

Smart Predictive Maintenance for Centrifugal Pumps: How IoT Sensors Reduce Downtime by Monitoring Vibration, Current, and Seal Integrity

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ABSTRACT

This study presents the development of an IoT-based real-time monitoring system designed to optimize predictive maintenance protocols for three-phase industrial centrifugal pump motors. The investigation focuses on three critical failure parameters—mechanical seal integrity, motor current load, and pump vibration—which serve as primary indicators of incipient equipment failure. Employing a Research and Development (R&D) methodology, the system incorporates three specialized sensors: an ADXL345 triaxial vibration sensor exhibiting average 0.69% measurement error across X and Z axes), a high-sensitivity mechanical seal leakage detector (demonstrating 100% detection accuracy), and an SCT-013 non-invasive current transducer with average 6.0% measurement error. The IoT-enabled platform facilitates real-time data acquisition, visualization, and automated alarm generation based on thresholds. Experimental validation confirms the system's efficacy in early fault detection, with spectral vibration analysis proving particularly effective in diagnosing bearing wear and shaft misalignment. Current monitoring reliably identified overloading conditions, while the seal integrity system instantaneously detected fluid containment failures. Notable limitations include the restricted scope of field testing under varied operational conditions and pump configurations. The study did not encompass complementary failure indicators such as thermal variations or high-frequency bearing vibrations. However, these constraints suggest that the implementation of the Internet of Things (IoT) could substantially reduce unplanned downtime in industrial applications. Future research directions include optimizing the cost-benefit ratio for small to medium-sized enterprises and integrating supplementary predictive parameters. This work is a significant step forward in developing Industry 4.0-compliant maintenance solutions.

Keywords: Preventive Maintenance; Three-Phase Motor; Centrifugal Pump; Internet of Things (IOT); Research and Development Method.

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I. INTRODUCTION

Pumps are mechanical devices designed to periodically transfer fluids and serve as critical components in supporting industrial production processes. To maintain optimal performance and reliability, preventive maintenance (PM) is essential [1]. PM encompasses a series of scheduled maintenance actions, including inspection, repair, component replacement, lubrication, and pump adjustment, aimed at extending the pump's operational lifespan and minimizing production downtime due to failures [2]. Centrifugal pumps, in particular, play a pivotal role in industrial applications due to their ability to efficiently transport fluids via rotating impellers that generate centrifugal force [3]. However, centrifugal pumps are susceptible to two primary failure modes: operational issues (e.g., cavitation, reduced fluid flow or pressure, and temperature fluctuations) and mechanical faults (e.g., mechanical seal leakage, excessive vibration, and motor current irregularities)[4].

To mitigate mechanical failures, an Internet of Things (IoT)-based real-time monitoring system is proposed to detect early anomalies such as seal leakage, abnormal vibration, and motor current deviations, enabling prompt corrective actions and long-term data-driven analysis [5]. IoT integration in PM not only enhances workforce efficiency by reducing manual inspections but also minimizes machine downtime and repair costs[6]. This study focuses on developing an IoT-based monitoring system for three critical parameters: mechanical seal leakage, pump vibration, and motor current, providing real-time notifications upon anomaly detection [7]. Prior research has demonstrated that IoT systems significantly improve the accuracy of machinery condition monitoring. Microelectromechanical systems (MEMS) accelerometers effectively detect impeller imbalance through vibration analysis[8], while current sensors identify motor overload conditions [9].

Additionally, seal leakage monitoring via humidity or flow sensors can prevent catastrophic failures [10]. The integration of sensor data with pumps is crucial for effective operation. Pumps are mechanical devices designed to periodically transfer fluids and serve as critical components in supporting industrial production processes. To maintain optimal performance and reliability, preventive maintenance (PM) is essential [1]. PM encompasses a series of scheduled maintenance actions, including inspection, repair, component replacement, lubrication, and pump adjustment, aimed at extending the pump's operational lifespan and minimizing production downtime due to failures [2]. Centrifugal pumps, in particular, play a pivotal role in industrial applications due to their ability to efficiently transport fluids via rotating impellers that generate centrifugal force [3]. However, centrifugal pumps are susceptible to two primary failure modes: operational issues (e.g., cavitation, reduced fluid flow or pressure, and temperature fluctuations) and mechanical faults (e.g., mechanical seal leakage, excessive vibration, and motor current irregularities) [4].

To mitigate mechanical failures, an Internet of Things (IoT)-based real-time monitoring system is proposed to detect early anomalies such as seal leakage, abnormal vibration, and motor current deviations, enabling prompt corrective actions and long-term data-driven analysis [5]. IoT integration in PM not only enhances workforce efficiency by reducing manual inspections but also minimizes machine downtime and repair costs [6]. This study focuses on developing an IoT-based monitoring system for three critical parameters: mechanical seal leakage, pump vibration, and motor current, providing real-time notifications upon anomaly detection [7]. Prior research has demonstrated that IoT systems significantly improve the accuracy of machinery condition monitoring. Microelectromechanical systems (MEMS) accelerometers effectively detect impeller imbalance through vibration analysis [8], while current sensors identify motor overload conditions [9]. Additionally, seal leakage monitoring via humidity or flow sensors can prevent catastrophic failures [10]. The integration of sensor data with cloud platforms facilitates predictive analytics through machine learning algorithms to estimate the remaining useful life (RUL) of components [11]. This approach aligns with Industry 4.0 trends, where big data and IoT form the backbone of industrial asset management [12].

The proposed system offers scalability, high accuracy, and compatibility with diverse pump types [13]. However, challenges such as network latency, sensor calibration, and data security must be addressed [14]. Industrial case studies indicate that IoT solutions can reduce downtime by up to 30% and maintenance costs by 25% [15], establishing a replicable model for IoT-based PM in other industrial machinery. This study aims to implement an IoT-based monitoring system for detecting mechanical seal leakage, nominal motor current load, and vibration in centrifugal pumps, enabling early fault detection during operation. The system is expected to significantly benefit maintenance departments by optimizing workforce efficiency and preventing severe pump damage, thereby ensuring uninterrupted production processes. IT cloud platforms facilitate predictive analytics through machine learning algorithms to estimate the remaining useful life (RUL) of components [11]. This approach aligns with Industry 4.0 trends, where big data and IoT form the backbone of industrial asset management [13]. The proposed system offers scalability, high accuracy, and compatibility with diverse pump types [14]. However, challenges such as network latency, sensor calibration, and data security must be addressed [15]. Industrial case studies indicate that IoT solutions can reduce downtime by up to 30% and maintenance costs by 25% [16], establishing a replicable model for IoT-based PM in other industrial machinery.

This study proposes the development and implementation of an Internet of Things (IoT)-enabled monitoring system for real-time detection of mechanical seal leakage, motor current anomalies, and excessive vibration in centrifugal pumps. Despite the critical role these parameters play in early fault detection and predictive maintenance, existing monitoring approaches remain largely reactive and isolated. By integrating sensor data analytics into a unified IoT framework, the proposed system addresses a notable gap in proactive condition monitoring of rotating machinery. The anticipated outcomes include enhanced maintenance planning, reduced unplanned downtime, and sustained operational continuity, which collectively contribute significantly to both industrial reliability and workforce optimization.

II. METHOD

Real-time Monitoring and alerting are critical features of the system, enabling it to provide real-time data acquisition, visualization, and automated threshold-based alarm generation, which is essential for effective predictive maintenance and prompt intervention. This method, as shown in Fig., was selected due to its capability to address the need for innovative, application-oriented, and measurable technological development. In this research, the R&D approach is employed to design, develop, and evaluate a preventive maintenance monitoring tool for centrifugal pump motors utilizing an IoT platform.

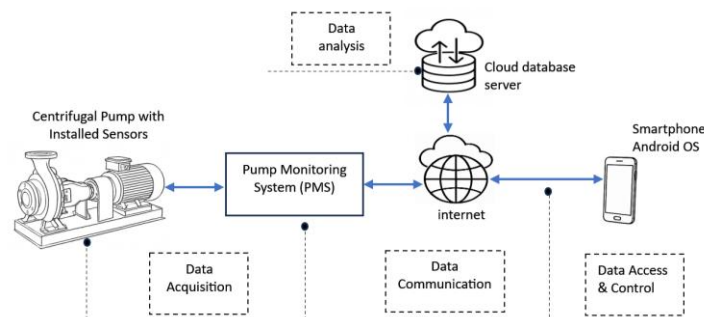


Fig.1. Workflow Diagram of Smart Predictive Maintenance

A. Hardware implementation

The hardware components of the device consist of a centrifugal pump motor from Worthington ERP 100-400, a power bank module serving as portable power supply for PMS module, feature ESP32 custom module functioning as the monitoring unit, which reads data from a rain drop sensor, ADXL345 sensor, and SCT 013 sensor sending data to cloud database of firebase [17]. The ADXL345 accelerometer works by measuring the acceleration due to forces (including gravity) applied to the sensor, where sensitivity is the scaling factor (LSB/g) for the outputs. It provides a 16-bit signed integer for each axis (X , Y , and Z). The acceleration value a in g (gravitational acceleration) is calculated using Equation (1) [18].

$$ag = \frac{(ADC_{value} - Offset)}{Sensitivity} \tag{1}$$

Acceleration Measurement for ADXL345 sensor. The sensor output is proportional to acceleration for each axis (x , y , and z) using Equation (2) [19]. Where the scale factor depends on the selected range (e.g., $\pm 2g = 3.9 \text{ mg/LSB}$), the resolution output is 10-13 bits (configurable).

$$a = \frac{Output - Offset}{Sensitivity} \text{ (in } g) \tag{2}$$

Tilt Calculation (Static Acceleration) for ADXL345 sensor, for tilt angles (θ) relative to gravity) using Equations (3) and (4) [20], [21]. Where A_x , A_y , A_z are acceleration components.

$$\text{Roll: } \theta_x = \tan^{-1} \left(\frac{A_x}{\sqrt{A_y^2 + A_z^2}} \right) \tag{3}$$

$$\text{Pitch: } \theta_y = \tan^{-1} \left(\frac{A_y}{\sqrt{A_x^2 + A_z^2}} \right) \tag{4}$$

The centrifugal pump motor, monitored using a WORTHINGTON ERP 100-400 system, has the following specifications. Power input rating: 110 kW, Supply input voltage: 3-phase, Speed rating: 2965 rpm, with a current rating of 193 Amp. Vibration data were collected in compliance with ISO 10816-7, which defines severity thresholds for industrial machinery, with a reference vibration threshold of 4.5 mm/s. This value serves as the benchmark for evaluating vibration performance.

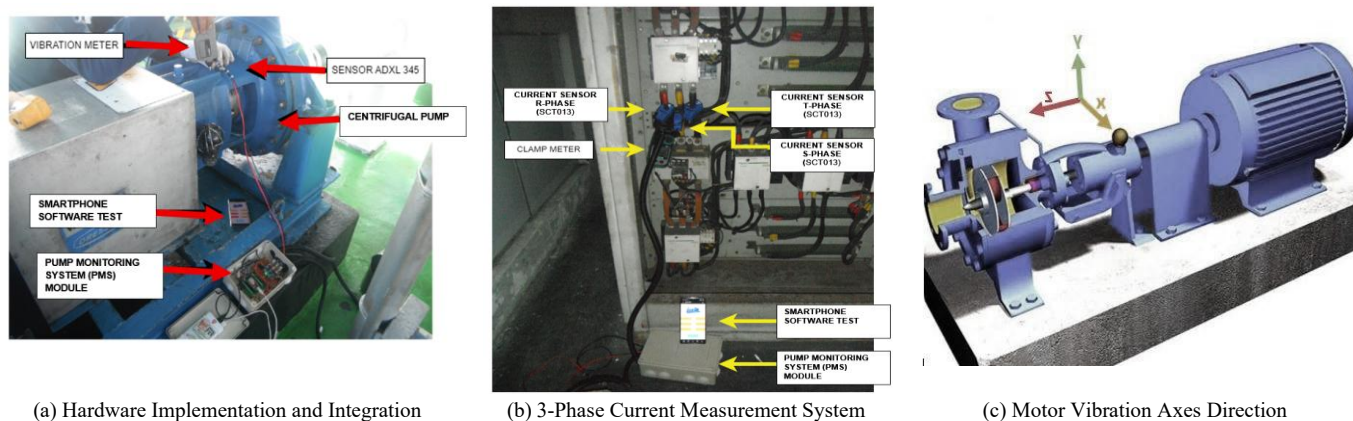


Fig.2. Three-Dimensional Vibration Profiling

This three-dimensional vibration profiling enables a comprehensive analysis of mechanical oscillations and their spatial orientation, as shown in Fig. 2. It illustrates the sensor installation and integration with the Power Monitoring System (PMS) module in Fig. 2(a). Demonstrates the experimental setup, where the monitoring device is positioned adjacent to the control panel in Fig. 2(b). In this configuration, three SCT013 current sensors are deployed on the three-phase power cables (R, S, and T phases) to facilitate comprehensive current measurement. Illustrates the triaxial vibration measurement of the centrifugal pump motor in Fig.2(c), quantifying displacement amplitudes along the orthogonal X , Y , and Z axes[22].

B. Software implementation

The software architecture incorporates an ESP32 microcontroller for real-time acquisition of sensor data. In Fig.3, the acquired data is transmitted to Google Firebase Cloud for storage and processing. Subsequently, the data is accessed and visualized via a smartphone interface developed using MIT App Inventor, enabling remote monitoring and analysis.

Fig.3 presents the user interface display, which provides real-time system monitoring of: (i) motor vibration amplitude, (ii)

three-phase current measurements (R, S, T phases), and (iii) mechanical seal leakage detection alerts. The interface integrates these critical operational parameters into a unified dashboard, providing a comprehensive assessment of equipment health.

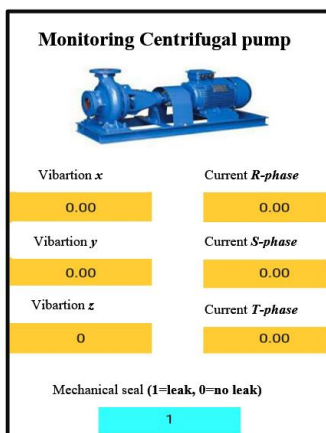


Fig.3. User Interface On Smartphone

III. RESULT AND DISCUSSION

A. Current Sensor Performance

The monitoring system was strategically positioned adjacent to the control panel. Table I shows the SCT013 current sensors installed on each phase conductor (R, S, T) of the three-phase power supply. For validation purposes, comparative measurements were simultaneously recorded using a reference-grade Yokogawa KEW 2007R clamp meter (accuracy class 0.5%, compliant with IEC 61010-1 safety standards). With average error rating on phase R around 3,4 - 3,9%, on phase S with average error rating around 8,7 - 9,0%, and average error rating on phase T around 6,9 – 7,3%.

TABLE I
 CURRENT SENSOR PERFORMANCE EVALUATION

Exp.	Sensor reading current (Amp.)			Clamp Meter (Amp.)			Error deviation (%)			Work description
	R	S	T	R	S	T	R	S	T	
1	30,2	28,5	29,1	31,3	30,3	31,8	3,5	8,9	7,1	No load
2	31,2	29,6	30,1	32,4	30,9	32,7	3,6	8,7	7,0	No load
3	36,0	34,1	34,8	37,4	35,7	36,2	3,7	8,8	6,9	No load
4	77,3	73,1	74,3	80,1	76,1	78,1	3,5	8,7	7,2	with load
5	80,5	76,0	77,3	83,3	80,3	82,6	3,4	8,8	7,2	with load
6	82,3	77,8	79,2	85,3	83,6	84,3	3,5	8,8	7,2	with load
7	77,3	73,0	74,3	80,0	77,0	78,2	3,4	8,8	7,1	with load

The SCT013 sensor effectively monitors the current in a three-phase system, as shown in Fig.4. The R-phase current increases gradually, while the S-phase and T-phase currents rise sharply after the 7th data point. The error values for all phases remain low and consistent, indicating the sensor's accuracy. Additionally, the readings from the SCT013 align closely with those from the Clamp Meter, confirming the sensor's reliability in real-world conditions. Overall, the SCT013 sensor demonstrates strong performance with minimal errors, making it a reliable tool for current monitoring in three-phase systems.

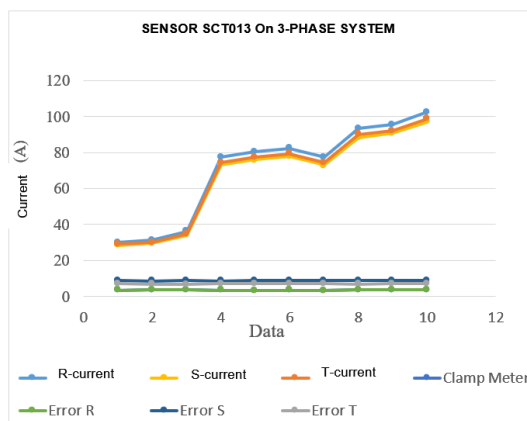


Fig.4. SCT013 Performance on 3-Phase System

B. Vibration Sensor Performance

This study presents performance measurements from the ADXL345 accelerometer, including alarm threshold testing to validate the effectiveness of the IoT monitoring system. The evaluation protocol involved continuous data acquisition, with the system programmed to trigger visual alerts (color-coded interface changes) and audible alarms when sensor readings exceeded predefined operational thresholds. These automated warnings indicate critical anomalies in the centrifugal pump motor, enabling prompt maintenance intervention to prevent equipment failure. The results demonstrate the system's capability to detect mechanical faults in real-time through integrated sensor diagnostics. The Table 2 shows that vibration levels were normal (yellow status, alarm off) until 10:12, when they exceeded the threshold, entering the "red" zone (overload) with values rising from 4.53 mm/s to 7.63 mm/s by 11:55. The alarm status switched to "ON," indicating a need for attention to prevent potential system failure.

TABLE 2
 VIBRATION SENSOR PERFORMANCE EVALUATION (X AXES)

Exp.	Time	Horizontal vibration -X (mm/s)	Box color status on Apps	Alarm status	Work Description
1	09:15	0,97	yellow	OFF	Normal
2	09:18	1.35	yellow	OFF	Normal
3	09:25	1,85	yellow	OFF	Normal
4	09:28	2,18	yellow	OFF	Normal
5	09:45	3,33	yellow	OFF	Normal
6	09:50	3,68	yellow	OFF	Normal
7	10:12	4,53	Red	ON	Overload
8	10:30	6,21	Red	ON	Overload
9	11:40	6,77	Red	ON	Overload
10	11:55	7,63	Red	ON	Overload

Table 3 shows that the horizontal vibration measurements are consistently within the "yellow" status range, with values fluctuating between -0.75 mm/s and 1.45 mm/s. The alarm status remains "OFF" throughout all the measurements, indicating that the vibration levels were within acceptable limits and did not trigger any alerts. These findings suggest that the system was operating normally during the monitoring period, with no significant deviations or malfunctions in the vibration sensor's performance.

TABLE 3
 VIBRATION SENSOR PERFORMANCE EVALUATION (Y AXES)

Exp.	Time	Horizontal vibration -X (mm/s)	Box color status on Apps	Alarm status	Work Description
1	09:15	0,34	yellow	OFF	Normal
2	09:18	0,56	yellow	OFF	Normal
3	09:25	-0,33	yellow	OFF	Normal
4	09:28	1,37	yellow	OFF	Normal
5	09:45	1,45	yellow	OFF	Normal
6	09:50	-0,75	yellow	OFF	Normal
7	10:12	-0,54	yellow	OFF	Normal
8	10:30	1,05	yellow	OFF	Normal
9	11:40	0,96	yellow	OFF	Normal
10	11:55	0,74	yellow	OFF	Normal

As presented in TABLE 4, the performance evaluation of the vibration sensor reveals that the majority of *Z-axis* measurements initially fall within the "yellow" status range, indicating nominal horizontal vibration levels between 9.65 millimeters per second (mm/s) and 12.46 mm/s. During this interval, no alarms were triggered, indicating stable operational conditions. However, commencing at 10:30, a marked escalation in vibration is observed, with values surpassing the predefined threshold and entering the "red" zone, thereby activating the alarm system. It is noteworthy that while the *Z-axis* values trigger an alarm, they remain numerically lower than the *X-axis* readings that caused alarm activation in TABLE 2 (e.g., 4.53 mm/s). This discrepancy suggests two possible explanations. First, it suggests that distinct threshold values are applied across measurement axes. Second, it suggests that axis-specific sensitivities are at play. These sensitivities could be due to sensor orientation or the inherently different dynamic behavior of axial (*Z-axis*) versus radial (*X-axis*) vibrations. While a reference threshold of 4.5 mm/s is cited in the Introduction, the uniform application of this limit is exceeded across. It is therefore imperative to provide clarification and justification for axis-dependent criteria to ensure accurate interpretation and operational reliability.

TABLE 4
 VIBRATION SENSOR PERFORMANCE EVALUATION (Z AXES)

Exp.	Time	Horizontal vibration -X (mm/s)	Box color status on Apps	Alarm status	Work Description
1	09:15	12,32	yellow	OFF	Normal
2	09:18	12,38	yellow	OFF	Normal
3	09:25	12,46	yellow	OFF	Normal
4	09:28	11,73	yellow	OFF	Normal
5	09:45	11,27	yellow	OFF	Normal

Exp.	Time	Horizontal vibration -X (mm/s)	Box color status on Apps	Alarm status	Work Description
6	09:50	10,99	yellow	OFF	Normal
7	10:12	10,77	Red	ON	Overload
8	10:30	10,25	Red	ON	Overload
9	11:40	9,87	Red	ON	Overload
10	11:55	9,65	Red	ON	Overload

Fig. 5 illustrates the vibration readings of the ADXL345 sensor along the three axes (X, Y, Z) over time, providing valuable insights into the system's operational behavior. Initially, vibration levels on all axes remain low, particularly on the X and Y axes, with minimal fluctuations. However, from 10:12 onwards, there is a notable surge in vibration intensity along the Z-axis, with values exceeding 12 mm/s, suggesting a significant increase in mechanical movement or stress. In contrast, the X and Y axes maintain a consistent, stable pattern throughout the observation period. These findings indicate that while the system operates within normal vibration thresholds in the early stages, the sudden spike in Z-axis vibrations post-10:12 signals a potential anomaly or overload. This observation serves as an early indicator for predictive system monitoring, where further analysis is necessary to mitigate the risk of system failure and optimize performance. By integrating predictive analytics, the system could proactively identify such issues before they escalate, enhancing operational efficiency and preventing downtime. Lateral displacement of the X-axis manifested as horizontal oscillations (left-right movement) and longitudinal displacement of the Z-axis exhibited axial vibrations (front-back movement) of the centrifugal pump motor due to the load on the motor coupling and pump mechanism.

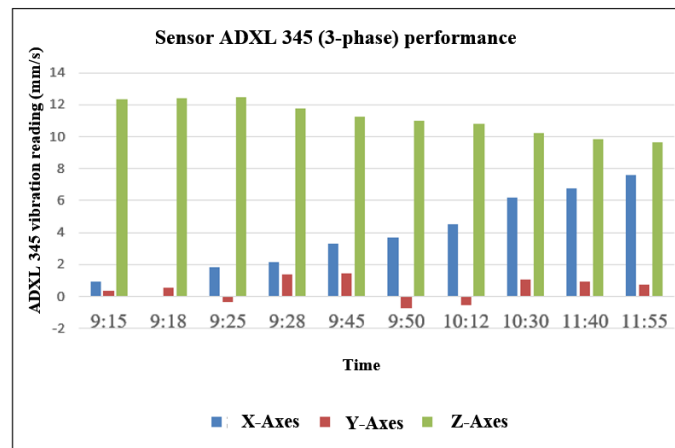


Fig.5. Vibration Readings Across Three Axes (X, Y, Z)

Based on Table 5, it is clear that the sensor readings from Mechseal fluctuate between "0" (indicating no leak) and "1" (indicating a leak). The corresponding app's box color and alarm status reflect these changes, with the red color and "ON" alarm status consistently associated with leakage events. In contrast, the blue color and "OFF" alarm status correspond to no leakage. This pattern is observed consistently throughout the dataset, where the alarm is triggered for leakage at specific time intervals (e.g., 10:02, 10:04, 10:09, 10:08, and 10:12). The work description further supports these findings by confirming the presence of leakage when the sensor reading is "0" and the box turns red, and vice versa for "1" with no leakage. Overall, the data suggests a reliable correlation between sensor readings, app status, and the presence or absence of leakage, reflecting effective monitoring of the system.

TABLE 5
 MECHANICAL SEAL SENSOR PERFORMANCE

Exp.	Time	Sensor reading of Mechseal	Box color status on Apps	Alarm status	Work Description
1	10:01	1	Blue	OFF	No leakage
2	10:02	0	Red	ON	Leak
3	10:04	0	Red	ON	Leak
4	10:06	1	Blue	OFF	No leakage
5	10:08	0	Red	ON	Leak
6	10:09	0	Red	ON	Leak
7	10:11	1	Blue	OFF	No leakage
8	10:12	0	Red	ON	Leak
9	10:15	0	Red	ON	No leakage
10	10:16	1	Blue	OFF	No leakage

Fig.6 displays sensor readings over time. The values fluctuate slightly between 0.8 and 1.0, suggesting that the mechanical seal's performance is relatively stable throughout the test period. There are no significant spikes or drops in the data, indicating

consistent leakage behavior. The sensor readings taken at 2-minute intervals show minimal variation, indicating that the seal's leakage performance remains steady throughout the observed period.

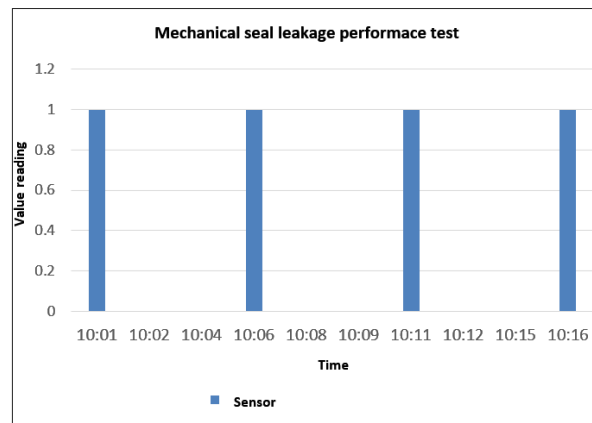


Fig.6. Mechseal Performance Test

The SCT013 current sensors installed on the three-phase system exhibit a significant error margin, ranging from 3% to 6%. This error margin is particularly noticeable when these sensors are integrated with electric motor installations. The primary cause of this issue appears to be the substantial fluctuation in electrical current during startup, which prevents the system from effectively managing the surge or jump start from the centrifugal pump motor.

In contrast, the ADXL345 sensor mounted on the centrifugal pump motor chassis is highly effective in detecting vibrational anomalies. This system allows for the prediction of motor vibration direction, whether lateral (left-to-right) or vertical (up-and-down). This capability is essential for what is referred to as Smart Predictive Maintenance. By analyzing the motor's vibrational movements, the system can accurately identify misalignments or other mechanical issues, enabling timely adjustments based on the detected fault. Additionally, the mechanical leak detection system demonstrates high accuracy in identifying liquid leaks caused by centrifugal pumps, specifically in applications involving aviation fuel (avtur) and water. Early detection of such leaks ensures that maintenance and repair of faulty seals can be promptly executed, preventing leaks from escalating and potentially damaging the entire system.

IV. CONCLUSION

The design and implementation of this IoT-based centrifugal pump motor monitoring system for preventive maintenance demonstrate its viability for industrial applications. Experimental validation revealed excellent performance across all sensors: the ADXL345 vibration sensor achieved a 0.69% average error in measuring lateral (X-axis) and longitudinal (Z-axis) displacements, enabling precise detection of right-left and forward-backward motor vibrations; the mechanical seal leakage sensor showed 100% accuracy in identifying seal failures; and the SCT-013 current sensor exhibited a 6% average error in monitoring motor load. The integrated alarm system effectively alerted operators to abnormal conditions (seal leaks, overcurrent, or excessive vibration), facilitating timely maintenance interventions and enabling 24/7 operational monitoring. The design and implementation of this IoT-based centrifugal pump motor monitoring system demonstrate strong industrial viability; however, it lacks complementary indicators such as thermal variations and high-frequency bearing vibrations. To further enhance the system, future endeavors should prioritize improving cable quality to ensure reliable data transmission and adopting higher-range accelerometers (>10g) to capture extreme acceleration events. These findings substantiate the system's operation in accordance with its intended design, thereby establishing a solid foundation for industrial predictive maintenance strategies.

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