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POWER QUALITY CHARACTERIZATION OF NANO AND MICRO VOLTAGE TRANSIENTS IN DOMESTIC GRID-CONNECTED SOLAR POWER SYSTEMS

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Abstract

One of the major concerns associated with increasing photovoltaic (PV) penetration is the degradation of power quality. Poor power quality can result in system disturbances and significant economic losses. This study presents practical approaches for investigating the transient behavior of domestic grid-connected solar power systems as a power-quality issue. These issues have been widely reported in grid-connected PV systems, particularly regarding voltage disturbances and transient phenomena affecting distribution networks. A domestic solar power system located in Kaldemulla, Sri Lanka was selected for transient measurements. Power quality was analyzed using the output voltage of the solar panels under real domestic operating conditions. The analysis was further carried out to identify characteristic signatures of transients in both time and frequency domains. A total of 54 transient waveforms were recorded and analyzed using empirical methods to extract key transient parameters. Based on burst duration, two types of oscillatory transients were identified: Nano transients (33 events) and Micro-transients (21 events). For Nano transients, the average positive peak, negative peak, and peak-to-peak values were 21.59 V, −20.33 V, and 41.92 V, respectively. For Micro-transients, the corresponding values were 27.54 V, −43.90 V, and 71.43 V. The average burst durations were 99.67 ns for Nano transients and 881.6 µs for Micro-transients. Rise times for Nano transients ranged from 1.5 ns to 10.5 ns, while Micro-transients ranged from 9.0 µs to 113.0 µs. Fall times ranged from 1.0 ns to 7.2 ns for Nano transients and 11.0 µs to 200.0 µs for Micro-transients. Continuous exposure to such transients in electronic systems may lead to both latent degradation and catastrophic failures. Therefore, the findings of this study provide important insights for the design and implementation of effective transient suppression techniques to improve power quality in solar power systems.

Keywords. *Power Quality, Voltage Transients, Nano Transients, Micro-transients, Photovoltaic Systems, Grid-Connected Solar Systems, Transient Analysis, Power Quality Disturbances.*

1. Introduction

Electrical power generation is one of the most important research and development fields in the modern world. As power systems become increasingly complex, power quality has become a major concern in electricity generation. Numerous power quality issues are associated with electrical power systems. According to IEEE classifications, power quality disturbances are categorized into seven types, among which voltage sags, harmonics, and transients have the most significant impact on industrial customers [1,2]. These power quality issues can lead to plant downtime, reduced capacity, production losses, equipment failure, utility penalties, and significant financial losses. Therefore, it is essential to address these problems through appropriate technical solutions [3]. Transients play a major role in power systems as a critical concern for power quality. Typically, transient voltages last from nanoseconds to milliseconds. IEEE 1159:2019 defines two main types of transients: impulsive transients and oscillatory transients [3,4]. The energy contained in a transient is a key factor in determining its impact on electrical components and systems [5]. Transient-related issues can cause sudden equipment damage due to insulation failure, physical damage, latent faults, permanent degradation, or malfunction of sensitive loads such as electronic instrumentation. The severity of these effects depends on parameters such as magnitude, burst duration, rise time, fall time, and frequency. These transients may arise from lightning, switching inductive or capacitive loads, short circuits, and other disturbances. In Sri Lanka, the primary sources of power generation include coal, large and mini-hydro, oil, wind, and solar energy. Among these, solar energy has emerged as one of the most promising and rapidly growing energy solutions, gaining increasing attention from both research and industrial communities. Grid-connected solar power generation systems are widely

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used in domestic applications. A grid-connected solar power system is integrated with the utility grid, and its main components include solar panels, a grid-tied inverter, and a net meter that records the energy supplied to the grid and the energy consumed by household appliances [6]. However, power generated by solar panels can introduce power quality issues within the system. Therefore, it is important to investigate these issues and identify appropriate solutions based on their root causes. Extensive research has been conducted to study power quality issues in solar power systems from various perspectives and under different operating conditions [7–9]. Although transient analysis in low-voltage power systems has been conducted by several researchers across different environments [10-19], limited attention has been given to transient behavior in solar energy-harvesting systems, particularly in both the voltage and current domains. This study presents practical approaches for investigating the transient characteristics of domestic grid-connected solar power systems as a power-quality issue. The power quality of the system is analysed by examining the signatures of the output voltage generated by solar panels in a domestic environment. High-voltage peaks generated by transients may exceed the voltage ratings of system components, while low-amplitude transients with longer durations can result in high energy impacts on PV system devices. Therefore, parameters such as amplitude, rise time, fall time, and burst duration are critical for analyzing transient behavior in PV systems [7]. In addition, peak values and burst duration can be used to estimate the energy associated with transients, which is essential for evaluating their impact on power quality [20]. Accordingly, this study focuses on identifying the characteristic signatures of transients in terms of peak values, rise time, fall time, burst duration, and energy content, in both time and frequency domains.

2. Experimental Setup

Fig. 1(a) illustrates the block diagram of the experimental setup used to measure voltage transients at the DC breaker box of a solar power system. The photovoltaic (PV) system investigated in this study is located in Kaldemulla, Sri Lanka. The technical configuration of the setup is consistent with previously reported experimental arrangements [10-13]. Common-mode voltage transients were measured using a Tektronix P6015A high-voltage probe with a 1000× attenuation factor. The signals were captured using a PicoScope 3206A oscilloscope with a 200 MHz bandwidth, a 250 MS/s sampling rate, and 8-bit resolution. The oscilloscope was powered through the USB port of a battery-powered Acer Aspire E15 laptop to ensure electrical isolation from the main power supply during measurements. Data acquisition and analysis of the captured waveforms were performed using PicoScope 6 software (version 6.7.40.3). The experiment was designed to measure common-mode transients on the live conductor **relative to** system ground in a domestic environment. Fig. 1(b) presents the complete measurement setup, including the connection arrangement at the DC breaker box used for capturing domestic transient events. A 1 m long three-core cable was used to connect the DC output from the solar panels, via the DC switch breaker, to the Tektronix P6015A high-voltage probe. The probe was directly connected to Channel A of the PicoScope oscilloscope. Before recording the actual measurements, a set of five preliminary test waveforms was captured to ensure proper triggering conditions and signal stability. This procedure ensured accurate recordings with an appropriate trigger level for subsequent analysis.

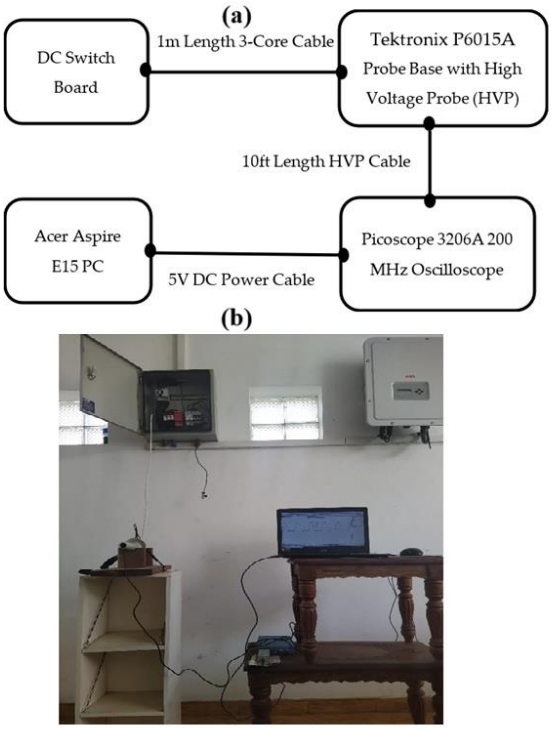

Fig. 1. Experimental setup. (a) Block diagram of the experimental setup. (b) Measurement setup.

3. Results and Analysis

A total of 55 transient events were identified from 576 recorded waveforms. Based on burst duration, two types of oscillatory transients were classified: Nano transients (34 events) and Micro-transients (21 events). Nano transients were observed in the nanosecond range, whereas Micro-transients occurred in the microsecond range.

1. Nano Transients

Nano transients were identified based on the transient waveforms' burst durations, which range from nanoseconds to microseconds. The observed burst durations ranged from 60 ns to 160 ns, with an average duration of 99.67 ns. Two subcategories of Nano transients were identified based on the polarity of the initial peak: positive-type (p-type) and negative-type (n-type). A total of 34 Nano transient events were recorded, comprising 27 p-type transients and 7 n-type transients. The subsequent analysis is based on this classification.

It was observed that multiple transient bursts can occur within a single captured waveform. For instance, as illustrated in Fig. 2(a), five transient events were recorded within waveform No. 46, with a representative transient shown in Figure 2(b). This indicates the repetitive and clustered nature of Nano transient occurrences in the system. The amplitude characteristics of Nano transients show that the average positive peak voltage is 21.59 V, the average negative peak voltage is −20.33 V, yielding an average peak-to-peak value of 41.92 V. Individual transient events exhibit variations around these values, reflecting the stochastic behavior of transient generation in the system.

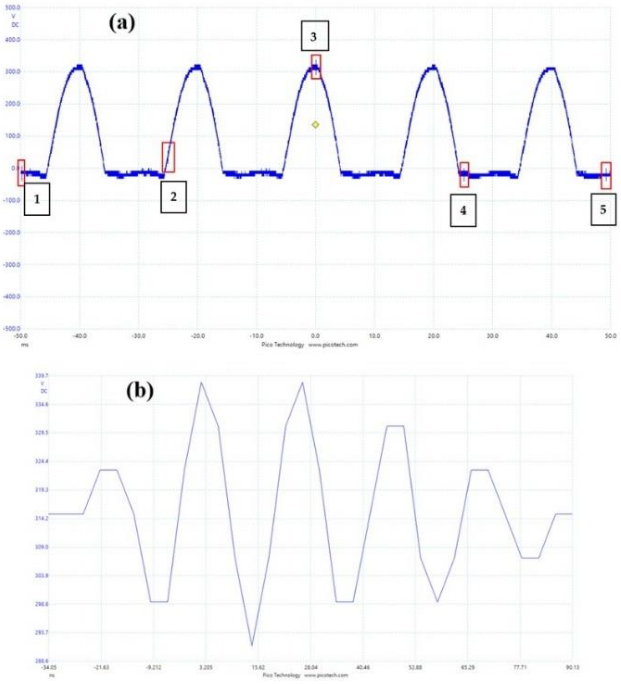

Fig. 2. (a) Recorded waveform (No. 46) over a 100 ms duration illustrating multiple transient bursts; (b) Enlarged view of a representative transient event (46–3).

A detailed pulse-wise analysis revealed that, in p-type Nano transients, the second negative peak and third positive peak exhibit the largest amplitudes, with average values of approximately −18.31 V and 21.5 V, respectively. In n-type transients, the third negative peak and fourth positive peak showed the highest amplitude magnitudes, with average values of −20.83 V and 20.8 V, respectively. The rise time characteristics of Nano transients were observed to be within the range of 1.5 ns to 10.5 ns. For p-type transients, the rise times of individual pulses were relatively consistent, typically within the range of approximately 3 ns to 5 ns, with the first positive peak (p1p) showing a comparatively higher average rise time of around 5.0 ns. In contrast, n-type transients exhibited slightly greater variability in rise time, generally ranging from 2.8 ns to 6.1 ns. Fall times of Nano transients ranged from 1.0 ns to 7.2 ns. For p-type transients, the fall times of individual pulses were mostly within the range of approximately 2.5 ns to 6.5 ns, with a gradual decreasing trend observed across successive peaks. In n-type transients, fall times were typically in the range of 2.4 ns to 4.6 ns, with the third peak showing the highest average fall time. In terms of waveform structure, Nano transients exhibit oscillatory behaviour with multiple peaks within a single transient event. P-type transients typically contain up to 14 peaks, although six peaks were most commonly observed. N-type transients generally contain up to nine peaks. Fig. 3 illustrates the variation of amplitude, rise time, and fall time across individual peaks for both p-type and n-type Nano transients. It can be observed that both types exhibit oscillatory behavior in amplitude variation. The rise time variation in p-type transients is relatively stable, whereas n-type transients show greater fluctuations. In terms of fall time, p-type transients exhibit a gradual decay pattern, while n-type transients display more irregular variations, with the highest fall time occurring at the third peak. The distribution of burst durations for all Nano transients is presented in Fig. 4. As shown, the burst durations are confined within the range of 60 ns to 160 ns, with an average value of 99.67 ns across all observed events.

2. Micro-transients

Micro-transients represent the second category of oscillatory transients identified in this study, characterized by burst durations in the microsecond range. The observed burst durations ranged from approximately 480 µs to 1300 µs, with an average duration of 881.6 µs. A total of 21 Micro transient events were recorded during a 12-hour measurement period. Fig. 5(a) illustrates a representative waveform containing a transient event within a 100 ms time window, while Figure 5(b) presents a magnified view of a single transient, highlighting its detailed structure and associated noise components. Based on the polarity of the initial peak, Micro-transients were classified into two subcategories: positive-type (p-type) and negative-type (n-type). Among the recorded events, 15 were identified as p-type transients and 6 as n-type transients. The amplitude of Micro-transients is significantly higher than that of nano-transients. The average positive peak voltage was 27.54 V, with values ranging from approximately 15 V to 46 V. The average negative peak voltage was −43.90 V, ranging from approximately −71 V to −23 V. The peak-to-peak voltage exhibited considerable variation, with values ranging from 39.37 V to 110.2 V and an average value of 71.43 V. A pulse-wise analysis of p-type Micro-transients shows that the second negative peak and third positive peak exhibit the most significant amplitude values, with average magnitudes of −43.4 V and 24.32 V, respectively. In n-type transients, the first negative peak and second positive peak dominate, with average values of −44.48 V and 33.61 V, respectively. The rise-time characteristics of Micro-transients exhibit greater variation than those of nano-transients. For p-type transients, rise times ranged approximately from 13.0 µs to 68.0 µs, with the second peak typically showing the highest rise time, averaging around 67.57 µs. In n-type transients, rise times generally ranged from 27.0 µs to 52.0 µs, with the third peak exhibiting the highest rise time.

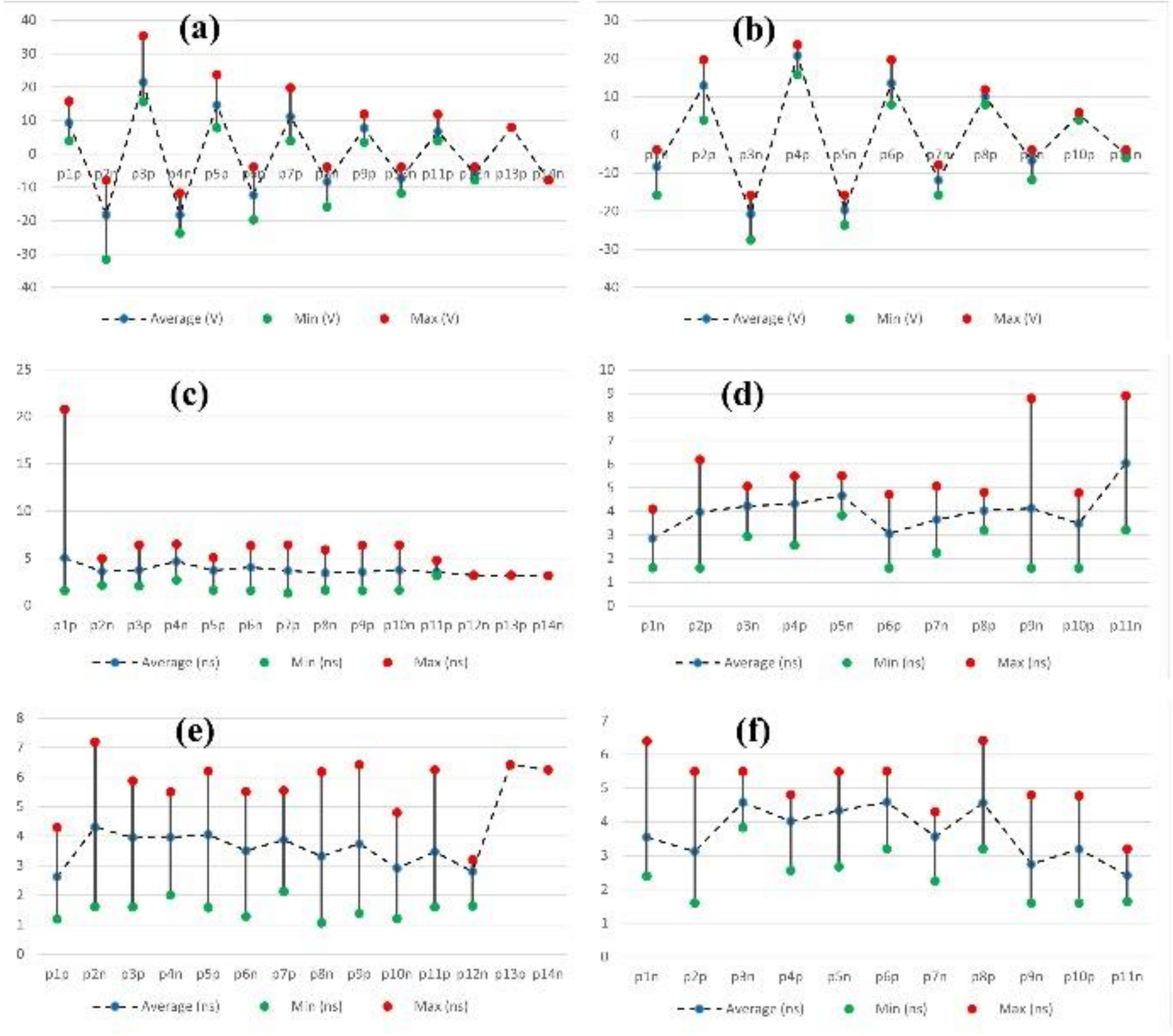

Fig. 3. Variation of transient parameters for Nano transients: (a) Amplitude variation of p-type transients; (b) Amplitude variation of n-type transients; (c) Rise time variation of p-type transients; (d) Rise time variation of n-type transients; (e) Fall time variation of p-type transients; (f) Fall time variation of n-type transients.

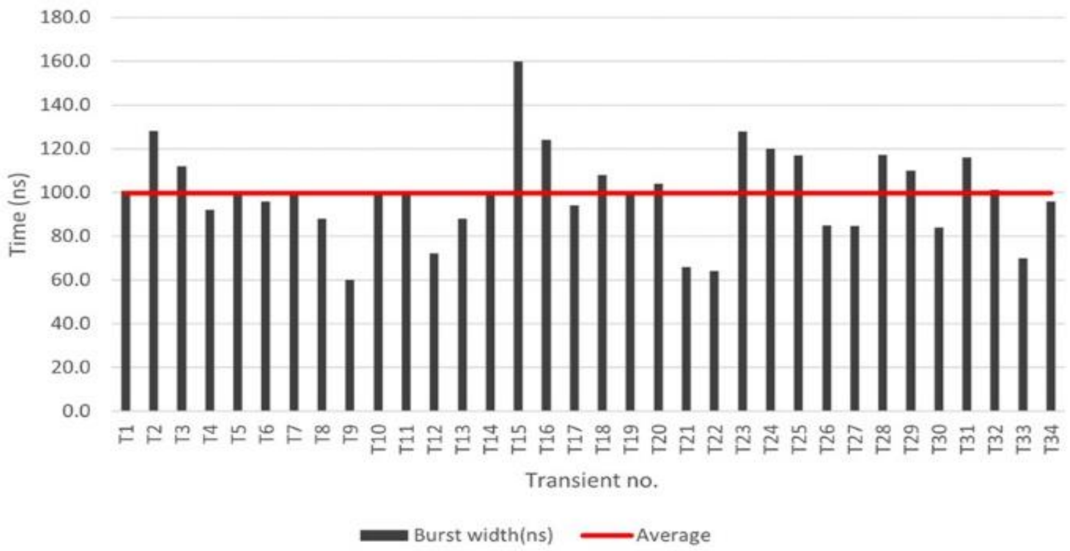

Fig. 4. Variation of burst duration for Nano transients.

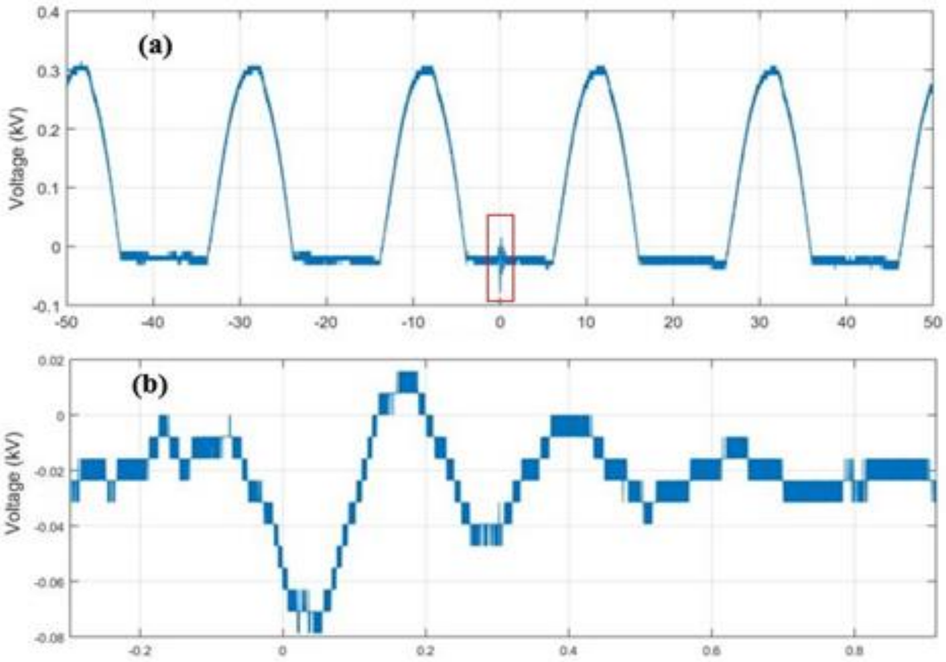

Fig. 5. (a) Representative waveform (No. 8) over a 100 ms time window showing a Micro transient event. (b) Magnified view of the transient illustrating its detailed structure and associated noise components.

Fall times of micro-transients were observed within the range of approximately 28.0 µs to 79.0 µs. In p-type transients, fall times typically varied between 28.0 µs and 73.0 µs, while in n-type transients, fall times extended up to approximately 79.0 µs, indicating a relatively slower decay compared to Nano transients.

In terms of waveform structure, Micro-transients also exhibit oscillatory behavior with multiple peaks within a single event. P-type transients were observed to contain up to 11 peaks, whereas n-type transients typically exhibited up to 10 peaks. Figure 6 illustrates the variation of amplitude, rise time, and fall time across individual peaks for both p-type and n-type Micro-transients. Both types exhibit oscillatory amplitude behavior.

However, unlike Nano transients, the rise-time variation in Micro transients is more pronounced, making it difficult to identify a consistent pattern. In contrast, fall-time characteristics exhibit a general decaying trend for both types, with n-type transients showing comparatively higher fall-time values. The distribution of burst durations for Micro-transients is shown in Fig. 7. As shown, the burst durations are confined to approximately 480 µs to 1300 µs, with an average of 881.6 µs. Frequency-domain analysis, as illustrated in Figure 8, reveals distinct spectral characteristics of Micro-transients compared to nano-transients. While Nano transients exhibit a dominant single-frequency component around 42.4 MHz, Micro transients contain multiple high-frequency components, notably around 31.3 MHz, 62.5 MHz, and 93.75 MHz.

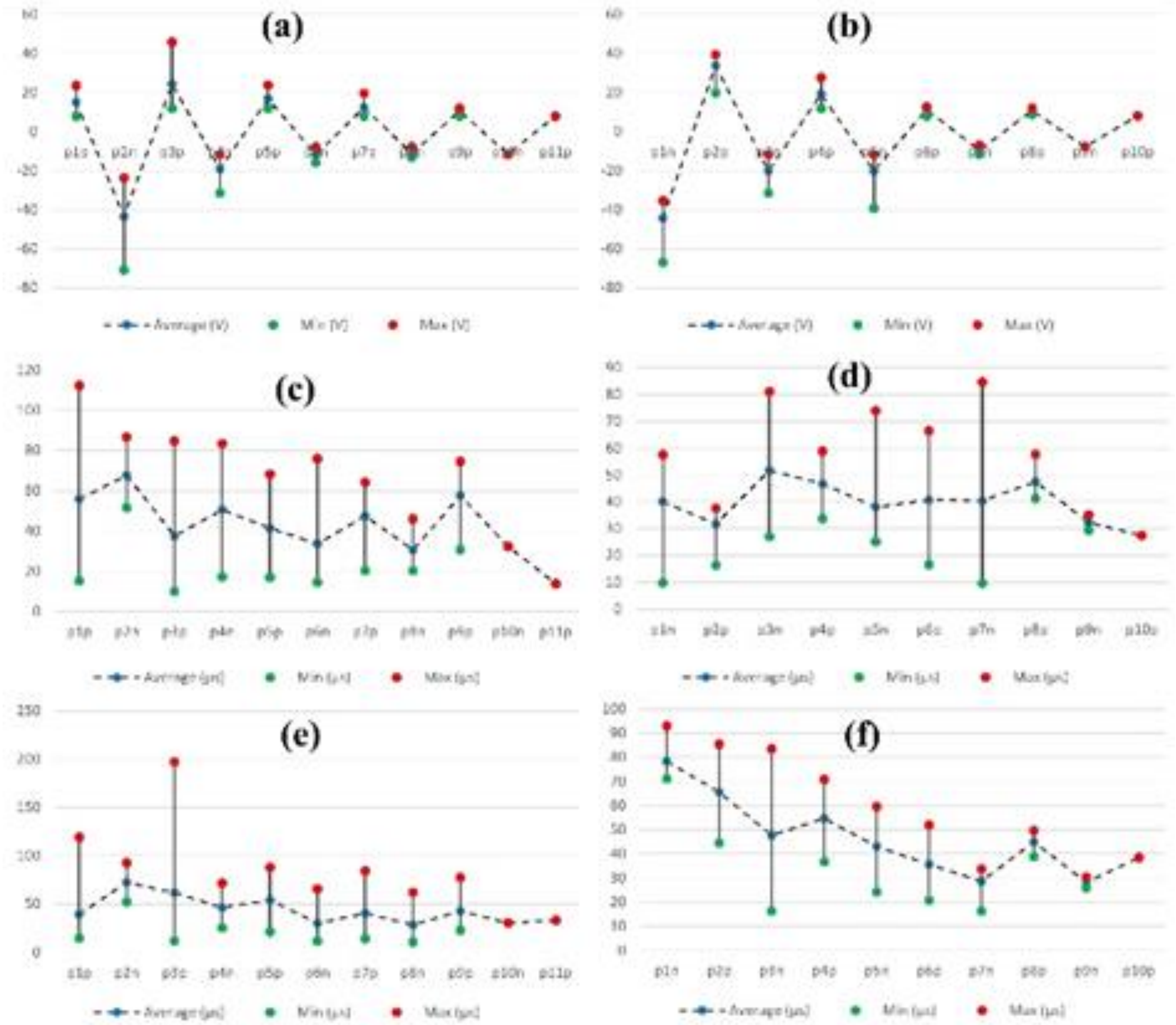

Fig. 6. Variation of transient parameters for Micro-transients: (a) Amplitude variation of p-type transients; (b) Amplitude variation of n-type transients; (c) Rise time variation of p-type transients; (d) Rise time variation of n-type transients; (e) Fall time variation of p-type transients; (f) Fall time variation of n-type transients.

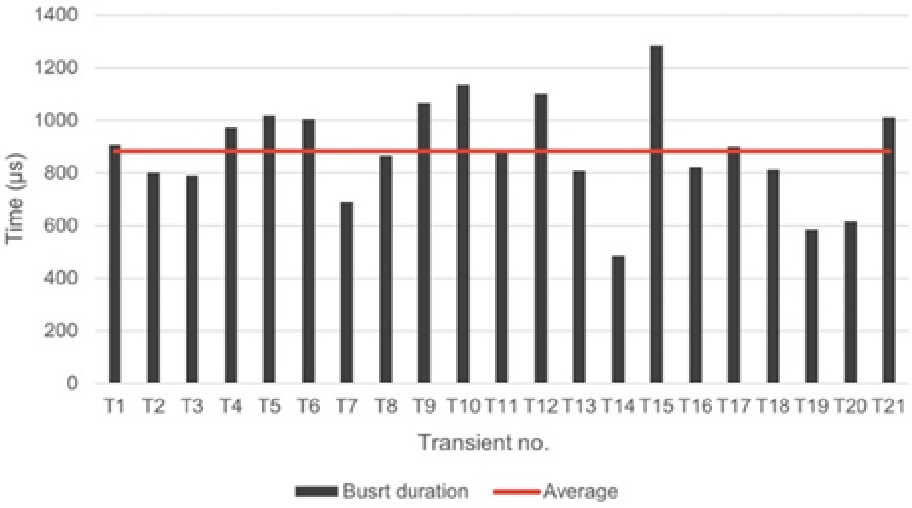

Fig. 7. Distribution of burst durations for Micro-transients.

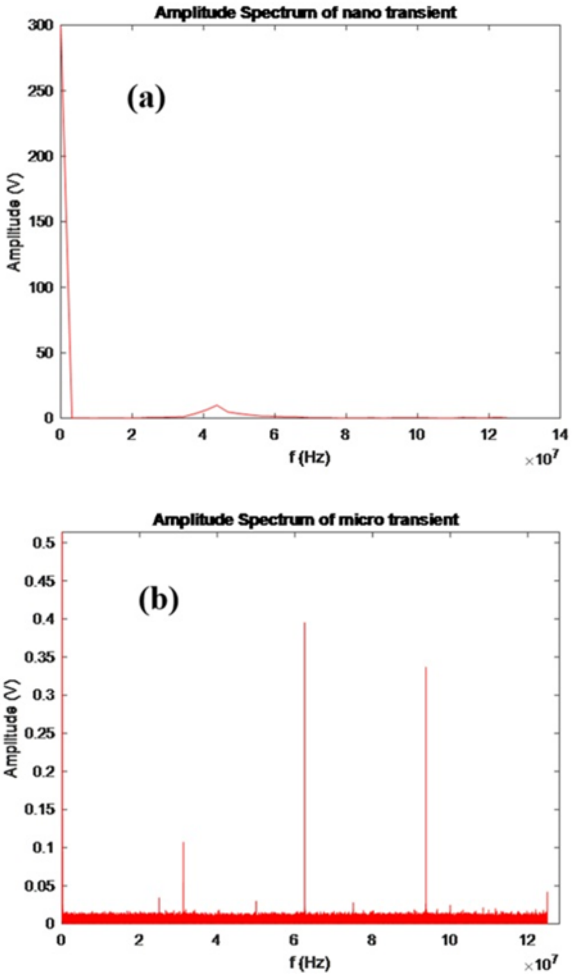

Fig. 8. Frequency-domain representation of (a) Nano transients and (b) Micro-transients.

These high-frequency components can significantly affect sensitive electronic components in solar inverters, including BJTs, MOSFETs, H-bridge circuits, and capacitors. The presence of multiple frequency components may contribute to harmonic distortion and voltage fluctuations, thereby degrading the overall power quality of the inverter output. In some cases, the existing filtering mechanisms in inverters may not be sufficient to suppress these high-frequency components, further deteriorating power quality.

4. Discussion

MOSFETs, IGBTs, and control circuitry within PV inverters. Therefore, nano-transients are more closely associated with immediate or catastrophic failures, whereas Micro-transients contribute more significantly to long-term degradation. The energy associated with a transient can be estimated by integrating the transient voltage squared over its duration, accounting for the system's load and output resistances [6,7,18]. Based on this principle, the analysis conducted in this study indicates that Micro-transients contain more energy than nano-transients, primarily due to their longer burst durations and higher amplitudes. Consequently, Micro-transients are more likely to contribute to thermal stress, insulation degradation, and reduced lifespan of electrical components. However, it is important to note that multiple Nano transients were frequently observed within a single waveform, indicating their repetitive nature. The cumulative effect of these high-frequency, short-duration transients may also pose a significant risk to PV systems. Repeated exposure to such events can lead to progressive degradation mechanisms, including dielectric fatigue and failure of protective circuits. Therefore, both Nano and Micro-transients must be considered in a comprehensive power quality assessment.

From a power network perspective, the presence of high-frequency transient components can adversely affect inverter performance and the quality of the output power supplied to the grid. These transients can propagate through the inverter and interact with switching devices, passive components, and control systems, potentially leading to harmonic distortion, electromagnetic interference, and instability in control loops. Furthermore, existing filtering mechanisms in standard inverters may not be sufficiently effective in mitigating high-frequency transient components, particularly in the MHz range identified in this study. To mitigate the adverse effects of such transients, several technical solutions are currently available. These include surge protection devices (SPDs), metal-oxide varistors (MOVs), transient-voltage-suppression (TVS) diodes, and RC snubber circuits, which are commonly used to limit voltage spikes and suppress high-frequency oscillations. In addition, improved grounding techniques, shielding, and optimized inverter design can further reduce the impact of transients. Advanced filtering approaches, such as high-frequency EMI filters and active filtering techniques, may also be required to address the multi-frequency characteristics observed in Micro-transients. These observations agree with previous studies indicating that power electronic interfaces in PV systems, particularly inverters, play a significant role in shaping power quality characteristics and may act as sources or propagation paths for transient disturbances [8,9].

While previous research has primarily focused on general power quality issues and low-frequency disturbances in PV systems [7–9], limited attention has been given to the characterization of high-frequency transient signatures in the nano- and microsecond ranges. Therefore, this study's findings provide new insights into the high-frequency transient behavior of domestic PV systems. Future improvements in PV system design should focus on enhancing the transient immunity of power electronic components and developing more effective suppression techniques tailored to the specific characteristics of Nano and Micro-transients. This includes optimizing circuit layouts to reduce parasitic inductance, improving inverter switching strategies, and integrating adaptive protection mechanisms that respond to high-frequency transient events.

5. Conclusion

This study investigated transient overvoltages in domestic grid-connected solar power systems in Sri Lanka, intending to characterize transient parameters and evaluate their impact on power quality and associated electrical and electronic components. Two types of oscillatory transients were identified: Nano transients and Micro transients, based on their burst duration. Nano transients had short nanosecond durations and fast rise and fall times, whereas micro transients had longer microsecond durations and higher amplitudes. These findings are consistent with existing literature on power quality issues in grid-connected PV systems, which highlights the impact of distributed generation on voltage stability and system disturbances [7–9]. Unlike previous studies that primarily focus on low-frequency disturbances and general power quality metrics, this study provides a detailed empirical characterization of high-frequency transient phenomena in domestic PV systems. This contribution is particularly important for understanding the mechanisms underlying transient-induced stress in modern power electronic devices.

The results indicate that Micro-transients possess higher magnitudes and energy levels, making them a significant contributor to the long-term degradation of system components. In contrast, Nano transients, despite their lower energy content, exhibit extremely fast switching characteristics that can induce high dv/dt stresses and cause sudden failures in sensitive electronic devices. The study further demonstrates that both types of transients can adversely affect the performance and reliability of photovoltaic systems. Continuous exposure to these transient events may lead to cumulative degradation, including latent failures and catastrophic damage in electronic components. Therefore, transient phenomena represent a critical power quality issue in domestic solar power systems. The findings of this study provide important insights into the transient behavior of PV systems and highlight the need for effective mitigation strategies. These results can support the design and implementation of improved transient suppression techniques, such as enhanced surge protection, optimized filtering, and robust inverter design, thereby improving power quality and system reliability.

The outcomes of this research can assist engineers and system designers in developing more robust PV systems by incorporating appropriate transient-mitigation techniques and improving the resilience of power-electronic interfaces under real operating conditions.

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