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Impact of Passive Filter Capacitor Failure on Harmonic Propagation in VSD-Driven ESP Systems

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ABSTRACT

Passive LC filters are commonly installed at the output of Variable Speed Drives (VSDs) to limit harmonic distortion in Electrical Submersible Pump (ESP) systems. However, capacitor degradation may reduce filter effectiveness and alter the electrical behavior of the entire drive system. This paper examines the impact of passive filter capacitor failure in a 390 kVA VSD-driven ESP installation using field measurements obtained under three operating conditions: before the filter, during normal LC filter operation, and after disconnection of a failed 200 µF capacitor while the output reactor remained in service. Harmonic performance was evaluated in accordance with IEEE Std 519-2022, followed by impedance and resonance analyses to explain the measured responses. The results indicate that capacitor removal increased THDi from 4.30% to 12.30% and THDv from 39.50% to 61.23%, confirming a substantial reduction in harmonic suppression capability. The analytical evaluation further shows that changes in filter impedance promote resonance between the output reactor and the downhole cable capacitance. A preliminary single-tuned passive filter design is finally proposed to improve harmonic mitigation under comparable operating conditions.

KEYWORDS: *Electrical Submersible Pump, Harmonic Distortion, Passive Filter, Resonance, Variable Speed Drive.*

1. INTRODUCTION

Electrical Submersible Pumps (ESPs) have become one of the most widely adopted artificial lift technologies for maintaining oil production from mature reservoirs where natural reservoir pressure is no longer sufficient to sustain continuous flow [1,2].Their ability to deliver relatively high production rates while operating under a wide range of well conditions has made ESPs an attractive solution for medium- and high-capacity oil wells. In current industrial practice, ESP systems are commonly operated using Variable Speed Drives (VSDs), allowing motor speed to be continuously adjusted to match production demand while improving overall operational efficiency.

The majority of industrial VSDs generate variable voltage and frequency through pulse-width modulation (PWM) using high-frequency switching of insulated gate bipolar transistor (IGBT) devices[3,4].Although this approach provides excellent speed control and contributes to energy savings, the inverter output is inherently non-sinusoidal. As a result, harmonic currents and voltages are introduced into the electrical system. These harmonic components can propagate through transformers, power cables, passive filters, and the downhole induction motor, causing additional electrical losses, deterioration of power quality, increased equipment stress, and a reduction in system reliability [5].

To limit harmonic distortion, passive LC filters are generally installed between the VSD and the ESP motor. By presenting low impedance at selected harmonic frequencies while maintaining minimal impedance at the fundamental frequency, these filters effectively reduce harmonic propagation without significantly affecting normal power delivery [6,7]. Their performance is typically evaluated according to the recommendations of IEEE Std 519-2022, which specifies acceptable harmonic distortion limits for industrial electrical systems [8-10].

Despite their relatively simple structure and widespread industrial use, passive filters are not immune to long-term deterioration. Among all filter components, capacitors experience the highest operational stress because they are continuously exposed to harmonic currents, electrical overvoltage, and thermal loading. Over prolonged operation, these conditions accelerate dielectric degradation and may eventually result in capacitor failure. In remote oil production facilities, replacement parts are often unavailable within a short time, making immediate maintenance difficult. Consequently, operators frequently continue production by isolating the failed capacitor bank while keeping the VSD in

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service with only the output line reactor [11,12]. Although this emergency practice helps avoid production shutdowns, it substantially changes the filter impedance characteristics and weakens its capability to suppress harmonic distortion.

A considerable number of studies have reported the design of passive filters and various harmonic mitigation techniques for industrial power systems. Nevertheless, investigations focusing on the operational consequences of passive filter capacitor failure in VSD-driven ESP installations under actual field conditions remain limited. In particular, there is still insufficient discussion regarding how capacitor failure influences harmonic propagation, resonance behavior, and overall power quality during real operating conditions.

Motivated by this research gap, this study examines the electrical impact of passive filter capacitor failure in a 390 kVA VSD-driven ESP installation using field measurement data collected under three representative operating conditions. The measured harmonic characteristics are evaluated to determine the changes in power quality caused by capacitor failure. Based on these findings, baseline design parameters for a single-tuned passive filter are proposed as a practical reference for mitigating dominant harmonic components and improving the electrical performance of VSD-operated ESP systems.

2. METHODOLOGY

2.1 System Description and Operational Parameters

The investigation was conducted on a VSD-driven ESP installation at Well 5C-33. The system consists of a surface VSD, a passive LC output filter, step-up and step-down transformers, an 823 m downhole power cable, and an 80 HP ESP motor. The passive filter comprises a 0.12 mH output line reactor and a 200 µF capacitor bank designed to suppress harmonic components generated by the PWM inverter.

The analysis focuses on the electrical characteristics of the VSD and passive filter because harmonic propagation originates from the inverter switching process. Mechanical components such as pump stages, intake, and protector are considered outside the scope of this investigation.

Table 1: Technical specifications of the investigated VSD-driven ESP system

Equipment Category	Operational Parameter	Specification Value
Passive LC Filter	Rated Voltage / Current	600 V/320 A,50/60Hz
	Nominal Inductance (L)	0,12 mH (2,3 kHz)
	Filter Capacitance (C)	200 µF (690 V)
ESP Unit (DX-UT)	Motor Capacity	80 HP
	Nominal Voltage/ Current	964 V / 52,2 A
	Downhole Cable Length	823 m
	Cable Insulation Rating	5 kV
Komponen Mekanis	Pump Model	SN 2600 (48 stages)
	Intake Type	ARZ 540 SR
	Protector Device	BSL 540

2.2 Configuration of the Investigated System

Figure 1 illustrates the electrical configuration evaluated in this study. Power is supplied from the utility grid to the VSD through a step-down transformer. The inverter output is connected to the passive LC filter before being transmitted through a step-up transformer and an 823 m downhole cable to the ESP motor. During normal operation, the passive filter consists of both the output line reactor and the capacitor bank. Following dielectric failure of the 200 µF capacitors, the capacitor bank was disconnected while the output reactor remained in service. Consequently, the filter operated as a predominantly inductive network, providing the basis for evaluating the electrical and thermal consequences of capacitor failure.

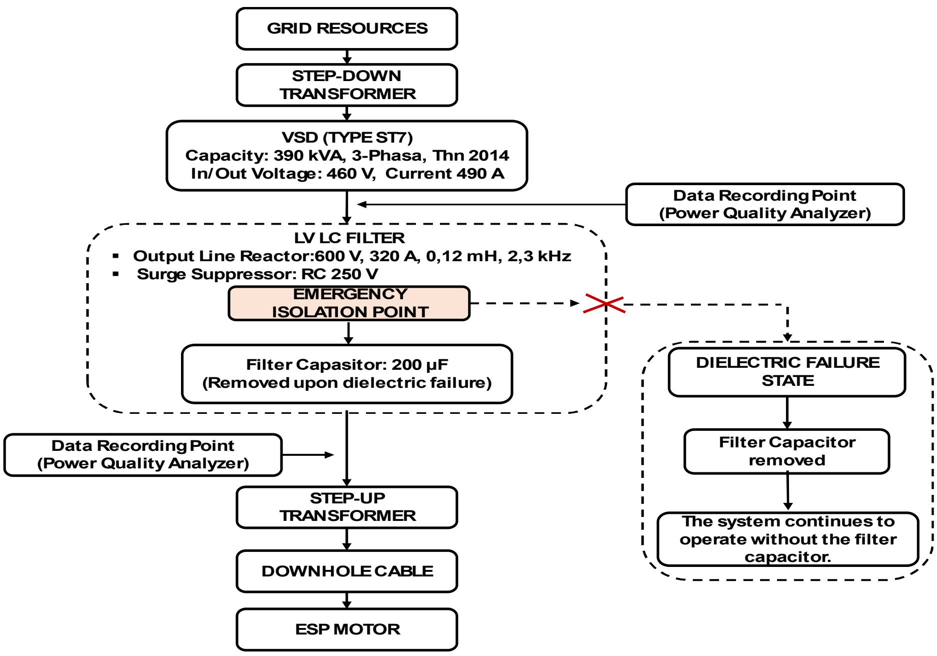

Figure 1: Electrical configuration of the investigated VSD-driven ESP system

2.3 Experimental Data Acquisition

Power quality measurements were carried out under three operating conditions:

- Condition 1: Harmonic content measured at the filter input, representing baseline distortion generated directly by the PWM inverter.
- Condition 2: Normal operation with both the 0.12 mH reactor and the 200 µFcapacitorsfunctioning as the designed LC filter.
- Condition 3: Emergency operation after the failed capacitor was disconnected, leaving only the output line reactor connected to the system.

For each operating condition, the Power Quality Analyzer recorded RMS voltage, RMS current, THDv, THDi, and individual harmonic spectra obtained through Fast Fourier Transform (FFT) analysis.

2.4 Harmonic Assessment Based on IEEE Std 519-2022

The measured harmonic characteristics were evaluated according to IEEE Std 519-2022 [10],[13]. For the investigated 460 V low-voltage network, the recommended THDv limit is 8%, while individual voltage harmonics are limited to 5%. Particular attention was given to high-order harmonic components because these frequencies strongly influence conductor losses, resonance phenomena, and thermal stress in inverter-fed motor systems.

2.5 Analytical Modeling of Harmonic Propagation

To evaluate the electrical impact of passive filter capacitor failure, an analytical framework was established by integrating harmonic distortion assessment, passive filter impedance analysis, resonance evaluation, and passive filter redesign. The proposed methodology follows the propagation of harmonic components generated by the PWM inverter through the VSD output network, enabling the electrical behavior of the system to be examined under both normal and degraded operating conditions.

The analysis begins with an evaluation of power quality based on the recommendations of IEEE Std 519-2022. Harmonic performance is quantified using Total Harmonic Distortion of Current (THDi) and Total Harmonic Distortion of Voltage (THDv), calculated using Equations (1) and (2), respectively [10,13-15]

$$THD_I = \frac{\sqrt{\sum_{h=2}^{n} I_h^2}}{I_1}\ x\ 100\% \qquad (1)$$

$$THD_V = \frac{\sqrt{\sum_{h=2}^{n} V_h^2}}{V_1} \times 100\% \qquad (2)$$

where I_h and V_h denote the RMS values of the current and voltage at harmonic order h, while I_1 and V_1 represent the RMS values of the corresponding fundamental components.

The calculated THDi and THDv values were subsequently compared with the harmonic limits specified in IEEE Std 519-2022 to evaluate the compliance of each operating condition. This comparison also provides a quantitative measure of the deterioration in power quality resulting from passive filter capacitor failure.

Following the harmonic assessment, the electrical characteristics of the passive filter are investigated by analyzing its equivalent impedance. During normal operation, the filter consists of an output reactor connected with a shunt capacitor, forming an LC network that provides low impedance at selected harmonic frequencies. The equivalent harmonic impedance under this operating condition is expressed by Equation (3) [16,17].

$$Z_h = J\omega_h L + \frac{1}{j\omega_h C} \qquad (3)$$

Where $\omega_h = 2\pi hf$ is the angular frequency associated with harmonic order h. When the capacitor bank is disconnected because of component failure, the output reactor remains connected to maintain system operation. Under this condition, the passive filter no longer behaves as an LC network but predominantly exhibits inductive characteristics. The corresponding equivalent impedance is expressed by Equation (4).

$$Z_h = j\omega_h L \qquad (4)$$

A comparison of Equations (3) and (4) demonstrates how capacitor removal changes the impedance characteristics of the filter. This alteration reduces the effectiveness of harmonic attenuation and allows a larger portion of harmonic currents to propagate throughout the electrical system.

Capacitor disconnection also modifies the interaction between the output reactor and the distributed capacitance of the 823 m downhole cable. Under certain conditions, this interaction may create resonance at particular harmonic frequencies, resulting in harmonic amplification. To identify the frequencies at which resonance is likely to occur, the resonant frequency of the system is estimated using Equation (5) [17].

$$f_r = \frac{1}{2\pi\sqrt{LC}} \qquad (5)$$

The calculated resonant frequency is then compared with the harmonic spectrum obtained from Fast Fourier Transform (FFT) measurements. This comparison makes it possible to determine whether the dominant harmonic components coincide with the predicted resonant frequency and to identify harmonic orders that are most susceptible to resonance following capacitor failure. Based on the measured harmonic spectrum and the analytical results obtained from the previous stages, a preliminary design of a single-tuned passive filter is developed to mitigate the dominant harmonic components identified in the investigated system. The tuning frequency is first determined using Equation (6).

$$f_t = hF_1 \qquad (6)$$

Where h is the target harmonic order and f_1 is the system fundamental frequency. The reactive power required from the filter capacitor is then calculated using Equation (7)

$$Qc = 2\mu f C V^2 \qquad (7)$$

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The corresponding filter capacitance is obtained from the reactive power requirement using Equation (8).

$$C = \frac{Qc}{2\pi f V^2} \quad (8)$$

Finally, the reactor inductance required to achieve the desired tuning frequency is determined using Equation (9)[16,17].

$$L = \frac{1}{(2\pi f_2)^2 C} \quad (9)$$

The parameters obtained from Equations (6)–(9) provide the preliminary design specifications of the proposed single-tuned passive filter. These analytical results serve as the basis for reducing dominant harmonic components, improving harmonic suppression, and enhancing the overall electrical performance of the VSD-driven ESP system.

3. RESULTS AND DISCUSSION

3.1 Field Measurement Results

Power quality measurements were performed under three operating conditions to evaluate the influence of passive filter capacitor failure on the electrical performance of the investigated VSD-driven ESP system. The measured RMS voltage, RMS current, Total Harmonic Distortion of Voltage (THDv), and Total Harmonic Distortion of Current (THDi) obtained from the Power Quality Analyzer are summarized in Table 2.

Table2: Electrical parameters under three operating conditions

Parameter	Condition 1: Input Filter (Initial VSD Distortion)	Condition 2: Normal Output Filter (Intact LC)	Condition 3: Filter Defect (Capacitor Removed)
Line Voltage RMS (V)	354.18 V	354.18 V	354.18 V
Line Current RMS (I)	76.94 A	72.73 A	79.45 A
THDv (%)	63.73%	39.50%	61.23%
THDi (%)	11.63%	4.30%	12.30%

The measured data demonstrate that the harmonic performance of the passive filter strongly depends on the operating condition of the capacitor bank. During normal operation (Condition 2), the LC filter effectively attenuated harmonic currents generated by the PWM inverter. The measured THDi decreased from 11.63% at the filter input to 4.30%, corresponding to a reduction of approximately 63%. According to IEEE Std 519-2022, this value satisfies the recommended limit for current harmonic distortion in industrial power systems [10].

The improvement in harmonic performance is attributed to the combined action of the output reactor and the shunt capacitor, which establishes a low-impedance path for harmonic currents while allowing the fundamental-frequency component to be supplied to the ESP motor. Consequently, the passive filter effectively suppresses harmonic propagation through the distribution system.

A significantly different operating characteristic was observed after the 200 µF capacitor was disconnected because of dielectric failure. Under this emergency operating condition (Condition 3), THDi increased to 12.30%, while THDv increased from 39.50% to 61.23%. These values substantially exceed the limits recommended by IEEE Std 519-2022, indicating that capacitor isolation severely reduces the harmonic attenuation capability of the passive filter.

The increase in harmonic distortion observed in Condition 3 is consistent with the analytical model presented in Section 2.5. As described by Equations (3) and (4), removing the capacitor changes the passive filter from an LC network to a predominantly inductive circuit. This modification increases the equivalent harmonic impedance and allows a larger proportion of harmonic current to propagate toward the downhole cable and ESP motor.

The deterioration of harmonic performance following capacitor isolation can also be observed directly from the measured voltage and current waveforms. Representative waveforms recorded at the passive filter output under Condition 3 are presented in Figure 2. Figure 2 shows that the voltage and current waveforms deviate considerably from their ideal sinusoidal shape. High-frequency oscillations become more pronounced around the waveform peaks, indicating the presence of switching harmonics generated by the PWM inverter. These waveform distortions confirm that the remaining output reactor alone is unable to provide adequate attenuation after the capacitor has been removed.

Although the waveform distortion provides a qualitative indication of harmonic deterioration, it does not identify the harmonic components responsible for the observed increase in THDi and THDv. Therefore, a frequency-domain analysis was performed using the Fast Fourier Transform (FFT), as discussed in the following subsection.

3.2 Harmonic Spectrum Analysis and Resonance Characteristics

To identify the dominant harmonic components contributing to the increase in harmonic distortion, the measured voltage and current waveforms were analyzed using the Fast Fourier Transform (FFT). The resulting voltage and current harmonic spectra are presented in Figures 3 and 4, respectively. Figure 3 indicates that several higher-order voltage harmonics experienced noticeable amplification following capacitor isolation. The increase in harmonic magnitude suggests that the passive filter no longer provides sufficient attenuation at frequencies generated by the PWM inverter.

The current spectrum presented in Figure 4 exhibits a similar trend. Several dominant harmonic components increased significantly after capacitor removal, indicating that harmonic currents propagated more readily through the electrical network. This phenomenon can be explained by the analytical model developed in Section 2.5. Under normal operating conditions, the LC filter provides a low-impedance path for harmonic currents. However, once the capacitor is disconnected, the equivalent impedance is governed by Equation (4), resulting in a predominantly inductive circuit.

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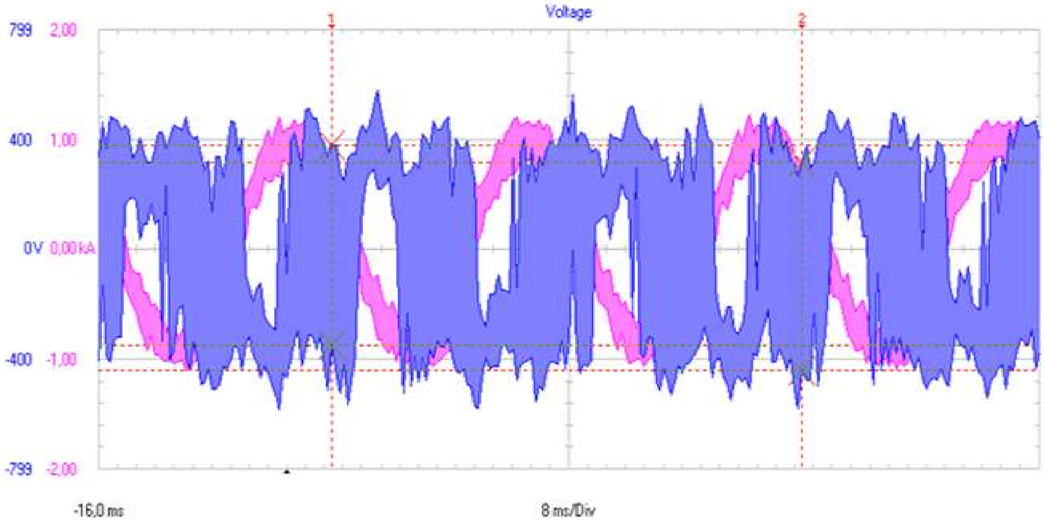

Figure 2: Measured voltage and current waveforms after passive filter capacitor removal

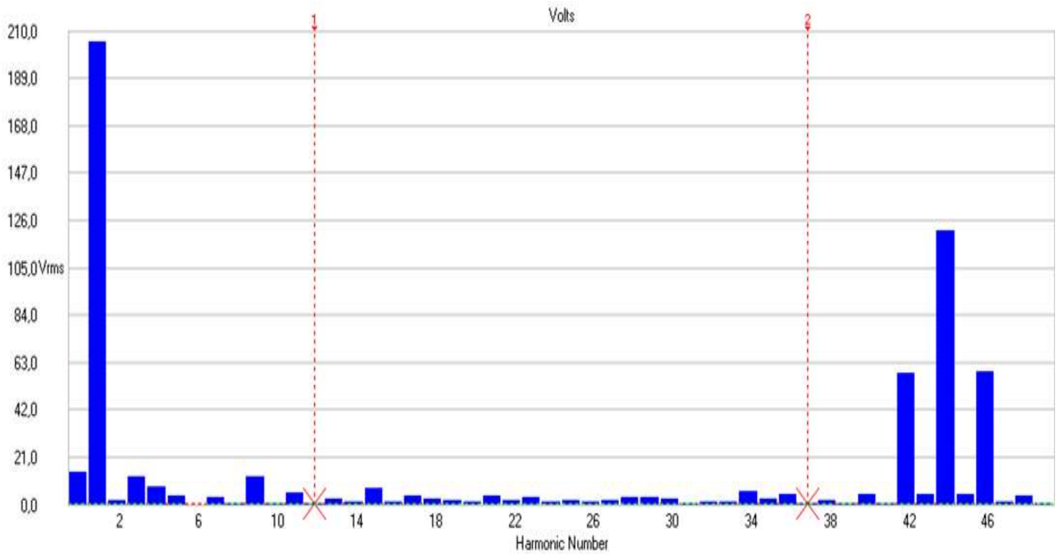

Figure 3: Measured THDv spectrum after passive filter capacitor removal

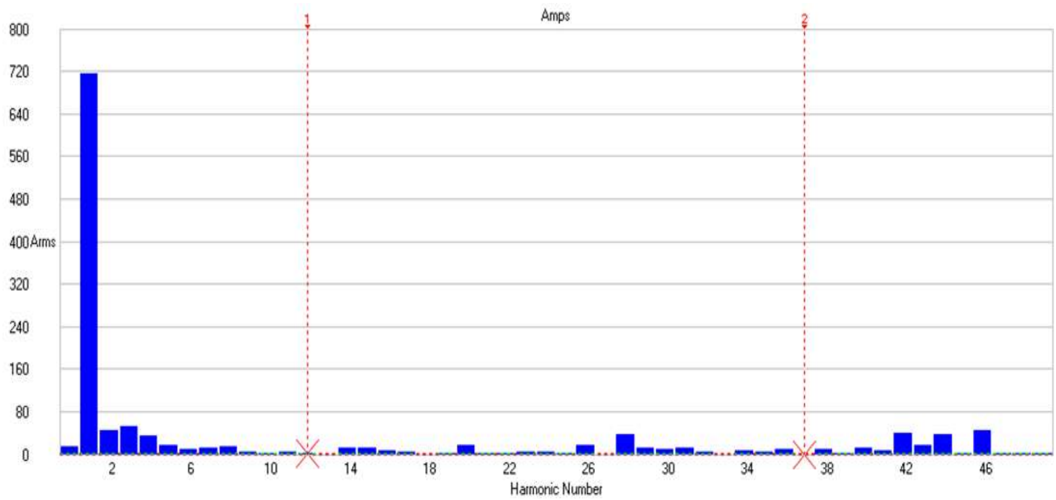

Figure 4: Measured THDi spectrum after passive filter capacitor removal

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Furthermore, the remaining output reactor interacts with the distributed capacitance of the 823 m downhole cable, creating a resonant electrical network. As predicted by Equation (5), harmonic frequencies located near the resonance frequency experience impedance reduction, allowing harmonic currents to increase substantially. The agreement between the analytical model and the measured FFT spectra indicates that the observed increase in THDi and THDv is primarily associated with resonance effects caused by passive filter capacitor failure rather than by changes in the VSD operating condition.

4. CONCLUSION

Field measurements demonstrate that the performance of the passive LC filter is strongly influenced by the condition of its capacitor bank. Under normal operation, the filter effectively reduced harmonic distortion, whereas capacitor disconnection increased THDi from 4.30% to 12.30% and THDv from 39.50% to 61.23%, exceeding the limits recommended by IEEE Std 519-2022. The analytical results indicate that capacitor failure changes the filter impedance characteristics and promotes resonance between the output reactor and the distributed capacitance of the downhole cable, leading to increased harmonic propagation. Based on these findings, preliminary parameters for a single-tuned passive filter were developed to restore harmonic attenuation and improve the electrical performance of VSD-driven ESP systems.

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