Condition Monitoring Systems in Power Plants to Determine the Type of Maintenance Using Multiple Types of Sensors

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Abstract—**Condition monitoring systems play an essential role in operating and maintaining power plants. The impact of such systems is manifested by preserving the different equipment in power plants through monitoring each equipment's operational conditions. This way, the technical staff can establish the appropriate time frame for maintenance, improve equipment reliability, increase production, and reduce unjustified periodic maintenance losses without any real sign of any anticipated failure. The condition monitoring system in the Haditha hydropower plant implemented in the 110 MW Kaplan generation unit will be studied. The work includes investigating the different sensors used for this system, representing the essential part of the system's operational activities.**

Keywords - condition monitoring, power plants, maintenance, sensors

I. Introduction

The condition monitoring system can be defined as implementing several different modern technologies to monitor various industrial equipment operating conditions. Using such a system is to aid in the detection and early perdition of any technical issues in the kit. Detecting and analyzing errors and faults are the main objectives of such systems to ensure health and safe operation [1]. Within the area of energy generation from various types (hydro, wind, gas... etc.), it is very recommended to take advantage of the different benefits that the condition monitoring systems can provide to maintain the entire operation of the generating units and the auxiliary systems. The priorities of implementing condition monitoring systems rely on the process importance and the type of the machines and equipment within this process. Hence, the system focus is to monitor the condition of the equipment within the process, in addition to any other essential parts of the equipment itself whose stoppage leads to a complete shutdown of the system (unit generation), which could result in a total loss in energy production.

The condition monitoring phrase refers to the different techniques and procedures that can be implemented to monitor the operating condition of machinery and equipment relying on the performance changes. These changes depend on the functional properties of the equipment so that it can be used to determine the equipment's needs. The machine's operational status history line is essential in the condition monitoring process. It plays a crucial role in predicting the different events related to machine performance. Other sensors are usually implemented to monitor the device's status. The sensors will act as data-collecting devices (physical parameters) related to the equipment's physical condition. Next, the collected data are analyzed using special tools to find what type of action is required, like the maintenance or corrective actions that must be done on the equipment to perfume at an optimal level and close to the original design condition [2]. Multiple parameters can be measured and monitored using condition monitoring systems [1, 3]. Such parameters include temperature, vibration, and rotational speed. Also, electrical measurements such as current and voltages, the gap between the stator and rotor, magnetic flux, etc., can be collected. All previous information can be used to estimate the required type of maintenance for the machine. Three types of care [2] can be implemented, which are:

A. *Reactive Maintenance*

This means to apply maintenance on the equipment only when needed, i.e., when the machine fails and stops working. This is also known as breakdown maintenance. Such maintenance will only include replacing the defective equipment with a new one.

B. *Preventive Maintenance*

In this type, the equipment is turned off and taken out of service periodically, so it is called periodic maintenance; for example, the generation units in the Haditha power plant are maintained annually according to the manufacturer's recommendations. In this type, the equipment is maintained even if there are no fault indications or defects in the kit—this way, and the equipment is preserved from failure to ensure good performance until the next maintenance date. The equipment will be maintained before it fails and be out of service. However, one of the most important disadvantages of this type of maintenance is that it does not rely on the actual status of the equipment. Hence, the equipment may not even be in for any kind of maintenance, which will mean productivity loss and unjustified maintenance costs.

C. *Predictive Maintenance*

This maintenance type relies on the previous history and the current operational state of the equipment, i.e., it depends on monitoring the on-time and actual condition of the equipment. This point shows the importance of the condition monitoring system approach, which is based on this type of maintenance. Again, as mentioned earlier, equipment condition is monitored using pre-defined sensor types with additional techniques to analyze the collected data and register any changes in the collected data. Then, based on this information, it is possible to expect the time at which the equipment might fail. Hence maintenance is conducted before the failure occurs. In this way, the maintenance is only performed when an accurate indication is presented, saving time and the cost of maintenance. Finally, the importance of monitoring the condition of equipment in preparing predictive maintenance programs appears as follows [2]:

- Reduce maintenance costs.
- Fewer equipment breakdowns.
- Less repair downtime.
- Lower stock of small parts.
- Longer life of the equipment.
- Increase production.
- Operator safety improvement.

Usually, the condition monitoring system contains four main parts [1, 4]: Sensors, data acquisition system, fault detection, and diagnosis. Sensors of various types convert variables and physical phenomena into electrical signals transferred to the central processing unit, which collects and analyzes these signals, detects errors compared to average values, and diagnoses and displays warnings. The sensors and other parts of the system were linked together using different types of cables (Optical, coaxial, BNC, and signal) according to the type of sensor, and other communication protocols were used [5].

II. SENSORS

The monitoring system in the Haditha dam power plant monitors the following values [3]:

- Relative shaft displacement and axial thrust on guide bearings – 7 sensors
- Generator housing vibrations – 1 sensor
- Rotating speed – 1 sensor
- Air gap – 5 sensors
- Temperature – 15 sensors
- Partial discharge – 3 couplers
- Magnetic induction – 1 sensor
- Cavitation – 2 sensors
- Current – 3 measuring transformers
- Voltage – 3 measuring transformers

A. *Vibration Measurements*

Vibration is one of the features of mechanical machines. It may cause dangerous operating performance [3]. Therefore, observing the vibration of the parts of the generation units is one of the priorities in the condition monitoring systems. The increase of the vibration beyond the permissible limits leads to significant damage. Vibration can be measured by its displacement, speed, or acceleration [2]. In this system in the Haditha power plant, two types of vibration sensors were used as follows:

1) Radial displacement sensors type proximity eddy current sensors (6 pieces). The shaft displacement relative to the (Bearing housing) is measured in three positions for the unit bearings (upper, lower, and turbine bearing). Two sensors for each class are fixed at a 90-degree angle between the two sensors (X, Y) within the same level to obtain the maximum measurement of the relative displacement vector.

Principle of sensor operation

The sensor types of inductive proximity [6] consist of:

- Sensor coil and ferrite core
- Oscillator circuit
- Detector circuit
- Solid-state output circuit

As shown in Fig. 1

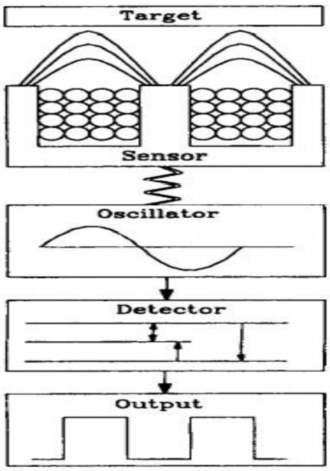


Figure 1. Inductive proximity sensor (Operating principle).

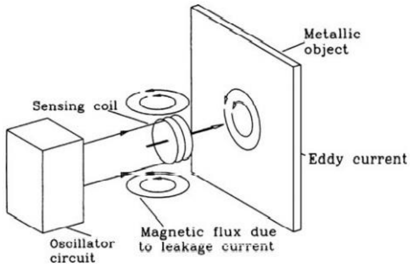


Figure 2. Induced eddy current.

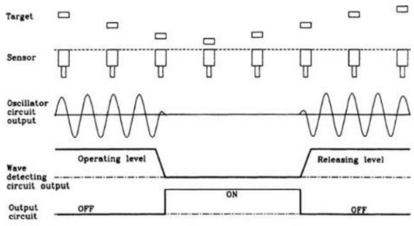


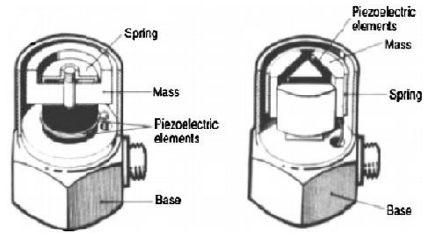
Figure 3. Detection cycle.

When an AC flows through a coil, magnetic flux occurs in the ring. When the magnetic flux passes through a metal object, it creates eddy currents that generate a magnetic field that tends to oppose changes in the wind. As a result, the inductance of the coil changes. The function between the distance from the coil to the object is defined in terms of the variation of the inductance, and the displacement distance can be calculated (Fig. 2). As the distance between the metal object and the Sensor Head decreases, eddy currents increase, and the oscillation amplitude of the oscillation circuit decreases.

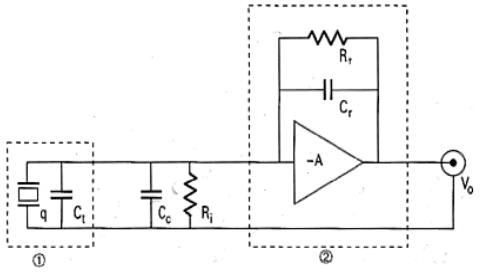
Conversely, as the distance between the metal object and the Sensor Head increases, eddy currents decrease, and the oscillation amplitude of the oscillation circuit increases. The oscillation amplitude of the oscillation circuit changes as the position of the metal object changes, so measurements are taken by detecting these changes in oscillation amplitude, Fig. 3 [6].

2) Axial displacement sensor: it is measured by a single sensor fixed vertically concerning the unit shaft (Z) in the upper guide bearing of the unit and its inductive action, such as the displacement sensor above.

3) Stator absolute vibration sensor: Absolute vibration is measured using a single sensor fixed on the outer wall of the generator housing. The type of sensor is (Accelerometer), and this type



a)



b)

Figure 4. (a) Accelerometer sensor; (b) Accelerometer sensor with measuring circuit.

shown if Fig. 4a. and Fig. 4b. is used Piezoelectric elements which convert mechanical vibration into electric voltage [2], [3]. The Accelerometer measures the pulse of the objects formed in contact with it, unlike the relative displacement sensor, which measures the pulse of an object corresponding to the non-contact sensor. The accelerometer sensor has two main parts: a piezoelectric material such as crystal and a mass of known properties as one of the sides of the piezoelectric material is supported by a column attached to the sensor's base. On the other hand, it is connected to mass with known properties; when the sensor is subjected to vibration, a force will be formed that affects the piezoelectric material, and according to Newton's law of motion F= m*a, the amount of this force will be equal to the product of the acceleration multiplying with the known mass. Therefore, the charge generated inside the sensor will be proportional to the known mass acceleration, and thus the absolute displacement can be calculated [2].

B. Rotational Speed

The rotation speed of the generation unit is measured by using a single sensor type (Tachometer). This type is an inductive sensor [2, 3] that is installed in front of the shaft, a piece of metal (tooth) is placed on the shaft of the turbine, as shown in Fig. 5. When this tooth

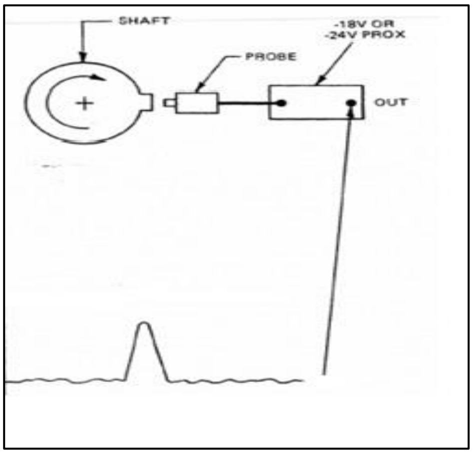


Figure 5. Rotational speed.

passes in front of the sensor, it cuts the magnetic field generated by the sensor, and a pulse is generated every time the tooth is cut. The area represents one rotation for the shaft calculated by the inductive proximity switch.

C. Air Gap Measurement

Measuring the air gap between the stator and the rotor is essential because it provides information about the state of the rotor and stator where the change in the magnetic field leads to the occurrence of vibrations. "This is based on the fact that any change in the normal flux distribution in the motor will cause a change in the vibration spectrum" [1]. Stator and rotor are affected by many factors such as aging, centrifugal force, temperatures, magnetic flux strength, vibrations, expansion of mechanical parts, and expansion of concrete structures. Etc., and accordingly, knowing the condition of the stator and rotor through the monitoring system gives operators and specialists sufficient information to take the unit out of service and perform maintenance before an extensive series of damages occurs due to friction of the parts. The air gap measurement is a measurement of the relative distance or the clearance between the outer circumference of the rotor and the inner bore of the stator. Capacitive type sensors (5 pieces) were used, and they were installed on the inner surface of the stator with equal distances. This sensor is designed to operate in a highly magnetic environment, resistant to dust, moisture, oil, and vibration [5]. The sensor works as a capacitor (the sensor represents the first plate of the capacitor, and the second part of the capacitor is represented by the pole of the rotating part when it passes in front of the sensor). The insulaelement part between them represents the dielectric. Therefore, any change in the distance between them will lead to a change in the capacitance of the capacitor. This signal is sent to the processing unit that Its transformation into a space between the stator and the rotor. "Air gap sensor consists of the electronic unit for signal processing SZR1, coaxial cable, and measurement probe SZRS50. The air gap is a measure of distance between the rotor and stator in a rotating machine. On the basis of air gap data, information on rotating machine conditions can be obtained. The measurement probe is made from printed circuit board material. The probe is mounted on the inner surface of the generator stator. The change in distance between the probe surface and the rotor shows as a change in the probe's capacity. Coaxial cable connects measurement probe with electronic unit SZR1. The output signal from SZR1 is proportional to the momentary distance between the rotor and stator on the probe location (air gap). The output signal is usually sent to a remote central monitoring unit, located up to 100 meters from the generator" [5] as shown in Fig. 6.

The capacitive sensors have the same component as inductive sensors [6]

- • Sensor (the dielectric plate)
- • Oscillator circuit
- • Detector circuit
- • Solid-state output circuit.

However, the concept of sensitivity differs where the capacitive depends on the capacitor dielectric [6]. "The oscillator circuit in a capacitive switch operates like one in an inductive proximity switch. The oscillator circuit includes feedback capacitance from the external target plate and the internal plate. In a capacitive switch, the oscillator starts oscillating when

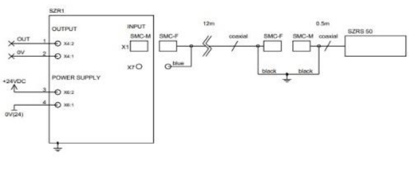


Figure 6. Capacitive sensor SZR50 and an electronic unit for signal processing SZR1.

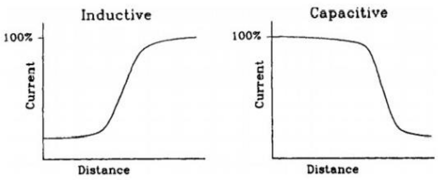


Figure 7. Oscillator damping of inductive and capacitive sensors.

sufficient feedback capacitance is detected. In an inductive proximity switch, the oscillation is damped when the target is present" as shown in Fig. 7.

D. Temperature Measurement

Increasing the temperature of the equipment above the permissible limit is an abnormal condition that leads to rapid aging and damage to the equipment parts. the effect of the temperature on the generation unit is directly on the insulation of the coils as well as on the mechanical parts. Therefore, temperature monitoring by modern methods such as the condition monitoring system is an important priority. At Haditha dam station, two types of sensors were used with a condition monitoring system to measure the temperature, which is a thermocouple and RTD where 15 sensors were installed as follows:

- 6 measurements of stator winding (RTD)
- 1 measurement in the upper guide bearing segment (thermocouple)
- 1 measurement in the lower bearing segment (thermocouple)
- 2 measurements in the lower thrust bearing pad (thermocouple)
- 1 measurement of the temperature of a bearing oil in lower combined bearing (thermocouple)
- 1 measurement of the temperature of a bearing oil in upper bearing (thermocouple)
- •3 measurements on the turbine bearing - one measuring oil temperature, other one segment, and the third one measures turbine oil head temperature (thermocouple)

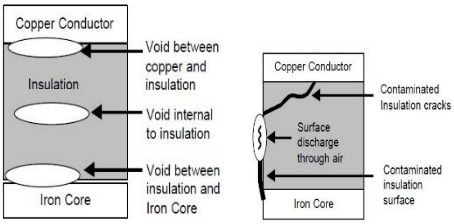


Figure 12. Partial discharge.

In the condition monitoring system, partial discharge is measured using capacitors designated for high voltage (16 KV) EMC type (Epoxy Mica Capacitors). A pair of these capacitors are connected to the end of each phase. These capacitors eliminate electrical noise from the power signal while maintaining sensitivity to the signals received from the electrical generator [9]. The pure signal sends to the PD analyzer, which analyzes the electrical signal. In the case of deformation in the power signal as in Fig 13, the probability of partial discharge is high according to the severity of the distortion and this requires a maintenance procedure before the matter gets worse and the stator windings are completely damaged.

Failure in isolation of the stator windings leads to stopping the unit from working. the procedure of replacing the damaged windings requires long periods of time and large sums of money [9] in addition to the loss of productivity. Therefore, monitoring partial discharge online through the condition monitoring system may avoid such damages and give warning signals before the windings' insulation collapses, so they are maintained at a lower cost and time.

F. Magnetic Flux Measurement

Measurement of the magnetic flux in the gap between the stator and the rotor to find out if there is asymmetry magnetic which caused by the shape deflection of the rotor or short circuit in the pole's windings. In the monitoring system of the Haditha dam station, the magnetic flux is measured using a single Hall sensor, The working principle of the Hall sensor is to measure the voltage resulting from the influence of the magnetic field on the semiconductor, as shown in Fig. 14. "A Hall effect device is a four-terminal solid-state semiconductor material commonly composed of materials like silicon, germanium, indium arsenide, or gallium arsenide. When a Hall device is inserted in a soft iron core around the current-carrying conductor and a current is applied in a direction perpendicular to the magnetic field, a Hall effect voltage is generated proportional to the current flowing in the conductor. Essentially, the Hall effect is another way of detecting the magnetic field around a current-carrying conductor" [2].

G. Cavitation Measurement

Cavitation is one of the dangerous phenomena in hydropower plants that directly affect the turbine blades and it occurs because of air bubbles colliding with the surface of the turbine blades. Its energy will transfer to the surface of turbine blades and cause stress to concentrate on it [2, 4]. With the passage of time, this surface will become brittle and start to crack and pit, the result is a loss in the efficiency of the turbine and a decrease in the life span of the turbine. The cavitation is monitored by two sensors installed on the outer wall of the draft tube at the level of the turbine blades [4, 5, 10, 11]. The measurement of the cavitation is based on the acoustic emission technique that has developed in recent years. The sounds produced by the cavitation phenomenon are transmitted as a result of the bursting of water bubbles on the turbine blades, and these sounds are transmitted through the water to the outer wall, where the sensors transfer the frequencies of these sounds to the central processing units that analyze and compare them with the standard values. These sensors sense the frequencies (1 KHz - 20 MHz), when the frequency exceeds certain limits, this

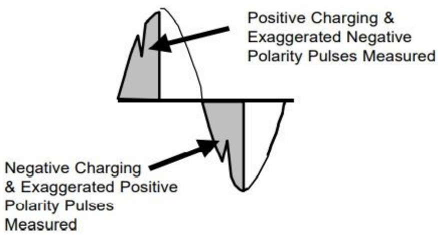


Figure 13. Power signal with partial discharge.

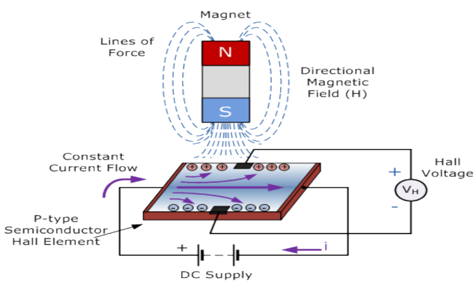


Figure 14. Hall sensors working principle.

means that the operation is within the limits of the cavitation phenomenon, so the condition monitoring system will warn the operators to change the load and work within the safe state of the production unit.

H. Electrical Measurements

Measuring transformers (CT's & VT's) are used to measure the currents and voltages of phases for the generating unit. Thus, active power (Megawatt), reactive power (Mega VAR), and power factor can be calculated and monitored. Fig. 15 shows the method for distributing sensors on the parts of the Kaplan type turbine.

III. CONCLUSION

The influence of some physical phenomena such as cavitation in addition to other factors resulting from the aging of equipment like vibration and partial discharge, which directly affect the turbines and generators in the hydropower plants are usually very crucial for the plant operation. Therefore, measuring and monitoring these factors is very important to maintain this equipment and ensure its high efficiency. The use of the condition monitoring system to collect sufficient information for the equipment by using multiple types of sensors enables the specialists to predict errors before the equipment's condition worsens to conduct maintenance in a timely manner. This helps preserve equipment and increase efficiency and productivity. In a Haditha dam power plant, the condition monitoring system was installed in 2013, where the need to continuously monitor some of the parameters that occur to the unit during work and affect directly on these units. The results of using this system brought many benefits:

1. Avoid operating the units within the cavitation phenomenon, as it is now possible for the operator to know the permissible limits through the Acoustic sensors that send warning signals through the condition monitoring system in the event the operation is within the cavitation phenomenon.

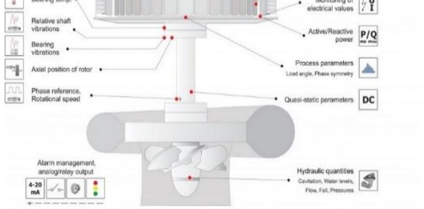


Figure 15. Sensors sites in the generation unit.

2. Avoid operating in case of vibration higher than the permissible limit, as various types of vibration sensors send warning signals that help the operator to change the load to reduce vibration.
3. The possibility of monitoring the status of stator windings through the partial discharge sensor and this does not need to stop the unit to perform an isolation check in the traditional way (megger test).
4. Monitoring turbine and generator temperatures using different types of sensors.
5. Monitoring the magnetic flux and the air gap between the stator and the rotor by using capacitive sensors gives sufficient information in case of a misalignment of the rotor.
6. The possibility of monitoring the rotational speed of the unit, as well as electrical measurements such as active power (Megawatt), reactive power (Mega VAR), and power factor.
7. The possibility of storing data for very long periods in the database to be used as a reference in future maintenance.

The selection of the parameters to be monitored depends on the extent to which these variables affect the equipment. Therefore, the selection of the sensors in terms of accuracy, range, precision, repeatability, sensitivity, and response time is very important to obtain the best measurements that help to indicate the condition of the equipment.

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