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# Application of INPO AP-913 process to EHC pump failure experience

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## 1. Introduction

A hydraulic fluid pump of the Electrohydraulic control (EHC) system in one of Westinghouse type NPP was failed during normal operation in 2018. As a result, the hydraulic fluid pressure decreased and one of the high-pressure turbine stop valves was closed. The failure was due to damage of swash plate and piston. Wear and tear were observed on several slipper pads of the hydraulic fluid pump. Turbine output was reduced by 6% with timely operator action.

In this study, we applied INPO AP-913 process to the event to find the way to improve its performance. INPO AP-913 (Equipment Reliability Process) process is widely used in U.S to improve Nuclear Power Plant (NPP) equipment reliability [1]. There are six elements as shown Fig. 1: Scoping and Identification of Critical Components, Performance Monitoring, Corrective Action, Continuing Equipment Reliability Improvement, PM Implementation, and Life Cycle Management. We would examine corrective action and continuing equipment reliability improvement to identify the cause of the hydraulic fluid pump and find out the appropriate preventative maintenance tasks.

We examined EHC system and hydraulic fluid pump (HFP). The failure of HFP caused the transient. Then, we conducted failure mode and effects analysis (FMEA) for major moving parts in HFP to identify failure mode. The preventative maintenance tasks in preventive maintenance template (PMT) were compared to the FMEA results. Based on the comparison, we identified a few options to improve EHC pump reliability.

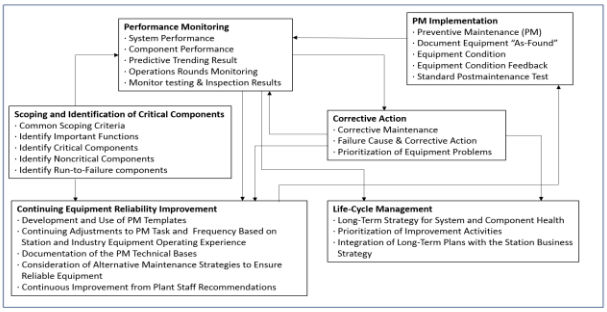



Fig. 1. INPO AP-913 equipment reliability process

## 2. Electrohydraulic control system

Main Function of EHC system is to supply high pressure hydraulic fluid to main steam stop valves, main steam control valves, and combined intermediate valves to control turbine speed and power. When the turbine protection signal is generated by turbine control system, all of turbine valves are closed by blocking the hydraulic fluid within the limited time. In this study, key components are described. The hydraulic fluid pumps are examined in detail.

### *2.1 Major components*

EHC system consists of an oil reservoir, hydraulic fluid pumps, coolers, accumulators and valve actuators as shown Fig. 2 [2].

- Reservoir: hydraulic oil of 200~ 300 gallons is contained in the reservoir. The level sensors and transmitters are installed inside.
- Hydraulic fluid pumps: there are two axial displacement pumps. The pump increases hydraulic fluid oil pressure to 1600 psi. The pressure can be adjusted by changing angle of a swash plate. In the suction of pump, a metal wire-cloth strainer is installed to remove particles more than 10 μm.
- Cooler: two heat exchangers are installed. The hydraulic fluid goes through the shell side and the cooling water circulates to the tube side. There are kept constant by the temperature control valve at the downstream of the cooler.
- Accumulators: they are installed at the downstream of the pump to control the pulsation of the displacement pump and keep the hydraulic pressure constant.
- Valve actuators: it is to control the hydraulic fluid according to electric signals from turbine control system.

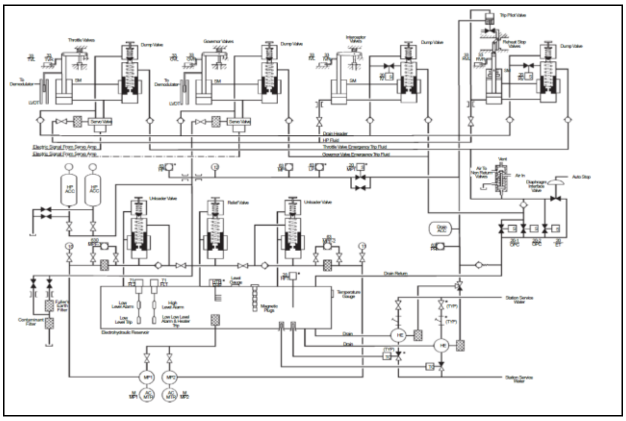
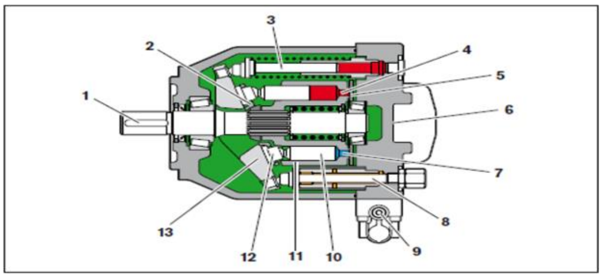


Fig. 2. Westinghouse Turbine EHC system diagram

### *2.2 Hydraulic fluid pump*

The hydraulic fluid pump consists of 13 major parts [3]. Its function is to supply high pressure hydraulic fluid to turbine control valves. Fig. 3 shows schematic diagram. Hydraulic fluid pressure is increased to 1600 psig by the rotational motion of the piston. In order to transfer driving force to the piston, a motor offers torque to the drive shaft (1 in Fig. 3) which is connected to the cylinder (11) and pistons (10). The magnitude of one stroke is dependent on the angle of the swash plate (13). The pistons are hold on the slipper pads (12). Slipper pads are fixed and guided both swash plate and the retaining plate (2).

Hydraulic fluid is fed in and drained out through the two control slots which ar installed in the control plate (5). Hydraulic fluid passes from suction side (7) to high-pressure side (4). The angle of the swash plate could be changed variably by adjusting length of stroke piston (8) and opposing piston (3).




| |
|---|
| 1. Drive shaft: transferring the torque from the motor to the pistons |
| 2. Retaining plate: to fix slipper pad with swash plate |
| 3. Opposing piston: making angle of swash plate |
| 4. High-pressure side: drain out of oil |
| 5. Control plate: providing flow path for feeding and draining hydraulic fluid |
| 6. Port plate: fixing the inner items |
| 7. Suction side: feeding in oil |
| 8. Stroke piston: making angle of swash plate |
| 9. Control valve: contorting amount of hydraulic fluid |
| 10. Piston: increase of hydraulic fluid pressure |
| 11. Cylinder: fixing piston |
| 12. Slipper pad: holding piston and connecting to the piston |
| 13. Swash plate: offering driving force to piston |

Fig. 3. Schematic diagram and function of HFP

## 3. Current Preventive Maintenance Practice

Maintenance tasks for most of equipment are based on PMT. Table I shows the PMT for Turbine-EHC [4]. The function of the HFC is critical. The pump continuously operates and the operating condition is severe due to the high humidity and temperature of area where pump is installed. Function importance determination (FID) is critical, high and severe (CHS) category. There are two types of maintenance tasks required in PMT of Turbine-EHC for the HFP.

### *3.1 Condition Monitoring Task*

Condition Monitoring Task consists of operator rounds, the vibration analysis and system engineer walkdown. Operator rounds are performed several times a day. The vibration analysis and system engineer walkdown are performed once a month.

Most parts of the HFP of Westinghouse type NPPs are installed within the reservoir except the motor. It is difficult to detect failures by visual inspection. Furthermore, it is hard to detect pump failure by monthly vibration analysis due to the severe vibration during normal operation. Thus, the effectiveness of condition monitoring tasks needs improvement.

### *3.2 Time Directed Task*

Time directed task is the pump overhaul, which conducted every three fuel cycles. There are main three tasks.

- Inspection for wear and looseness in all moving part
- Replacement with all bearings, seals, O-rings and gaskets
- Refurbishment to as-new condition

| **Component Template: Turbine – EHC** | | | | |
|---|---|---|---|---|
| Function importance determination (FID) | | | | |
| Importance | Critical(C) | | | |
| Frequency | High(H) | Low(L) | High | Low |
| Environment | Severe(S) | | Mild(M) | |
| PM Task | CHS | CLS | CHM | CLM |
| Condition Monitoring Task | | | | |
| Vibration Analysis | 1 month | - | - | - |
| Hydraulic Analysis | 1 month | - | - | - |
| System Engineer Walk-down | 1 month | - | - | - |
| Operator Rounds | 1 shift | - | - | - |
| Time Directed Task | | | | |
| Pump Overhaul | 3 fuel cycle | - | - | - |

Table I: Preventive maintenance template for Turbine – EHC

## 4. Implementation and Demonstration of FMEA

### *4.1 FMEA*

Identifying failure mode of major parts and its effect is first step. Once the failure mode is identified, the appropriate preventive maintenance tasks can be identified. Table II shows the FMEA result of the HFP. Wear and crack are general failure modes. The failure causes are wear and crack due to excessive stress or particles, and assembly error. Symptoms of wear and crack are noise, vibration and temperature increase.

Table II. FMEA

| Function: Supplying High Pressure Hydro fluid to Turbine Control Valve | | | | |
|---|---|---|---|---|
| Sub System: Axial displacement Pump | | | | |
| Function: Changing low pressure hydro fluid into high pressure hydro fluid and supplying hydro fluid | | | | |
| **Item** | **Failure Mode** | **Failure Effect** | **Cause** | **Mechanical Symptom** |
| Drive shaft fail (to transfer the torque from the motor to the pistons) | crack wear | - decrease of amount of hydraulic fluid and pressure | - friction - misalignment - ageing | - higher level of noise - increase of vibration - increase of temperature |
| | broken | - stop to supply hydro fluid | | |
| Retaining plate (to fix slipper pad with swash plate) | wear crack | - decrease of amount of hydraulic fluid and pressure | - friction between swash plate and slipper pad - assembly error - particle | - higher level of noise - increase of vibration - increase of temperature |
| Control plate (to provide flow path for feeding and draining hydraulic fluid) | wear crack | - more leakage between control plate and cylinder block - decrease of amount of hydraulic fluid | - assembly error | - higher level of noise - increase of vibration |
| Port plate (to fix the inner items) | crack | - becoming unstable | - assembly error | - increase of vibration - higher level of noise |
| Stroke piston Opposing piston (to fix swash plate) | wear broken | - decrease of amount of hydraulic fluid and pressure | - assembly error | - increase of vibration - higher level of noise |
| Control valve (to control amount of hydraulic fluid) | wear | - decrease of amount of hydraulic fluid | - ageing | - slight increase of noise and vibration |
| Piston (to supply hydraulic fluid and increase hydraulic fluid pressure) | wear crack | - decrease of amount of hydraulic fluid and pressure | - assembly error - friction - particle | - higher level of noise - increase of vibration - increase of temperature |
| | broken | - fluctuation of pressure -insufficient suction vacuum | | |
| Cylinder (to fix piston) | wear crack | - decrease of amount of hydraulic fluid | - assembly error - friction | - higher level of noise - increase of vibration - increase of temperature |
| Slipper pad (to hold piston and be connected to the piston) | wear crack | - decrease of amount of hydraulic fluid and pressure | - friction between retaining plate and swash plate - assembly error - particle | - higher level of noise - increase of vibration - increase of temperature |
| Swash plate (to offer angle for movement of slipper pad) | wear crack | - decrease of amount of hydraulic fluid and pressure | - friction among piston, slipper pad and swash plate - assembly error particle | - higher level of noise - increase of vibration - increase of temperature |

### *4.2 Examination of EHC pump failure event*

A hydraulic fluid pump in the EHC system was failed during normal operation. As a result, the hydraulic fluid pressure decreased and one of the high-pressure turbine stop valves was closed. When shift workers arrived at EHC system, they could listen to audible noise from the HFP. It was presumed that the noise is caused by friction between the swash plate and slipper pads. Once the pump was disassembled, the tracks of wear were found on the surface of the swash plate and slipper pads as shown Fig. 4. The failure was due to damage of swash plate and pistons.

| Slash plate | Slipper pad |
|---|---|

Fig. 4. Damaged slash plate and Slipper pad

## 5. Equipment Reliability Improvement

As shown in Table II, wear and crack are general failure modes on the HFP. The causes of wear and crack are friction, particle or assembly error. A metal wire-cloth strainer installed in suction of the pump prevents particle in fluid. Friction and assembly error would be likely causes. Common symptom is vibration and temperature increase. However, due to temperature control, the temperature rise is minimal. Coolers keep fluid temperature constant by controlling amount of cooling water. Therefore, vibration is only viable indicator. We will focus on how to measure vibration and crack caused by friction. As recommended by INPO AP-913 process, three options are considered: PdM, PM improvement (O/H-NDE) and design change.

### *5.1 Predictive Maintenance*

There are two difficulties to measure vibration of the hydraulic fluid pump. One is location and the other is high vibration during operation. The pump body is installed within the reservoir. Vibration monitoring is performed at motor. It is difficult to measure pump vibrations directly. Also, vibration of hydraulic fluid pumps itself is high during operation. Therefore, the results of vibration measurement are not precise.

Noise and vibration are caused by other components in EHC system as well. A portable detector, used for vibration measurement, could get the bad wave signal from these.

Hence, on-line vibration monitoring with sensors installed directly on pump body is recommended. Thus, vibration measurement is not interrupted. Vibration from other components would not affect the signal. The basic concepts of on-line vibration analysis are as follows.

- Vibration sensors are installed on pump’s body.
- The results have to be transmitted to plant monitoring system (PMS).

- Warning alarm should be provided to operators if the values are beyond standard.

Also the PMT should be modified. Vibration analysis (off-line) becomes a supplementary method when on-line vibration fails.

Table III: Modified Preventive maintenance template for Turbine – EHC

| **Component Template: Turbine – EHC** | | | | | |
|---|---|---|---|---|---|
| Function Importance Determination(FID) | | | | | |
| Importance | | Critical(C) | | | |
| Frequency | | High(H) | Low(L) | High | Lo |
| Environment | | Severe(S) | | Mild(M) | |
| PM Task | | CHS | CLS | CHM | CLM |
| Condition Monitoring Task | | | | | |
| Vibration analysis | Vibration Analysis | As required | - | - | - |
| | On-line Vibration Analysis | 1 month | - | - | - |

### *5.2 PM Improvement Non-Destructive Examination*

If any cracks occur on rotation parts such as slipper pad or swash plate, it is impossible to detect through the visual observation. Moreover, it is important to find crack quickly to prevent the faults similar to slipper pad incidence experienced. I recommend that all of rotation parts such as slipper pads, swash plate, and retaining plate should be inspected by NDE during OH [5].

- Inspection for wear and looseness in all moving part by NDE such as ultrasonic test, radiation test and etc.
- Replacement with all bearings, seals, O-rings and gaskets
- Refurbishment to as-new condition

### *5.3 Design change*

If the above two options are not feasible or too expensive, then one needs to consider design changes. Two types of design changes can be considered. The first is to change the equipment to other company and the other is to change original design. EHC system of Westinghouse Nuclear Power Plant is complicated. We don't have any experiences changing original design. Safety must be considered as the top priority for design changes. Equipment change seems to be more practical option.

## 6. Summary

HFP are important equipment controlling turbine speed and power. If HFPs fail, NPPs would go through either transient or shutdown. We examined the failure experienced in Westinghouse type NPP and develop options for improving equipment reliability. INPO AP-913 process is followed for this purpose.

We conducted FMEA for identifying failure mode. Based on the failure modes and failure causes, we identified three methods to improve hydraulic fluid pump reliability. There are on-line vibration monitoring, NDE as a part of OH inspection, and design change. The current condition monitoring is deficient with installation location and vibration measurement spot.

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