

Article

A Study on Equivalent Series Resistance Estimation Compensation for DC-Link Capacitor Life Diagnosis of Propulsion Drive in Electric Propulsion Ship

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Abstract: This study proposes a novel fault diagnosis algorithm based on Equivalent Series Resistance (ESR) estimation to enhance the accuracy of capacitor life diagnosis techniques for the DC link in marine electric propulsion systems. Accurate ESR estimation is critical for maintaining the reliability and efficiency of DC-Link capacitors, which play a key role in stabilizing voltage, reducing harmonics, and ensuring the smooth operation of electric propulsion systems. By preventing capacitor failures, this algorithm contributes to reducing the risk of catastrophic damage to entire systems. The ESR value is determined by extracting AC voltage and current data within the frequency range of 10 kHz to 30 kHz using a band-pass filter. To improve reliability, the algorithm compensates for input errors based on the modulation index and switching pattern, with error data stored in a lookup table. By addressing limitations in existing ESR estimation techniques, the proposed method reduces estimation errors across the entire range and enhances fault diagnosis accuracy. Experimental results validate the algorithm's improved accuracy, reliability, and stability, demonstrating its effectiveness in preventing damage to power conversion devices.



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1. Introduction

In recent years, environmental protection has become a major focus across various industries, driving the development of technologies aimed at reducing carbon emissions. In the shipping industry, the Marine Environment Protection Committee of the International Maritime Organization has continued to enforce the greenhouse gas reduction strategy for global shipping, emphasizing the importance of developing eco-friendly ships. These eco-friendly vessels are typically classified as electric propulsion ships, which either use environmentally friendly fuels such as ammonia or methane to power engines or drive motors using electric energy [1–3].

The ship's electric propulsion system is generally composed of a power generation source, a distribution panel (handling both direct current and alternating current), power conversion devices (such as active front end rectifiers and propulsion drives), and a propulsion motor. The power generation sources include generators, batteries, and fuel cells, which supply DC current or AC current to the distribution panel. The distribution panel

then supplies energy to the propulsion motor based on control signals from the energy management system. The power conversion device adjusts the energy from the distribution panel, converting it to the appropriate magnitude and frequency required by the propulsion motor. Furthermore, a DC stage capacitor is installed at the rear of the active front end rectifier in the power conversion device to eliminate harmonic components [4].

The majority of ship DC terminal capacitors, installed for stabilizing DC terminal voltage, are aluminum electrolytic capacitors. These capacitors reduce voltage ripple and help remove harmonics, enhancing the efficiency of the entire system. However, due to their tendency to degrade under high temperatures and excessive current, a system for diagnosing the capacitor's lifespan is essential [5–10]. Two primary methods for diagnosing the lifespan of electrolytic capacitors are monitoring their capacitance and measuring their Equivalent Series Resistance (ESR). ESR represents the internal resistance of the capacitor, which tends to increase over time. This rise in ESR leads to higher heat generation and a reduced lifespan, making low ESR essential for ensuring durability and reliability. The capacitance-based approach can be unreliable due to manufacturing errors in the design phase of the capacitor. In contrast, the ESR-based approach offers a more practical and reliable means of estimating the capacitor's condition, though it is challenging to measure ESR directly in real time within a functioning power system. Therefore, ESR is often indirectly estimated using voltage and current measurements from the DC-Link capacitor [11–16].

Typically, ESR is monitored over time, and when it reaches a value roughly twice the initial ESR, the capacitor is considered to have reached the end of its useful life. Current ESR estimation techniques can be broadly divided into data-based techniques and model-based techniques. Data-based techniques utilize artificial neural networks or deep learning to extract data from the time domain [17–19]. However, data-based approaches require significant computational resources and big data infrastructure, which makes real-time ESR prediction difficult. Model-based techniques, on the other hand, include methods using an average power loss or band-pass filter, both of which extract data from the frequency domain. The average power-loss-based method estimates ESR by analyzing the energy loss of the capacitor, dividing the average power loss by the square of the capacitor's current [20,21]. In contrast, the band-pass-filter-based method utilizes the characteristic of band-pass filters that allow only signals within a specific frequency range to pass, calculating impedance across different frequencies to estimate ESR [5,22–24]. While the average power-loss-based ESR estimation method is intuitive and simple, it has the drawback of being susceptible to noise and nonlinear effects. In contrast, the band-pass-filter-based method analyzes specific frequency bands, offering higher accuracy and reliability. Ren et al. [5] measured the RMS value of the ripple current in the output capacitor of a boost converter using filtered signals to estimate ESR. Ren et al. [22] modeled the inherent frequency response characteristics of the capacitor and estimated ESR based on filtered data. Xia et al. [23] used a band-pass filter to extract voltage and current signals of the capacitor from specific frequency bands, and then applied wavelet transform and a convolutional neural network model to estimate ESR. Agarwal et al. [24] used a band-pass filter to extract high-frequency ripple components from current and voltage signals, calculated the RMS value, and combined it with a power loss model to estimate ESR.

Despite extensive research into model-based techniques, several limitations and challenges still exist. To address this, this paper proposes a simplified compensation technique to reduce the prediction error of ESR in existing model-based methods. The proposed method calculates compensation values by analyzing various operational conditions, focusing on ESR estimation using the band-pass filter technique. Accurate ESR estimation not only enhances the reliability of the diagnostic process but also significantly improves

the performance and energy efficiency of electrical propulsion systems. By minimizing prediction errors in ESR, the proposed approach ensures the optimal functioning and prolonged life of key system components, particularly in marine applications.

Moreover, ships require systems that are easy to maintain and highly accurate. Accurately tracking ESR offers significant advantages in terms of stable operation and maintenance. By enabling proactive prevention of system failures and predictive maintenance, accurate ESR estimation reduces operating costs and maximizes uptime. This approach greatly contributes to enhancing the overall reliability and efficiency of ships.

In electric propulsion ships, PWM regulates the inverter's output voltage and current to control motor speed and torque, while the modulation index (MI), defined as the ratio of reference to carrier signal amplitude, directly affects output voltage and waveform quality [25–28]. In this study, we identified the PWM control methods and MI as key factors influencing ESR prediction error. ESR values were estimated by applying four different PWM methods (SPWM, SVPWM, 30° DPWM, and 60° DPWM) and a modulation index range of 0.3 to 0.8. The proposed method achieves greater reliability and accuracy in ESR prediction by compensating for errors based on the PWM methods and modulation index. The effectiveness of the proposed method was verified by comparing its performance to existing techniques in a 5 kW class propulsion drive system. The proposed compensation method is well suited for implementation in real-world shipboard systems. During the manufacturing stage, key model parameters can be predetermined through rigorous measurement and testing processes to derive compensation values effectively. Additionally, the proposed method's reliability has already been validated using various existing models, ensuring its feasibility for practical applications. By applying this method to shipboard propulsion systems, manufacturers can enhance diagnostic accuracy and operational stability, effectively addressing performance and maintenance challenges in marine environments.

Section 1 introduces the background and objectives of this study. Section 2 reviews existing ESR estimation techniques. Section 3 presents the proposed method. Section 4 details the experimental setup and results. Section 5 compares the performance of the proposed method with that of existing methods, and Section 6 provides the conclusion.

2. Conventional ESR Estimation Methods

Among the fault diagnosis techniques for electrolytic capacitors, the ESR estimation method is widely applied for predicting failures in power converters due to its various advantages. One commonly used approach is the model-based estimation technique, which primarily relies on mathematical modeling. Figure 1 illustrates the configuration of an electric propulsion system. By diagnosing the lifespan of the capacitor installed in the DC stage, this method enables the prediction of potential failures, thereby enhancing the stability and reliability of the onboard power system.

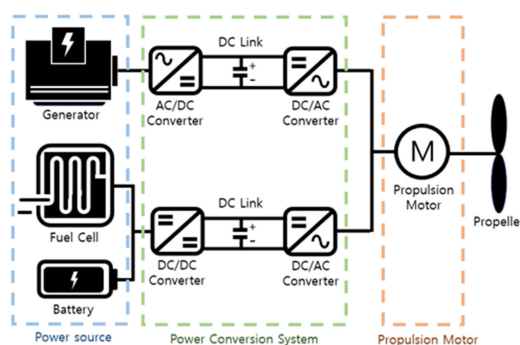


Figure 1. Configuration of the electric propulsion system.

2.1. Model-Based ESR Estimation Techniques

2.1.1. ESR Estimation Technique Using Band-Pass Filter

The ESR estimation technique utilizing a band-pass filter leverages the impedance characteristics of the capacitor. Figure 2 illustrates these impedance characteristics. In the low-frequency region, the impedance is determined by the capacitance, as represented by the blue dashed line. In the high-frequency region, the impedance is governed by the equivalent series inductance (ESL), depicted by the orange dashed line, which represents the inductive component in a capacitor's impedance model. The green dashed line corresponds to the ESR, which dominates at the resonant frequency. At this frequency, where the capacitance and ESL are equal, the impedance is determined by the ESR. The ESR values are calculated by extracting data from this resonant frequency domain.

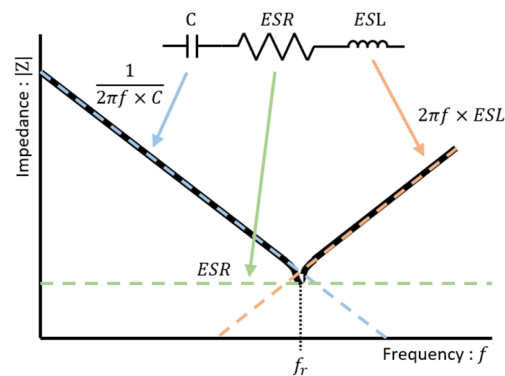


Figure 2. Capacitor impedance characteristics.

Since the electrolytic capacitors used in the DC stage exhibit resonant frequencies in the range of several kHz to MHz, AC coupling is first applied to extract the AC component from the voltage (V_C) and current (I_C) across the capacitor [11]. The extracted AC voltage and current data are then passed through a band-pass filter to isolate the data within the resonant frequency range, which is the targeted frequency band. The ESR value of the capacitor is calculated using Equation (1), which computes the RMS value of the voltage and current data that have passed through the band-pass filter [14,15]. $V_{C,rms}$ and $I_{C,rms}$ represent the effective voltage and current value of capacitor, respectively. Figure 3 presents the block diagram of the ESR estimation technique employing the band-pass filter.

$$ESR_{estimation} = \frac{V_{C,rms}}{I_{C,rms}} \quad (1)$$

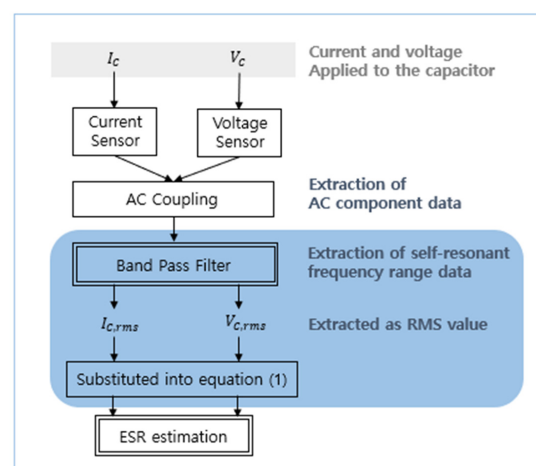


Figure 3. Block diagram of the ESR estimation technique using a band-pass filter.

2.1.2. ESR Estimation Techniques Using Average Power Loss

The ESR estimation technique based on average power loss utilizes the loss characteristics of the capacitor. It leverages the loss caused by the phase difference between the current flowing through the capacitor and the voltage, which is primarily attributed to ESR. In an ideal capacitor, the current leads the voltage by a phase angle of 90° . However, practical capacitors contain not only capacitance but also resistance in the form of ESR, which is generated as current flows, and ESL, caused by the magnetic field produced by the current. In the high-frequency region, which corresponds to the resonant frequency of the electrolytic capacitor, the phase difference between the current and voltage becomes lower than 90° as the ESR increases. This characteristic is used to estimate the ESR value of the capacitor.

Similar to the band-pass filter technique, the voltage and current data across the capacitor are AC-coupled, and the voltage of the extracted AC component along with the RMS value of the current are used in Equation (2) to calculate the average power loss of the capacitor. Using this average power loss value, the ESR of the capacitor is then computed by substituting it into Equation (3). Figure 4 presents the block diagram of the ESR estimation technique based on average power loss.

$$P_{Loss} = V_{C,rms} \times I_{C,rms} \times \sin \theta \quad (2)$$

$$ESR_{estimation} = \frac{V_{C,rms} \times I_{C,rms}}{I_{C,rms}^2} = \frac{P_{Loss}}{I_{C,rms}^2} \quad (3)$$

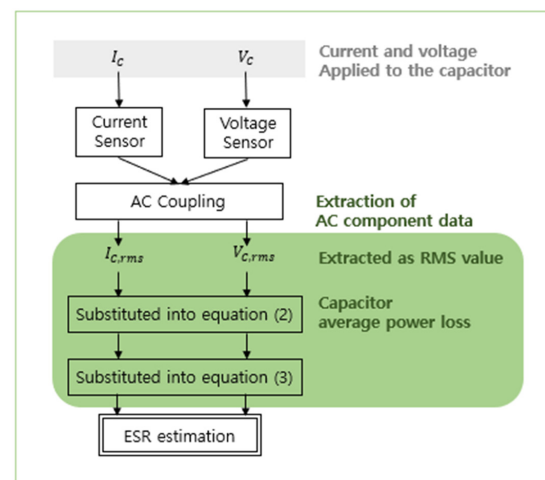


Figure 4. Block diagram of the ESR estimation technique using average power loss.

The ESR estimation technique using a band-pass filter processes the measured time-domain voltage and current data through a band-pass filter, and then converts it into frequency-domain data using the Fast Fourier Transform (FFT), enabling the analysis of frequency components in the signal. The calculation is performed by pairing the voltage and current data at the same frequencies, using only the data from the frequency range where the ESR determines the capacitor's impedance. In contrast, the ESR estimation technique using average power loss simplifies the calculation process by using the RMS values and phase angles of the voltage and current measured in the time domain. When comparing the results of the two methods, it was found that the data from the ESR estimation technique using average power loss showed an error rate that was more than 20% higher than the results from the ESR estimation technique using a band-pass filter.

2.1.3. Data-Based ESR Estimation Techniques

The data-based ESR estimation technique involves training an artificial neural network by collecting capacitor voltage and current data under various conditions and then applying the trained network to the actual system [29–31]. Figure 5 illustrates the structure of both artificial neural networks (ANNs) and deep neural networks (DNNs), categorized based on the number of hidden layers. Data-based techniques enhance the reliability of artificial neural networks by extracting frequency data in the ESR region through AC coupling and FFT, emphasizing the importance of large volumes of high-quality data. For effective operation in actual systems, the data input must match the format used during training. While data-based techniques generally offer greater precision compared to model-based methods, they require substantial data and involve complex data preprocessing to ensure compatibility with the trained data format. Figure 6 provides a block diagram of the data-based ESR estimation technique.

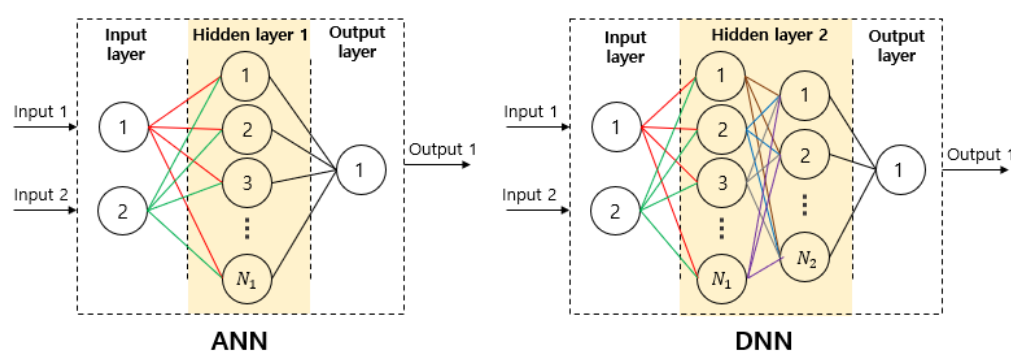


Figure 5. Structure of artificial neural networks and deep learning.

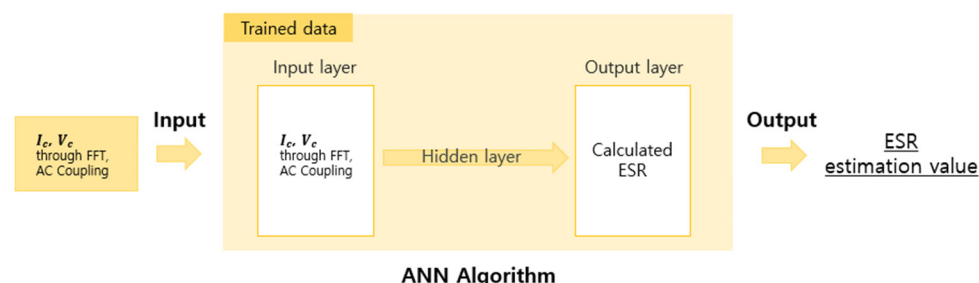


Figure 6. Block diagram of the data-based ESR estimation technique (ANN).

3. Proposed ESR Estimation Compensation Technique

Errors remain a significant challenge in existing ESR estimation techniques, primarily influenced by operational characteristics such as PWM methods and modulation indices. In this study, the ESR estimation error rates were analyzed with respect to critical factors, including the modulation index, capacitor size, and PWM method, all of which play a pivotal role in determining the accuracy of the estimation.

As depicted in Figure 7a, the band-pass filter method exhibits the highest error rate at a modulation index of 0.5 and the lowest at 0.8. Additionally, the error rate increases with larger ESR values of the capacitor. Conversely, as shown in Figure 7b, the average power loss method demonstrates a similar trend, where larger ESR values result in higher error rates. However, for most cases, the lowest error rate is observed at a modulation index of 0.3, except for an ESR value of 490 mΩ. Notably, the highest error rate for this method occurs at a modulation index of 0.5. When comparing the overall error rates, the band-pass filter method achieves error rates ranging from 2.4% to 17.4%, whereas the average power loss method demonstrates significantly higher error rates, ranging from 6.8% to 34.2%.

These findings suggest that the band-pass filter method, which isolates data within a specified frequency range, provides lower error rates and greater accuracy in diagnosing capacitor faults compared to the average power loss method.

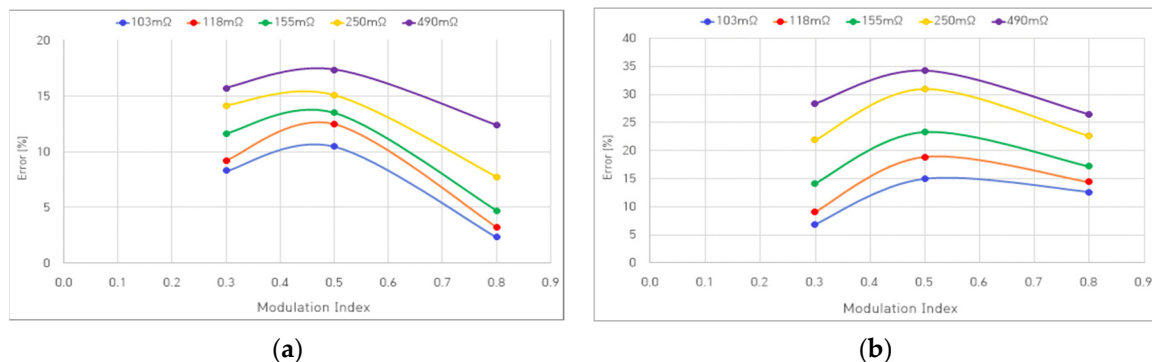


Figure 7. Errors due to modulation index. (a) Band-pass filter techniques. (b) Average power loss techniques.

Nevertheless, the band-pass filter method still presents notable error rates, which limit its utility for precise capacitor fault diagnosis. While data-driven techniques exhibit the lowest error rates, they demand substantial amounts of training data to enhance accuracy, posing practical challenges. To overcome these limitations, this paper proposes an advanced error compensation method built upon the band-pass filter technique. By employing a lookup table (LUT) containing pre-determined error values based on modulation indices and switching patterns, the proposed approach compensates for the errors in ESR estimation. This technique adjusts the calculated ESR values, thereby improving accuracy and enabling a more reliable capacitor fault diagnosis. Additionally, no extra hardware is required, making the approach cost-effective, lightweight, and easy to implement.

Figure 8 illustrates the configuration of the propulsion drive used in this study for analyzing ESR errors. Based on this configuration, simulations were conducted using PSIM version 9.3.2 software. The main power source utilizes alternating current at 60 Hz and 440 V, consistent with the ship's power characteristics. For ESR estimation, a band-pass filter technique with relatively low error rates, based on a mathematical model, was employed. The cutoff frequency was set between 10 kHz and 30 kHz, aligning with the magnetic resonance frequency range of the electrolytic capacitor. The modulation index was analyzed across seven cases, ranging from 0.3 to 0.9 in 0.1 intervals. Additionally, the impact of capacitor size on ESR was examined in four cases: 103.6, 121.9, 155.3, 229.5, and 490.8 [mΩ]. The PWM methods were analyzed in four types, SPWM, SVPWM, 30° DPWM, and 60° DPWM, which are commonly used in practice.

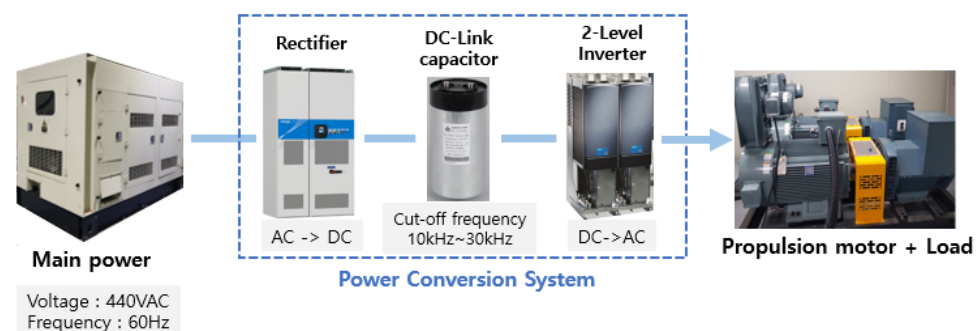


Figure 8. Configuration of the propulsion drive.

Figure 9 illustrates the algorithm for the proposed ESR estimation compensation technique. This method estimates the expected ESR value by analyzing the voltage and current data of the DC-Link capacitor, utilizing the existing band-pass filter technique. The approach incorporates compensation values from a lookup table (LUT) based on various modulation indices and PWM methods.

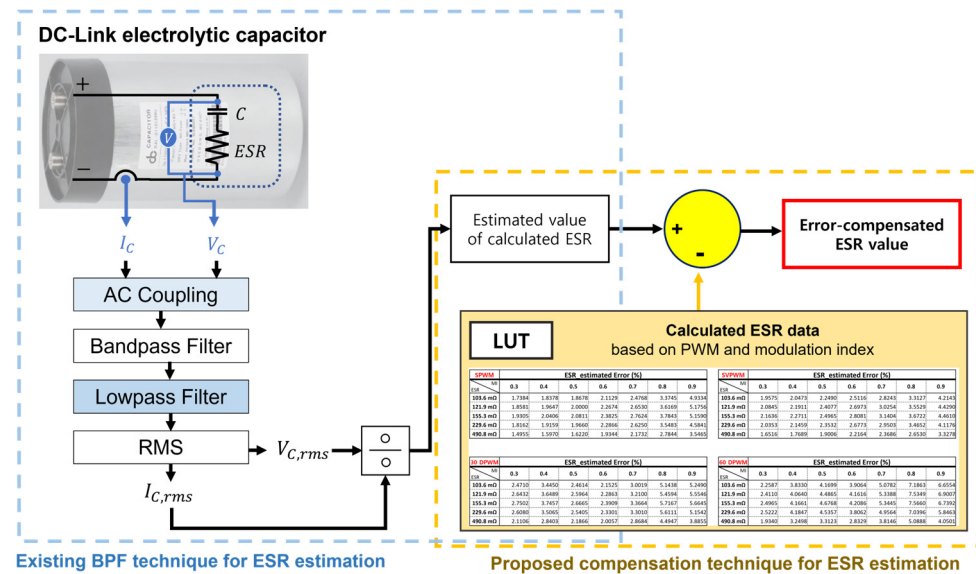


Figure 9. Proposed ESR estimation compensation technique algorithm.

As shown in Figure 9, the proposed ESR estimation algorithm enhances the accuracy of the ESR value by compensating for errors identified through the LUT, which is derived from the band-pass filter technique used to evaluate the lifespan of electrolytic capacitors. The band-pass filter effectively removes harmonic components and noise caused by voltage ripple from the power converter's switching operation during data measurement, filtering the voltage and current data exclusively within the 10 kHz to 30 kHz frequency range.

The measured data, initially in the time domain, underwent FFT transformation to transition into the frequency domain. By focusing on the frequency range where ESR determines the capacitor's impedance, this transformation reduces error rates and ensures a more accurate ESR estimation. This process allows for matching the data within the same frequency range, thereby improving the reliability of ESR estimation.

The components of the LUT are as follows: four PWM methods—SPWM, SVPWM, 30° DPWM, and 60° DPWM—and a total of eleven modulation index data points, increasing in increments of 0.05 from 0.3 to 0.8. Since the error rate varies with the modulation index for each PWM method, voltage and current data from the DC-Link electrolytic capacitor were measured across these 11 modulation indices for the four commonly used PWM methods. These measurements, recorded at 100 kS/s using an oscilloscope, were processed with a band-pass filter technique, and the resulting errors were compared with the actual ESR values. Figure 10 displays the estimated ESR error values corresponding to different modulation indices for each PWM method. These data serve as the input to the LUT, allowing for compensation based on the specific PWM switching patterns.

Figure 11 presents a flowchart of the proposed ESR estimation compensation algorithm. The algorithm begins by measuring the real-time voltage and current of the DC link. The measured data are then processed through AC coupling to remove the DC component, followed by a band-pass filter (10 kHz to 30 kHz) to extract the desired frequency range of the signal. A low-pass filter is applied next to remove high-frequency components. The signal is analyzed in the frequency domain using FFT, which allows for the calculation of

the RMS values of the voltage and current. Using the calculated RMS values, the initial ESR estimation is performed. The algorithm then determines the switching pattern and modulation index, which are used to retrieve the corresponding error value from a pre-defined LUT. Based on the retrieved error value, the proposed ESR estimation algorithm adjusts the initial estimate to produce a compensated ESR value. This algorithm takes as inputs the PWM methods and modulation index data from the LUT, outputs the corresponding error values, and adjusts the ESR estimates calculated by the band-pass filter technique to enhance the accuracy of actual ESR tracking.

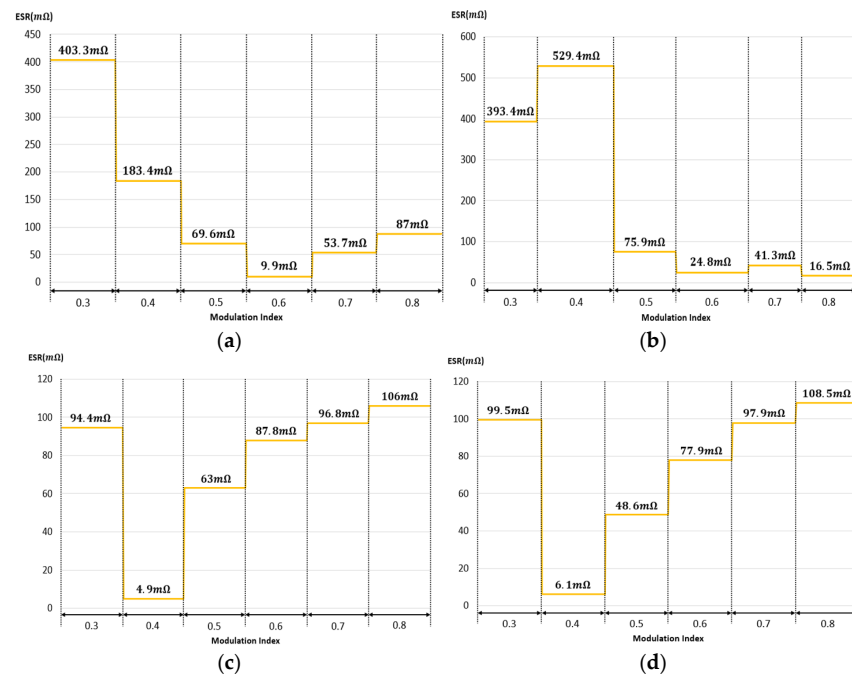


Figure 10. Expected ESR error values by modulation index for each PWM method (Expected ESR Error Value = Estimated ESR Value—Actual ESR Value). (a) SPWM. (b) SVPWM. (c) 30° DPWM. (d) 60° DPWM.

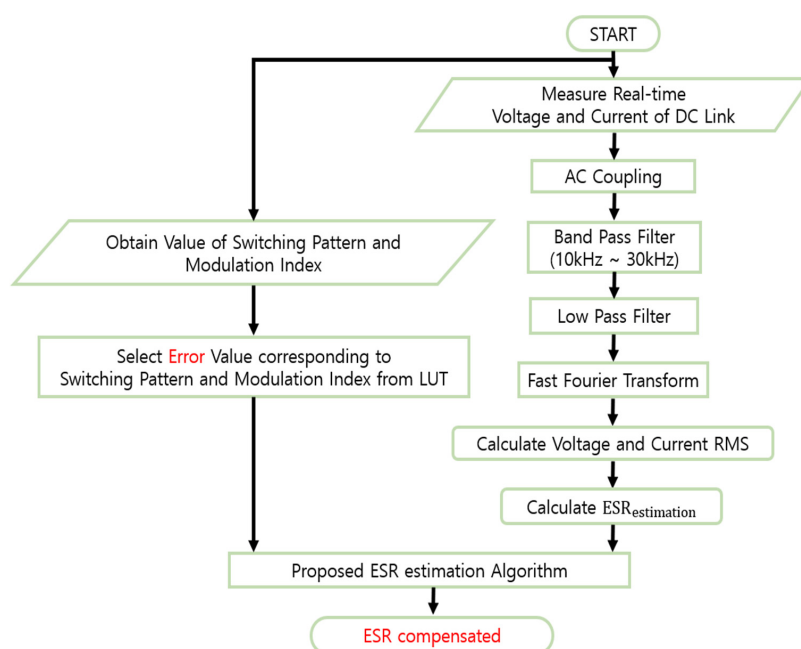


Figure 11. Flowchart of the proposed ESR estimation compensation algorithm.

4. Experiment Results

4.1. Experimental System Environment

Figure 12 illustrates the experimental setup for estimating the ESR of the capacitor installed at the DC terminal of the power board. A DC power supply delivers power directly to the DC terminals, and the PWM method and modulation index values are programmed into the DSP board via the JTAG emulator using Code Composer Studio version 12.3.0 software. The control board processes the input signal into a switching signal, which is then fed into the propulsion drive. This setup allows the propulsion motor to operate under varied conditions, including different PWM methods and modulation indices.

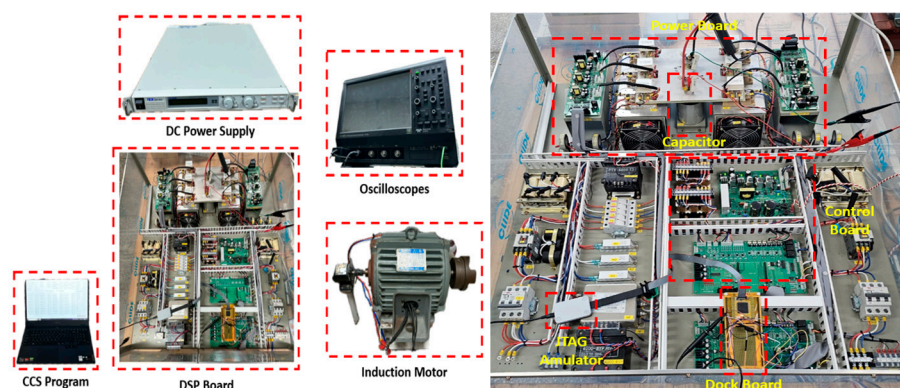


Figure 12. Experimental environment and DSP board configuration.

The experimental configuration comprises a small two-level inverter (representing the propulsion drive) and an induction motor (representing the propulsion motor) to emulate the power conversion environment found in actual maritime systems. Key parameters include a DC power supply set to 220 V, a capacitor with an ESR of 160 mΩ, and a motor with 220 V, 1720 RPM specifications. The modulation indices were adjusted as follows: MI = 0.8 from 0 to 3 s, MI = 0.5 from 3 to 6 s, MI = 0.3 from 6 to 9 s, MI = 0.4 from 9 to 14 s, and MI = 0.6 from 14 to 20 s. Voltage and current data for the DC terminal electrolytic capacitor were monitored in real time using an oscilloscope.

4.2. Experimental Methods and Data Configuration

Figure 13 presents the experimental results for various PWM methods and changes in the modulation index. The current and voltage of the DC-Link capacitor were measured under 11 different modulation index conditions across a total of 4 PWM switching patterns. Since the voltage measurement device uses a 50× attenuation scale, the actual voltage values can be determined by multiplying the values shown in Figure 13 by 50.

Voltage was measured across the terminals of the DC-Link capacitor, while current was measured at the rear end of the capacitor. Voltage and current data were collected using an oscilloscope. Sampling of the oscilloscope was set at 100 Ks/s, and voltage values of the DC power supply were set at 220 V. ESR estimation involved extracting only the AC components from the voltage and current data through AC coupling. Data in the frequency range of 10 kHz to 30 kHz were isolated using FFT analysis.

- Current and voltage measurement by PWM switching pattern: four switching patterns were used: SPWM, SVPWM, 30° DPWM, and 60° DPWM.
- Current and voltage measurement by modulation index: measurements were taken at 11 modulation index values: 0.3, 0.35, 0.4, 0.45, 0.5, 0.55, 0.6, 0.65, 0.7, 0.75, and 0.8.

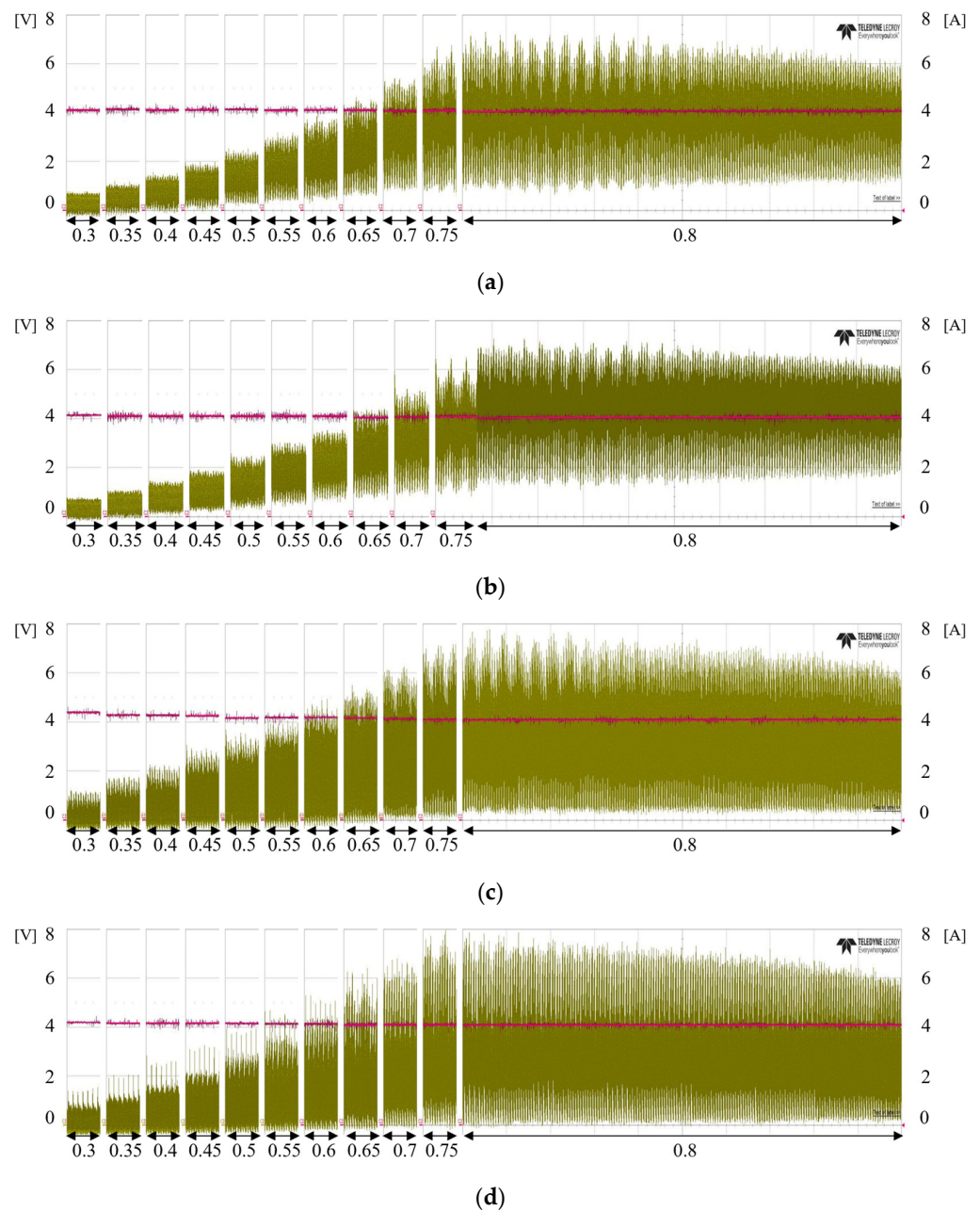


Figure 13. Current and voltage measurement data by PWM method and modulation index (MI: 0.3–0.8). (a) SPWM. (b) SVPWM. (c) 30° DPWM. (d) 60° DPWM.

5. Results and Discussion

5.1. Factors Affecting ESR Estimation

5.1.1. Error Analysis by Modulation Index

Using the ESR estimation technique based on the band-pass filter method, the error rates for four PWM methods were analyzed across a modulation index range of 0.3 to 0.9 with five actual ESR values. The reference ESR of the capacitor is pre-measured in the serial equivalent circuit mode using an HIOKI IM3523 LCR Meter, manufactured by HIOKI E.E. Corporation, located in Nagano, Japan. The error is calculated by comparing the reference values with the estimated values. The measurement signal was set to $1V_{rms}$ to ensure reliable readings, and data were collected with a high accuracy of $\pm 0.05\%$. As shown in Figure 14, the magnitude of the error varies irregularly with the modulation index for all five ESR values. These variations can be attributed to the impact of the modulation

index on the shape of the voltage and current waveforms. At lower modulation indices, the waveforms maintain a relatively smooth sine wave, while higher modulation indices introduce more harmonic components into the waveform. Therefore, the modulation index plays a critical role in ESR estimation and must be considered to account for these waveform variations.

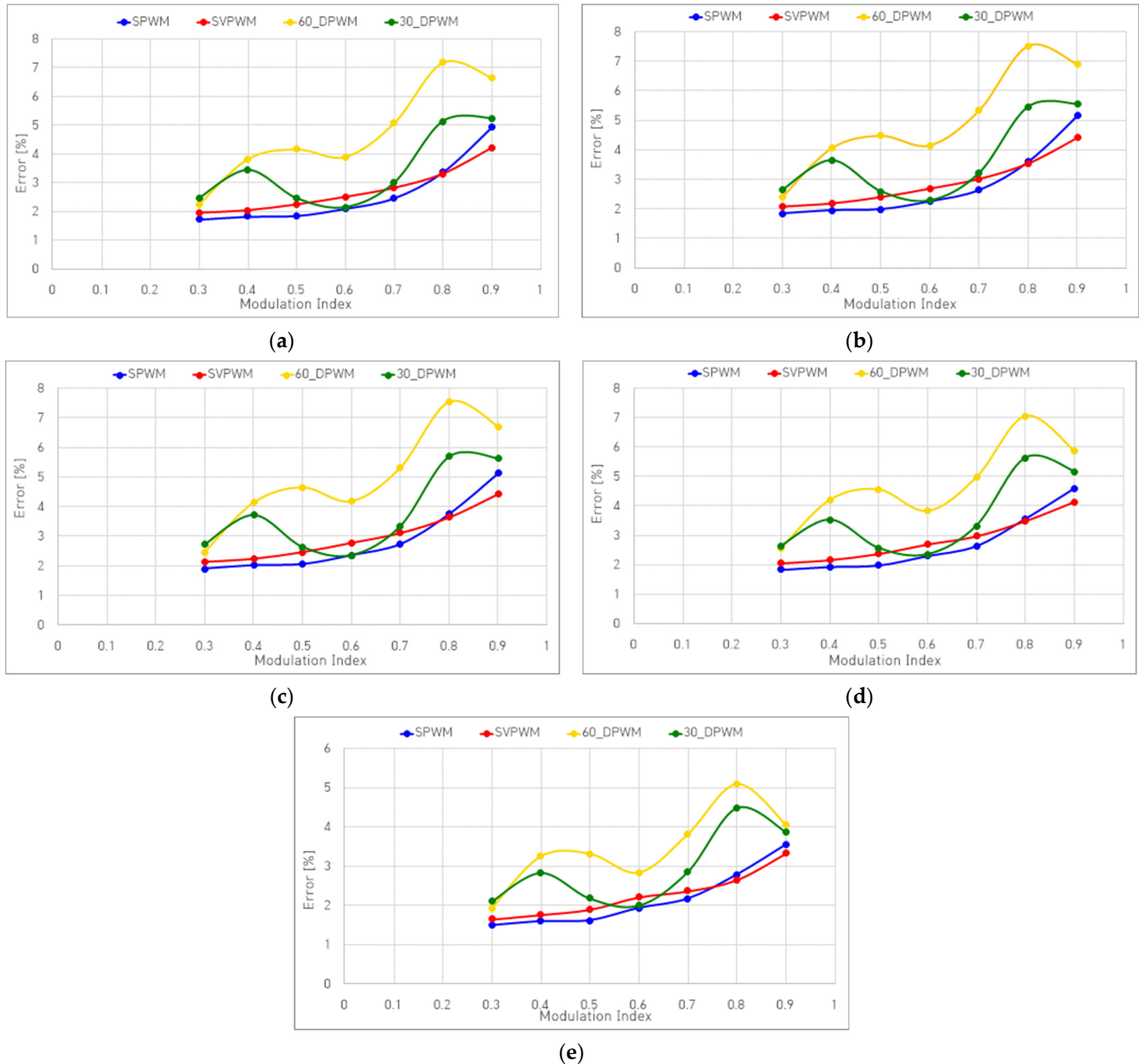


Figure 14. Expected ESR error values by modulation index for each PWM method. (a) ESR: 103.6 mΩ. (b) ESR: 121.9 mΩ. (c) ESR: 155.3 mΩ. (d) ESR: 229.5 mΩ. (e) ESR: 490.8 mΩ.

5.1.2. Error Analysis by Capacitance Variation

Using the ESR estimation technique based on the band-pass filter method, the error rates were analyzed for modulation indices ranging from 0.3 to 0.9, with capacitance values of 106.9 μF , 219.0 μF , 330.9 μF , 442.5 μF , and 553.6 μF , as shown in Figure 15. The analysis was conducted across four PWM switching patterns to evaluate their impact on the estimation of actual ESR values. The fluctuation in error rates across these capacitance values was relatively minor. Therefore, it is concluded that capacitance variation does not

have a significant effect on error size when estimating ESR, and thus, capacitance size was not considered a primary factor in this study.

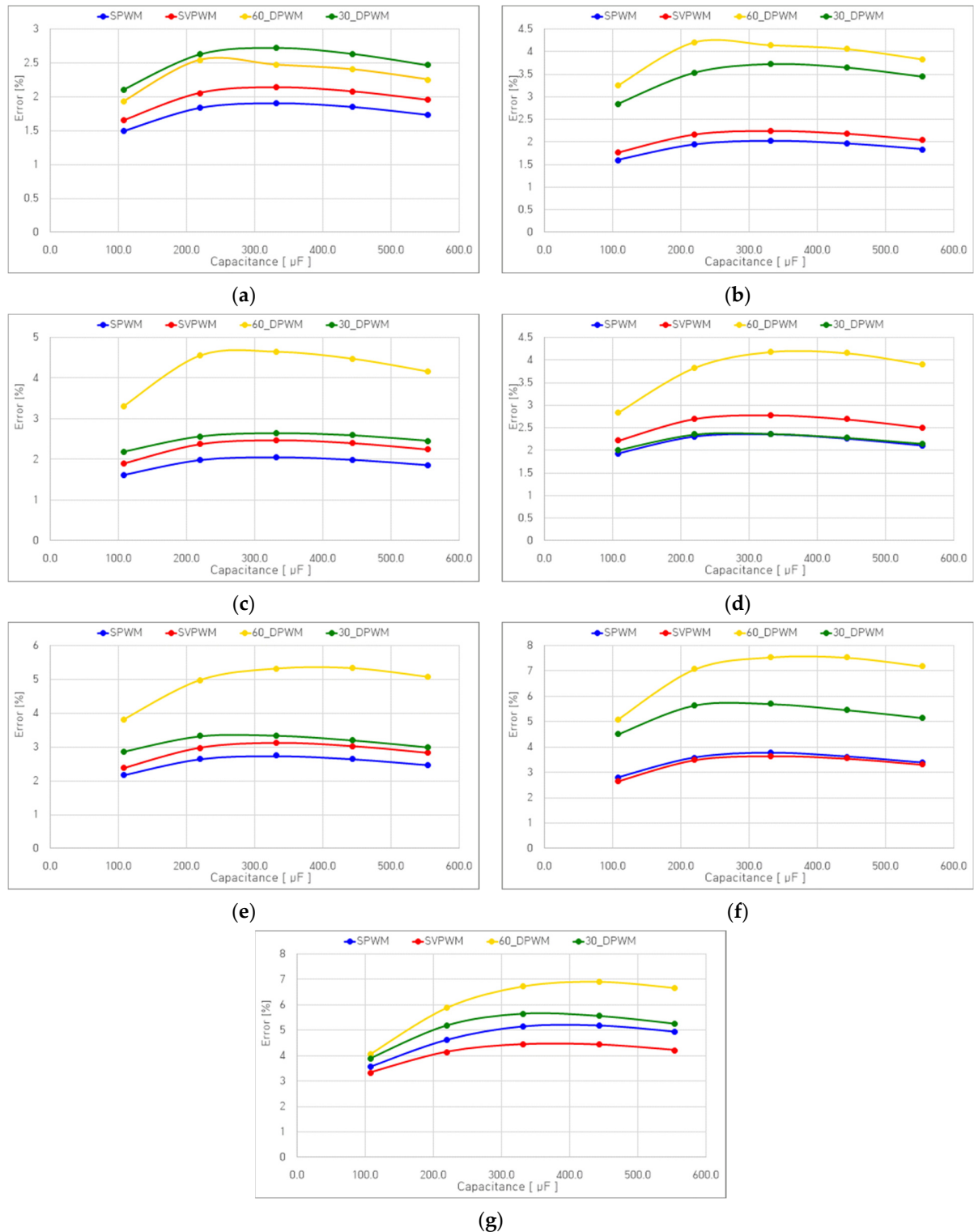


Figure 15. Expected ESR error values by capacitance for each PWM method. (a) MI: 0.3. (b) MI: 0.4. (c) MI: 0.5. (d) MI: 0.6. (e) MI: 0.7. (f) MI: 0.8. (g) MI: 0.9.

5.1.3. Error Analysis by PWM Switching Pattern

The error in ESR values estimated using the band-pass filter technique compared to the actual ESR values was analyzed across seven modulation index conditions for various

PWM methods. As the modulation index increased, discrepancies between the actual ESR value and the estimated ESR value also increased for all PWM methods. Specifically, the errors observed were as follows: SPWM exhibited a minimum error of 1.5% and a maximum of 5.2%, SVPWM ranged from 1.7% to 4.5%, 30° DPWM showed errors between 2.0% and 5.7%, and 60° DPWM errors ranged from 1.9% to 7.6%. These results indicate that both the modulation index and the PWM switching pattern are significant factors contributing to errors in ESR estimation. The magnitude of harmonic components varies depending on the characteristics of each PWM modulation technique, leading to different errors in ESR estimation. Therefore, the proposed ESR estimation technique incorporates a LUT configured according to the modulation index and PWM methods to address these factors.

5.2. Comparison of ESR Estimation Performance Using the Proposed Method with LUT

The performance of estimating the actual ESR value of 160 mΩ was compared across different PWM methods using both the existing band-pass filter method and the proposed ESR estimation method with LUT across various modulation index sections. The conclusions based on each PWM method and modulation index are as detailed below.

5.2.1. SPWM

Figure 16 illustrates the ESR values estimated using both the existing band-pass filter technique and the proposed method when the modulation index changes randomly within the SPWM method. The comparison of the ESR estimation performance reveals that the existing band-pass filter technique showed significant fluctuations in error, particularly in the 0.3 and 0.4 modulation index sections, with a reduced error in the 0.8 section. In contrast, the proposed technique consistently reduced errors across all sections. Specifically, the error rates were 48.1% at a modulation index of 0.8, 28.3% at 0.7, 4.1% at 0.6, 9.3% at 0.5, 71.1% at 0.4, and 172.1% at 0.3. When averaging the error rates across the entire modulation index range, the proposed method achieved a 55.5% reduction in average error compared to the existing technique, resulting in an overall average error rate of 19.5%.

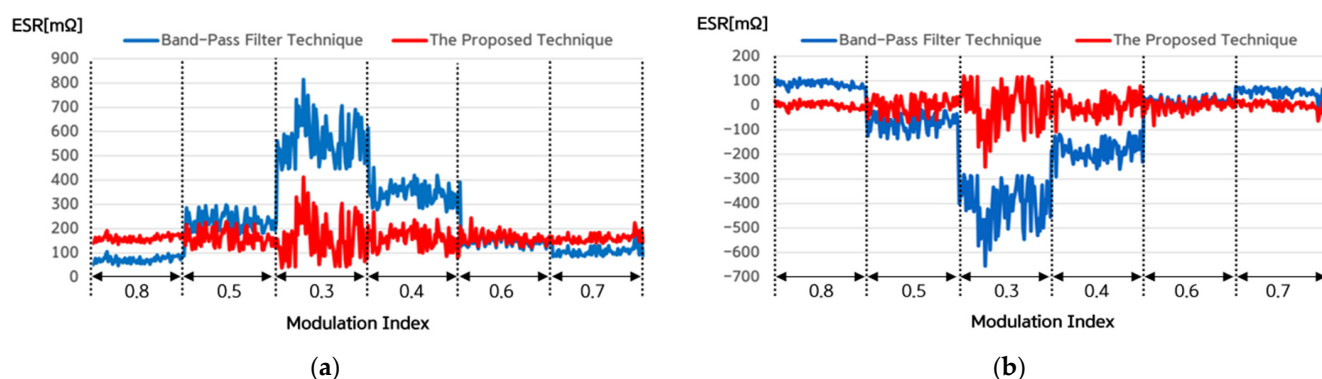


Figure 16. Comparison of ESR values with random changes in modulation index (SPWM). (a) Expected ESR values. (b) Error compensation values.

5.2.2. SVPWM

Figure 17 displays the results of ESR estimation using both the existing band-pass filter technique and the proposed ESR estimation compensation technique with SVPWM. The analysis reveals that the existing technique exhibited significant modulation index fluctuations in the 0.3, 0.4, and 0.5 sections. In contrast, the proposed technique demonstrated improved accuracy in estimating the ESR of the capacitor, even with random variations in the modulation index.

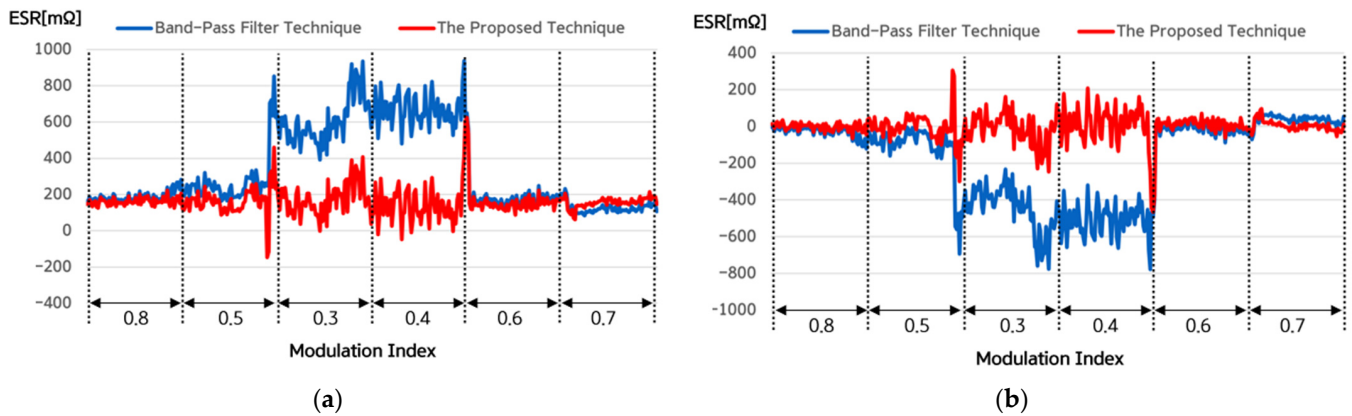


Figure 17. Comparison of ESR values with random changes in modulation index (SVPWM). (a) Expected ESR values. (b) Error compensation values.

Comparative results show that the proposed technique reduced the error rates by 21.4% at a modulation index of 0.7, 11.5% at 0.5, 238.8% at 0.4, and 166% at 0.3. When averaged across all experimental sections, the proposed technique achieved a 75.6% reduction in the overall error rate compared to the existing technique, resulting in an average error rate of 27.8%.

5.2.3. 30° DPWM

Figure 18 illustrates the results of ESR estimation using both the existing band-pass filter technique and the proposed ESR estimation compensation technique with 30° DPWM. The existing technique showed significant fluctuations in the modulation index during the 0.3 and 0.4 intervals. Conversely, the proposed technique accurately estimated the ESR of the capacitor even with random changes in the modulation index.

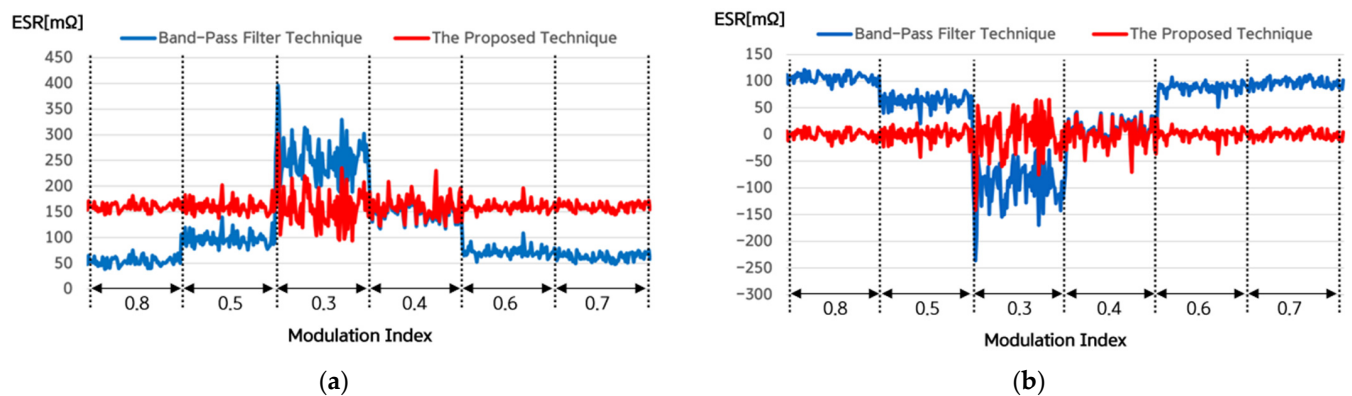


Figure 18. Comparison of ESR values with random changes in modulation index (30° DPWM). (a) Expected ESR values. (b) Error compensation values.

When comparing the results, it was observed that the proposed technique reduced the error rate by 58.9% at a modulation index of 0.8, 53.8% at 0.7, 48.5% at 0.6, 34.3% at 0.5, 1.9% at 0.4, and 22.4% at 0.3. Overall, the proposed technique achieved a 36.7% reduction in the average error rate across all experimental sections, resulting in an average error rate of 13.0% compared to the existing technique.

5.2.4. 60° DPWM

Figure 19 presents the results of ESR estimation using both the existing band-pass filter technique and the proposed ESR estimation compensation technique with 60° DPWM. The existing technique exhibited significant fluctuations in error rates with modulation

indices of 0.3 and 0.4. In contrast, the proposed technique successfully estimated the ESR of the capacitor even with random changes in the modulation index.

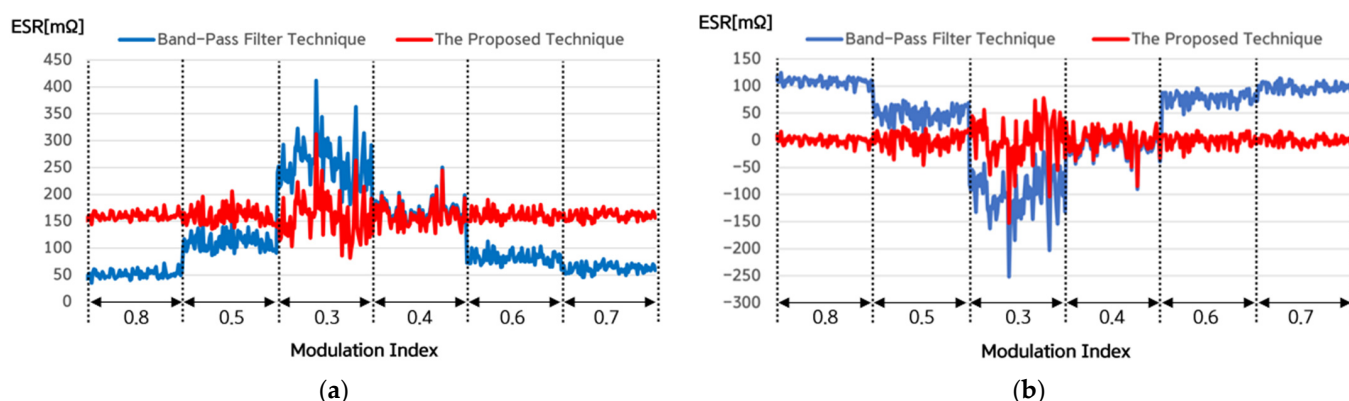


Figure 19. Comparison of ESR values with random changes in modulation index (60° DPWM). (a) Expected ESR values. (b) Error compensation values.

Comparing the results, the proposed technique demonstrated a reduction in the error rates by 60.3% at a modulation index of 0.8, 54.4% at 0.7, 43.1% at 0.6, 26% at 0.5, and 24.2% at 0.3. Overall, when averaging the error rates across all experimental conditions, the proposed technique achieved a 34.2% reduction in the average error rate compared to the existing technique, resulting in an average error rate of 13.2%.

The application of the improved ESR estimation technique using the band-pass filter, as proposed in this paper, consistently reduced the average error rate across all four PWM switching patterns and showed minimal fluctuation even with random modulation index changes.

6. Conclusions

This paper proposes a novel technique for lifespan diagnosis aimed at preventing failures in electrolytic capacitors by minimizing the error inherent in existing ESR estimation methods, specifically those utilizing model-based band-pass filters. Accurate ESR estimation is essential for maintaining the reliability and efficiency of DC-Link capacitors and preventing system-wide damage.

The proposed method compensates for the average error caused by the PWM switching pattern and modulation index—key variables affecting ESR estimation accuracy—ensuring more precise fault diagnosis for DC-Link capacitors. By measuring the average error resulting from these variables and incorporating the data into a LUT, the proposed method adjusts the ESR values calculated using the existing band-pass filter technique. The modulation index and PWM switching pattern data are obtained from the system controller, enabling the ESR values to be compensated based on the error data stored in the LUT.

Experimental validation was conducted by measuring the voltage and current data of the DC link, extracting frequency domain data between 10 kHz and 30 kHz through a filtering process and FFT, and estimating the capacitor's ESR. By compensating for the average error in the estimated ESR values through the LUT—particularly when the modulation index changes randomly across switching patterns—the proposed method significantly reduces the ESR estimation error rate across the entire spectrum. The experimental results validate the effectiveness of this approach.

This method provides significant benefits beyond laboratory environments, offering practical advantages in the operating conditions of electric propulsion ships. Accurate ESR estimation enhances propulsion system stability by preventing premature DC-Link capacitor failures and optimizing power conversion system efficiency. A notable feature of

the proposed method is its seamless integration into existing system architectures without requiring additional hardware. By leveraging pre-calculated error values in a lookup table, the method reduces implementation complexity, enabling cost-effective adoption in real-world applications.

Furthermore, this study addresses the common ESR estimation errors in conventional power conversion systems, enabling early maintenance and reducing the risk of overheating or damage to critical components within power converters. This advancement improves fault prediction system reliability, benefiting ship operators and system designers by ensuring safety and performance during long-term maritime operations.

In conclusion, by resolving the ESR estimation errors inherent in traditional band-pass filter methods, this paper presents a reliable fault diagnosis technique that enhances the accuracy and stability of electrolytic capacitor failure prediction. An improved ESR estimation reduces the risk of power converter damage, thereby increasing the overall reliability of electric propulsion ships.

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Abbreviations

DPWM	Discontinuous Pulse Width Modulation
ESL	Equivalent Series inductance
ESR	Equivalent Series Resistance
FFT	Fast Fourier Transform
LUT	Lookup Table
MI	Modulation Index
PWM	Pulse Width Modulation
SPWM	Sinusoidal Pulse Width Modulation
SVPWM	Space Vector Pulse Width Modulation

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