

# Condition-Based Monitoring for Industrial Control Panel

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**Abstract.** Reliability of industrial control panels is critical to ensure smooth running of operations in process and manufacturing industries. Conventional preventive maintenance, despite wide usage, often ignores the real-time measurements of the health of the equipment, leading either to redundant interventions or unexpected breakdowns. This work presents a Condition-Based Monitoring (CBM) system specifically designed on industrial control panels, and such a system integrates multi-sensor data gathering, predictive modeling, and decision-making aids. It employs IoT-facilitated sensors to monitor thermal, electrical, environmental, vibration, and gas parameters, along with machine learning algorithms to detect anomalies and estimate Remaining Useful Life (RUL). A three-month pilot at a manufacturing plant demonstrated the effectiveness of the system, achieving a fault detection accuracy level of 93.5%, RUL estimation accuracy level of 89%, along with significant reduction in unplanned downtime by as much as 28%, and maintenance expenses by as much as 22%. Findings confirm that CBM significantly enhanced the level of operational reliability and cost-effectiveness compared to the conventional approaches of preventive maintenance.

**Keywords:** Condition-Based, Monitoring, Industry, Control Panel, Sensors.

## 1 Introduction

Traditional preventive maintenance methods, although widely employed, often cause undue interventions or overlooking of breakdowns due to hard-coded schedules that do not take into account real-time conditions of the equipment [1], [2]. Smart manufacturing is the integration of traditional manufacturing practices with high-end information and communication technology (ICT) in order to embrace Industry 4.0. It is a paradigm that incorporates different concepts such as the concept of direct digital manufacturing, cloud-based manufacturing, and sustainable manufacturing. Smart manufacturing integrates manufacturing resources with sensors, computational platforms, and predictive engineering in order to drive the next industrial revolution[3]. With industries advancing towards smart manufacturing and the concept of Industry 4.0, Condition-Based Monitoring (CBM) emerges as a viable method for predictive and adaptive maintenance [4].

The use of real-time sensor and monitoring data enables CBM to evaluate the condition and health status of the equipment, such that maintenance is conducted on a need-based basis [5]. This approach not only reduces downtime and maintenance costs but also extends the lifespan of assets by addressing issues before they escalate. CBM, through the real-time condition monitoring, also facilitates the transition from reactive maintenance approaches towards proactive maintenance strategies, consequently overall increasing the efficiency and productivity in operations[6].

CBM involves the continuous collection, processing, and analysis of condition data from industrial plant assets in order to evaluate the health status and forecast possible plant failures before they happen [7]. For industrial control panels, which act as the nerve center in handling power distribution, motor drives, and automated functions, reliability is critical. Industrial control panels play a critical role in handling power distribution, motor drives, and automation[8]. Putting up automation on electric distribution networks entails cost considerations, control infrastructure type selection, and justification through a business case. Control and Automation of Electric Power Distribution Systems addresses details on automation solutions on substations and feeders, such as distribution planning, performance computations, and protection[8]. Control panel breakdowns can be expensive unplanned shutdowns, safety risks, as well as production disruptions. It is thus possible, through the integration of CBM on control panel operations, that the lifecycle on equipment is increased, maintenance is lowered, and overall system performance is enhanced[9].

By implementing condition-based monitoring (CBM) strategies, organizations can proactively monitor the health of control panels and address potential issues before they escalate[10]. This approach involves using sensors and predictive analytics to detect early signs of equipment degradation, allowing for timely maintenance and repairs. The approach involves using sensors and predictive analytics to detect early signs of equipment degradation, enabling timely interventions and preventing costly unplanned shutdowns. Predictive models can forecast asset degradation and pinpoint critical failure points by leveraging data from sensors and historical performance records[11].

By integrating CBM into control panel functions, companies can ensure fewer unexpected breakdowns and keep maintenance as efficient as possible through predictive maintenance strategies. Predictive maintenance, or PdM 4.0, is when data analytics and AI are utilized to detect patterns and predict possible issues before they occur. It has been discovered that predictive maintenance can decrease maintenance costs and downtime by up to 25%, as well as increase energy production by up to 3%[12]. By monitoring the performance of individual control process systems and predicting potential failures, companies can optimize energy production, reduce costs, and increase the lifetime of the equipments[12].

The adoption of a proactive maintenance strategy is aimed at boosting overall performance, increasing the life of tangible assets, reducing maintenance costs, and improving the operability of equipment[13]. By continuously evaluating the status of critical assets and guessing possible complications before their actualization, organizations can ensure that their activities continue uninterrupted and with increased efficiency. Adoption of Condition-Based Maintenance (CBM) in control panel operation is a viable investment, as it can potentially enhance operational efficiency through Industry 4.0-based CBM strategies. Adoption of data analytics and deploying

competent staff to ensure maintenance enhancement projects align with the goals of I4.0-based CBM can facilitate continuous progress and achieve high operational performance[14].

Previous CBM works have taken into account rotating plants, power transformers, and other industrial-scale plants [15], [16]. Control panels in industrial plants, however, are, though, significant. They don't have to be as high maintenance as large-scale plants [17]. Focus on efficiency improvement in other areas of CBM frameworks could have broader total operational performance improvements[18].

Through the integration of CBM with Industry 4.0 technologies, the oil and gas sector can increase operational effectiveness, identify areas for enhancement, and substantiate new I4.0-based CBM constructs[18]. Enhancing operational effectiveness through I4.0-based CBM constructs ensures the oil and gas industries have a clear direction and clear steps towards the integration of I4.0 into CBM, with assured guided recommendations on increasing operational effectiveness through strategic CBM and I4.0 integration[18].

This paper bridges that gap by exploring the application of CBM approaches tailored for industrial control panels, featuring the integration of IoT-based sensors, real-time data, and predictive analytics. By including Industrial Revolution 4.0 as part of CBM, efficiency can be enhanced through operation, but complexity can also be introduced along with potential technical issues that can stagnate rather than accelerate efficiency. By analyzing industrial control panels in isolation, the broader scope that CBM applies into the oil and gas industry is left out.

The purpose of this work is to develop, apply, and test a CBM system for industrial control panels. It integrates hardware instrumentation, data-based condition monitoring, and analytical modeling in such a way that the framework can detect anomalies, recognize degradation modes, and provide time-based recommendations on interventions. Industries can shift from reactive or schedule-based maintenance strategies to a more savvy, condition-based one that is reliable as well as cost-effective through the use of CBM.

## **2 Method**

### **2.1 Design Architecture**

The suggested framework of Condition-Based Monitoring (CBM) of industrial control panels is organized into three levels, namely data acquisition, data processing, and decision-making. The data acquisition layer is comprised of different instrumentation and sensors that capture real-time information on the operational performance as well as condition of the control panels. The data processing level utilizes advanced algorithms and analytical tools to assess the information collected and detect any irregularities or degradation indicators. In the case of big data solutions, the data processing level utilizes advanced algorithms and analytical tools for the determination of the collected data. It is fed with both streaming and historical data, which are further processed through certain analytical tools specific to the level of the application. Finally, the decision-making level utilizes the information obtained through the data processing level to suggest prompt interventions or maintenance activities that can be taken with the intention of curtailing possible degradation and ensuring the operational reliability of the control panels.

To reduce the risk of possible failures and ensure control panel reliability, maintenance strategies such as decreasing the rate of process demand, increasing barrier availability, intrinsic reliability through design changes, training staff, revising the protocol, and ensuring that the procedure is up-to-date, relevant, and works may be adopted. This systematic approach allows industries to maintain proactive control of the condition of their plant as well as maintain optimum maintenance schedules, reducing the eventual downtime. Condition-Based Monitoring is a systematic plan aimed at recognizing degradation in the equipment, pinpointing malfunctions, predicting possible failures, as well as maintain the proactive health of plant equipment. Industries can ensure optimum plant operational availability, reduce the number of unplanned shutdowns, and maintain economically viable maintenance by frequently checking the condition of the plant and performing maintenance activities on the basis of measured parameters.

The control panel at the hardware level is a low-voltage motor control center (MCC) rated as 400 V, and is equipped with circuit breakers, contactors, relays, programmable logic controllers (PLCs) as well as power distribution busbars. Because these parts have the tendency to undergo malfunctions such as overheating, overload, and degradation of insulations, the condition-based monitoring (CBM) system incorporates a number of sensor modules as well as communication devices to provide real-time observation and evaluation of their running conditions.

## **2.2 Sensor Implementations**

The sensor modules utilized in the CBM system consist of temperature sensors, current sensors, vibration sensors, and gas sensors. Such sensors are positioned on critical points on the control panel to obtain real-time information on temperature, current flow, level of vibration, and level of gas contamination. The sensors' specifications allow for high accuracy, reliability, and sensibility to note any deviations or irregularities from normal running conditions. Temperature sensors are installed around critical points like circuit breakers and contactors to note any unusual levels of heat that may show possible faults.

The electrical load on the system is determined through the use of current sensors, which detect any possible overloads that might cause equipment failure. Vibration sensors are also in use as a way to detect any unusual vibrations that might be an indication of mechanical issues in the MCC. There are specific specifications on the sensor that depend on the type of data that is being collected[19]. It is through the continuous check on these parameters that the CBM system is able to issue early warnings on possible failings, thus making possible proactive maintenance activities that can prevent unscheduled shutdowns and ensure a better overall maintenance plan.

Moreover, the CBM system is integrated with centralized monitoring software that gathers and interprets the data from all the sensors in real-time. This software is embedded with algorithms that can forecast equipment breakdowns on the basis of history as well as trends, giving maintenance teams data-driven insights to fix problems before they occur. Besides, the system creates automated alarms as well as notifications that inform maintenance people about any irregularity or possible breakdown, allowing fast response as well as reducing downtime. This proactive maintenance not only extends the life as well as reliability of the equipment, but also minimizes maintenance expenditure as well as boosts the overall efficiency of the operations. In order to capture vital condition data, the following sensors are installed inside the control panel.

**Table 1.** Sensor Deployment and Specifications for CBM in Industrial Control Panel.

Sensor Type	Deployment Location	Measured Parameter	Range	Accuracy	Purpose
Temperature Sensor (RTD/NTC)	Near busbars, circuit breakers, and relays	Temperature (°C)	-20 °C to 120 °C	±0.5 °C	Detect overheating, loose connections, and abnormal heat buildup.
Current Transformer (CT)	Main incoming line and motor feeders	Current (A)	0–200 A	±1%	Monitor current flow, imbalance, and overload conditions.
Voltage Sensor	Across key control and power circuits	Voltage (V)	0–500 V	±0.5%	Detect undervoltage, overvoltage, and harmonic distortion.
Humidity Sensor	Near insulation and sensitive electronics	Relative Humidity (%)	0–100% RH	±2% RH	Identify condensation risk and moisture ingress that may degrade insulation.
Vibration Sensor (Accelerometer)	Mounted on high-power contactors and relays	Vibration (g) / Acceleration	0–50 g / 0–500 Hz	±5%	Detect abnormal vibration due to mechanical looseness or contact wear.
Gas Sensor (VOC/CO Sensor)	Inside enclosure, near insulation and plastic parts	Gas concentration (ppm)	0–1000 ppm	±5 ppm	Detect harmful gases from overheating, arcing, or insulation degradation.

Sensor data is read at a frequency of 1 Hz for environmental parameters such as temperature and humidity, whereas electrical and vibration signals are read between 10 to 20 Hz in order to capture the transient conditions suitably. Data transmission is carried out via industrial communication protocols, such as Modbus TCP/IP via wired communication and MQTT via wireless communication. A data acquisition unit is connected with the sensor, allowing communication with a local edge device. In this way, the real-time conditions inside the enclosure can be observed, helping to facilitate prompt identification of possible issues that can threaten the integrity of the insulations and other components. By continuously reading factors like humidity, vibration, and gas concentration, the operator can initiate suitable preemptive action in order to correct anomalies before these can evolve into something more serious. Overall, then, this comprehensive monitoring system boosts overall operational efficiency and safety through the provision of earlier notification on potential deterioration of insulations and other hazards.

The gathered raw data is then subject to statistical and signal-processing analysis that is focused on extracting features relevant to detecting faults. Such can be helpful in determining potential

issues before they are developed into costly failures, allowing maintenance to be done on schedule and prevent unexpected downtime. Overall, the integration of sensor data gathering, communication protocols, and advanced analytics within the monitoring system significantly improves the reliability and performance of the equipment. While the combination of sensor data and advanced analytics can have the capability in improving the detection of faults, such will not be completely fail-safe, as limitations would apply in terms of the accuracy of the predictive models or unknown variables that could impact the reliability of the equipment. In addition, a sole focus on the use of machine learning algorithms will ignore human errors or other variables that could be another cause of equipment breakdowns.

The decision level integrates predictive outputs with a rule-based decision support system. Alarms are triggered when values exceed predetermined limits or when the predicted RUL is at a critical level. This facilitates a hybrid approach to fault detection that takes into consideration both machine learning output and human expertise. In this way, the system can provide a more robust and reliable means of detecting potential breakdowns in machinery. Ultimately, the hybrid approach can help organizations cut downtime, reduce maintenance cost, and better optimize the efficiency of operations.

### **3 Results and Discussion**

The proposed Condition-Based Monitoring (CBM) system was tested on a low-voltage industrial control panel in a production setting for an unbroken monitoring period of three months. A total of six different sensor types were utilized, generating over 10 GB of time-series data. During the data preprocessing stage, outliers and noise were removed, eliminating approximately 2% of the data and ensuring high-quality datasets ready for further analysis. Sensors' uptimes were kept at a high level of 99.6%, reflecting the reliability of the combined IoT infrastructure. This constant flow of data enabled real-time health assessments as well as predictive modeling with respect to the degradation of components.

An examination of the temperature profiles indicated the presence of recurrent thermal irregularities within the primary busbar area. The resistance temperature detector (RTD) sensors identified temperature surges reaching 78 °C, which surpass the advised limit of 70 °C when subjected to a load of 120 A. The source of the anomaly was traced to an inadequate connection at a circuit breaker terminal. Following the execution of corrective maintenance, the maximum temperatures were reduced by 15%, achieving stability at 66 °C under comparable loading conditions. This observation confirms the system's capability to recognize abnormal thermal conditions prior to failure and underscores the significance of thermal monitoring in averting insulation deterioration or fire risks. Table 3 provides a summary of the findings across all observed parameters, encompassing temperature, current imbalance, vibration, and Remaining Useful Life (RUL) prediction.

**Table 2.** Visual Results from CBM Monitoring.

Parameter	Before Intervention	After Intervention	Threshold / Limit	Discussion
Temperature (Busbar)	Peak 78 °C	Stabilized at 66 °C	70 °C	Loose breaker terminal caused overheating; maintenance reduced peak by ~15%.
Current Imbalance	Up to 12% between phases	Reduced to <4%	10%	Real-time monitoring enabled load balancing, improving efficiency safety.
Vibration (Contactor)	RMS 0.40 g, abnormal peaks	RMS 0.18 g, stabilized	0.30 g	Mechanical wear detected; replacement normalized vibration patterns.
RUL Prediction	Predicted failure in 180 hrs	Component replaced before failure	Critical limit: 40 hrs	LSTM model predicted degradation trend; early replacement avoided downtime.
Vibration Sensor (Accelerometer)	Mounted on high-power contactors and relays	Vibration (g) / Acceleration	0 – 50 g / 0 – 500 Hz	±5%
Gas Sensor (VOC/CO Sensor)	Inside enclosure, near insulation and plastic parts	Gas concentration (ppm)	0–1000 ppm	±5 ppm

The electrical condition monitoring identified current imbalances up to 12% between three phases during peak usage periods. Preventive maintenance checks had not identified the imbalance previously because they were only done on a monthly schedule. CBM enabled real-time information, and predictive modeling confirmed that there was indeed a relationship between load imbalance and overheating episodes. Remedial load rebalancing reduced the current imbalance to under 4%, increasing efficiency as well as part life. This demonstrates that CBM can correct operational inefficiencies that would remain uncorrected through ordinary preventive maintenance.

The environmental monitoring further revealed fluctuations in humidity levels between 40% and 85% relative humidity inside the panel enclosure, especially when the weather was rainy. On two separate instances, the humidity sensor raised premature alarms when values went beyond the 75% limit, corresponding to the high risk of condensation. Confirmatory measurements from the gas sensor indicated slight increments in the level of volatile organic compounds (VOCs) at 25 ppm, almost definitely triggered as a result of the presence of partial discharge in humid environments. These results highlight the importance of adopting multiple sensors, as the combination between the humidity and the gas data presents a more comprehensive interpretation of insulation integrity compared to either parameter separately.

Vibration surveillance conducted on high-capacity contactors detected irregular patterns denoted by RMS values surpassing 0.4 g, in contrast to a baseline range of 0.1–0.2 g. An examination in the frequency domain uncovered harmonic peaks that were indicative of

mechanical deterioration on the contact surfaces. Predictive modeling via an LSTM network projected a Remaining Useful Life (RUL) of 180 operating hours for the impacted contactor. Consequently, maintenance was planned, and subsequent data following the replacement indicated normalized vibration characteristics. This outcome exemplifies the benefits of predictive analytics in orchestrating targeted interventions that effectively reduce downtime.

The overall system performance evaluation revealed that the CBM system was able to detect faults with the accuracy level of 93.5% and estimate RUL with the accuracy level of 89%, compared with the history maintenance data and ground truth inspections. Compared with the traditional preventive maintenance, the CBM system reduced the unplanned downtime by 28%, as well as maintenance cost by 22%, within the observation period. Table 2 is the comparative performance between CBM and preventive maintenance.

**Table 3.** Comparison of Preventive Maintenance and CBM Performance.

Performance Metric	Preventive Maintenance	Condition-Based Monitoring (CBM)
Fault Detection Accuracy	70% (based on periodic checks)	93.5%
RUL Prediction Accuracy	Not applicable	89%
Unplanned Downtime Reduction	Baseline	28% reduction
Maintenance Cost Reduction	Baseline	22% reduction
MTBF (Mean Time Between Failures) Improvement	Baseline	15% improvement

These outcomes demonstrate not only that CBM can increase reliability, but that they also yield tangible economic payback. Incorporating thermal, electrical, environmental, vibration, and gas monitoring provided a multi-dimensional insight into control panel condition, facilitating the move from reactive maintenance practices towards predictive maintenance methods in industrial practices.

## 4 Conclusion

We did a study to see if a Condition-Based Monitoring (CBM) setup could help with industrial control panels. It used sensors, data analysis, and ways to help people decide what to do. What we found is that CBM can spot when parts start to fail—like when things get too hot, the current is off, something is shaking too much, or gases are leaking. It can spot these problems before anything really bad happens. The system used some pretty clever computer learning to guess how much longer things would last, so you could plan when to fix them.

We tested this setup at a factory for three months, and it worked well. It was better than just doing maintenance at set times. It found problems more accurately (93.5%), guessed how long things would last pretty well (89%), and cut down on unexpected stops by 28%. It also saved about 22% on maintenance costs. So, CBM seems like a good way to keep things running smoothly and save money in today's factories.

Using a bunch of different sensors—like ones for temperature, electricity, humidity, shaking, and gas—helped us get a full view of how the control panel was doing. This was really important for matching up tricky problems, like when a load was off and things were getting too hot at the same time. Plus, it also makes things safer by lowering the chance of overheating, water getting in, or wires breaking down.

In the future, we should try using this setup on more panels and in different types of factories. We should also use computer programs that learn and change as they see how equipment is being used. Security is also super important, so we need to make sure the data is sent and stored safely, especially if it's on the cloud. All in all, using CBM is a smart move toward making factories more modern, where maintenance is planned and smart, making things reliable, safe, and cheap.

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