The Methods of Condition Monitoring for Circulator of HTGR

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Abstract. Circulator is one of the important components in an HTGR to meet the plant safety and availability. Several methods have been applied for the condition monitoring and in-service inspection especially of reactor cooling pump, which mainly for the light water reactor such as the vibration monitoring, acoustic emission and motor current signature analysis (MCSA). Despite the long experience of these condition monitoring implementation in light water nuclear power plant, however, research is still required to understand the most suitable method for a condition monitoring of the reactor cooling pump for the HTGR based on all possible monitoring methods. It is because that each method is known having its own sensitivity to detect specific faults, sensitive only on one side either the electrical motor side or the pump as well as having its own capability to meet the criteria’s to be implemented in a condition monitoring. Therefore, this paper aims to study various condition monitoring methods that are suitable for the implementation in online condition monitoring of circulator in HTGR. Because the circulator or blower has not been commonly explored for the HTGR, this paper describes the common faults in cooling pump of light water reactor, various condition monitoring, and the comparison of the applicability of each method to identify each type of faults. This paper also discusses the challenges and opportunities for further improvement in this condition monitoring research. This research highlighted that the combination of more than one online monitoring techniques with the performance may provide a better solution in identifying various faults and motor degradation.

Keywords: Condition monitoring, cooling pump, nuclear reactor

1. Introduction

The online monitoring is required to keep the integrity of circulator to meet the plant safety and availability in the HTGR. Unlike the common industrial pump or blower, in the nuclear reactor especially in HTGR, the primary pump involve high temperature, high pressure and radioactive primary coolant flow which must be maintained in normal operation as well as in the accident stages. Considering these extreme conditions, International Atomic Energy Agency (IAEA) highlighted several methods to be applied for the condition monitoring and in-service inspection of reactor cooling pump [1-4] based on the research and experiences in Light Water Reactor (LWR). Even though the circulator of HTGR is different with the cooling pump of LWR, however the circulator has similar principal as rotating machine. These monitoring methods for rotating machine are vibration monitoring, acoustic emission monitoring, motor electrical signature analysis.
Among these monitoring techniques, vibration monitoring is the earliest method [5, 6] as well as applied extensively in nuclear power plant [1-4, 7-9]. For example, the vibration monitoring system for the coolant pump have been installed PWRs and BWRs in Germany [10], in Yongkwang NPP unit 3 Korea [11], China [12]. Tennessee Valley Authority Sequoyah Unit 1, Westinghouse PWR [13, 14]. In addition, the acoustic emission has been also applied not only for the reactor coolant pump, but for the assessment of integrity of the reactor structure in PWR [7, 15, 16]. Another popular method, Motor Current Signature Analysis (MCSA) was also introduced in Nuclear Power Plant (NPP) lately, such as demonstrated in [9, 17, 18].

Despite the long experience of these condition monitoring implementation in LWR NPP, however, research is still required to determine which method is the most suitable for a condition monitoring of the circulator HTGR based on all possible monitoring methods. It is because that each method has its own sensitivity to detect a specific faults, either mechanical related faults, or electrical related faults [19] and has not been applied for the circulator or blower in common. In addition, it should be a further investigation to confirm that the measurement system, detection and diagnosis of a certain condition monitoring are reliable, capable of recognizing the severity level of the faults and determining remaining run-life time of the cooling pump of reactor as suggested in [19].

The cooling pump or rotating machine of NPP basically composed of two parts, the driver side, usually an induction motor and the pump side, which can be in various types. Several condition monitoring methods focus on the driver side or the electric machine of the cooling pump [20-28] and the pump side [29-38] which is mostly covered in the performance evaluation of the pump. However, little information [36, 38] is provided showing the comprehensive approaches which consider both side of pump as well as demonstrate the most suitable condition monitoring.

Therefore, this paper is aimed to review and study the condition monitoring methods that are suitable for the implementation in online condition monitoring of cooling pump in nuclear reactors. This study provides main contribution by discussing all the possible online condition monitoring, compare the research achievement and the best practice monitoring approaches. This paper also highlighted each capability of condition monitoring for the most suitable fault detection cases.

This paper is organized as follows. First, the common faults in cooling pump are presented in Section 2. Various condition monitoring as well as the performance monitoring is explained in Section 2. The Section 2 also compare the applicability of the each methods to identify each type of faults. The Section 3 discuss the challenges and opportunities for the researcher in this condition monitoring field.

2. Common Faults in Condition Monitoring

A fault can be identified when there is a decrease of the rotating machine capability from the rated performance [21]. The degradation may be due to normal wear, poor design, poor mounting (including poor alignment), wrong use, or a combination of these. The study in [39] prescribed that an effective condition monitoring by focusing on the common type of failures. This strategy can be used to anticipate the highest probabilities of rotating machine/ circulator faults as well as provide enough practical interpretation of the real condition of coolant pump for the operator of nuclear reactors.

Survey results indicates the common faults in electric motor as the driver section of coolant pump as reported by EPRI and IEEE-IAS in [26, 28, 40], and another one reported in [21] for a specific industry. The survey covered about 5000 electrical machines, which 97% were induction motors. In addition of this survey, a survey specific for the pump side is given in [41].
Table 1. The percentage of frequency common faults in the motor driven pump [26, 28, 40]

| Type of Faults       | EPRI (%) | IEEE-IAS (%) | Petro Survey (%) |
|----------------------|----------|--------------|------------------|
| Bearing related      | 41       | 44           | 52               |
| Stator related       | 36       | 26           | 16               |
| Rotor related        | 9        | 8            | 5                |
| Shaft/coupling       | -        | -            | 2                |
| Others               | 14       | 22           | 10               |
| External Devices     |          |              | 15               |

Table 2. The percentage of frequency common faults of the pump

| Type of Faults     | (%) | Type of Faults | (%) |
|--------------------|-----|----------------|-----|
| Sliding ring seal  | 31  | Rotor          | 9   |
| Bearing related    | 30  | Clutch         | 4   |
| Leakage            | 10  | Split pipe     | 3   |
| Driving motor      | 10  | Casing         | 3   |

These survey results clearly indicate the bearing-related faults is the biggest contributor. It was more than 40% of the total failures for the motor side and the second biggest for the pump (30%). For the pump, in most cases, the seal of pump is also the weakest part component. Two additional survey studies in [42, 43] also reported that air-gap eccentricity was another common faults in various industries. Based on these surveys, the above mentioned failures, such as bearing, stator, rotor, eccentricity and seal fault, are considered as the common faults which should be considered for the development of condition monitoring system.

3. Condition Monitoring Techniques
The condition monitoring techniques is examined carefully to categorize the most suitable technique in detecting the symptoms of certain failures. In other words, certain methods may be more sensitive in detecting signals of damaged parts than others. Table 3 are given to briefly describe these on-line line monitoring techniques of including their advantages and disadvantages. Special techniques such as temperature monitoring and chemical-related techniques are not discussed in this paper.

Shown in the table that, generally, online techniques provide assessment of the electric motor driven in cooling pump without stopping their operation. In other words, implementation of the online techniques does not need to interrupt plant production. The table shows that most of on-line techniques offer multiple fault recognitions, non-invasive and safe. The most important point is that the online techniques allow frequent data capturing and analyzing which is valuable for understanding the trend of the cooling pump.
Table 3. The online monitoring techniques

| Monitoring                  | Description                                                                 | Advantages                                                                 | Disadvantages                                                                 |
|-----------------------------|-----------------------------------------------------------------------------|----------------------------------------------------------------------------|--------------------------------------------------------------------------------|
| Residual Saturation Harmonics [44] | Measuring harmonic frequencies of stator induced voltage after a motor is switched-off | • Useful to determine stator faults. • Does not require motor parameters • Unaffected by voltage imbalance and stator currents • Faulty phase can be identified | • Motor must be turned off. • Does not cover the pump faults |
| Vibration [45-49]           | Fault of certain parts in machines generates specific vibration spectrum which can be measured by vibration sensors | • Sensors can be non-invasive or invasive • The most developed technique. It is covering most of the faults. It has ISO specific standard for the severity classification. • Has been applied for the various feature extraction analysis signal processing • Covered some of thermohydraulic pump phenomena very well • More sensitive to mechanical-related faults (bearing, mechanical unbalance, misalignment, and soft foot) as well as the pump side | • Expensive sensors • Less sensitive to electrical-related faults • Sensitive to mobility of machine • Effect of attenuation of path from a vibration source to sensors • Effect of accelerometer characteristic (no true DC response, ground loop problems, mounting surface problems and cable length sensitivities) • Load sensitive |
| Shock Pulses [50, 51]       | Detecting mechanical ultrasonic shock generated by contact of damage ball bearings with the raceways of bearing or debris, or vice versa | • Excellent for ball bearing monitoring for the motor and pump • Can be invasive or non-invasive • Need simple signal processing (time domain analysis) | • Sensitive to direct modulation • No information for the electrical related faults |
| Acoustic Emission Monitoring [52-54] | Monitoring elastic waves which is produced spontaneously within a material under stress (audible or ultrasound) | • Particularly promising for bearing/mechanical related faults • Non invasive • Easy to set up microphone (non-contact sensors) | • Source of faults can be easily attenuated (airborne acoustic monitoring) • Expensive for the contact- direct sensor • Might be difficult to be implemented in environment with noisy backgrounds • Difficult to interpret the signals |
| Stator Current [17, 19, 55, 56] | Sensing electrical signal of motor supply currents, which contain a direct by-product of rotating flux components caused by specific faults | • Covers almost all faults for the electric motor side (currently is the most popular technique) • Non-invasive • More sensitive to electrical-related faults (stator, rotor, and eccentricity problems) • Low-cost system | • A possible misinterpretation of sideband frequencies with the motor current modulation produced by other events • In large motors, a spidered structure tends to produce a magnetic asymmetry whose effect is similar to rotor electrical asymmetry • Influenced by electric supply, static and dynamic load conditions, noise, motor geometry, and fault conditions • Research is limited in case of thermohydraulic phenomenon |
| Flux Monitoring (search coils in stator or around shaft) [43] | Monitoring small part of sinusoidal leakage flux, which can be affected by various asymmetries and fault conditions | • Can be used to wide range of fault conditions • Can be invasive (in stator) or less invasive (around shaft) • Transducers do not need isolation or protection against current/voltage | • Sometimes not practical to install search coil for large motors • Output voltage drift (temperature sensitive) • Very load-dependent |
| Monitoring                          | Description                                                                 | Advantages                                                                                   | Disadvantages                                                                 |
|-----------------------------------|------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------|------------------------------------------------------------------------------|
| Voltage induced Monitoring [57, 58] | Monitoring of stator voltages, which may contain valuable line frequency or other information | ▪ Non-invasive  
▪ Providing valuable information for air gap torque and instantaneous power monitoring  
▪ Unaffected by motor drive system  
▪ The integration of phase to phase voltage give better results | Lack of publications presenting this monitoring technique |
| Residual Saturation Harmonics [44] | Measuring harmonic frequencies of stator induced voltage after a motor is switched-off | ▪ Useful to determine stator faults.  
▪ Does not require motor parameters  
▪ Unaffected by voltage imbalance and stator currents  
Faulty phase can be identified | Motor must be turned off.  
Does not cover the pump faults |
| Vibration [45-49]                 | Fault of certain parts in machines generates specific vibration spectrum which can be measured by vibration sensors | ▪ Sensors can be non-invasive or invasive  
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Load sensitive |
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| Stator Current [17, 19, 55, 56]   | Sensing electrical signal of motor supply currents, which contain a direct by-product of rotating flux components caused by specific faults | ▪ Covers almost all faults for the electric motor side (currently is the most popular technique)  
▪ Non-invasive  
▪ More sensitive to electrical-related faults (stator, rotor, and eccentricity problems)  
▪ Low-cost system | A possible misinterpretation of sideband frequencies with the motor current modulation produced by other events  
In large motors, a spidered structure tends to produce a magnetic asymmetry whose effect is similar to rotor electrical asymmetry  
Influenced by electric supply, static and dynamic load conditions, noise, motor geometry, and fault conditions |
### Monitoring Techniques Overview

| Monitoring                  | Description                                                                                                                                                                                                 | Advantages                                                                                       | Disadvantages                                                                                   |
|-----------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------|
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• Can be invasive (in stator) or less invasive (around shaft)  
• Transducers do not need isolation or protection against current/voltage | • Research is limited in case of thermohydraulic phenomenon  
• Sometimes not practical to install search coil for large motors  
• Output voltage drift (temperature sensitive)  
• Very load-dependent  
• Flux can be easily attenuated by frame for a complex steel frame of large motor (axial search coil)  
• Not applicable for the pump side |
| Voltage induced Monitoring [57, 58] | Monitoring of stator voltages, which may contain valuable line frequency or other information  | • Non-invasive  
• Providing valuable information for air gap torque and instantaneous power monitoring  
• Unaffected by motor drive system  
• The integration of phase to phase voltage give better results | • Lack of publications presenting this monitoring technique |

Among several types of online condition monitoring techniques as given in Table 4, the vibration monitoring, stator current monitoring, flux monitoring (axial external search coil), voltage monitoring seems the suitable techniques to be implemented. Most of these techniques meet the first four factors suggested in [19] for condition monitoring purposes, such as non-invasive, detecting a wide-range fault of induction motors and widely implemented using reliable sensors and instrumentations. The summary of the capabilities of these techniques including the severity level quantifications is presented in Table 5.

### 4. Challenges and Opportunity

#### 4.1. Vibration monitoring

The vibration detection technique is undoubtedly the most developed technique among commercial condition monitoring systems. Finley et.al [84], and, Singh and Al Kazzaz [28], reported a comprehensive list of vibration frequency components due to mechanical or electrical faults. The vibration monitoring technique covers many principal areas in condition monitoring of cooling pump as suggested in [98]. In addition, several vibration based feature extraction approaches have been established, such as overall level monitoring, 1/3 octave spectrum monitoring, frequency spectrum monitoring, and cepstrum analysis [98].

However, compared with mechanical-related faults, there are only few papers discussing vibration monitoring in relation to electrical related faults. Most of these papers are still in the stage of explaining the relationship between electrical faults and vibration signals such as given in [94, 99]. It is also pointed out in [45] indicated that the primary difficulties in recognizing electrical-related faults through vibration monitoring technique are because of the complexity interaction between vibrations of mechanical and electrical force.

Vibration measurement using accelerometer, displacement or velocity transducers have inherent weaknesses due to the accelerometer characteristics, such as high impedance output, no true DC response, ground loop problems, mounting surface problems and cable length sensitivities [100] and the effect of the transmission path [52]. In addition, the vibration monitoring is also sensitive to mobility or flexibility of the machine [98]. Therefore, caution in vibration measurement should be exercised especially from adjacent, coupled or other near-vibration sources which may generate beat frequencies or slightly change the natural vibration of the real faults.

#### 4.2. Stator current monitoring

Stator current monitoring is simpler and less intrusive than the vibration technique, as the technique does not require delicate/expensive transducers or direct access to the motor’s site. Motor stator current
monitoring can be done by sensing electrical signals of the motor supply currents, caused by asymmetrical related problems or specific motor faults. The modulation frequency of the motor supply current can be extracted to identify each fault. In practical applications, the stator current monitoring technique can also be successfully applied through an on-line system for large motors [56] as well as small motors [43] in various industries.

However, in terms of bearing fault analysis, many studies have underlined several difficulties. One study pointed out that stator current monitoring is less sensitive recognizing mechanical defects compared with vibration monitoring [76]. A bearing fault study in [73] was carried out extensively. The early stage of bearing damage were not proved, and might even be difficult to pinpoint. In addition, with stator current monitoring it is probably difficult to differentiate which one of the two bearings either in electric motor or the pump contributes most to the defect frequencies. In terms of feature extraction, high magnitude ratio of the supply frequency and bearing defects [73] could lead to a significant problem in peak detection, even though in [101] this ratio problem was overcome by applying a digital/analog cancelling technique. In addition, because of modulation frequencies among bearing defects [45], in real cases the bearing defect frequencies may be more difficult to be extracted because the bearing modulated frequencies could be modulated by the stator harmonic frequencies modulation. In addition, for the pump side faults, further investigation is required to prove the applicability of this method.

4.3. **Voltage induced monitoring**

Compared with other monitoring techniques, supply voltage monitoring is rarely chosen as an independent monitoring technique. In most cases, this monitoring technique is combined with stator current monitoring, allowing for another type of monitoring technique such as instantaneous stator power [60] and air gap torque [59]. Stator voltage monitoring is sometimes used to confirm specific fault frequencies of an electric motor, obtained from analysis of stator current monitoring [97]. Regardless of the potential capabilities as listed in Table 4, stator voltage monitoring might be used to provide valuable information to confirm certain faults, or to provide exact fundamental line frequency of the electric motor in the cooling pump.

4.4. **Flux leakage monitoring**

This flux leakage monitoring method is a general-purpose detection method, which can also show various types of faults using only one sensor. This technique can be carried out by detecting small parts of the total flux leakage both from the rotor and stator sides [78]. A basic idea of this monitoring technique is that a small failure of the electric motor causes asymmetry, which in turn increases the existent flux leakage [102]. This flux leakage appears as flux frequency spectrum through a monitoring system.

Because flux leakage is affected by any change in the space harmonic distribution in the air gap due to any faults, it is claimed in [83] that flux leakage monitoring is capable of identifying both various type and the location of faults [82] such as in stator windings related faults. In one study, the flux leakage monitoring was found more sensitive compared with the stator current to detect broken damper bar or short-circuited turns in power generator rotor windings [103]. This means that this technique might be better monitoring results than the stator current technique if the disadvantages can be minimized.

5. **Conclusion**

It can be summarized from the techniques reviewed above that each condition monitoring technique might not provide a similar result in relation to each fault. For example, vibration monitoring seems to be the best method to detect mechanical problems such as bearing and set-up faults as well the pump side. However, stator current monitoring, can be an effective method for several electrical-related problems, such as stator faults, eccentricity faults, and broken rotor bar faults. Therefore, it is suggested that a combination of three or four online monitoring techniques may provide a better solution in identifying various faults. In addition, these monitoring technique can be improved by the application of pump parameter measurements or the pump performance monitoring. Based on this combined
approaches, it can be found the root cause of performance degradation based on the parameter of motor location which can be correlated with the type of faults as well as the locations.

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