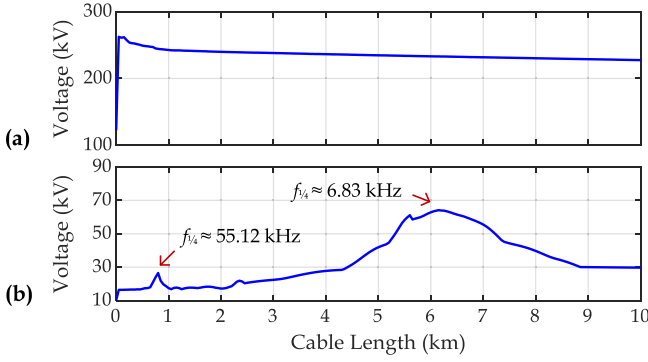


Fig. 21. The effect of cable length on the maximum generated transformer terminal voltages during energization: (a) HV-side terminal, (b) LV-side terminal.

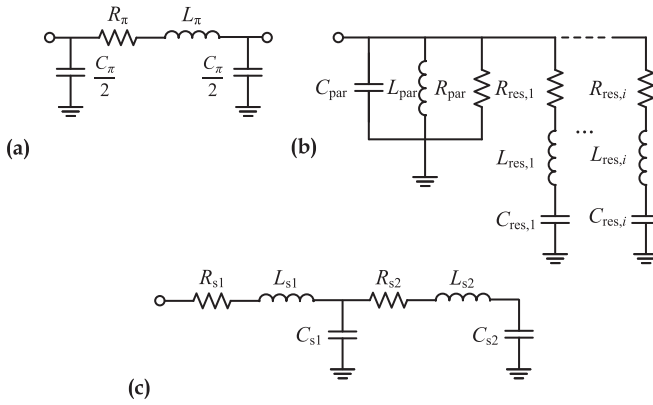


Fig. 22. Simplified equivalent RLC circuits of system components: (a) Cable, (b) Transformer, (c) Cable-transformer system.

around 785 m and around 6.15 km, as shown in Fig. 21(b). For these lengths, the fundamental quarter-wavelength resonance frequency of the cable $f_{1/4}$ becomes approximately equal to the transformer series resonance frequencies at 55.12 kHz and 6.83 kHz, respectively.

From Fig. 21(b), it is evident that the highest resonance OV_s occur when the quarter-wavelength resonance frequency of the cable matches the transformer 6.83 kHz resonance frequency, causing much higher OV_s compared to the case for which the cable-transformer resonance frequency matched at 55.12 kHz. This can be explained by analysing the simplified equivalent circuits of the cable-transformer system shown in Fig. 22. Cable response around its fundamental resonance frequency ω_0 can be approximated by the π -circuit shown in Fig. 22(a), where $\omega_0 = 1/\sqrt{L_\pi(C_\pi/2)}$, and $Z_0 = \sqrt{L_\pi/(C_\pi/2)}$ denotes the cable characteristic impedance. The transformer can be represented by the circuit shown in Fig. 22(b), derived from the measured harmonic impedance at the HV transformer terminal [21]. In this circuit, each transformer resonance frequency $f_{\text{res},i}$ is represented by a series RLC branch.

Assuming that around each resonance frequency, the effect of other branches is negligible, the total cable-transformer system can be represented by a two-stage RLC ladder circuit shown in Fig. 22(c). The resonating capacitances and inductances of the

TABLE IV
VALUES OF THE APPROXIMATE TWO-STAGE MODEL OF FIG. 22(c)

$f_{\text{res},i}$	55.12 kHz	6.83 kHz
R_{s1}	0.562 Ω	780 Ω
L_{s1}	0.069 mH	0.542 mH
C_{s1}	121.68 nF	944.4 nF
R_{s2}	1.703 Ω	1254 Ω
L_{s2}	307.3 mH	903.5 mH
C_{s2}	0.027 nF	0.6 nF

circuit in Fig. 22(c) are calculated as:

$$L_{s1} = L_\pi = \frac{2Z_0 l}{\pi v'}, \quad (18a)$$

$$C_{s1} = C_\pi + C_{\text{par}} = \frac{2l}{\pi Z_0 v'} + C_{\text{par}}, \quad (18b)$$

$$L_{s2} = L_{\text{res},i} = \frac{R_{\text{res},i}}{2\pi \Delta f_{\text{res},i}}, \quad (18c)$$

$$C_{s2} = C_{\text{res},i} = \frac{\Delta f_{\text{res},i}}{2\pi f_{\text{res},i}^2 R_{\text{res},i}}. \quad (18d)$$

In (18c) and (18d), $\Delta f_{\text{res},i}$ represents the 3 dB bandwidth of the transformer's impedance around the resonance frequency $f_{\text{res},i}$. According to (18a) and (18b), as the cable length increases, the values of L_{s1} and C_{s1} increase accordingly. Given that $f_{\text{res},i} = 1/(2\pi\sqrt{L_{s1}C_{s1}})$, implying that longer cable lengths result in lower resonance frequencies. As expressed by (18d), a lower resonance frequency corresponds to larger capacitance, $C_{s2} = C_{\text{res},i}$. Higher values of L_{s1} and C_{s1} contribute to higher oscillating energy and, as a result, higher OV_s prevail. The values of the resonating capacitances and inductances of the approximate circuit in Fig. 22(c) for each resonance frequency are given in Table IV. As can be seen, the values of the capacitances and inductances are greater for lower resonance frequencies, consistent with the results in Fig. 21.

V. EXPERIMENTAL ANALYSIS

An experimental setup has been designed, as shown in Fig. 23, to analyze mutual cable-transformer resonance. This setup includes a cast-resin dry-type transformer with foil-type windings, connected to a cable at the HV terminal. The test cable is an MV cable with oil-impregnated paper insulation, wound on a spool due to space constraints. The test transformer is a specially designed rectifier transformer with customized ratio of 21.65/0.525 kV, a nominal power of 660 kVA, which is connected in Yy configuration.

An Omicron Bode-100 vector network analyzer (VNA) is applied to measure the harmonic impedance characteristics for a wide frequency range. Fig. 24(a) shows the occurrence of series resonances at the points where the transformer terminal impedance characteristic intersects with the SC impedance characteristic of cable, i.e., at 539 kHz and 1.5 MHz. Likewise, Fig. 24(b) shows how parallel resonance frequencies are formed at the points where the harmonic impedance of the transformer and cable OC impedance intersect (at 411 Hz and

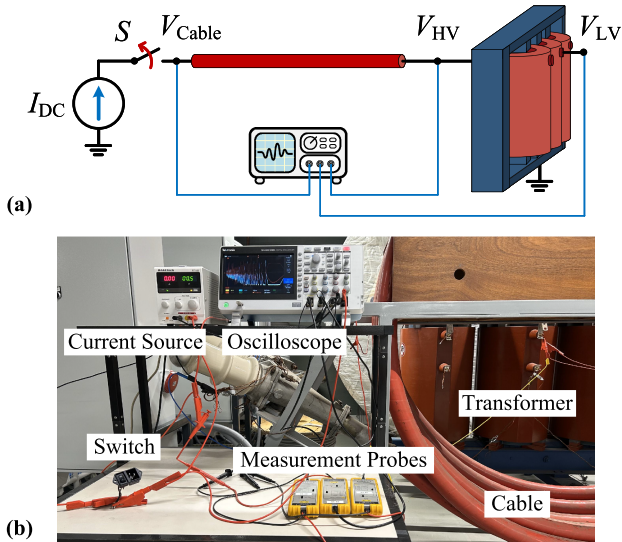


Fig. 23. Experimental cable-transformer setup.

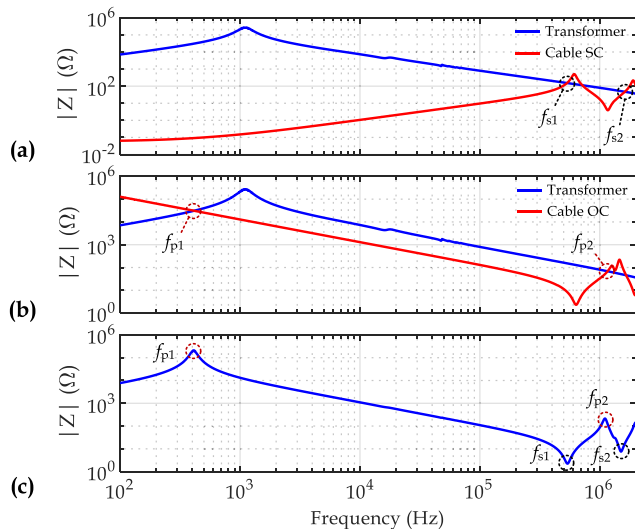


Fig. 24. Measured harmonic impedance characteristics of the experimental setup: (a) Cable SC and transformer terminal impedance, (b) Cable OC and transformer terminal impedance, (c) Cable-transformer system impedance.

110 kHz). In Fig. 24(c), the mutual resonance frequencies of the cable-transformer system are represented by the impedance characteristic of the system, where the created series and parallel resonance frequencies are marked with black and red circles, respectively.

To excite the system's resonance frequencies, the setup is first charged by a small DC current. Then, an LV switch is utilized to disconnect the current, as shown in Fig. 23(a). The resulting transients are recorded by a Tektronix digital oscilloscope and are shown in Fig. 25.

As the switch opens, multiple reignitions occur, and the resonance modes of the systems are triggered. In Fig. 25(a), arc ignition is marked on the voltage waveforms recorded at the cable and transformer HV terminals. As can be seen, the recorded waveforms have a dominant component with a

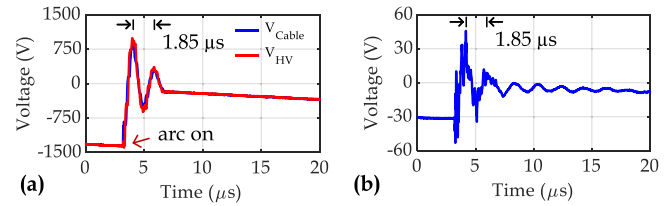


Fig. 25. Measured transient voltages in experimental setup at: (a) Cable and transformer HV-side terminals, (b) Transformer LV-side terminal.

period of $1.85 \mu\text{s}$, corresponding to approximately 539 kHz. This excitation imposes a transient OV on the LV terminal, as shown in Fig. 25(b). The voltage on the LV terminal has a frequency of around 539 kHz, which continues to oscillate briefly after the arc extinguishes. As marked in Fig. 24(a) and (c), a series resonance frequency occurs in the cable-transformer system around 539 kHz. According to the experimental results in Fig. 25, arc reignition excites this resonance frequency, resulting in the resonance OV of $1.85 \mu\text{s}$ period at the cable and transformer terminals. This outcome is consistent with the mathematical analysis in Section II-A and the simulation results in Section IV-B2, and therefore, validates the analysis.

VI. CONCLUSION

Resonance in electrical networks can lead to severe OVs, resulting in insulation failure of critical equipment. This effect is noticeable in cable-transformer systems, and in this way, the analysis is essential for the secure operation of the system. This paper investigates the effect of transients due to CB prestrikes during transformer energization.

By conducting a theoretical analysis, the conditions under which resonance occurred in the cable-transformer system are determined. Unlike previous works that attributed resonance frequencies to the transformer or cable alone, this study shows that the excited frequencies result from mutual cable-transformer interactions and do not correspond to either component alone.

Theoretical hypotheses are validated by simulations performed on a test system by applying suitable models for the CB, cable, and transformer. Mutual interactions were analyzed with and without a cable connected to the transformer. The results confirm how mutual cable-transformer resonance frequencies are formed and show that upon arc reignition or CB closure, currents and voltages oscillate at series resonance frequencies, while after arc interruption, they oscillate at parallel resonance frequencies. In the analyzed test system, when the resonance frequencies of the cable and transformer matched at 55.12 kHz, two new series resonance frequencies emerged at 54.47 kHz and 55.56 kHz, along with a parallel resonance frequency at 55.17 kHz.

Moreover, the effect of the cable length is analyzed, demonstrating that when the resonance frequencies of the cable and transformer match, severe resonance OVs occur, increasing up to 64 kV at the transformer LV terminal. It is also shown that when the resonance points coincide at lower frequencies (corresponding to a longer cable), higher resonating OVs are generated; in the test system, matching at 55.12 kHz resulted

in a peak OV of 26.45 kV, while matching at 6.83 kHz led to a significantly higher peak of 64.11 kV at the transformer LV terminal.

The analysis is also validated by experimental measurements in a laboratory environment. The results confirm the performed analysis on how mutual cable–transformer interactions lead to the formation of resonance frequencies, including two new series resonance frequencies at 539 kHz and 1.5 MHz, and a parallel resonance frequency at 110 kHz, and the resultant overvoltages at the cable and transformer terminals. These findings are validated by theoretical analysis and simulations.

A better understanding of the interactions between the cable and transformer helps reduce resonances and the resulting OVs. First, understanding the severity and frequency of expected resonances enables effective protection strategies against dangerous transients. Furthermore, understanding the occurrence of these resonances is essential for finding suitable protection solutions. In addition, this helps ensure that the CB can withstand resonances and function reliably.

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