Identification of Load Behavior Using Digital Signal Processing with Time-Varying Harmonics

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Abstract-- **This paper presents a time–frequency analysis based on Wavelet Packet Decomposition (WPD) to characterize load behavior through time-varying harmonic components. The method was applied to current signals measured on the secondary side of a three-phase transformer connected to a 13.8 kV medium-voltage distribution network. The experiment topology includes an elevator driven by a Variable Frequency Drive (VFD), general-purpose loads, and a photovoltaic generation unit. This configuration allows the isolation and identification of the elevator's operating events, duration, and movement patterns (ascent and descent) from its distinct time-varying harmonic signature. The results show that the proposed approach has the potential to be used across a broader range of equipment types and operational scenarios.**

Index Terms-- **load signature; harmonic distortion; time-varying-harmonics; signal processing; power quality.**

I. Introduction

The impact of power electronics on the grid has been noted for decades, particularly with the increasing presence of non-linear loads. These devices generate harmonic distortions in voltage and current, which lead to thermal losses, damage to sensitive equipment, malfunction of protection and control devices, resulting in deterioration in power quality [1-2].

Non-linear devices connected to the grid exhibit unique harmonic signatures, which enable non-invasive load monitoring [3-7]. This monitoring allows for the identification of connected equipment and the timing of its operation.

For steady-state signals, harmonics can be analyzed using the Discrete Fourier Transform (DFT), which is computationally optimized by the Fast Fourier Transform (FFT).. However, this method is less effective for signals with time-varying frequencies or for non-stationary signals. Another limitation is its inability to pinpoint the exact timing of changes in the signal spectrum [8-9]. To address this, the Short-Time Fourier Transform (STFT) applies FFT over short cycles within a sliding time window, allowing observation of frequency variations over time [10].

Another approach for harmonic analysis in power systems is the Wavelet Transform, which uses a mother wavelet scaled over different window sizes: smaller windows analyze high frequencies, while larger ones analyze low frequencies [11]. In the discrete method (DFT), digital filters and down-sampling split the signal into low- and high-frequency components, then reduce the sampling rate. This process continues on the low-frequency component to achieve the desired frequency division level, resulting in frequency bands for analyzing time-variant components [12-15].

A variation of Wavelet Transform is the Wavelet Packet, which follows a similar process as DFT but divides both low- and high-frequency components, creating uniform frequency bands based on the sampling rate [16-17].

This paper aims to identify the operational events of an elevator load installed at a research building at the Federal University of Itajubá (UNIFEI) by analyzing its time-varying harmonic signature. Activation times, as well as ascent and descent movements, are determined through analysis of the harmonic distortion signature observed at the building's substation transformer. Additionally, this paper presents a qualitative comparison of the analytical techniques employed. Some of the authors are active members of the IEEE PES Task Force on Harmonics Modelling, Simulation and Assessment where this topic is considered very timely. In fact, some preliminary results of this activity have been presented in a panel sessions titled "Identification of Models for Harmonic Studies based on Field Measurements" sponsored by the T&D Committee at the 2025 IEEE PES General Meeting (Austin USA). This paper represents an initial step toward a broader study being conducted by the Task Force, aimed at extending and validating the proposed approach across a wide range of equipment types and operating scenarios. The next phase of this effort will involve the sharing of member databases and the application of advanced signal processing techniques to further characterize load behavior.

Wavelet Packet - Frequency and Time-Frequency Analysis

The Wavelet's Packet Transform (WPT) uses the same Wavelet's Discrete Transform (DFT) filter equations ((1) and (2)). In the DFT, it's used the calculation through filters, which is a successive filtration of a discrete signal x[n]. In successive filtering the signals are subsampled by a factor of 2, preserving Nyquist's theorem, as (1) and (2) [18-29]:

$$y_{high}[n] = \sum_{k=-\infty}^{\infty} x(k) \,.\, h(2n-k) \quad (1)$$

$$y_{low}[n] = \sum_{k=-\infty}^{\infty} x(k) \,.\, g(2n-k) \quad (2)$$

The g[n] filter decomposes the signal resulting in components called signal approximation (low frequencies) and the h[n] filter (high pass) results in components called detail (high frequencies). Only the approximation component is subdivided in the DFT.

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The difference between WPT and DFT is that both the approximation coefficients and the detail coefficients are decomposed. The result is a complete decomposition, as shown in the coefficient tree of Fig. 1.

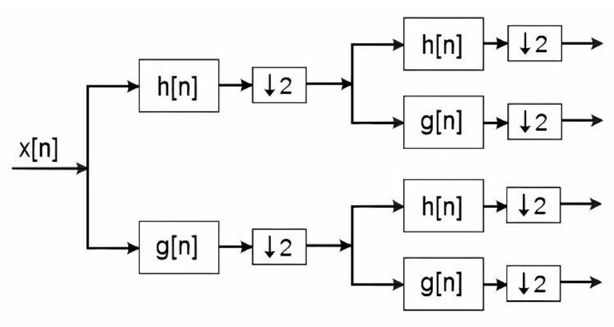

Fig. 1. Decomposition of the Wavelet Transform Package tree.

In the decomposition using the wavelet packet transform, the frequency bands are uniform in comparison to the discrete wavelet transform, which is of great importance for the harmonic analysis (Fig. 2).

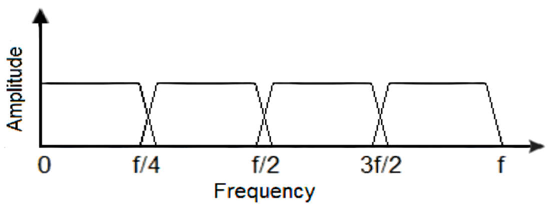

Fig. 2. WPT frequency spectrum.

For this paper, an eight-level wavelet packet decomposition was employed, based on the sampling frequency of the signal (15,360 Hz). With this configuration, the output bandwidth of each filter bank corresponded to approximately 30 Hz (Fig. 3).

In the analysis of harmonics for 60 Hz power systems, the fundamental component and its corresponding harmonics are located near the edges of the passbands of two adjacent filters, causing the signal energy to be distributed between them. To address this effect, a wavelet packet technique was applied to decompose the harmonic components [22–24]. In this approach, the filter output is centered on the desired harmonic by summing the reconstructed signals (synthesis) from the two adjacent subbands (Fig. 3).

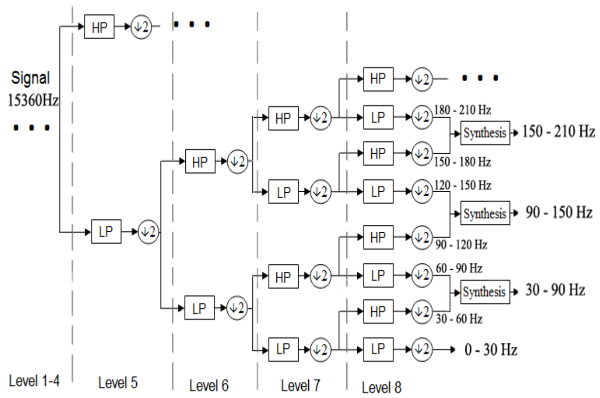

Fig. 3. WPT decomposition for 8 levels and adapt WPT filters to harmonic frequencies.

II. The Experiment Methodology

The data used in this paper pertain to a building at the Federal University of Itajubá, Brazil. This building is connected to a three-phase medium-voltage system (13.8 kV) via a 150-kVA transformer and includes a photovoltaic distributed generation system with a rated capacity of 27 kWp.

Typical loads in the building include computers, printers, lighting, refrigerators, real-time digital simulators (RTDS), uninterruptible power supplies (UPS), and an elevator, among others.

Current measurements were taken at the transformer secondary (denoted as M1 in Fig. 4) and at the photovoltaic system inverter output, designated as M2 (Fig. 4), to observe the effects of harmonic injection caused by the inverter's operation, irradiation fluctuations, and other factors. Both measurements were conducted sequentially during a typical workday. The elevator was activated six times during the measurement at M1 and two times during the measurement at M2, within a five-minute (300-second) measurement interval.

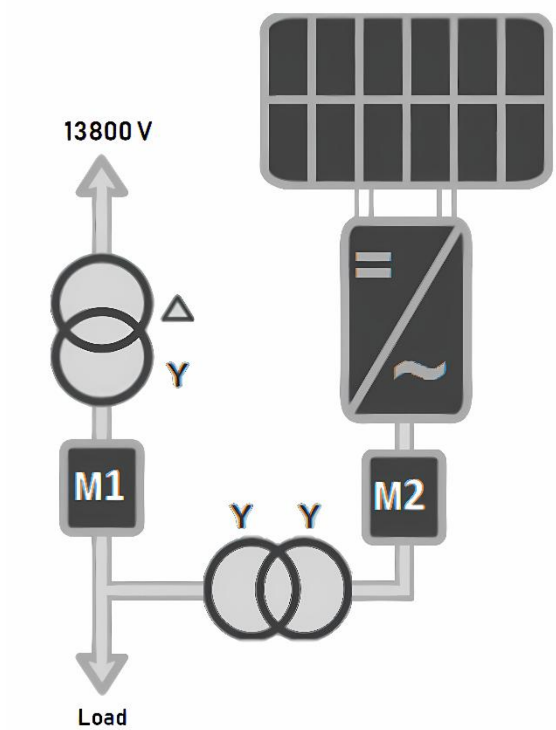

Fig. 4. Diagram of the measured system.

The sampling rate used was 15360Hz (256 points per cycle), for the electrical grid frequency of 60Hz. For data acquisition, the 16-bit NI USB-9162/9215 100 kS/s system has been used along with an anti-aliasing filter.

The three-phase current waveform at the measuring point M1 is shown in Fig. 5 and the inverter's current waveform measured at the measuring point M2 is shown Fig. 6, along with a zoom showing some periods.

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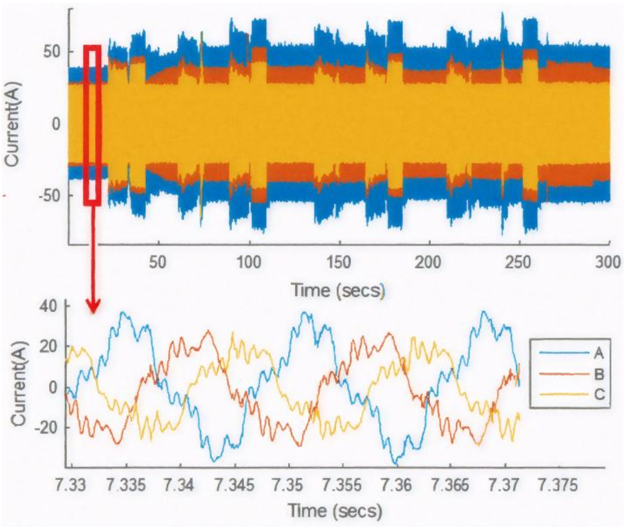

Fig. 5. Current in phases A, B and C at M1.

Different from Fig. 5, it can be seen at the Fig. 6, that the current from M2 does not present significant harmonic distortion.

The techniques mentioned were applied to verify the behavior and characteristics caused by the elevator's activation event in the harmonic currents. In particular, the aim was to identify the elevator's activation events through the harmonic signature of the load.

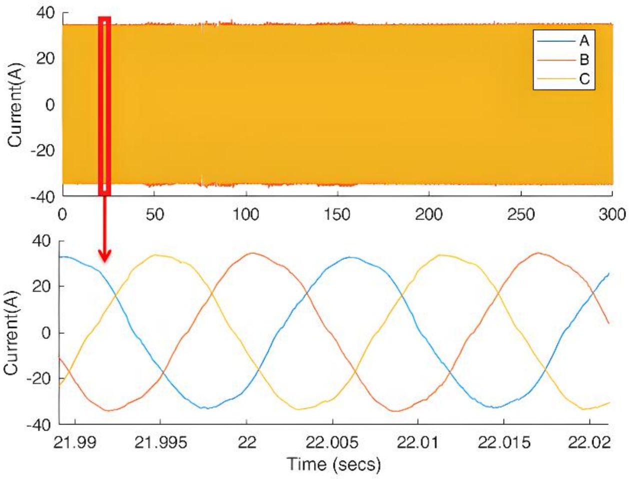

Fig. 6. Current in phases A, B and C at inverter's output (M2)

III. Results

When the elevator load is activated, the frequency inverter that controls its activation injects different harmonics in the grid. These harmonics vary over time, as can be seen in Fig. 7. This figure shows the waveform of the phase A current, highlighting the waveform before and during an activation at measuring point M1.

The wavelet packet transform was applied using an eight-level decomposition with the db45 mother wavelet. From the synthesis stage of the filter bank, the reconstructed harmonic components were extracted, enabling the separate analysis of each harmonic waveform. Fig. 8 illustrates the extracted fundamental component.

The third, seventh, and ninth harmonics did not exhibit significant variations associated with the elevator activation events, maintaining relatively constant behavior. This can be observed in Fig. 9, which shows the third harmonic as a representative example.

In contrast, the fifth, eleventh, and thirteenth harmonics displayed distinct time-varying behavior, with clear changes corresponding to elevator activation events. These variations allow the identification of the type of movement (ascent or descent), the duration of the activation event, and the exact timing of its occurrence. Fig. 10 presents the extracted eleventh harmonic.

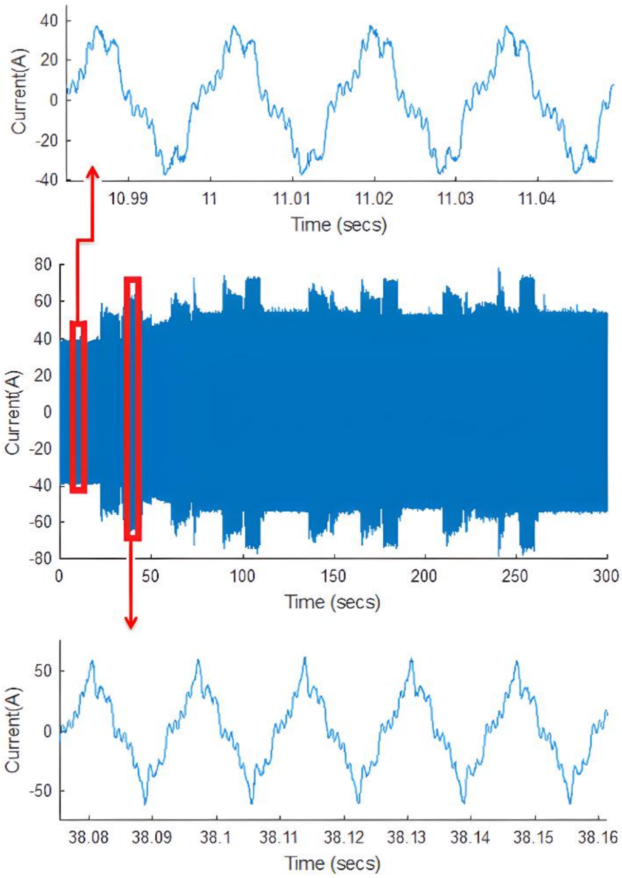

Fig. 7. Current in phases A, details before and during an activation (M1).

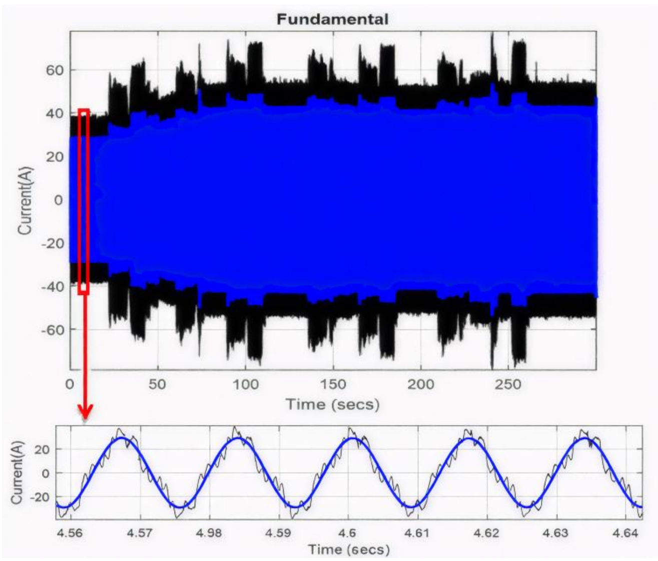

Fig. 8. Current waveform and fundamental component (M1).

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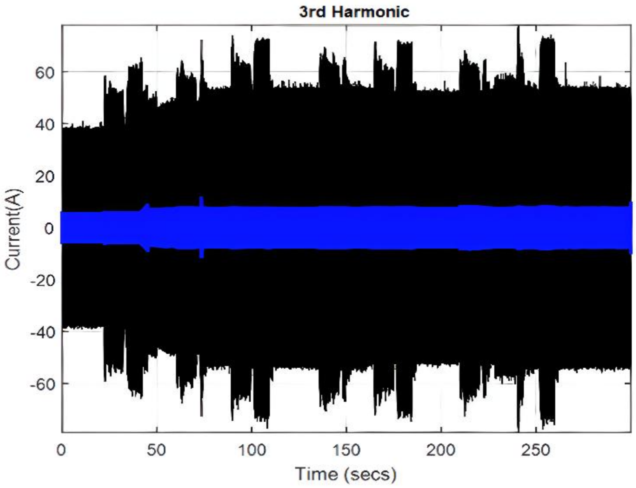

Fig. 9. Current waveform and third harmonic component (M1).

Fig. 11 shows the identified pattern for the eleventh harmonic, where the ascent and descent movements are differentiated. The elevator's ascent has a 16s duration, and the descent 24s.

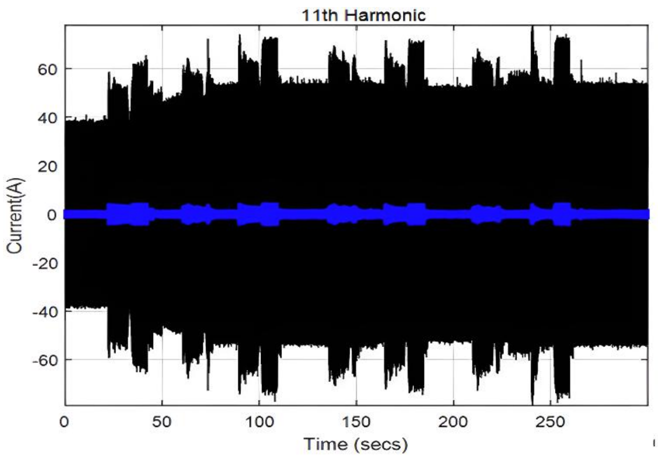

Fig. 10. Current waveform and eleventh harmonic component (M1).

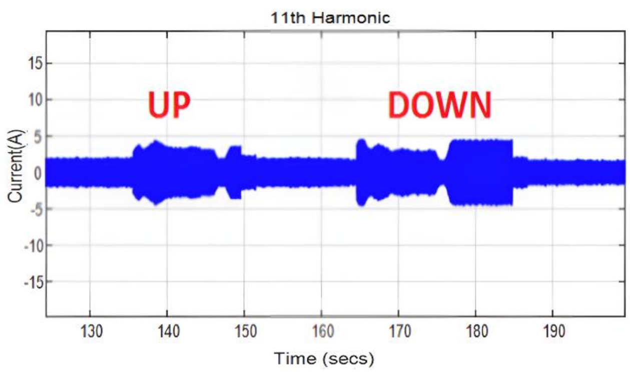

Fig. 11. Detail of the signature of elevator going up and down in the 11th harmonic (M1).

It is possible to pinpoint the exact instants of the elevator's activations in the sampled signal by analyzing the 11th harmonic patterns, which distinctly reflect the upward and downward movement shapes (Fig. 12).

The same study was performed using the wavelet packet at the measurement at M2 (Fig. 12), and the same pattern was identified. Therefore, showing that the 11^{th} time-varying harmonic is the result of the load's activation.

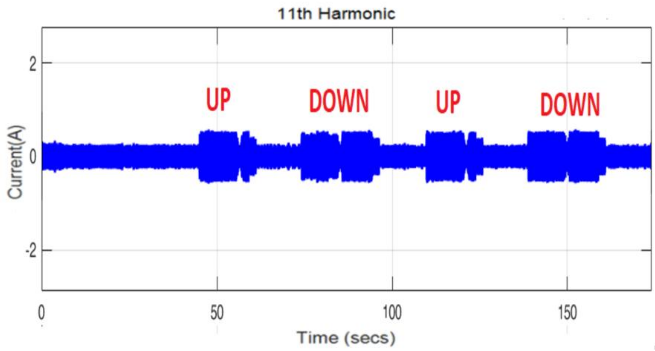

Fig. 12. Current waveform and eleventh harmonic component from M2 sensor.

The results demonstrate the effectiveness of the wavelet-based approach as a tool for identifying load behavior in power systems. Unlike traditional time-domain analysis, the Wavelet Packet Transform enables the visualization of time-varying harmonic content by decomposing the signal into uniform frequency bands. This time–frequency representation confirms that certain harmonics, particularly, in this case, the 11th harmonic, are strongly correlated with elevator operating activation events, whereas others (e.g., the 3rd and 7th harmonics) remain relatively stable. This time–frequency-domain analysis substantiates the use of WPT for identifying transient and non-stationary load behaviors.

IV. Conclusion

Time-frequency analysis techniques were employed to enhance our understanding of electrical load behavior and events. The Wavelet Packet proved effective for this study, enabling the identification of the elevator's activation instants through characteristic variations in the 11th time-varying harmonic. This analysis can be extended to other types of loads (e.g., air conditioning, pumps, compressors, UPS) as well as distributed renewable energy sources, energy storage systems, and system-level events.

Beyond the immediate findings, the Wavelet Packet provides additional insights, including the time-dependent harmonic spectrum, allowing for a more comprehensive assessment of harmonic distortion impacts on the electric grid.

The findings of this study demonstrate that the Wavelet Packet Transform (WPT) is an effective tool for identifying elevator load behavior through time-varying harmonic signatures. Beyond this specific application, the results indicate that the proposed approach is potentially transferable to other loads employing power electronic converters, such as air conditioners, water pumps, and variable-speed drives in industrial systems.

In addition, the methodology shows promise for detecting switching events in distributed energy resources and for monitoring abnormal operating conditions, including faults and power quality disturbances. Future work will focus on validating the proposed approach across a broader range of equipment types and operational scenarios.

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The next phase of this research will involve the sharing of member databases of the IEEE PES Task Force on Harmonics Modelling, Simulation and Assessment and application of other advanced signal processing techniques to further characterize load behavior, and equipment and power systems events..

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