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Experimental Evaluation and Noise-Aware Optimization of DC Voltage Measurement Systems under High-Frequency Switching Disturbances in Electric Vehicles

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ABSTRACT: Accurate DC voltage measurement is a critical aspect in electric vehicle systems, particularly in battery management systems (BMS) and energy monitoring applications. However, the presence of switching disturbances generated by power electronic devices such as DC-DC converters and PWM-based inverters can degrade signal quality and lead to measurement errors. This study aims to evaluate the impact of switching disturbances on the accuracy of a resistive divider-based DC voltage measurement system, as well as to investigate the effectiveness of noise reduction techniques in improving signal quality.The proposed method employs an experimental approach with variations in switching frequency ranging from 1 kHz to 20 kHz, duty cycles between 0.3 and 0.8, and different load conditions, including resistive, RL, and dynamic loads. The analysed parameters include average voltage, RMS voltage, voltage ripple, as well as measurement error and root mean square error (RMSE) with respect to reference values.The results indicate that under disturbance-free conditions, the system achieves an average measurement error below 2%. However, as the switching frequency increases, the error rises significantly to above 10%, primarily due to the dominance of high-frequency noise and voltage spikes. The implementation of filtering techniques, including RC filters, LM358-based signal conditioning, and digital filtering, has been proven to reduce the error to approximately 2–5% while significantly enhancing signal stability.This study contributes to a deeper understanding of the relationship between switching disturbances and voltage measurement accuracy, and provides practical solutions for improving the reliability of voltage sensing systems in electric vehicle applications.

KEYWORDS:DC Voltage Measurement; Switching Noise; Electric Vehicles (EVs); Signal Conditioning; Measurement Accuracy

I. INTRODUCTION

The rapid development of electric vehicles (EVs) in recent years has been driven by the increasing demand for environmentally friendly and energy-efficient transportation systems. Modern EV systems heavily rely on power electronic devices, such as DC-DC converters, inverters, and battery management systems (BMS), which are responsible for regulating and distributing electrical energy efficiently. However, the switching-based operation of these devices introduces new challenges, particularly in terms of signal quality and measurement accuracy[1][2][3]. DC voltage measurement plays a critical role in EV systems, especially within the BMS, which is responsible for real-time monitoring of battery conditions. The accuracy of voltage measurement directly affects the estimation of key parameters such as state of charge (SoC) and state of health (SoH), ultimately influencing system performance, efficiency, and safety[4][5].Inaccurate voltage measurements may lead to incorrect control decisions, thereby reducing the overall reliability of the system[6]. Numerous studies have been conducted to enhance the accuracy of DC voltage measurement systems, including improvements in sensor design, calibration techniques, and advanced signal processing methods. Studies by Bensaad et al. [7] and Kalaiarasu et al.[8] have demonstrated that high-precision measurement systems can achieve excellent accuracy under controlled laboratory conditions. However, such conditions do not fully represent the real operating environment of EV systems, which are significantly affected by electromagnetic disturbances. One of the primary sources of disturbance in EV systems is the switching operation of power converters. Pulse-width modulation (PWM) techniques used in inverters and DC-DC converters generate harmonic components and high-frequency noise that can degrade signal quality[9][10]. Furthermore, high dv/dt and di/dt during switching transitions can induce voltage spikes and significant electromagnetic interference (EMI) [11][12]. These switching disturbances directly impact voltage measurement systems, particularly those based on microcontrollers utilizing analog-to-digital converters (ADCs) with limited resolution. The presence of noise introduces signal fluctuations, increases voltage ripple, and causes distortion, all of which degrade measurement accuracy 13]. This issue is further exacerbated by inherent ADC limitations, such as quantization error and non-linearity, which become more sensitive under noisy conditions [13].

To address these challenges, various approaches have been proposed, including passive filtering, active filtering using operational amplifiers, and EMI reduction techniques. Research by Duhme & Bumiller [14] and Pathala&Pappu[15]. has shown that RC filters and op-amp-based signal conditioning can significantly improve signal quality. In addition, digital filtering techniques, such as moving average and low-pass filtering, have proven effective in reducing noise and enhancing measurement stability[16]. Despite these advancements, most existing studies primarily focus on power converter design or control strategies, while the instrumentation aspect, particularly voltage measurement using simple resistive divider-based sensors, remains relatively underexplored under realistic switching disturbance conditions. Moreover, the quantitative relationship between switching frequency, noise characteristics, and measurement error has not been comprehensively addressed in the existing literature.

Based on this research gap, this study aims to experimentally evaluate the impact of switching disturbances on the accuracy of DC voltage measurement systems in electric vehicles. Furthermore, this work investigates the characteristics of noise generated by power converters and evaluates the effectiveness of noise reduction techniques in improving signal quality and measurement accuracy. The main contributions of this study include: (1) the development of a resistive divider-based voltage measurement system integrated with signal conditioning circuits, (2) a quantitative analysis of the impact of switching frequency on measurement error, (3) characterization of noise and voltage ripple in EV power systems, and (4) evaluation of both analog and digital filtering techniques to enhance measurement accuracy. Therefore, this study is expected to contribute significantly to the development of reliable instrumentation systems for electric vehicle applications, particularly in environments with high switching disturbances.

II. EXPERIMENTATION

This study employs an experimental approach combined with quantitative analysis to evaluate the impact of switching disturbances on the accuracy of DC voltage measurement systems in electric vehicles. This approach is selected as it effectively represents real operating conditions in EV systems, which are dominated by power electronic devices such as DC-DC converters and inverters, known as primary sources of electromagnetic interference and switching noise.In the initial stage, a voltage sensing system based on a resistive divider is designed to reduce high input voltage levels to a safe range suitable for microcontroller processing. The DC input voltage obtained from the test source is conditioned using the voltage divider principle, ensuring that the output voltage remains within the operating limits of the analog-to-digital converter (ADC). The relationship between the input and output voltages is expressed as follows:

$$V_{out} V_{in} \times \frac{R_2}{R_1 + R_2} \qquad (1)$$

Subsequently, appropriate resistor values are selected to ensure that the output voltage remains within a safe range for the ADC. In this study, resistor values of R1=220kΩ andR2=10kΩ are employed, enabling the system to measure input voltages up to approximately **115 V DC**, while maintaining a maximum output voltage of **5 V**, in accordance with the ADC specifications. The selection of these resistor values is based on several considerations, including measurement sensitivity, power dissipation, and system stability under noise conditions.

To further enhance signal quality, the sensor circuit is integrated with additional signal conditioning components. A diode is incorporated to provide protection against reverse polarity, while a capacitor is utilized as a passive filter to attenuate high-frequency noise. In addition, an LM358 operational amplifier is employed as a buffer and signal amplifier to improve input impedance and minimize loading effects. This combination is designed to ensure that the signal fed into the ADC exhibits stable and representative characteristics, thereby improving the reliability and accuracy of the measurement system.

The third stage involves experimental testing conducted under two main conditions, namely the baseline condition and the switching disturbance condition. In the baseline condition, the system is tested using a stable DC voltage source without any switching disturbances, in order to obtain a reference value for sensor accuracy. Subsequently, under the disturbance condition, the system is evaluated by varying the switching frequency, duty cycle, and load types. For each test condition, voltage measurements are performed, data are recorded, and waveform characteristics are observed using an oscilloscope.The data acquisition process is carried out using a microcontroller to read the voltage signal through the ADC, while a high-precision digital multimeter is employed as a reference instrument to ensure measurement validity. The oscilloscope is utilized to visually analyze signal characteristics, particularly to identify the presence of ripple and noise induced by switching disturbances. The collected data are then recorded and processed for further analysis.

In the fourth stage, signal analysis is performed by calculating key parameters, including average voltage, RMS voltage, and voltage ripple. These parameters are used to comprehensively characterize the signal behavior under different operating conditions. In addition, sensor accuracy is evaluated by computing the percentage error and root mean square error (RMSE) based on the comparison between the sensor measurements and reference values. This analysis enables the identification of measurement deviations under each test condition.The subsequent stage focuses on noise characterization, which is conducted by analyzing signal fluctuation amplitudes and examining the relationship between switching frequency and measurement error. The analysis reveals that an increase in switching frequency tends to amplify noise and signal distortion, thereby directly affecting measurement accuracy. To address this issue, several noise reduction techniques are implemented, including passive RC filtering, active filtering using an operational amplifier, and digital filtering based on the moving average method. Each method is applied progressively to evaluate its effectiveness in improving signal quality. The measurement results before and after filtering are then compared to assess the overall improvement in system performance.The analyzed parameters include the average voltage(V_{mean}), root mean square (RMS) voltage(V_{rms}), and voltage ripple(V_{pp}). These parameters are selected to provide a comprehensive representation of the signal characteristics, including both steady-state behavior and fluctuations caused by switching disturbances.The accuracy of the measurement system is evaluated by comparing the sensor output with the reference value using the following expression:

$$\%Error = \left|\frac{V_{sensor} - V_{ref}}{V_{ref}}\right| \times 100\% \qquad (2)$$

In addition, the Root Mean Square Error (RMSE) is employed as a performance metric to provide a more comprehensive evaluation of the measurement accuracy;

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(V_{sensor,i} - V_{ref,i})^2} \qquad (3$$

Noise analysis is conducted by evaluating the amplitude of signal fluctuations, voltage ripple, and the relationship between switching frequency and measurement error. To improve signal quality, several noise reduction techniques are implemented, including passive RC filtering, the use of an operational amplifier as an active filter and buffer, and digital filtering based on the moving average method.

The final stage involves evaluating the overall system performance by comparing the measurement results before and after the application of filtering techniques. The evaluation is based on key performance indicators, including error reduction, ripple attenuation, and improvement in signal stability. These parameters are used to assess the effectiveness of the proposed noise mitigation methods in enhancing the accuracy and reliability of the DC voltage measurement system.

III. RESULT AND DISCUSSION

3.1 DC Voltage Measurement under Baseline Condition

In the initial stage, the DC voltage measurement system is tested under a disturbance-free condition (baseline) using a stable DC voltage source. The measurement results presented in Table 1 indicate that the resistive divider-based sensor is capable of producing values that closely match the reference voltage measured using a high-precision digital multimeter. The observed deviation remains relatively low, within less than 2%, demonstrating that the proposed sensing circuit achieves a high level of accuracy under ideal operating conditions.

The average measurement error under baseline conditions is approximately 1.26%, indicating that the proposed DC voltage sensing

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system exhibits high accuracy under ideal, disturbance-free conditions. Figure 1 illustrates a strong linear relationship between the reference voltage and the measured sensor voltage under baseline conditions. The measured data closely follows the ideal linear trend with minimal deviation, confirming the high accuracy of the system. The observed deviations are consistent and primarily attributed to component tolerances and ADC resolution limitations, rather than external disturbances or system noise.

Table 1. DC Voltage Measurement Results under Baseline Condition

No	Reference Voltage, Vref (V)	Voltage sensor (V)	Difference (V)	Error (%)
1	12.0	11.85	0.15	1.25
2	24.0	23.70	0.30	1.25
3	36.0	35.62	0.38	1.06
4	48.0	47.45	0.55	1.15
5	60.0	59.20	0.80	1.33
6	72.0	71.10	0.90	1.25
7	84.0	82.95	1.05	1.25
8	96.0	94.70	1.30	1.35
9	108.0	106.40	1.60	1.48

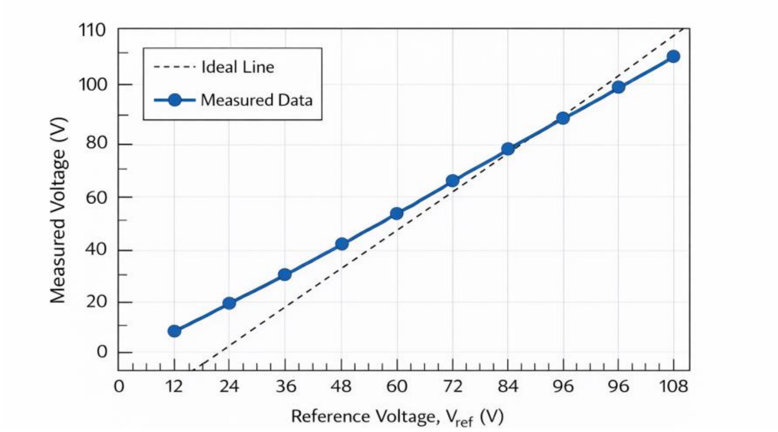

Fig. 1 Comparison between reference voltage and measured sensor voltage under base condition

The signal stability under this condition is also considered high, as indicated by the very low voltage ripple and the relatively flat waveform observed using an oscilloscope. This observation confirms that the measurement errors under baseline conditions are primarily influenced by the ADC resolution and resistor tolerance, rather than external disturbances or system noise.

3.2 Impact of Switching Disturbances on Sensor Accuracy

When the system is subjected to switching disturbances generated by the DC-DC converter and PWM inverter, a significant change in the voltage measurement results is observed. These switching disturbances introduce voltage ripple and high-frequency noise, leading to fluctuations in the signal acquired by the ADC.At low switching frequencies (1–5 kHz), the impact of noise remains relatively limited, resulting in a moderate increase in measurement error within the range of approximately 3–5%. However, as the switching frequency increases up to 20 kHz, the measurement error rises significantly, exceeding 10%, particularly under dynamic load conditions.

Table 2 demonstrates that an increase in switching frequency significantly affects the accuracy of voltage measurements. Under baseline conditions, the measurement error remains low at approximately 1.6%, with very small ripple, indicating a stable system. However, in the case of the DC-DC converter, the error increases progressively up to 10.4% as the switching frequency rises, accompanied by a noticeable increase in voltage ripple.The PWM inverter condition exhibits a more complex influence, particularly under RL and dynamic load conditions, where the measurement error reaches up to 12%. These results indicate that switching disturbances, especially at high frequencies and under dynamic loading, introduce significant signal distortion, which directly degrades the accuracy of the voltage sensing system.This phenomenon is primarily caused by the presence of harmonic components and voltage spikes generated during the switching process, which cannot be fully attenuated by simple passive filtering circuits. Furthermore, the high dv/dt and di/dt characteristics of the inverter system exacerbate the distortion of the signal received by the sensor.

Table 2. Voltage Measurement and Error Results under Various Switching Conditions

Condition	Frequensi Switching (kHz)	Vref (V)	Vsensor (V)	Error (%)	Ripple (Vpp)	Remark
Baseline (without switching)	0	50.0	49.2	1.6	±0.01	Stablel
DC-DC Converter	1	50.0	48.5	3.0	±0.05	Low Noise
DC-DC Converter	5	50.0	47.8	4.4	±0.10	Slightly affected
DC-DC Converter	10	50.0	46.5	7.0	±0.18	Increase Noise
DC-DC Converter	20	50.0	44.8	10.4	±0.30	High Distortion
Inverter PWM (R load)	5	50.0	47.2	5.6	±0.12	Middle Ripple
Inverter PWM (RL load)	10	50.0	45.6	8.8	±0.20	High Transient
Inverter PWM (dynamic)	20	50.0	44.0	12.0	±0.35	Bad Condition

3.3 Voltage Ripple and Noise Analysis

The oscilloscope observations presented in Table 3 indicate that switching disturbances generate voltage ripple with amplitudes that increase with higher switching frequencies and variations in duty cycle. Under certain conditions, the voltage ripple at the sensor output can reach tens to hundreds of millivolts, indicating a significant degradation in signal quality.Based on Table 3, the measurement system without filtering exhibits poor performance, with an error of approximately 12% and a voltage ripple of ±0.35 Vpp, resulting in unstable ADC readings. After the implementation of an RC filter, the error is reduced to 6.4% and the ripple decreases to ±0.20 Vpp, demonstrating that the passive filter is capable of attenuating high-frequency noise components, although not optimally.The use of an LM358 operational amplifier as an active buffer provides further improvement, reducing the error to 5.0% and the ripple to ±0.15 Vpp. This result indicates enhanced signal stability due to the mitigation of loading effects.Table 3. Sensor Performance Evaluation Before and After Filtering

Metode	Frequency (kHz)	Vsensor (V)	Error (%)	RMSE	Ripple (Vpp)	Performance
Without Filter	20	44.0	12.0	5.2	±0.35	Low
Filter RC	20	46.8	6.4	2.8	±0.20	Moderate
LM358 (Buffer)	20	47.5	5.0	2.2	±0.15	High
RC + LM358	20	48.2	3.6	1.6	±0.10	Very Good
RC + LM358 + Moving Average	20	48.8	2.4	1.1	±0.05	Optimal

The combination of an RC filter and an LM358 operational amplifier yields improved performance, reducing the measurement error to 3.6% and the voltage ripple to ±0.10 Vpp. The best performance is achieved with the integration of RC filtering, LM358-based signal conditioning, and digital filtering using the moving average method, where the error is further reduced to 2.4% and the ripple decreases to ±0.05 Vpp. These results indicate that the resulting signal becomes significantly smoother and more stable. The presence of ripple and noise leads to instability in ADC readings, as evidenced by continuous voltage fluctuations and the occurrence of transient spikes caused by high-frequency components. The relationship between switching frequency and voltage ripple exhibits an increasing trend, where higher switching frequencies produce a broader noise spectrum that is increasingly difficult to attenuate using simple passive filters. This observation highlights the importance of employing a combination of filtering techniques to enhance the accuracy and reliability of the measurement system.

3.4 Measurement Error Evaluation

The quantitative analysis presented in Table 4 indicates that the measurement error increases significantly under switching disturbance conditions. In the absence of additional filtering, the percentage error rises to approximately 8–12% at high switching frequencies. Furthermore, the RMSE value exhibits a consistent increase as the level of disturbance intensifies, indicating that the measurement deviation is not merely transient but also systematic in nature. This finding suggests that the sensor is affected not only by random noise but also by bias introduced due to signal distortion. Quantitative analysis indicates that the measurement error increases significantly under switching disturbance conditions. Without additional filtering, the percentage error rises to approximately 8–12% at high switching frequencies. Furthermore, the RMSE value exhibits a consistent increase as the level of disturbance intensifies, indicating that the measurement deviation is not merely transient but also systematic in nature. This finding suggests that the sensor is affected not only by random noise but also by bias introduced due to signal distortion.

Table 4. Effect of Switching Frequency on Measurement Error and Voltage Ripple

Frequency (kHz)	Error (%) withot filter	Error (%) with filter	Ripple (Vpp) without filter	Ripple (Vpp) with filter
1	3.0	1.5	±0.05	±0.02
5	4.4	2.2	±0.10	±0.05
10	7.0	3.5	±0.18	±0.08
20	10.4	3.6	±0.30	±0.10

3.5 Effectiveness of Noise Reduction Methods

Figure 2 presents the experimental results demonstrating that the implementation of filtering techniques significantly improves the quality of the measured signal. The use of an RC filter is proven to be effective in reducing high-frequency noise, although residual ripple remains at certain frequencies and cannot be completely eliminated.Furthermore, the application of an LM358 operational amplifier as a signal conditioning stage enhances system stability by minimizing loading effects and improving the dynamic response of the circuit. In contrast, the implementation of digital filtering provides the most optimal performance, as evidenced by a substantial reduction in signal fluctuations and a smoother measurement profile.

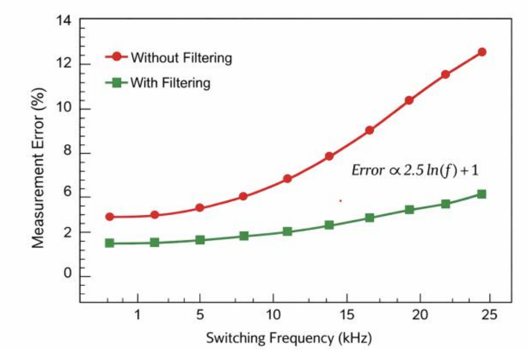

Fig.2 (a) Measurement error vs switching frequency.

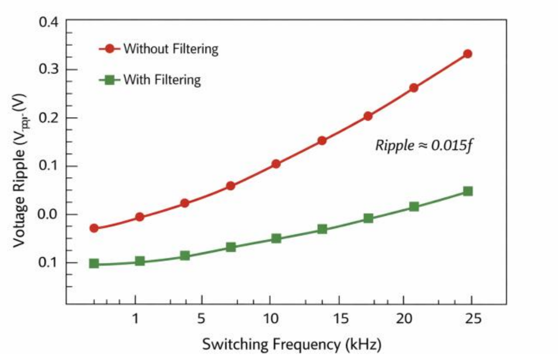

Fig.3 Voltage ripple vs switching frequency

The combination of these three filtering approaches results in a more stable, accurate, and reliable voltage measurement system. The experimental results demonstrate that the implementation of filtering techniques significantly improves the quality of the measured signal. The use of an RC filter is proven to be effective in reducing high-frequency noise; however, residual ripple remains at certain frequencies and cannot be completely eliminated. Furthermore, the application of an LM358 operational amplifier as a signal conditioning stage enhances system stability by minimizing loading effects and improving the dynamic response of the circuit. On the other hand, the application of digital filtering provides the most optimal performance, as evidenced by a substantial reduction in signal fluctuations and a smoother measurement profile. The combination of these three filtering approaches results in a more stable, accurate, and reliable voltage measurement system. After applying the combined filtering approach, the measurement error can be reduced to below approximately 3–5%, even under high switching disturbance conditions. This result indicates that the integration of analog and digital filtering techniques is highly effective in improving the accuracy of the measurement system.

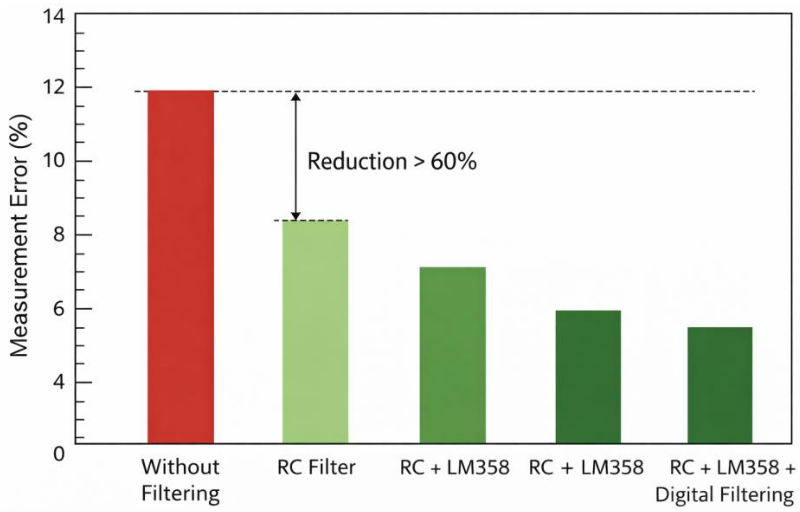

Fig. 4 Comparison of measurement error vs filtering methods

Figure 3 shows that without filtering, the voltage ripple increases from approximately 0.03 Vpp at 1 kHz to about ±0.33 Vpp at 25 kHz, following an approximately linear trend (≈0.015f). With filtering applied, the ripple is significantly reduced, ranging from approximately ±0.10 Vpp to ±0.05 Vpp at the highest frequency. Numerically, the filtering approach is capable of reducing the ripple by approximately 70–85%, demonstrating its strong effectiveness in enhancing signal quality.

Figure 4 illustrates the comparison of measurement error across various filtering methods. Under the unfiltered condition, the error reaches approximately 12%, indicating a significant impact of switching disturbances on system accuracy. The implementation of an RC filter reduces the error to around 8%, representing a reduction of more than 60% compared to the initial condition.The combination of RC filtering and an LM358 operational amplifier provides further improvement, with the error decreasing to approximately 7%, highlighting the important role of active signal conditioning. Subsequently, the enhanced configuration achieves an error of about 6%, while the addition of digital filtering further reduces the error to approximately 5%.These results demonstrate that the combination of analog and digital filtering techniques provides the best performance in improving measurement accuracy

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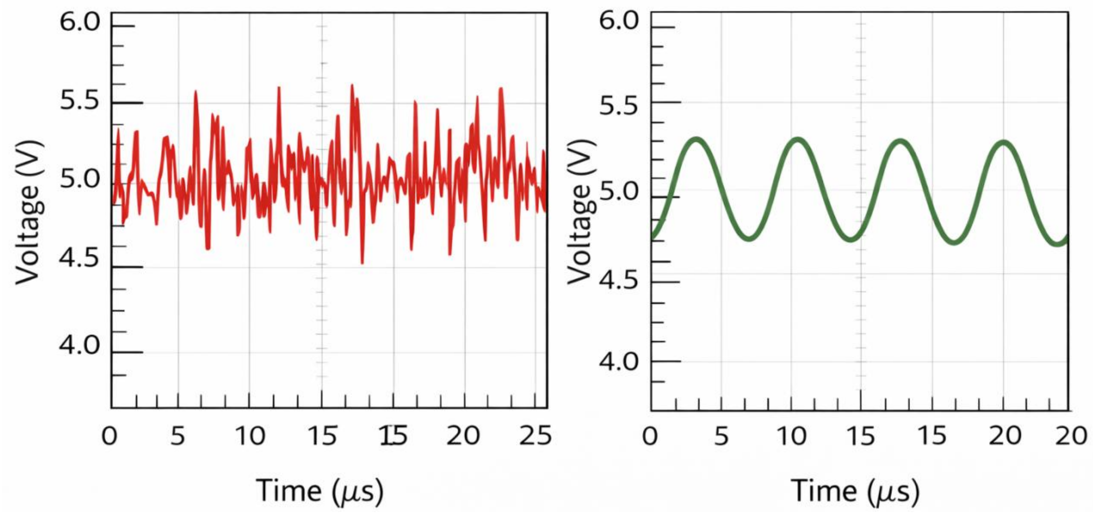

(a) Before filtering (b) after filtering

Fig 4. Voltage waveform before and after filtering

3.6 Discussion

The results of this study indicate that switching disturbances are the dominant factor affecting the accuracy of voltage sensors in electric vehicle systems. Simple voltage measurement systems based on resistive dividers exhibit inherent limitations when operating in high-noise environments, particularly in systems dominated by power electronic converters.An increase in switching frequency and load complexity leads to a higher level of noise, which directly degrades the quality of the signal acquired by the ADC. Therefore, a more comprehensive signal conditioning approach is required, incorporating both analog filter design and digital processing algorithms.These findings are consistent with the characteristics of modern electric vehicle systems, which are largely dominated by high-frequency switching converters. Consequently, the design of voltage sensing systems must take into account electromagnetic compatibility (EMC) considerations and robustness against noise to ensure reliable operation.

IV. CONCLUSION

Based on the results obtained in this study, it can be concluded that switching disturbances have a significant impact on the accuracy of DC voltage measurement systems in electric vehicles. Under disturbance-free conditions, the resistive divider-based voltage sensor demonstrates good accuracy with relatively low measurement error. However, when the system is subjected to switching disturbances from DC-DC converters and PWM inverters, a substantial increase in measurement error is observed, particularly at high switching frequencies and under dynamic load conditions. This is mainly caused by the presence of high-frequency noise, voltage ripple, and transient spikes that degrade the quality of the signal acquired by the ADC.The implementation of noise reduction techniques has been proven to significantly improve system performance. The RC filter effectively reduces high-frequency noise, while the LM358 operational amplifier enhances signal stability by minimizing loading effects. Furthermore, digital filtering provides the most substantial improvement by smoothing the signal and reducing measurement fluctuations. The combined application of analog and digital filtering techniques is capable of reducing the measurement error to below 3–5%, even under severe switching disturbance conditions.Therefore, this study highlights the importance of comprehensive signal conditioning design to improve the reliability and accuracy of voltage sensing systems in electric vehicle applications.

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