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"A COMPARATIVE IMPLEMENTATION OF WAVELET TRANSFORM ALGORITHMS FOR TRANSIENT FAULT ANALYSIS"

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Abstract:

Transient faults pose significant challenges in modern power systems and electrical networks due to their short duration, unpredictable nature, and potential to escalate into permanent failures if not detected promptly. Traditional signal processing techniques often struggle to accurately capture the time–frequency characteristics of these rapidly varying disturbances. This paper presents an efficient implementation of the Wavelet Transform (WT) for the precise detection, localization, and characterization of transient faults. By leveraging the multi-resolution capability of wavelets, the proposed approach decomposes the fault signal into different frequency bands, enabling detailed analysis of its dynamic behaviour.

In this paper, various mother wavelets were evaluated to determine the most suitable basis function for transient fault analysis, with Daubechies wavelets demonstrating superior performance due to their compact support and effective transient detection properties. The implemented WT algorithm processes sampled current and voltage signals to extract high-frequency components associated with fault inception. The detection method identifies sudden changes in wavelet coefficients, which serve as reliable indicators of transient disturbances.

Simulation results validate the effectiveness of the proposed approach, demonstrating enhanced accuracy in identifying fault initiation time, magnitude, and waveform distortion compared to conventional Fourier-based techniques. The method shows strong robustness against noise and system variations, making it highly suitable for real-time monitoring and protection applications. The findings highlight the potential of wavelet-based analysis to significantly improve diagnostic capabilities in power system fault detection and to support the development of advanced protection schemes.

***Index Terms*— Wavelet Transform; Transient Fault; Power System Protection; Signal Processing; Multi Resolution Analysis; Fault Detection; Daubechies Wavelet; Time–Frequency Analysis;**
Disturbance Classification; Real-Time Monitoring

INTRODUCTION

In overhead transmission networks, a significant proportion of electrical faults are characterized as transient events. These disturbances are typically short-lived and arise due to sudden irregularities within the power system. Transient phenomena manifest as rapid fluctuations that distort the steady-state alternating-current (AC) waveform, thereby affecting the stability and quality of power delivery. Such events commonly originate from abrupt changes in system conditions, including lightning strikes, switching operations, insulation breakdown, and momentary line contacts caused by environmental factors. Although brief in duration, these transients can impose considerable stress on electrical equipment and, if not properly detected and mitigated, may escalate into more severe and persistent system failures. Consequently, understanding the nature, causes, and characteristics of transient faults is essential for designing robust monitoring schemes and ensuring reliable operation of modern power networks. Common sources of such disturbances include lightning activity, switching operations, and various electrical fault conditions.

The impact of transient events on electrical equipment is cumulative, as successive occurrences can progressively degrade component performance. Due to their brief duration, these events are often challenging to detect. Approximately 80–90% of overhead-line faults fall into the transient category, while the remaining 10–20% are classified as semi-permanent or permanent. Transient faults are generally cleared through the immediate operation of one or more circuit breakers, after which normal line energization is usually restored successfully.

Reclosing attempts on transmission lines experiencing permanent faults pose significant risks to high-value power system equipment. During an unsuccessful reclosing operation, the system may again be subjected to large fault currents, which can severely damage circuit breakers, transformers, and other critical components. For this reason, accurate discrimination between transient and permanent faults is an essential requirement in modern protection schemes.

Transient disturbances are brief deviations in voltage or current that occur for only a short duration, typically lasting no more than one millisecond, or approximately one-sixteenth of a power-frequency cycle. These short-duration events are generally triggered by sudden changes in system conditions. Power-system transients are broadly classified into three major categories: impulsive transients, oscillatory transients, and transients generated due to fault conditions.

An impulsive transient is characterized by a predominantly unidirectional waveform, where approximately 77% of the peak-to-peak magnitude of the primary component exhibits the same polarity. Conversely, an oscillatory transient involves a sudden deviation from the steady-state operating point and contains alternating positive and negative polarity swings, indicating the presence of resonant or inductive-capacitive interactions within the network. Transients associated with fault conditions arise from phenomena such as insulation failure, the energization of large loads with high inrush currents, or intermittent contact in power wiring caused by poor or loose connections.

Each of the three main categories is further subdivided based on the frequency components present in the waveform, allowing for a more detailed representation of the underlying physical

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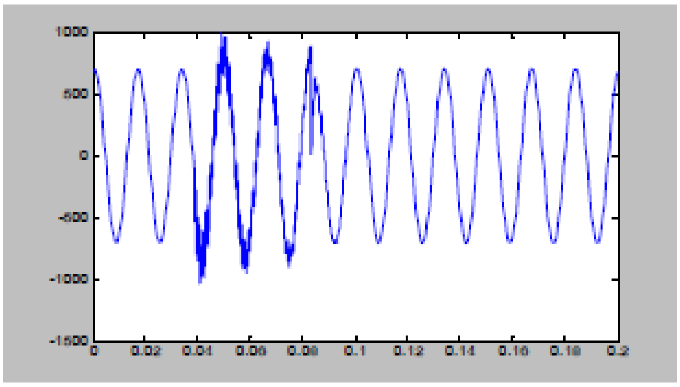
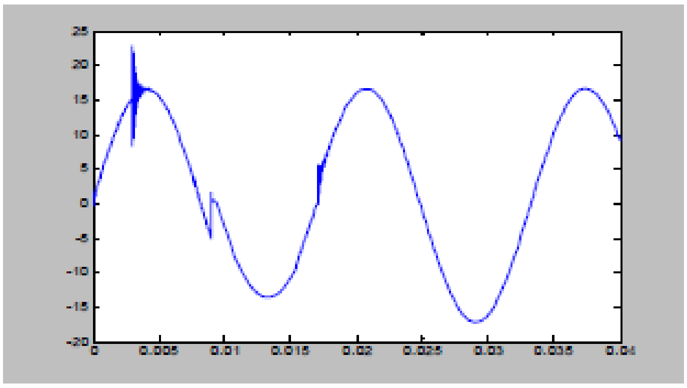
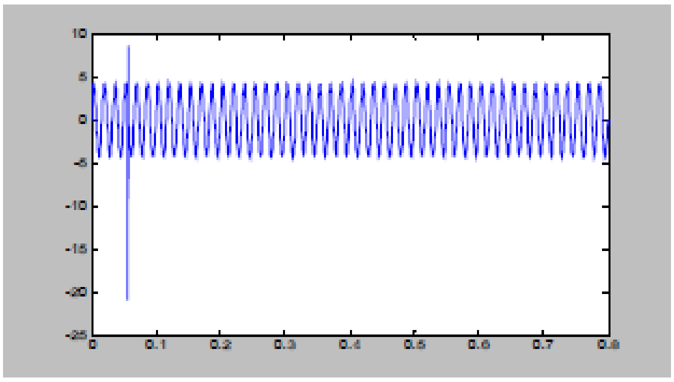
processes. These subclasses correspond to specific mechanisms within the power system, enabling more precise interpretation and effective application of advanced signal-processing tools—such as wavelet transforms—for disturbance analysis and fault classification.



Oscillatory transient



Transient due to fault



Impulsive transient

Low-frequency impulsive transients typically exhibit a rise time on the order of 0.1 ms and persist for durations exceeding 1 ms. Similarly, low-frequency oscillatory transients consist of waveform components extending up to nearly 5 kHz. These disturbances represent the most frequently observed transient phenomena in power systems. Their propagation is not limited to the point of origin; instead, they may travel throughout the network, where they can experience amplification due to resonant conditions inherent to the system's inductive and capacitive characteristics. Consequently, the detection and analysis of such low-frequency transients are critical across a wide range of monitoring, protection, and power-quality applications.

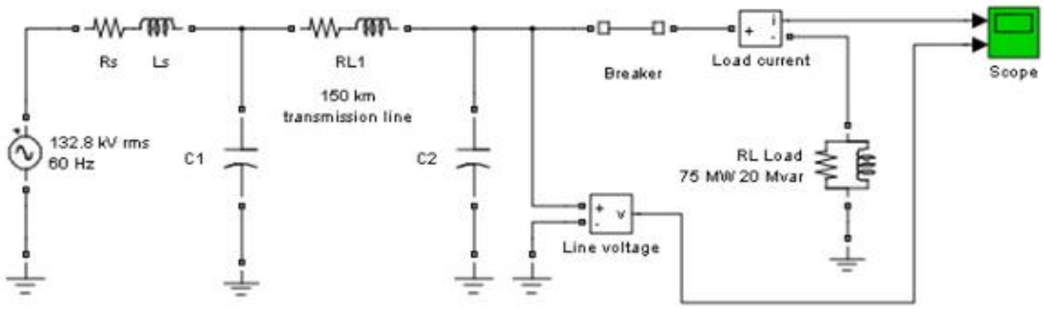
Medium-frequency transients are comparatively less common, yet they play a significant role due to their higher energy content. Impulsive transients within this range exhibit durations from approximately 5 ns to 1 ms, while oscillatory transients contain frequency components between 5 kHz and 500 kHz. Although these events occur less frequently than their low-frequency counterparts, they often manifest with considerably higher amplitudes, making them particularly relevant for equipment insulation assessment, surge protection coordination, and electromagnetic compatibility studies.

Medium-frequency transients generally do not propagate through the network as readily as low-frequency disturbances; however, their impact can be considerably more severe. These high-amplitude, short-duration events have the potential to initiate arcing faults within power distribution systems. Such faults introduce abrupt impedance changes and can trigger widespread voltage sags across multiple user networks. Even though their propagation range is limited, the localized disruptions they create can compromise equipment performance, reduce power quality, and, in severe cases, pose risks to system stability. As a result, accurate detection and characterization of these transients remain essential for effective power-system monitoring and disturbance mitigation.

High-frequency transient events with large amplitudes are typically detectable only in close proximity to their point of origin. The high-frequency impulsive transient generally exhibits a duration of less than 50 ns, whereas the high-frequency oscillatory transient features frequency components in the range of approximately 0.5 to 5 MHz.

The Wavelet Transform (WT) offers an effective framework for analyzing non-stationary signals by providing a time–scale representation rather than relying solely on traditional time–frequency techniques. Through this approach, a signal is decomposed into multiple scales, each corresponding to distinct frequency bands. This decomposition is achieved by translating (shifting in time) and dilating (compressing or stretching in time) a fundamental waveform known as the mother wavelet. By systematically applying these operations, the WT captures localized transient features that conventional Fourier-based methods often fail to identify.

Wavelet-based signal processing has emerged as a powerful tool in power-system engineering, particularly for transient analysis, power-quality disturbance identification, and transmission-line protection. Its inherent ability to detect abrupt signal changes makes it highly suitable for fault analysis, since the wavelet transform responds strongly to steep gradients and localized discontinuities within the waveform. As a result, WT facilitates precise identification of fault-generated transients, enabling more reliable fault classification and improved protection scheme performance.



Test system for generation of power system transients

Disturbances in power-system waveforms typically exhibit greater irregularity than the underlying steady-state signal. This irregularity produces sharper transitions and elevated gradients within the waveform. Since the Wavelet Transform is highly sensitive to such rapid changes, disturbance events generate wavelet coefficients with significantly larger magnitudes compared to those obtained from undisturbed or smooth regions of the signal. This characteristic makes the WT an effective tool for identifying, isolating, and characterizing abnormal events in power networks.

Multi-Resolution Analysis (MRA), a fundamental component of wavelet theory, further enhances this capability by decomposing a signal into its approximate (smoothed) and detailed components. When applied to power-system transients, MRA separates the original waveform into two distinct parts:

A low-frequency approximation, which represents a blurred or smoothed version of the power-quality disturbance, and

A high-frequency detail signal, which contains the abrupt discontinuities, sharp edges, and transitions associated with transient or fault-related phenomena.

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This decomposition enables the detailed and approximate components to be analyzed independently, thereby improving the accuracy of disturbance classification. By isolating transient features from the background signal, MRA provides a systematic and powerful method for distinguishing and evaluating a wide range of power-system disturbances.

Value of these parameter for normal condition, permanent fault, transient fault, load switching and capacitor switching

	NORMAL CONDITION	STEADY STATE FAULT	TRANSIENT FAULT	LOAD SWITCHING	CAPACITOR SWITCHING
Qd1	106.4263098	1408.141974	528.242745	382.709125	281.708018
Qd2	292.9447695	3874.122725	1451.60744	1044.69342	773.276446
Qd3	817.3285867	9811.408055	3668.38456	2804.0565	1967.33741
Qd4	2292.226122	17216.02768	6639.37844	6302.46295	4031.02434
Qd5	6360.455925	18212.43725	8554.2601	7360.05473	6810.8956
Qd6	16728.5212	48437.93392	16536.1403	20897.5227	17060.0884
Qd7	40504.55277	107509.2751	41626.9146	37702.0452	41626.873
Qd8	49231.52858	150681.1089	49496.758	49518.5875	50496.6192
Qd9	10518.8198	35222.16728	11106.3609	11401.268	10613.4751

Where,

For fault analysis, the energy distribution across different wavelet decomposition levels is quantified using the sum of the absolute values of detailed coefficients. For the line current signal, the detailed coefficient parameters are defined as follows:

Qd9 – Sum of the absolute values of the first-level detailed coefficients of the line current

Qd8 – Sum of the absolute values of the second-level detailed coefficients of the line current

Qd7 – Sum of the absolute values of the third-level detailed coefficients of the line current

Qd6 – Sum of the absolute values of the fourth-level detailed coefficients of the line current

Qd5 – Sum of the absolute values of the fifth-level detailed coefficients of the line current

Qd4 – Sum of the absolute values of the sixth-level detailed coefficients of the line current

Qd3 – Sum of the absolute values of the seventh-level detailed coefficients of the line current

Qd2 – Sum of the absolute values of the eighth-level detailed coefficients of the line current

Qd1 – Sum of the absolute values of the ninth-level detailed coefficients of the line current

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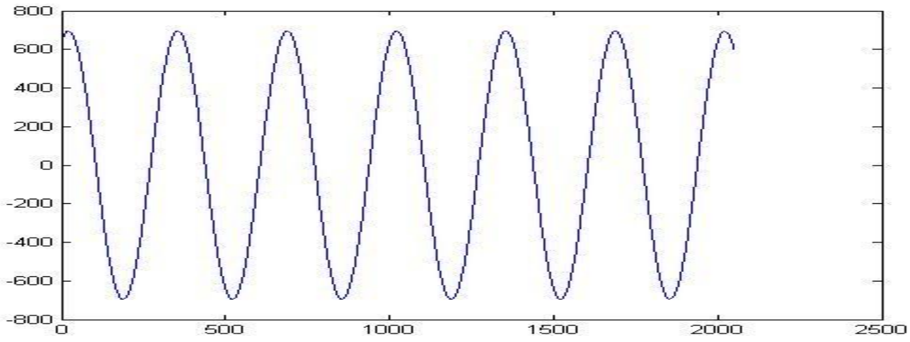
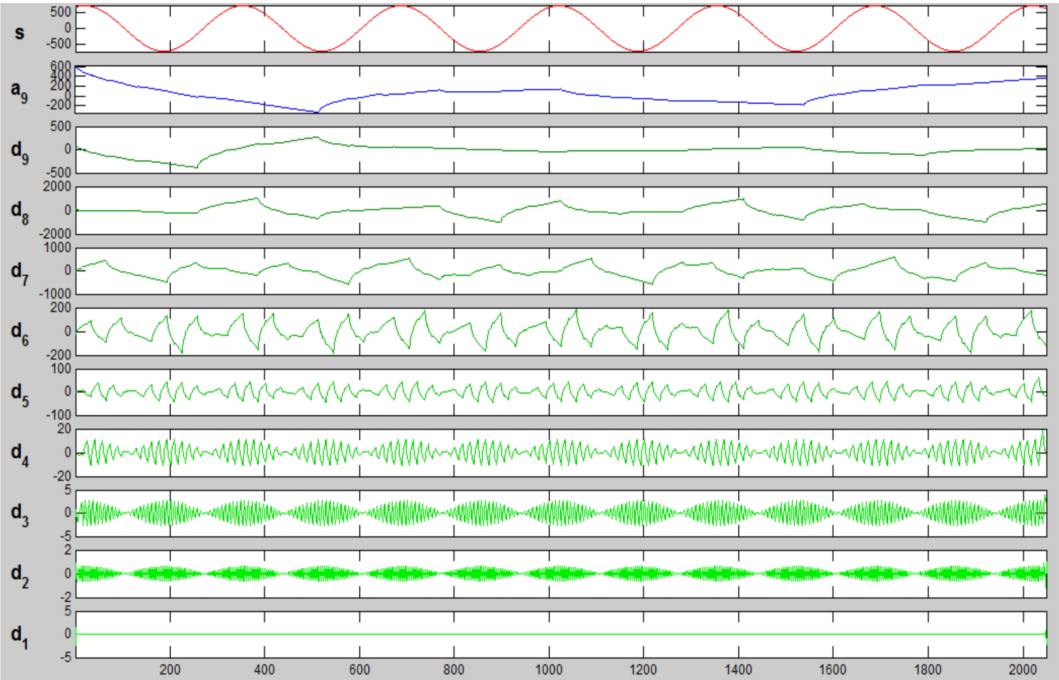
These parameters collectively represent the detailed energy distribution across multiple resolution levels and are widely used for transient detection and fault classification in power-system waveforms.

NORMAL CONDITION





Line current and its DWT decomposition for normal condition

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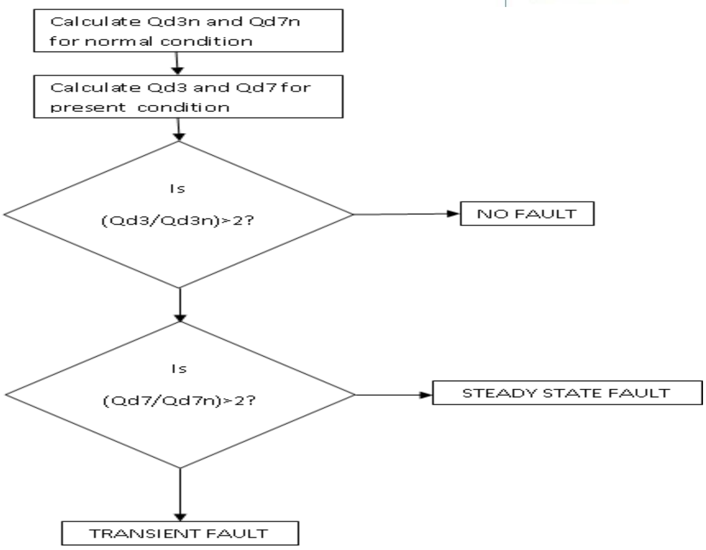
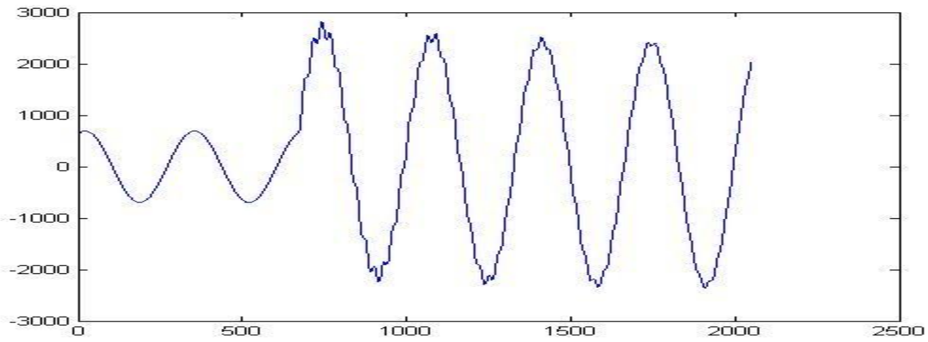
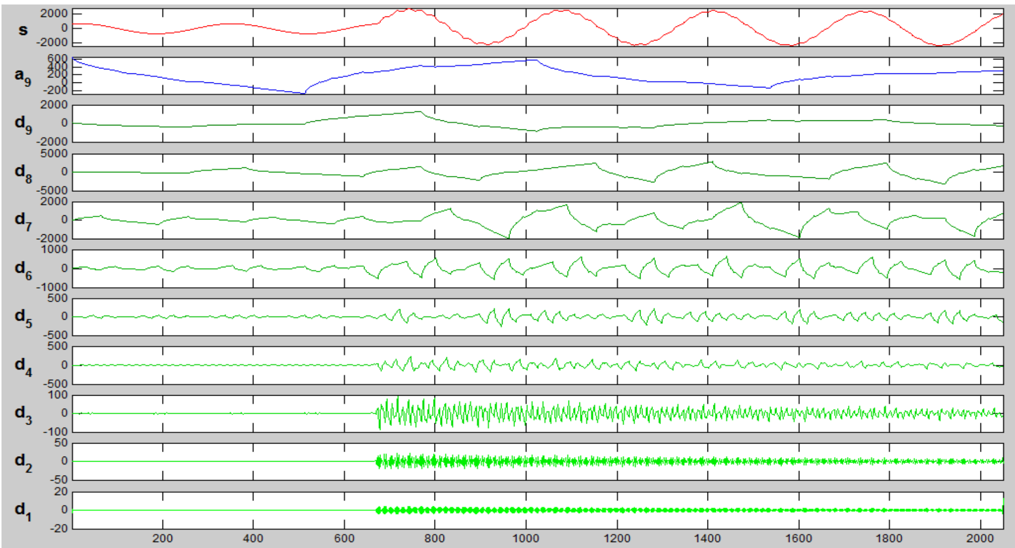


Algorithm for steady state transient fault classification

PERMANENT FAULT





Line current and its DWT decomposition for permanent fault

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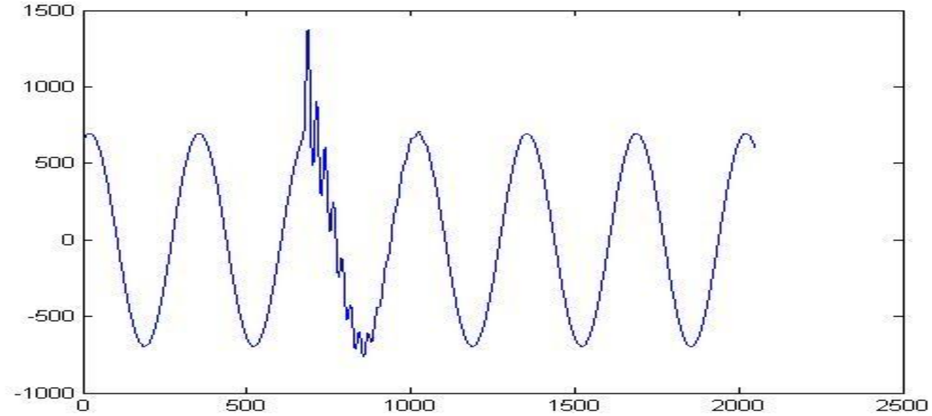
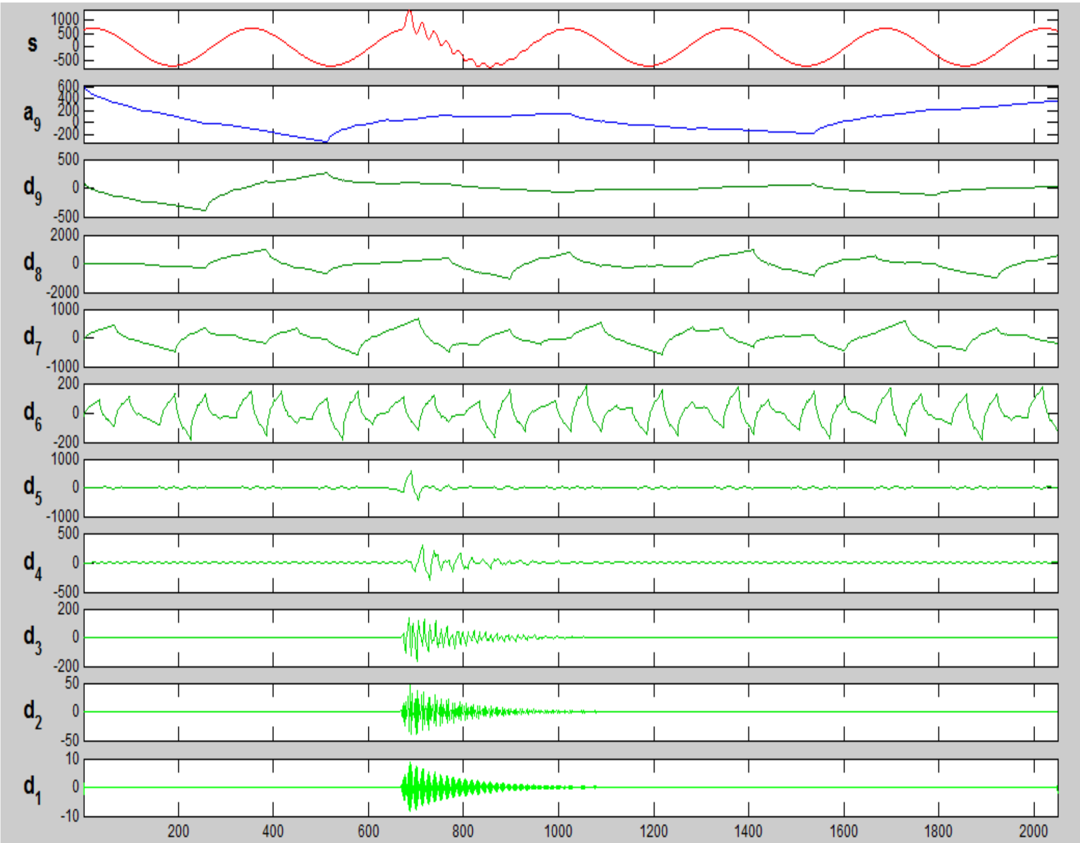
TRANSIENT FAULT





Line current and its DWT decomposition for transient fault

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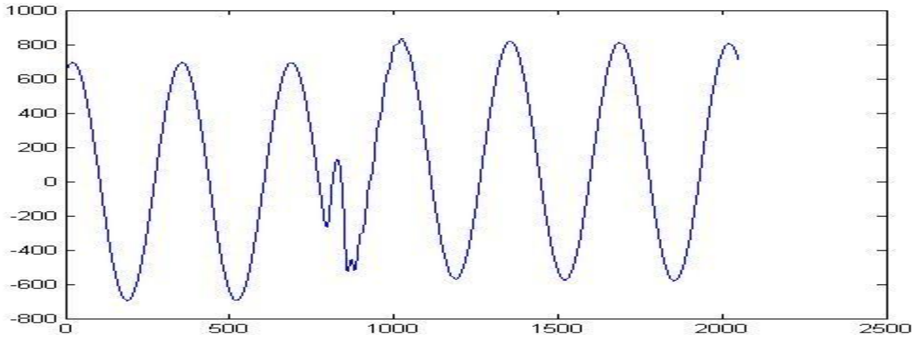
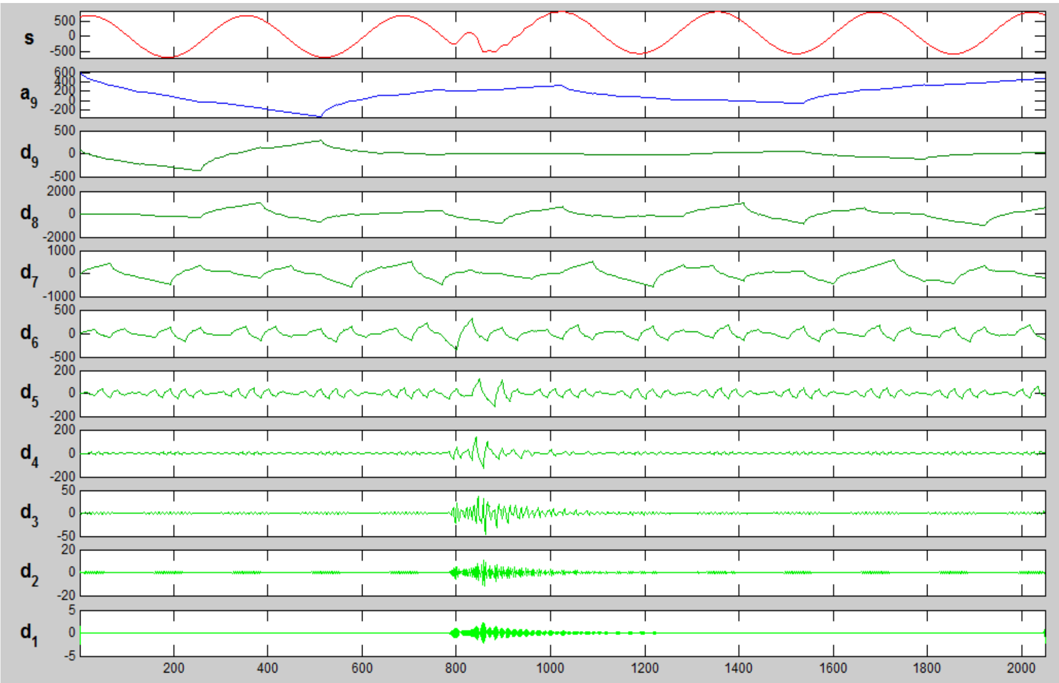
TRANSIENT DUE TO SWITCHING OF LOAD





Line current and its DWT decomposition for transient due to switching of load

The circuit under study represents a simplified single-phase equivalent of a 230-kV three-phase transmission system. Although the actual network is three-phase, only one phase is modelled to analyse system behaviour under various operating and fault conditions. The equivalent source is represented by an AC voltage source of magnitude 230 kVrms/√3, corresponding to a peak value of approximately 187.8 kV at 60 Hz, connected in series with its internal impedance (Rs,Ls).

A three-phase short-circuit capacity of 2000 MVA is assumed for the source, with an X/R ratio of 10. Based on this rating, the source reactance is computed as:

X= (230×103) 22000×10 6= 26.45 Ω,

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which corresponds to an equivalent source inductance of: L=X2πf=0.0702 H

The associated source resistance is obtained using the specified X/R ratio: R=X/10=2.645 Ω.

The source delivers power to an RL load through a 150-km transmission line.

The line is modelled using distributed parameters, with per-kilometre values of

R=0.035 Ω/km, L=0.92 mH/km, and C=12.9 nF/km.

For simulation purposes, the distributed line is approximated by a single pi-section model consisting of a series branch (RL1) with resistance 5.2 Ω and inductance 138 mH, along with two shunt capacitances C1 and C2, each valued at 0.967 μF.

The load is represented using a parallel RLC block corresponding to a per-phase demand of 75 MW and 20 Mvar. This modelling approach captures the essential dynamic behaviour of the transmission system while maintaining computational efficiency for transient and fault analysis studies.

Conclusion:

The analysis of various types of transient faults was successfully performed using the Discrete Wavelet Transform, demonstrating its effectiveness in capturing the time–frequency characteristics of rapidly varying disturbances. By comparing the detailed coefficients of different waveforms, clear distinctions between transient faults, steady-state faults, and healthy operating conditions were identified. This comparative evaluation confirmed that wavelet-based signal decomposition provides reliable indicators for detecting abrupt changes associated with fault initiation.

Based on these observations, a set of criteria for accurate transient fault identification was developed, enabling precise differentiation of fault types and improving diagnostic capability. The results highlight the robust performance of DWT in fault analysis and reinforce its potential for application in real-time monitoring and protection systems. Future work can extend this approach to hardware implementation or adaptive wavelet selection for enhanced performance under varying grid conditions.

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