Regular Article

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Switching transient analysis for low voltage distribution cable

https://doi.org/10.1515/eng-2022-0004
received July 10, 2021; accepted January 04, 2022

Abstract: Low voltage cable is primarily connected from the transmission system to several household applications. It is quite common that switching transient in the power system during the energization of the high voltage and low voltage cables have a very crippling effect on the cable as well as the power system components. Hence, an experiment has been performed in the laboratory with a low voltage cable-connected motor system. The experimental results have been validated in the simulation platform, and they are capable of predicting the transient behavior during power cable energization. The effect of transients on power cables during the energization of devices has been investigated in this study in the form of voltage, current, and frequency. Discrete wavelet transform is implemented for the decomposition of the transient current. The generated approximation signal is used to quantify the severity during switching transient condition.

Keywords: experimental setup, low voltage underground cable, switching transient, DWT analysis

1 Introduction

The power distribution network faces many challenging tasks due to rapid urbanization and huge demand for reliable, uninterrupted power supply. Unavailability of space and frequent occurrence of faults in overhead transmission system like hindrances majorly help in replacing overhead lines with underground (UG) cables. Nowadays, UG cable networks have become an essential element for smart cities and smart-grids. As the distribution systems are majorly dependent upon low voltage grid, continuous monitoring of low voltage cable is important for the proper protection of the power system. Besides, the integration of renewable sources with the distribution system, power quality improvement, and reliability study of low voltage cables creates a new platform to do further research in the field of UG cables. The low voltage power cables [1] are mostly considered as multi-conductor transmission lines. They experience very slow incipient fault as well as fast transients which not only reduces the efficiency of the cable but also creates severe power quality issues. The transients in UG cables are majorly induced due to load switching, faults, capacitor switching, transformer energization, etc. A specific reason behind the transients must be studied so that proper countermeasures can be taken care of in the future. A typical cable comprises many semiconducting and metallic layers, this causes significant changes in the current and voltage signals during transient disturbances. The authors of refs. [2,3] have classified switching transients into three main distinguishable groups. Energization, de-energization, and reclosure. Energization and de-energization [3,4] of the system elements like cable line, transformer, reactor, switches, and breaker create switching transient and multiple re-strikes in voltage and current waveform. The overvoltage reduces the reflection coefficient at the output terminal of the cable and thereby affect the voltage wavefront during transient conditions.

So in ref. [5], the authors have measured the peak switching overvoltage of a cable-connected motor system through experimental validation. Thirty percent of the rated voltage is mostly considered as overvoltage. Besides, flashover also causes a momentary outage because of the tripping of protective devices. Cable system parameters such as cable metallic sheath and jacket thickness, ferromagnetic shielding, and mechanical thermal effect also have a great influence on transient voltage waveform [6]. The authors in ref. [7] presented transmission cable system modeling and protection to avoid the temporary overvoltage. However, for transient studies, accurate modeling of UG cable is essential. Both series impedance and shunt admittance calculation are essential factors for electromagnetic

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transient modeling in UG cable. There are several methods for accurate calculation of impedance in UG cable. Ametani and Fuse [8] presented a numerical method for impedance and admittance calculation of the cable having an arbitrary cross-section. Habib and Kordi implemented modal analysis [9] for evaluating per unit parameter of an arbitrary cross-sectioned cable. Besides, the finite element analysis method (FEM) has been introduced in ref. [10] for impedance matrix formation of a three-core cable. Further improvisation has been made by Shafieipour et al. with the implementation of a novel method-of-moment [11] for parameter calculation of several structured cables. A comparative study has also been performed with FEM. The traveling wave phenomena [12] is also one of the methods used by many researchers in designing a basic model to analyze transients in UG cables.

Even though low voltage (LV) power cables are at low risk for their transient issues in comparison to medium voltage and high voltage cables, still, modeling of such cable and their transients are needed to be detected as quickly as possible. So, it is a challenging task to model and analyze the switching transient phenomena with a LV cable. It not only helps the power engineer for doing power quality assessment but also for studying fault analysis, proper circuit breaker operation, protection of electronic devices, and health monitoring of the network. Hence, in this study, switching LV cable-connected motor system has been modeled. Severity quantification of the switching transient has been performed by determining the detailed and approximate coefficient of the current signal implementing discrete wavelet transform (DWT).

Recent methods frequently rely on various techniques for extracting useful features from electrical signals. Besides, insulation breakdown, stress, cable aging, incipient fault, and switching transients like abnormalities should be continuously monitored before the permanent failure of the cable occurs. Several researchers have already presented many methods for detecting the incipient fault which is considered as small magnitude fault current, persists for one-fourth cycle to four cycles. Still, such fault needs to be detected as quickly as possible, so in ref. [13], the authors have mentioned CUSUM and ADALINE for incipient fault detection in a cable. The main features of ADALINE are online training which is based on input change, it has major advantages of high precision and high speed. But during switching [14] operation of a cable-connected system, circuit breaker opening or closing mainly causes overvoltage which might damage the power equipment as energy stored in inductance and capacitance interfaced with electrostatic and magnetic energy, respectively, and these electromagnetic forces produce extreme heat generation. When the current flows through the power cable, a time-varying magnetic field is developed and creates an induced current in the metallic conductor as well as metallic sheath. The conductors allow the alternating magnetic field for inducing eddy current which will ultimately heat up the UG cable. Besides, the resistance of the cable conductor is also one of the reasons for the generation of heat in the cable, which can be further studied for future analysis. This exemplifies the importance of transient studies [15–17] in power systems. Hossien Heydari et al. [18] used finite element analysis on the 20 kV side, 63 kV/20 kV for EMI mitigation for a LV cable due to switching effect. Feature extraction is an essential method for analyzing various transient signals. There are many applications of DWT in various fields, few of them are highlighted below. DWT [20,21] and fast Discrete S transform [19] are widely used methods to extract essential features from the current and voltage signals. The Fourier analysis is a commonly used signal processing tool that has been used to discover and diagnose problems in UG power cables [22]. DWT in ref. [23] is used as a motivational tool for the researcher where high-frequency components are being considered. For extracting important information from electrical signals, modern techniques mainly rely on numerous transformations. In addition, Patcharoen and Ngaopitakkul [24] implemented DWT for detection and discrimination of capacitor switching and inrush current under various conditions. Furthermore, the authors in ref. [25] suggested hybrid wavelet transform and a modular neural network-based fault detector, classifier, and locator with single-end data for six-phase lines. Besides, in ref. [26], a hybrid artificial neural network-DWT has been implemented to localize the fault in combined overhead line and UG cable. In ref. [27], the author has presented a brief review of various methods used for the detection and classification of faults in the transmission line. In addition, the application of DWT is highly appreciated for the health monitoring of UG cables even if it is difficult to decide the best mother wavelet for transient analysis. Furthermore, an improvised technique based on empirical wavelet transformation and a multi-layer perception extreme learning machine is suggested in ref. [28] to successfully identify complicated power quality disturbance for the categorization of power quality. The model employs a multi-resolution approach of DWT to extract classification features. So this DWT helps in the decomposition and reconstruction of various transient signals. However, the application of DWT in ref. [29] has also been proved as one of the best methods for the detection of fault in an induction motor. In ref. [30], nine power quality disturbances are detected and classified using

DWT with multi-resolution signal decomposition. Further improvisation is made by the authors in ref. [31], implementing extension neural network and DWT with Parseval's theorem for analyzing power quality. In many literature, DWT has been implemented for feature extraction and detection. Hence, further analysis is done by Radhakrishnan et al. [32] for extracting features from various power quality disturbances of a grid-connected photo voltaic system.

Though the above-reported literature is very rich and most of the authors have practically demonstrated the importance of modeling and various applications of DWT, but to the best of our knowledge, very few papers have modeled a LV cable. Generally, the time-dependent model is of two types lumped parameter model and the distributed parameter model. In the present problem, distributed parameter model has been applied to evaluate the result. Based on the distribution parameter theory, the cable has been modeled and impedance calculation of the LV four-core cable has also been significantly discussed in this article.

For the protection of any system, a real-time model is always helpful for analysis, design, and control. In this study, an experimental setup has been developed with a LV cable-connected induction motor system and the transient current signature has been validated in the simulation platform. Besides, DWT has been implemented for determining the detailed as well as approximate coefficient for further quantifying the severity of switching transient phenomena. Section 2 describes the research method. Section 3 represents the modeling of LV cable system. Section 4 represents the experimental setup and Section 5 represents the result analysis. Section 6 represents the conclusion of the work.

2 Research method

The cable under test having PVC insulation consists of four sector-shaped aluminum [1] conductors. The cable is shielded by aluminum strips. As per the diagram shown in Figure 1, it has been mathematically modeled based on distributed parameter theory. The formation of high-frequency voltage and current has the results of energizing a low voltage UG cable leading to the short and long-term breakdown of insulation. To protect the UG cable from all the hazards it is necessary to evaluate the performance of this high-frequency voltage and current. From the literature survey, it is found that the behavior of the transient voltage and current is being affected by several factors.

Transients in the UG cable depend upon the closing of the circuit breaker as well as the closing contact of power frequency voltage. This means that if the circuit breaker was closed except the zero-crossing point, then it produces a high transient current. Higher the rating of the current level, higher the chances of failure of insulation and nearby components present in the UG cable. Therefore, determination of peak value and its coordination among the protection scheme is a great challenge from the power quality evaluation point of view. Statistical, as well as dynamic, modeling of these power cables is necessary for calculating accurate frequency-dependent values. The detailed methodology for the analysis of transient phenomena occurring in an UG cable is shown in Figure 2 as a process flow chart.

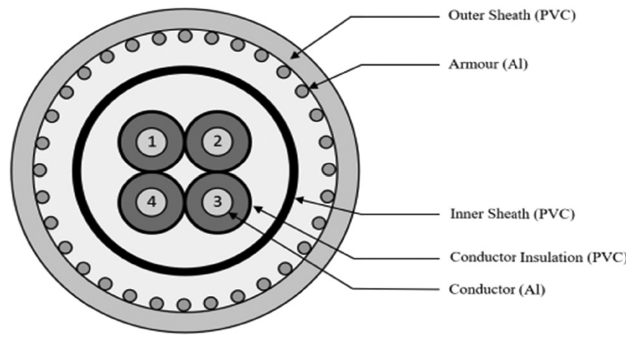

Figure 1: Four core sector-shaped cable.

In the present study, emphasis has been given to successfully evaluate the transient phenomena occurring in an UG cable with the help of DWT. This results in a successful design of power system components and its protection system related to UG cables. There are various types of UG cable model presented in refs. [34–36]. The detailed modeling of the UG cable has been illustrated in Section 3.

A detailed analysis can be initiated after capturing the signal from the UG cable. After successful initialization of the windows function, the DWT will evaluate the scaling of "h" followed by the calculation of DWT coefficients. Here in this present work, coefficients were evaluated from frequency range of 19.53–1,250 Hz.

3 Mathematical modeling

In Figure 3, cores P, Q, R, and N represent four cores [33], that is, three cores and one neutral wire, and G represents the armor of the cable. Here CP_G depicts the capacitance between conductor P and armor. Similarly, there exists capacitance between each conductor and the armor. Also, there exists a mutual capacitance between the

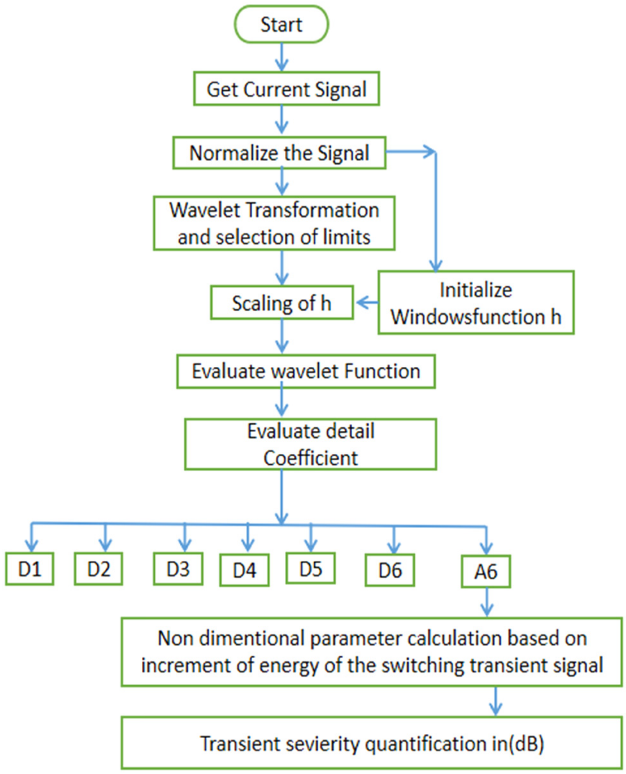

Figure 2: Process flow chart for transient analysis using DWT for an underground cable.

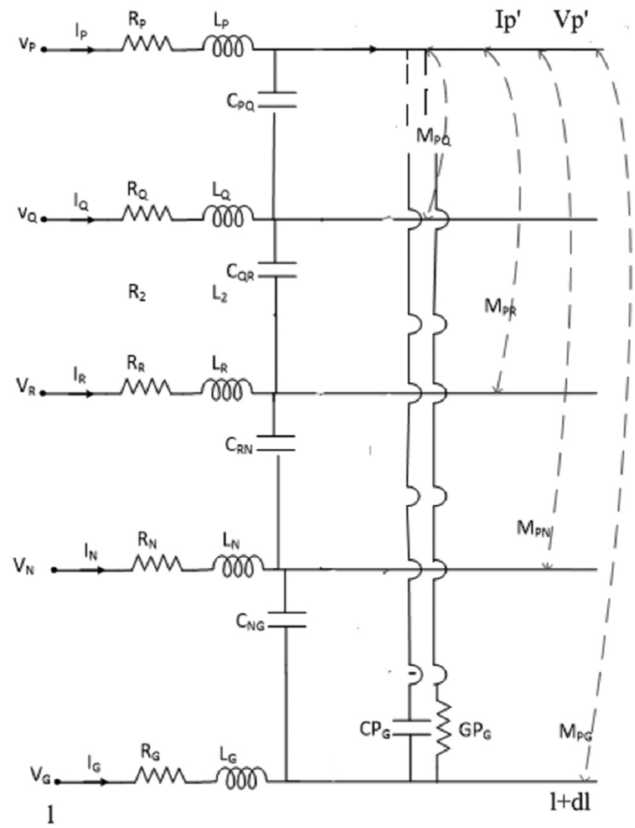

Figure 3: Mathematical modeling of four-core cable.

individual conductors. So the mathematical model [35–38,11] helps in calculation and formation of impedance and admittance matrix of the cable used in this system. R, L, C, and G symbolize resistance, inductance, conductance, and capacitance, respectively. $V(l, t)$ and $i(l, t)$ are calculated based upon the time t and distance l considered from sending end to the receiving end.

The current flow and the voltage drop across the core of each conductor ($n = P, Q, R, N$, and G) can be calculated by considering the physical and geometrical property of the cable used in the experiment. There exists mutual inductance between conductors n and s, which is represented as M_{ns}. So in Figure 4, as per the distributed parameter approach, voltage and current for pth conductor at a distance dl can be presented as given in equations (1) and (2). The derivative expression in equations (1) and (2) can be further presented as shown in equations (3) and (4).

$$V_p' = V_p + \frac{\partial V_p}{\partial l} \cdot \mathrm{d}l, , \tag{1}$$

$$I_p' = I_p + \frac{\partial I_p}{\partial l} \cdot \mathrm{d}l, \tag{2}$$

$$\begin{aligned} \frac{\partial V_n}{\partial l} = R_n I_n + L_n \frac{\partial I_n}{\partial t} + \sum_{\substack{s=P,Q,R,N,G \\ s\neq n}} M_{ns} \frac{\partial I_t}{\partial t} - R_G I_G - L_G \frac{\partial I_G}{\partial t} \\ - \sum_{t=P,Q,R,N,G} M_{sG} \frac{\partial I_j}{\partial t}, \end{aligned} \tag{3}$$

$$\begin{aligned} \frac{\partial I_n}{\partial l} = \sum_{s=P,Q,R,N,G} G_{ns}(V_n - V_s) \\ + \sum_{s=P,Q,R,N,G} C_{ns} \frac{\partial (V_n - V_s)}{\partial t}. . \end{aligned} \tag{4}$$

The above four equations can be represented in a simplified form as presented in equation (5).

$$\begin{bmatrix} \Delta V_p \\ \Delta V_Q \\ \Delta V_R \\ \Delta V_N \\ \Delta V_G \end{bmatrix} = \begin{bmatrix} Z_{PP} & Z_{PQ} & Z_{PR} & Z_{PN} & Z_{PG} \\ Z_{PQ} & Z_{QQ} & Z_{QR} & Z_{QN} & Z_{QG} \\ Z_{PR} & Z_{QR} & Z_{RR} & Z_{RN} & Z_{RG} \\ Z_{NP} & Z_{NQ} & Z_{NR} & Z_{NN} & Z_{NG} \\ Z_{PG} & Z_{QG} & Z_{RG} & Z_{NG} & Z_{GG} \end{bmatrix} \begin{bmatrix} I_p \\ I_Q \\ I_R \\ I_N \\ I_G \end{bmatrix}, \tag{5}$$

$$\text{Impedance matrix} = \begin{bmatrix} Z_{\text{core}} & Z_{\text{core-armour}} \\ Z_{\text{core-armour}} & Z_{\text{armour}} \end{bmatrix}, \tag{6}$$

$$\Delta V_p = V_P - V_P', , \tag{7}$$

Figure 4: Experimental setup consisting of motor load and cable.

where V_P signifies voltage of phase P with respect to ground. Here for this case, armor is grounded.

Z_{core} is a symmetrical square matrix of order 4 which evaluates self-impedance of the phase conductors that are represented as diagonal elements and the mutual impedance between individual phases are represented as off diagonal element. $Z_{\text{core-armour}}$ is the impedance between core and armor of different phases in off diagonal position. All the concentric neutrals of the cables are considered as one and connected to the ground. So R and L matrices have been directly calculated from the above calculation.

In the same way the admittance matrix or the capacitance matrix can be presented as shown in equation (8). From the above description, Z matrix of a four-core PVC cable can be represented as:

$$Z = \begin{bmatrix} Z_c & Z_m & Z_m & Z_d & Z_g \\ Z_m & Z_c & Z_d & Z_m & Z_g \\ Z_m & Z_d & Z_c & Z_m & Z_g \\ Z_m & Z_d & Z_m & Z_c & Z_g \\ Z_g & Z_g & Z_g & Z_g & Z_{gg} \end{bmatrix}, \tag{8}$$

where Z_c is the self-impedance of each sector, Z_m is the mutual impedance of two adjacent sectors, Z_d is the mutual impedance of two non-adjacent sectors. Z_g is the mutual impedance of each sector and the armor, and Z_{gg} is the self-impedance of the armor. The capacitance matrix of the above model can be represented in equation (9), where, $C_c$is the self-capacitance of each phase, C_m is the capacitance between two adjacent phases, $C_d$is the capacitance between two non-adjacent phases, C_{cg} is the capacitance between core and armor. C_{gg} is the capacitance of the armor.

$$C = \begin{bmatrix} C_c & C_m & C_m & C_d & C_{cg} \\ C_m & C_c & C_d & C_m & C_{cg} \\ C_m & C_d & C_c & C_m & C_{cg} \\ C_d & C_m & C_m & C_c & C_{cg} \\ C_{cg} & C_{cg} & C_{cg} & C_{cg} & C_{gg} \end{bmatrix}. \tag{9}$$

4 Experimental setup

An experimental setup has been designed with a four-core, PVC insulated, flat shaped armored cable with circular solid aluminum conductor having length of 50 m with rated voltage of 1.1 kV. The experimental setup is presented in Figure 4. A 400 V supply is connected with 10 mm^2, four-core, PVC insulated armored cable having approximate AC resistance of 3.95 ohm/km, approximate capacitance of 0.6 microfarad/km, and approximate reactance of 0.091 ohm/km with rated current of 46 A. To avoid unnecessary damage to the system proper protection has been taken care of using relay and circuit breaker. We also have used a 3-phase, 1 HP, 50 Hz, 415 V squirrel cage induction motor as a load to examine switching transient. The digital storage oscilloscope (DSO) used in the experiment is specified as 4 channel isolated Tektronix TPSn2014B. Figure 4 shows the experimental setup to determine the inrush transient current during switching of the cable-connected motor system. A standard circuit mentioned in ref. [5] has been considered as a bench marking model for modeling our setup. Modification has been done with the model parameters and the setup as mentioned in ref. [5], for conducting the experiment mentioned in this study. Real-time data has been implemented in the simulation platform to validate the model.

Figure 5 shows the transient current waveform as captured through DSO and its simulated signal compared to real-time signal is shown in Figure 6. The simulation model used to validate the real-time current signal is presented in Figure 7. All R, L, and C parameters and motor data have been implemented in the simulation model to validate the result. During the switching operation [38] of a circuit such as a breaker opening or closing mainly, concerned energy stored in inductance and capacitance interfaced with electrostatic and magnetic energy, respectively. Flashover generally causes a momentary outage because of the tripping of protective devices, if there is an

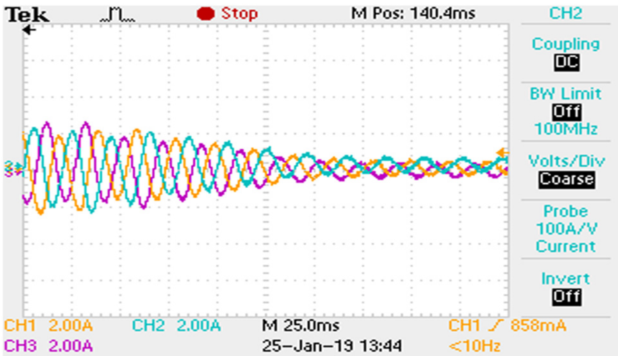

Figure 5: Current waveform captured through DSO.

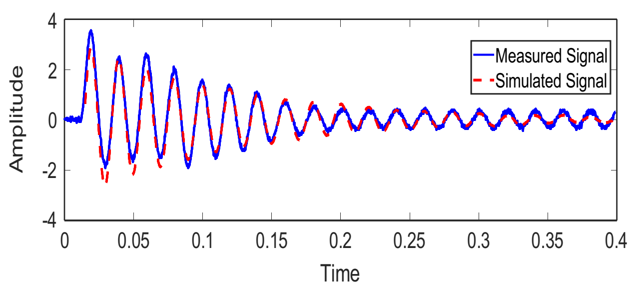

Figure 6: Simulated signal and real-time signal validation.

insulation failure, then it may cause permanent damage to the equipment. Hence, it is highly necessary to have a clear understanding of the circuit during the transient period so that necessary steps can be taken for avoiding and minimizing the damaging effect for the transient condition.

To study the effect on switching transients of a cable-connected motor system, application of wavelet transform has been focused. This DWT mainly selects the suitable wavelet for switching transient and extracts its high-frequency component. For extracting the frequency component, each wavelet signal is connected with a frequency band and f_s (in samples per second) is the sampling rate used. The detail signal D_i contains the signal components with frequencies in the interval. So DWT helps in selecting a very high frequency for mother wavelet to avoid overlapping between close bands.

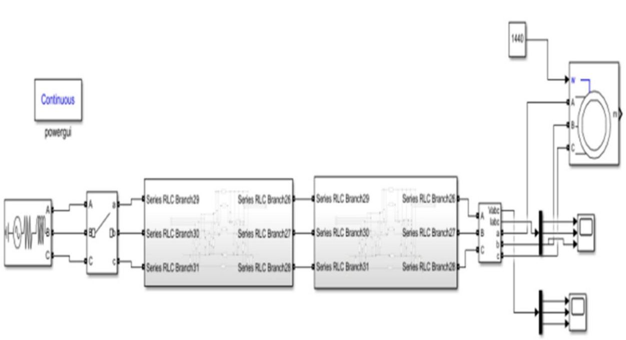

Figure 7: Simulated model of cable-connected motor system.

5 Result analysis

This study is focused to capture the current signature to analyze the impact of switching transient. The current signal generated with the cable-connected motor system is decomposed using DWT for further analysis. The DWT is a powerful tool that represents the non-stationary signal in terms of time-frequency with perfect time resolution. DWT acts as a filter bank with multiple decomposition levels. Both low pass and high pass filter compositions are presented at each level with detailed and approximate coefficients. Hence, appropriate choice of mother wavelet and calculation of decomposition level helps in the filtering process. A lot of research have already been done in studying various wavelet functions such as Mexican, Morlet, Daubechies, biorthogonal, Gaussian, Hat, Meyer, Coiflet, etc. Many trails have been implemented with several wavelet functions, and for this switching transient analysis Daubechies44 outperforms other wavelet functions. So Daubechies44 has been used as mother wavelet for the present work. The number of decomposition levels is mainly calculated using equation (12). N_f represents the number of decomposition levels and its value is 6 for the transient signature.

$$f(D_i) \in [2^{-(i+1)} \cdot f_s, 2^{-i} \cdot f_s] \text{ Hz}, \tag{10}$$

$$f(A_n) \in [0, 2^{-(n+1)} \cdot f_s] \text{Hz}, \tag{11}$$

$$N_f = \text{integer}\left[\frac{\log(f_s/f)}{\log(2)}\right], \tag{12}$$

where f_s and f represent the sampling frequency and natural frequency of oscillation, respectively. For the

Table 1: Frequency band for wavelet signal

Level	Signals	Frequency band for f_s = 2.5 kHz
D1	Detail signals	625–1,250 Hz
D2		312.5–625 Hz
D3		156.25–312.5 Hz
D4		78.12–156.25 Hz
D5		39.06–78.12 Hz
D6		19.53–39.06 Hz
A6	Approximation signal	0–19.53 Hz

Table 2: Calculation of degree of severity level

Test	Transient current	Test	Steady state current
Wavelet signal	A6	Wavelet signal	A6
N_b	0	N_b	599
N_s	598	N_s	2,000
Transient current	1,179.4 dB	Steady-state current	205.119 dB

present analysis, the sampling frequency is considered as 2.5 kHz. As per the number of samples per sec the sampling frequency has been chosen. Hence, Table 1 represents the associated frequency with each wavelet signal, which has been carried out by using equations (10) and (11). The decomposition of the transient current signatures and their subsequent reconstruction for six levels are shown in Figure 8. Notable changes can be observed from D4 onwards in the case of switching current. The wavelet energies can be extracted to quantify the information contained in these reconstructed signatures, which will be helpful to categorize UG cable transients in the future. These transients persist for a very small period, still, it has a high impact on the electrical equipment resulting in an unusual transient voltage and current. This overvoltage and overcurrent may cause insulation failure and excessive heat may also be produced if persist for a prolonged period of time. So it is highly necessary to know the severity level during transient conditions so that necessary

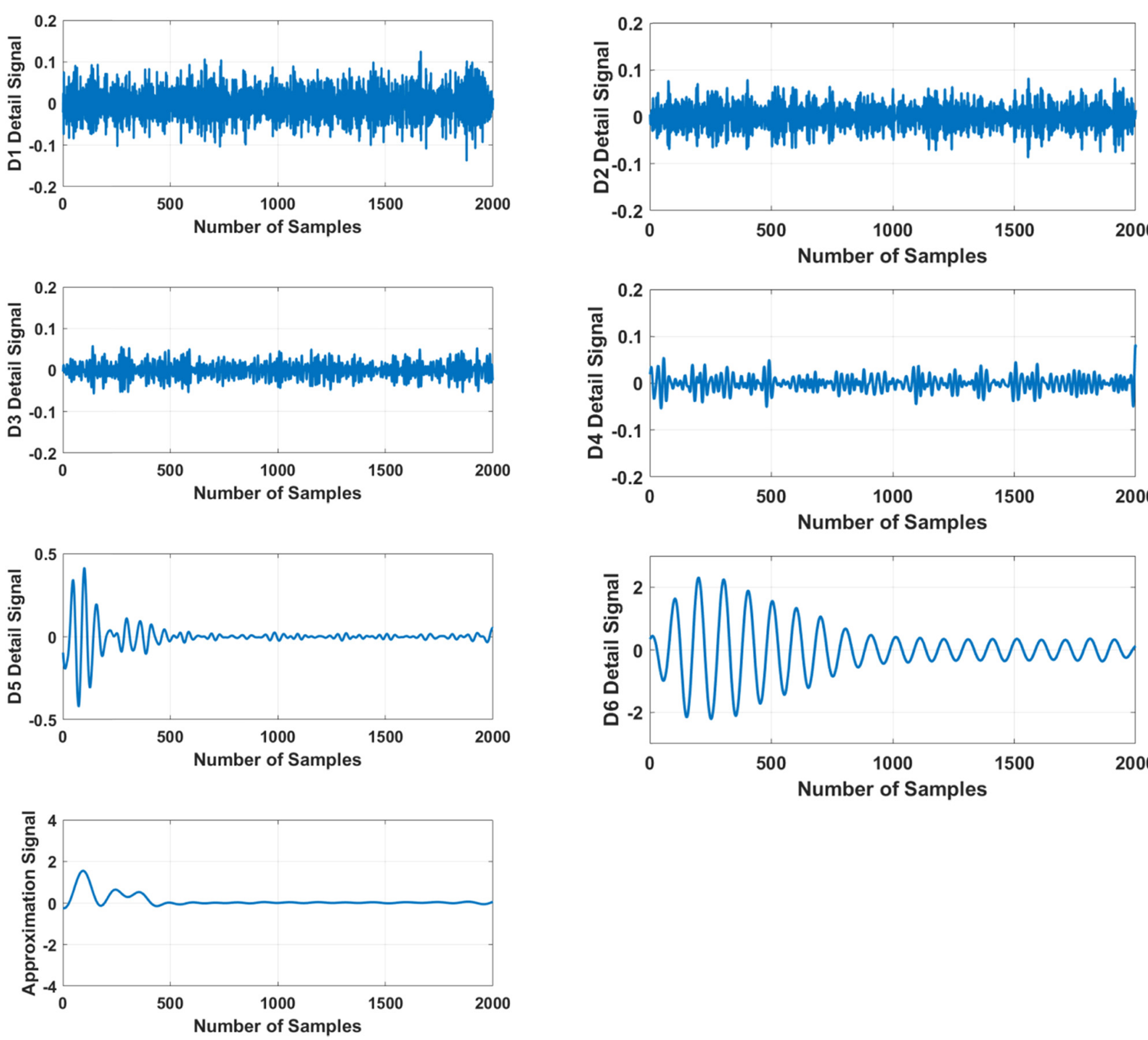

Figure 8: Reconstruction of the signal from the detail coefficients for transient current.

protection can be done to lessen and put off the negativity due to switching transients. It has been noticed how the transient oscillation shows the increase in the severity of the disturbance in the system. For calculating the non-dimensional parameter [29], a generalized expression can be evaluated by determining the energy level increment of the wavelet signal as given in equation (13).

$$\alpha_{nf}(dB) = 10 \log \left[\frac{\sum_{k=N_b}^{N_s} i_k^2}{\sum_{k=N_b}^{N_s} [[A_{nf}(k)]]^2} \right], \tag{13}$$

where i_k represents the kth sample of the given current signal and for the approximation signal, a parameter $A_{nf}(k)$ is represented as the kth element with an order of nf. N_s mainly calculates several samples for a signal, when the signal reaches the steady state region. Due to transient phenomena, oscillating behavior in the wavelet signal is represented as N_b. Here N_b represents the starting point of transient state and steady state current and N_s represents the endpoint of steady state and transient state current. By analyzing the approximate signal, it is understood that the transient starts at 0 sample position and ends at 598 sample position. In a similar manner, the steady state starts at 599 sample position and ends at 2,000 position. Mathematically we can calculate the quantification parameter as the ratio of the energy of the transient signal to the energy of the wavelet signal within the specified time interval, which is measured in decibel. Qualification of parameters for transient and steady state is shown at Table 2, where, it is observed that, a significant reduction in the parameter occurs when it changes to steady state from transient condition.

6 Conclusion

This article presents an experimental analysis of a LV cable-connected motor system. The experimental result has been validated in the simulation platform by proper modeling of the cable. Decomposition of the transient current signature has been performed by the application of DWT. The approximate signal is used to evaluate a non-dimensional parameter based on the increment of energy of the wavelet signal. This non-dimensional parameter quantifies the severity of the transient disturbance. It has been proved that it is highly case sensitive according to the analysis. The accuracy in the output result depends upon the accuracy in the Matlab Simulink model and the available input data. However, there are certain situations in the real-time problem where data are very limited, therefore an assumption has been made for evaluating the critical accuracy in the modeling. Accurate circuit breaker rating and the relay operation can be performed by proper quantification of the severity parameter. Various transients can be generated in the LV cable and DWT can be used as a feature extraction tool for classifying the transients. As per the nature of the transients, a proper protection method can be adopted to avoid unnecessary damage to the system.

Acknowledgements: The authors would like to thank the school of electrical engineering, KIIT University for providing the necessary laboratory facility and library for successful modeling and testing of the proposed system.

Conflict of interest: Authors state no conflict of interest.

Data availability statement: The authors confirm that the data supporting the findings of this study are available within the article and its supplementary materials.

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