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IMPACT OF EMERGENCY BACKUP GENERATORS ON LOW-VOLTAGE POWER SYSTEMS: STABILIZATION, TRANSIENTS, AND HARMONIC ANALYSIS

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Abstract

This study investigates the effects of distributed electricity generation using emergency backup generators in low-voltage power systems (LVPS). Three generators, PERKINS FG WILSON P60 (G01), Denyo DCA-220SPK3 (G02), and Honda EG-1000X (G03), were analyzed in terms of stabilization time, switching transients, and frequency harmonics. A total of 15 start-up waveforms were recorded to evaluate stabilization behavior. The results show that G01 required 10.42 s and 11.77 s to reach a 2% voltage fluctuation level in positive and negative voltages, respectively, whereas G02 and G03 achieved stabilization within approximately 2.35 s and 1.66-1.73 s. Transient analysis of G01 revealed multiple switching patterns, with switching-off transients exhibiting higher peak-to-peak voltages (mean: 366.32 V) than switching-on transients (mean: 105.36 V), indicating a greater potential impact on connected loads. Oscillatory transients demonstrated an average burst duration of 123.1 µs and a mean frequency of 12.195 kHz. A linear inverse relationship between burst time and frequency was identified. Harmonic analysis showed that G01 operates at 52.21 Hz, slightly deviating from the nominal 50 Hz, while the grid supply exhibited higher harmonic content. These findings highlight the importance of generator design and control systems in ensuring power quality, stability, and reliability in LVPS applications.

Keywords. *Emergency Backup Generators, Low-Voltage Power Systems (LVPS), Voltage Stabilization, Switching Transients, Power Quality and Harmonics.*

1. Introduction

Papers Today's world is fast-moving with new technologies. As a result, numerous electrical and electronic devices have been developed to make people's work easier. The main power source for many of those devices is grid electricity. With the electrification of a vast array of household and office appliances, as well as transportation and educational systems, electricity demand is likely to continue increasing over time. One of the main factors in electricity consumption is the quality of the electricity, which is always significant. The rising demand for electricity, driven by the increasing use of electrical and electronic devices, has heightened the need for reliable, efficient power distribution networks. To meet this demand, low-voltage power systems (LVPS) have been developed as electrical distribution networks that operate at lower voltages than high-voltage transmission systems. LVPS supplies electricity to residential, commercial, and industrial consumers at voltages of 1000 V or less [1]. The quality of the voltage supplied by LVPS is crucial to ensure the smooth operation of various electrical and electronic devices. Emergency backup generators are essential in ensuring an uninterrupted power supply to critical loads during power outages or other emergencies. A backup generator provides an alternative power source to keep essential equipment and systems running even when the main power supply is unavailable. Backup generators are commonly used in healthcare facilities, data centers, communication networks, and other critical infrastructures to ensure continuous operation during power outages. In these applications, even a brief power outage can have severe consequences, including loss of life, data, or revenue. Previous studies have extensively investigated switching transients and surge phenomena in low-voltage power systems under various operating conditions. For instance, transient behaviors in domestic and industrial LVPS environments have been reported in [2-4], while similar transient characteristics have also been observed in automotive electrical systems [5]. Furthermore, the response of surge protective devices (SPDs) and varistors under high-current and fast impulse conditions has been widely studied [6-10], highlighting their critical role in mitigating transient over voltages. These studies emphasize the importance of understanding the transient characteristics and protection

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mechanisms in LVPS, particularly in environments with rapid switching and nonlinear loading conditions. Distributed generation of electricity refers to the production of electricity at or near the point of consumption, rather than centralized generation at large power plants. The concept of distributed generation has gained popularity in recent years due to its potential to improve energy efficiency, reduce transmission losses, and increase the reliability of the electricity grid [11]. Distributed generation involves using smaller-scale power generation technologies, such as solar panels, wind turbines, and backup generators, to generate electricity at or near the point of consumption. It is reported that the generator purchases over these years have rapidly increased [12]. The purpose of this study is to report and analyze the technical effects of distributed electricity generation using emergency backup generators in LVPS. This is a revelation that possibly influences the quality of the power system. Emergency backup generators are widely used for power interruptions in LVPS. Reporting the important observations and analysis of these data is more important for further improvement in power quality and safety reasons [13]. This study analyzes voltage stabilization time, transient conditions, and frequency harmonics.

2. Experimental Setup

Fig. 1(a) illustrates the block diagram of the experimental setup, including the measurement system used for the study, whereas Fig. 1(b) provides a pictographic overview of the experimental and measurement systems.

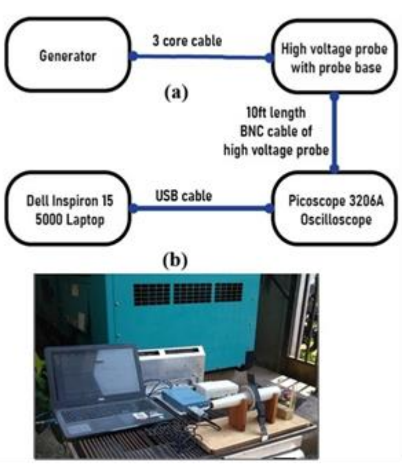

Fig. 1. Experimental and Measurement System. (a) Block diagram of the experimental and measuring system. (b) Pictographic overview.

Measurements were taken from three generators designed for Low Voltage Power Systems (LVPS). Selected three generators are; Generator 01 (G01): PERKINS FG WILSON P60 (60 kVA / 48 kW three-phase Generator), Generator 02 (G02): Denyo DCA-220SPK3 (220 kVA / 176 kW three- phase Generator), and Generator 03 (G03): Honda EG 1000x (850 VA single-phase Generator). A Tektronix P6015A 1000× attenuated high-voltage probe with a PicoScope 3206A, which has 100 MΩ input impedance and 75 MHz bandwidth, was used to collect voltage waveform data. With a 1 GS/s sampling rate, the Picoscope 3206A can capture signals with high precision and detail [14]. This means that even the subtlest changes in voltage can be detected and analyzed [2-5]. The Picoscope 3206A is powered by USB power from a Dell Inspiron 15 5000 laptop. While capturing data, this laptop operates on its battery and isolates the main power supply to remove common-mode noise at 50 Hz.

3. Methodology

The setup to study the effects of distributed electricity generation with backup generators involved careful planning and arrangement of measurement equipment to ensure accurate data and reduce interference. The experiment aimed to record the generator's output voltage over time, using a common-mode measurement approach. A three-core cable with banana clips was connected to the probe base. This setup allowed the AC voltage to travel through the three-core cable to the probe base, where it was connected to a high-voltage (HV) probe. To establish a stable reference point, the probe's ground clip was also attached to the ground line of the three-core cable. From the high-voltage probe (HV probe), a BNC cable was connected to Channel A of the PicoScope 3206A, which was connected to a Dell Inspiron 15 5567 laptop via a USB cable. Data was collected using PicoScope 7 software.

The 1-meter three-core cable carrying AC power, the 10 ft HV probe cable, and the PicoScope data cable (USB cable) were carefully laid out without crossing each other. Fig. 1(b) visualized the layout of the measurement system, including the electric distribution panel, standard three-core cable, HV probe with 10 ft BNC cable, PicoScope oscilloscope, and battery-powered laptop. In the Picoscope software, the low-pass filtering feature, activated in this study, allows applying a noise filter to a selected input channel to reject high-frequency noise. It was used to filter the recorded data to facilitate data analysis [2-4]. To analyze the stabilization time following generator start-up, waveforms were

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recorded using a sampling rate of 100 MS/s. Subsequently, all acquired signals were processed with a 200 Hz low-pass filter to improve the analysis. For transient characterization, both switch-on and switch-off events were examined. The study primarily focused on evaluating parameters such as stabilization time, peak-to-peak voltage, and burst duration. In addition, Fourier-transformed waveforms were employed to investigate the associated frequency harmonics.

4. Results & Observations

Based on the observed dataset, three principal analyses were performed. These comprised an assessment of the stabilization time of the emergency backup generator, an investigation of switching transients during generator operation, and an analysis of the generator's output frequency harmonics. The corresponding results and salient observations from each analysis are presented and discussed in the subsequent sections.

4.1. Analysis of Stabilization Time in LVPS Emergency Backup Generators

Observations indicate that, upon start-up, LVPS emergency backup generators require a finite time to deliver stable, acceptable-quality power output. This stabilization period can be influenced by several factors, including the generator start-up mechanism, fuel type, engine capacity, load characteristics, and associated control systems. If the electrical system is connected to the backup power source prior to voltage stabilization, it may result in improper operation or malfunction of connected equipment. Consequently, determining the stabilization time following generator start-up is critical. Analysis of the voltage-time dataset recorded during the switch-on of the emergency backup generator revealed a distinct and repeatable pattern, as illustrated in Fig. 2. Fig. 2(a) presents the raw voltage data captured from G01, illustrating the positive and negative peaks of the sinusoidal waveform. As shown in Fig. 2(b), the extracted peak points of the voltage waveform exhibit a distinct pattern. The sequence of these peak values can be further utilized to perform a detailed analysis of voltage fluctuations during generator operation.

Fig. 3(a) presents the analyzed peak datasets captured from Generator One (G01). All datasets exhibit a consistent pattern during generator start-up, indicating similar voltage behavior across repeated observations. Fig. 3(b) further illustrates the voltage differences between successive peak points, which are used to examine the generator's start-up characteristics in greater detail. After analyzing all datasets captured from Generator Two (G02), the voltage differences of the positive-side peak points are presented in Fig. 3(c). As shown in Fig. 3(b), voltage fluctuations exceeding 20 V were observed during the initial 4.56 s of operation for G01, indicating an unstable voltage output during the early start-up phase. A similar voltage fluctuation pattern was observed for G02. To analyze the stabilization time of the voltage output in Generator Three (G03), five datasets were examined. The final results of the positive-side peak voltage difference analysis for G03 are illustrated in Fig. 3(d).

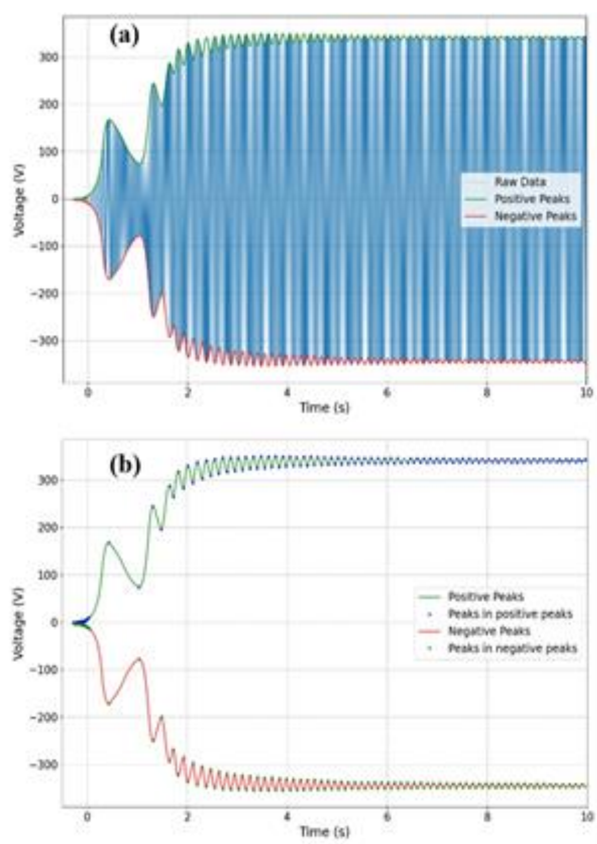

Fig. 2. Voltage variation as a function of time, showing the positive and negative peaks of the sinusoidal waveform: (a) raw voltage data captured from G01, and (b) identified peak points of the voltage sinusoidal waveform.

As shown in Fig. 4, Generator Two (02) reaches a stable voltage output in less than 2.5 s, while Generator Three (03) stabilizes in under 2 s.

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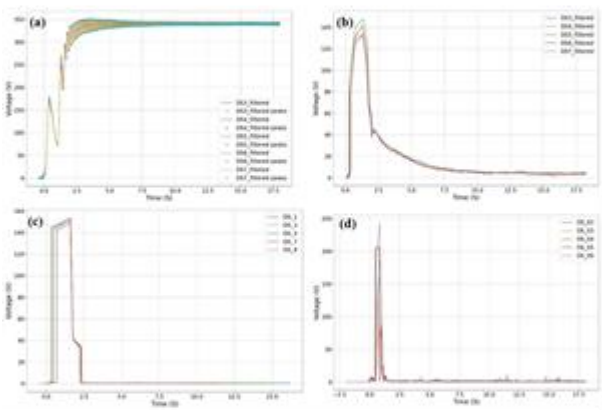

Fig. 3. Visualization of sinusoidal voltage waveform analysis of generators: (a) positive peaks of the voltage waveform captured from G01; (b) voltage differences between successive peak points for G01; (c) voltage differences between successive peak points for G02; and (d) voltage differences between successive peak points for G03.

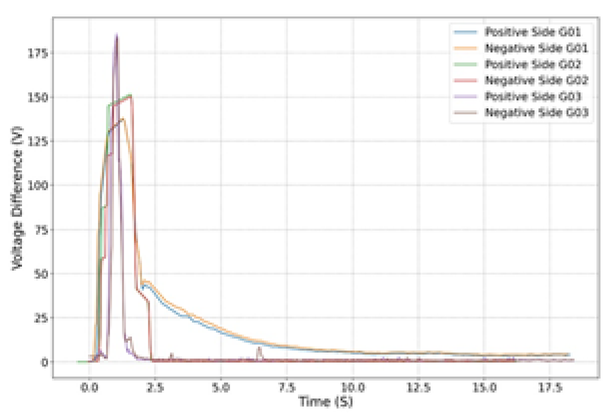

Fig. 4. Peak voltage differences observed during the start-up of generators G01, G02, and G03.

In contrast, Generator One (01) exhibits small voltage fluctuations even after 17.5 s. For further analysis, a 2% voltage fluctuation threshold was assumed to represent an acceptable level of stability. The stabilization time analysis indicates that the mean time required for G01 to reach an acceptable level is 10.42 s (±0.56 s) for positive voltage and 11.77 s (±1.56 s) for negative voltage. In comparison, G02 stabilizes significantly faster, with a mean time of 2.35 s (±0.05 s) for positive voltage and 2.34 s (±0.03 s) for negative voltage. G03 demonstrates the fastest response, with mean stabilization times of 1.66 s (±0.04 s) for positive voltage and 1.73 s (±0.05 s) for negative voltage. These results indicate that G03 exhibits the quickest stabilization performance, while G02 provides a balance between rapid response and high stability, and G01 shows comparatively slower dynamic performance.

4.2 Analysis of Stabilization Time in LVPS Emergency Backup Generators

Analysis of switching transients in LVPS emergency backup generators is critical, as these transient events can significantly affect power quality and the reliable operation of connected equipment in power systems [4]. Switching transient analysis serves multiple critical purposes in evaluating the performance of emergency backup generators. First, switching transients can influence the operational performance of connected electronic systems; therefore, measuring these transients enables assessment of the system response to switching events and verification of compliance with required performance criteria. Second, switching transients may act as indicators of underlying faults or abnormal operating conditions. Deviations from expected transient characteristics can be identified through detailed analysis, facilitating effective fault diagnosis and system troubleshooting. Finally, from a reliability and safety perspective, improperly managed switching transients can impose excessive electrical stress on system components, potentially leading to component degradation or catastrophic failure. Quantifying transient behavior enables evaluation of component stress levels and ensures safe operation, thereby improving overall system reliability and safety.

The switching transients of Generator One were recorded and analyzed under practical operating conditions, with the entire Physics Department building of the University of Colombo serving as the load. Both switch-on and switch-off transient events were captured during the experimental measurements. The observed data revealed distinct transient patterns associated with the different switching conditions.

4.2.1 Switching Transient Patterns

Fig. 5(a) illustrates a sample waveform recorded from Generator One during a switching-off event, showing the presence of transient phenomena. Fig. 5(b)-5(e) present expanded views of different transient patterns observed during switching off generator 1. The transient pattern A shown in Fig. 5(b) exhibits oscillatory behavior, with a peak-to-peak voltage of 405.430 V and a burst duration of 118.9 μs. According to IEEE 1159, this can be categorized as an oscillatory transient [15]. Fig. 5(c) also demonstrates an oscillatory transient;

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however, an abnormal response is observed at the initial stage of the waveform. This transient (Pattern B) has a peak-to-peak voltage of 401.570 V and a burst duration of 136.6 µs. Similarly, Fig. 5(d) shows Pattern C, an oscillatory transient with an initial abnormal behavior: the waveform begins with a sudden voltage peak, followed by a regular oscillatory pattern. This transient has a peak-to-peak voltage of 374.050 V and a burst duration of 128.5 µs. Fig. 5(e) is also characterized as an oscillatory transient (Pattern D) and shows abnormal behavior at the onset, with a peak-to-peak voltage of 464.660 V and a burst duration of 123.2 µs. These observed patterns are consistent with the oscillatory transient behavior defined in IEEE 1159 [15], which is typically associated with system switching operations and energy exchange between reactive components. Fig. 5(f) illustrates the typical switching-on transient pattern (Pattern E), which can be classified as an impulsive transient in accordance with IEEE 1159 [15]. This transient exhibits a peak-to-peak voltage of 187.640 V and a sudden, non-oscillatory change in voltage.

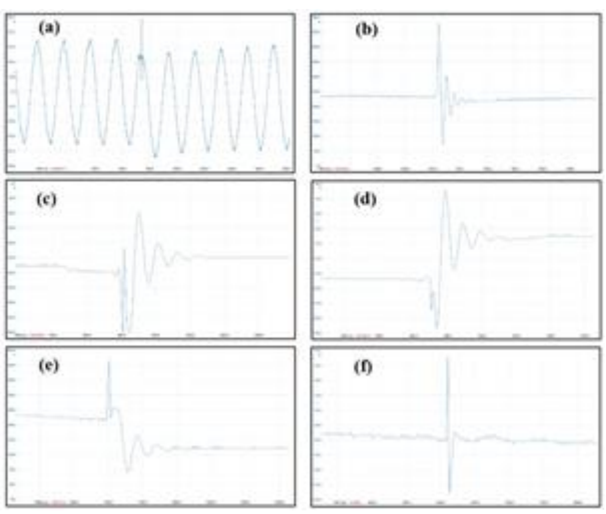

Fig. 5. Switching transient patterns observed in Generator One: (a) waveform showing recorded transients; (b) switching-off transient Pattern A; (c) switching-off transient Pattern B; (d) switching-off transient Pattern C; (e) switching-off transient Pattern D; and (f) switching-on transient Pattern E.

4.2.2 Peak-to-Peak Voltages of Switching Transients

Ten datasets were acquired during both switching-on and switching-off events of Generator One. The peak-to-peak voltage values of the resulting transients were measured manually using PicoScope software. The distribution of the measured data can be initially visualized using a scatter plot to provide a general understanding of the variability within each transient type, switching-on and switching-off, as shown in Fig. 6(a) and Fig. 6(b), respectively. The dataset mean is 105.36 V, representing the average peak-to-peak voltage of the switching-on transients. The median, 87.06 V, is lower than the mean, indicating a right-skewed distribution with a tendency toward higher voltages. The minimum and maximum peak-to-peak voltages were 35.437 V and 174.990 V, respectively. The standard deviation is 41.80 V, indicating substantial dispersion of individual measurements around the mean and highlighting significant variability in peak-to-peak voltage.

The mean peak-to-peak voltage of measured switching-off transients was 366.32 V, while the median was 403.5 V, indicating slight skewness in the distribution. The minimum and maximum peak-to-peak voltages were 31.497 V and 464.66 V, respectively. The standard deviation was 120.91 V, reflecting a high level of variability in the measured values.

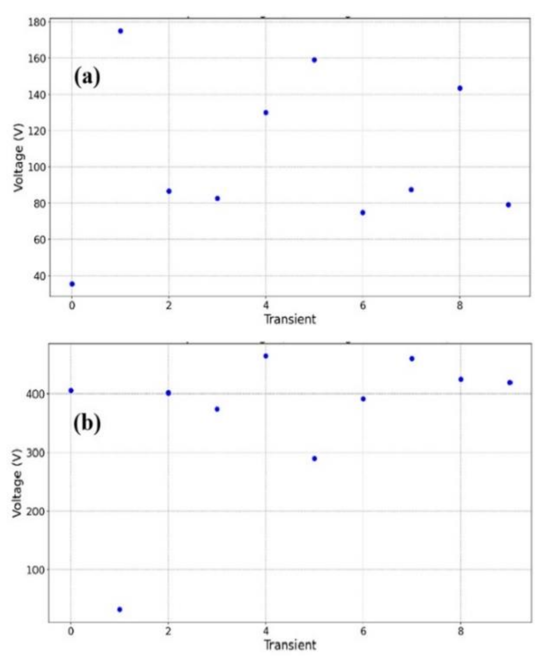

Fig. 6. Scatter Plot of Peak-to-Peak Voltages of Switching Transients. (a) Switching-on Transients (b) Switching-off Transients.

The statistical analysis of the peak-to-peak voltage values for switching-off transients provides important insights into their characteristics.

Understanding the statistical properties of these transients is crucial for designing and protecting electrical systems. The relatively high standard deviation indicates a wide dispersion of voltage values, suggesting significant variability in transient behavior. The range between the minimum and maximum values highlights the extent of voltage fluctuations, while the quartiles provide further insight into the data distribution. These findings are valuable for the design and protection of electrical systems, particularly in mitigating the impact of voltage transients.

4.2.3 Oscillatory Transients

Using the collected waveforms, oscillatory transients were identified, and their corresponding burst durations and frequencies were measured and recorded. Scatter plots were employed to visualize the distribution of raw data associated with transient events. Separate scatter plots were constructed for burst duration (Fig. 7(a)) and frequency (Fig. 7(b)). As shown in Figure 12(a), the burst durations are within the microsecond range. For the oscillatory transients observed in the collected waveforms, the majority of burst durations lie between 114.8 μs and 136.6 μs, with only one transient exhibiting a shorter duration of 100.7 μs. As observed, the oscillatory transients predominantly range from 10.31 kHz to 14.15 kHz, with a single higher value at 19.72 kHz.

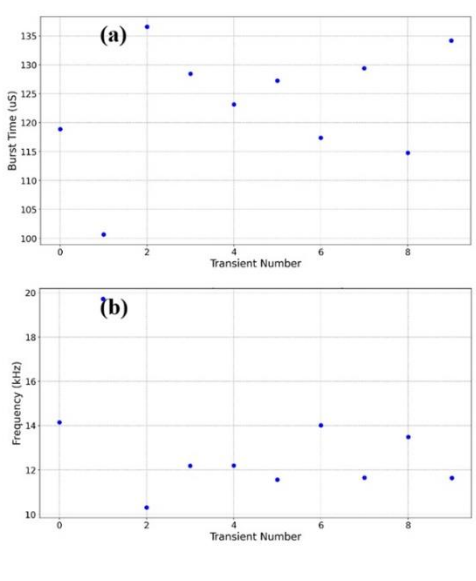

Fig. 7. Graphical visualization of Burst Times and Frequencies in Oscillatory Transients data. (a) Scatter Plot of Burst Times (b) Scatter Plot of Frequencies.

The burst time distribution for oscillatory transients shows a mean value of 123.1 μs and a median of 125.25 μs. The standard deviation of 10.06 μs indicates relatively low variability in burst durations. Similarly, the frequency characteristics of the oscillatory transients exhibit a mean of 13.093 kHz and a median of 12.195 kHz, with a standard deviation of 2.489 kHz. To further investigate the relationship between these parameters, a frequency-versus-burst-time plot was generated, enabling a comparative analysis of the interaction between transient duration and frequency. As illustrated in Fig. 8, the frequency and burst time datasets exhibit a clear inverse relationship, where an increase in frequency corresponds to a decrease in burst duration.

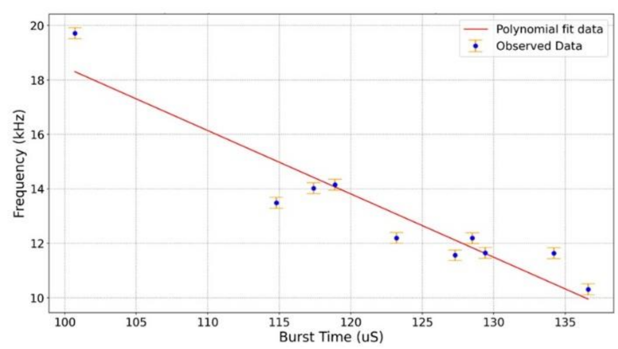

Fig. 8. Plot of Fitted data (Frequency Vs Burst Time)

4.3. Frequency Harmonic Analysis of LVPS Emergency Backup Generators

Frequency harmonic analysis was conducted to evaluate the distortion characteristics of generator output in comparison with the CEB power supply. Fourier analysis was employed to extract the dominant frequency components from the recorded voltage waveforms. The results indicate that Generator One (G01) operates with a fundamental frequency of 52.21 Hz and an amplitude of 46.96 dBu, showing a slight deviation from the nominal grid frequency. In contrast, the CEB power supply exhibits a fundamental frequency of 50.07 Hz with an amplitude of 49.65 dBu, which closely aligns with the standard 50 Hz supply. In addition to the fundamental component, G01 shows several harmonics, with notable frequencies at 260.59 Hz and 365.02 Hz. However, the harmonic content of the CEB supply is comparatively higher, with a broader distribution of high-amplitude frequency components extending to higher frequency ranges. This increased harmonic presence in the grid supply can be attributed to the influence of diverse industrial and domestic loads, including inductive and capacitive equipment connected to the network. Fig. 9

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presents a comparative visualization of the Fourier spectra of G01 and the CEB power supply. As illustrated, neither source produces a perfectly sinusoidal waveform; however, the CEB supply exhibits a denser harmonic spectrum compared to the generator output. These findings suggest that, despite a slight deviation in fundamental frequency, generator-supplied power may offer advantages in applications requiring lower harmonic distortion, particularly for frequency-sensitive equipment.

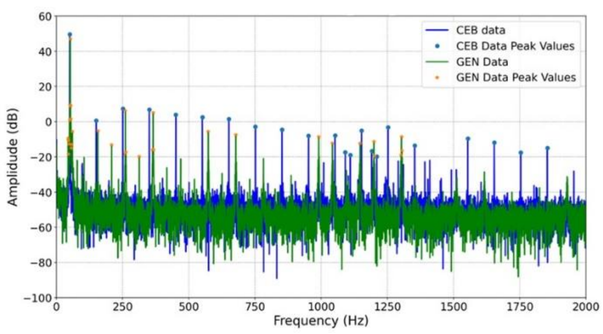

Fig. 9. Comparison of Fourier transform spectra of Generator One and the CEB power supply

5. Discussion

Emergency backup generators are widely used as an alternative power source during supply interruptions; therefore, it is essential to evaluate their performance and impact when integrated into low-voltage power systems (LVPS). In such systems, the alternator is driven by a fuel-powered engine, and the output voltage is directly proportional to the engine's rotational speed. Consequently, a finite duration is required for the generator to reach a stable operating condition. In addition, the generator control system requires time to regulate output parameters, such as voltage and frequency, to their rated values.

The results indicate that generator start-up is associated with a transient stabilization period during which voltage fluctuations occur. As shown in Fig. 4, G01 exhibits significant voltage variation during the initial 2 s, followed by a gradual reduction in fluctuation as the system approaches steady-state operation. Quantitatively, G01 requires 10.42 s (±0.56 s) to reach a 2% fluctuation level in the positive voltage and 11.77 s (±1.56 s) in the negative voltage. In comparison, G02 stabilizes more rapidly, achieving the same threshold within 2.35 s (±0.05 s) for positive voltage and 2.34 s (±0.03 s) for negative voltage. G03 demonstrates the fastest response, reaching the 2% fluctuation level in 1.66 s (±0.04 s) for positive voltage and 1.73 s (±0.05 s) for negative voltage.

The comparatively slower stabilization of G01 may be attributed to older control technologies, as the generator was manufactured in 1996. In contrast, G02 likely incorporates more advanced control mechanisms, resulting in improved performance. Notably, G02 achieves an overall voltage fluctuation level of 0.1% within 2.41 s (±0.03 s), indicating superior stability. Although G03 stabilizes rapidly, its overall performance is comparatively lower than that of G02, suggesting that rapid stabilization alone does not necessarily correspond to higher operational stability.

Transient analysis further revealed distinct switching transient patterns. A key observation is the difference in peak-to-peak voltage levels between these events. For G01, the mean peak-to-peak voltage of switching-on transients is 105.36 V with a standard deviation of 41.80 V, whereas switching-off transients exhibit a significantly higher mean value of 366.32 V and a standard deviation of 120.91 V. This indicates that switching-off transients impose greater electrical stress on connected loads and may therefore be more detrimental. Additionally, a DC component was observed following certain switching-off events, which may further influence system behavior.

Analysis of oscillatory transients in G01 shows a mean frequency of 12.195 kHz and a standard deviation of 2.489 kHz, while burst durations exhibit relatively low variability. A clear inverse relationship between burst time and frequency was identified (Fig. 8). This relationship was quantified using the polyfit function in Python, yielding the linear expression given in Eq. (1).

$$\textit{Frequency} = -0.2327(\textit{Burst time}) + 41.7374 \qquad (1)$$

This behavior is consistent with the physical characteristics of damped oscillatory systems, where longer-duration transients tend to be associated with lower dominant frequencies. Further analysis of transient effects can be conducted through power-based evaluations, as the impact of transients on electrical systems is primarily governed by the energy injected during these events. Given the high voltage levels observed during transients, such analysis is essential for assessing potential risks to system components and for ensuring appropriate protection strategies [16]. The power associated with transient events can be estimated from the system's output and load resistances, as given in Eq. (2).

$$W = \left(\frac{1}{R_{OUT}+R_L}\right) \cdot \left(\frac{R_L}{R_{OUT}+R_L}\right) \cdot \int_0^\infty V^2 \, dt \qquad (2)$$

Such power-based analysis provides further insight into the potential impact of transients, as the energy injected into the system during these events is a key factor influencing component stress and system reliability. Frequency harmonics significantly distort the ideal sinusoidal nature of AC power; therefore, their analysis is essential for the effective design and improvement of generator systems. According to the results, Generator One exhibits a fundamental frequency of 52.21 Hz with an amplitude of 46.96 dBu. A meaningful interpretation of these harmonics can be achieved by comparing them with the CEB power supply. The CEB system operates at a fundamental frequency of 50.07 Hz with an amplitude of 49.65 dBu, which closely aligns with the nominal grid frequency of 50 Hz used in Sri Lanka. In contrast, the fundamental frequency of G01 shows a slight deviation from this rated value. However, when considering the overall harmonic content, the CEB supply exhibits more harmonic components than G01. This is likely due to the presence of diverse industrial and domestic loads connected to the grid, including inductive and capacitive equipment, which contribute to harmonic distortion.

The observed oscillatory transient characteristics in this study are consistent with previously reported behaviors in low-voltage systems and surge environments [6-9]. The relationship between transient parameters, such as burst duration and frequency, can be linked to the dynamic response of nonlinear components and the system impedance, as discussed in [9, 10, 17]. Moreover, the high variability in peak-to-peak voltages during switching-off events aligns with earlier findings on surge propagation and varistor response under fast impulse conditions [6-10]. These similarities validate the experimental observations and highlight the relevance of established transient and protection models in interpreting generator-induced disturbances. It should be noted that both G01 and G02 are three-phase generators; however, the present study considered only a single phase from each system. A more comprehensive analysis incorporating all three phases would provide a more complete representation of generator performance. Furthermore, the study is subject to certain limitations. The sample size was restricted to three generators, which may limit the generalizability of the findings to other generator types and operating conditions. Practical constraints, including time and fuel costs, limited the extent of data collection. In addition, the analysis focused primarily on stabilization time, switching transients, and frequency harmonics, while other important performance factors such as efficiency, long-term reliability, and acoustic emissions were not considered. Future studies should address these aspects to provide a more holistic evaluation of emergency backup generator performance.

6. Conclusion

This study emphasizes the importance of evaluating the performance of emergency backup generators in low-voltage power systems (LVPS), particularly during power interruptions. Although generators are widely used as alternative power sources, the quality of their output varies depending on design characteristics, control mechanisms, and operating conditions. The analysis of stabilization behavior revealed that generators require a finite duration to reach acceptable voltage levels following start-up. G01 exhibited the slowest stabilization, requiring 10.42 s (±0.56 s) for positive voltage and 11.77 s (±1.56 s) for negative voltage to reach a 2% fluctuation threshold. In contrast, G02 achieved stabilization within 2.35 s (±0.05 s) and 2.34 s (±0.03 s), while G03 demonstrated the fastest response, stabilizing within 1.66 s (±0.04 s) and 1.73 s (±0.05 s), respectively. These results highlight the significant influence of generator technology and control systems on dynamic performance. Transient analysis identified multiple switching-on and switching-off transient patterns, with switching-off transients exhibiting substantially higher peak-to-peak voltages and variability. This indicates that switching-off events impose greater electrical stress on connected loads and may pose a higher risk to system components. In addition, oscillatory transients were observed, and a clear inverse relationship between burst duration and frequency was established, demonstrating the underlying dynamic properties of the transients. Such findings underline the importance of transient analysis in assessing system reliability and protection requirements. Harmonic analysis further revealed that the fundamental frequency of G01 (52.21 Hz) deviates slightly from the nominal grid frequency, whereas the CEB supply (50.07 Hz) closely matches the standard 50 Hz value. Despite this deviation, the CEB power supply exhibited higher harmonic distortion than the generator output, likely due to the influence of diverse industrial and domestic loads connected to the grid. This suggests that generator-supplied power may offer advantages in applications requiring lower harmonic distortion. It is important to note that this study limited its analysis to a single-phase approach despite the generators' three-phase configuration. A more comprehensive evaluation incorporating all phases would provide a more complete understanding of generator performance. Additionally, the study was confined to three generators and focused primarily on stabilization time, transient behavior, and harmonic characteristics. The findings are consistent with existing studies on transient behavior and surge protection mechanisms in LVPS, reinforcing the importance of coordinated protection and system design strategies [6-10, 17]. Future work should consider a broader range of generators and include additional performance metrics such as efficiency, reliability, and noise emissions. Overall, this study provides valuable insights into the operational characteristics of emergency backup generators in LVPS and highlights the need for improved control strategies and advanced technologies to enhance their performance, stability, and power quality.

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