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# Fuzzy logic-based safety design for high performance air compressors

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ABSTRACT

This paper presents problem of silted water causing equipment degradation. It proposes a safety design including instrumented and non-instrumented systems to resolve this issue by specifying safety life cycle activities including risk analysis, risk reduction, safety system requirements, safety system implementation and safety assurance. It uses case study as an example and proposes implementation of pressure transmitter linked with fuzzy logic to proactively take actions and report equipment condition to plant personnel. Analysis concluded that safety instrumented system (SIS) proposed will reduce maintenance burden, save resources, and improve system reliability by detecting failures proactively with better risk reduction factor (RRF). It is recommended that this SIS be implemented at all Nuclear Plants facing equipment problems related to silted water.

*Objective:* To investigate problem of silted water causing equipment degradation using safety instrument system and provide pathforward.

## 1. Introduction

Safety of workers, environment and public is a paramount importance to the Nuclear Sector. A Nuclear Power Plant produces energy that is used for various purposes in safe and reliable manner. Critical focus of any Nuclear Plant is reliable operation of instrumentation and control systems. Functionality of control systems and its instrumentation serves as a nervous system to the plant (Instrumentation and Control, 2012). Various detection methods are used to proactively act on problems before they become reactive. Instrument Air System is one such safety related system that is to be available and reliable at all times.

Instrument air is used to run various air-operated devices (valves, air motors, dampers etc) and also used as pressurized cover gas for various systems.

Typical Instrument Air System at a Nuclear Generation Plant in Ontario consists of four “33%, 0.307 $m^3$/s (650 scfm), 860 kpa gauge (125 psig), two stage, water cooled oil free rotary screw compressors each driven by a 150 kW (200 hp) motor” (Instrument Air Design Manual, 2010). All four compressors discharge air to four 7 $m^3$ (250 cu ft) air receivers with parallel arrangement, connected downstream to four air driers via common header (Fig 1).

Four 33% heatless type air dryer units each has outlet capacity of 0.307 $m^3$/s (650 scfm) are “twin tower, heatless, pressure swing solid activated alumina desiccant type giving an outlet dew point below minus 40 °C (−40F) at a rated gauge pressure of 860 kpa (125 psig)” (Instrument Air Design Manual, 2010) that provides dry air for station operation.

Once dry air is delivered, it is distributed via ring header to reactor buildings, reactor auxiliary bay, turbine auxiliary bay and turbine building at Nuclear Plant in Ontario. The headers consist of manual isolating valves for isolating the air for emergency purposes to avoid jeopardizing other air supply loads.

Individual compressed air stations consist of single/double manifolds with 8 outlets (1 cm diameter) installed with isolating valves to feed downstream equipment. Please refer to Fig 2 describing layout of instrument air circuits at typical Nuclear Plant in Ontario.

## 2. Problem definition

The instrument air compressor internals (oil coolers, intercooler, and aftercoolers etc) are cooled using service water to maintain critical operational parameters under acceptable limits. These include inlet water pressure, intercooler air pressure, oil temperature, water temperature compressor out, discharge air pressure, air filter, oil pressure, discharge air temperature and water temperature aftercooler out (Deol, 2013a).

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**Acronyms**

| | |
|---|---|
| SIS | Safety Instrumented System |
| PNGS | Pickering Nuclear Generating Station |
| OPG | Ontario Power Generation |
| CP | Compressor |
| RB | Reactor Building |
| IA CP | Instrument Air Compressor |
| HX | Heat Exchanger |
| SV | Solenoid valve |
| FT | Flow transmitter |
| PM | Preventative Maintenance |
| PdM | Predictive Maintenance |
| CM | Corrective Maintenance |
| PRA | Probability Risk Assessment Model |
| SCR | Station Condition Record |
| CAP | Corrective Action Plan |
| SPMP | System Performance Monitoring Plan |
| FMEA | Failure Mode and Effect Analysis |
| ECR | Engineering change request |
| MOD | Modification |
| WR | Work Request |
| PFD | Probability of failure on demand |
| SIF | Safety Instrumented Function |
| SIL | Safety Integrity Level |
| PFD | Probability of failure on demand |
| RRF | Risk reduction factor |

*Nomenclature*

| | |
|---|---|
| $T_{water,in}$ | Compressor water temperature in (°C) |
| $T_{water,out}$ | Compressor water temperature out (°C) |
| $T_{oil,in}$ | Compressor oil temperature in (°C) |
| $T_{oil,out}$ | Compressor oil temperature out (°C) |
| $C_{water}$ | Heat capacity rate of water (KW/°C) |
| $C_{oil}$ | Heat capacity rate of oil (KW/°C) |
| $C_{p,water}$ | Specific heat of water (KJ/Kg °C) |
| $C_{p,oil}$ | Specific heat of oil (KJ/Kg °C) |
| $U$ | Overall Heat Transfer Coeggicient $(W/m^{2\circ}C)$ |
| $\dot{m}_w$ | Water mass flow rate (kg/sec) |
| $\dot{m}_o$ | Oil mass flow rate (kg/sec) |
| $R_f$ | Fouling factor ($m^2$ °C/W) |
| $Nu$ | Nusselt Number |
| $\rho_w$ | Density of water ($Kg/m^3$) |
| $\rho_o$ | Density of oil ($Kg/m^3$) |
| $Pr$ | Prandtl number |
| $k$ | Thermal Conductivity (W/m °C) |
| $\mu$ | Kinematic Viscosity ($m^2/s$) |
| $h_i$ | Water Convection heat transfer coefficient ($W/m^2$ °C) |
| $h_o$ | Oil Convection heat transfer coefficient ($W/m^2$ °C) |
| $D_h$ | Hydraulic diameter (m) |
| $A_c$ | Area of circular tube ($m^2$) |
| $A_s$ | Total surface area of inner tube ($m^2$) |
| $\dot{Q}_{max}$ | Maxium heat transfer rate (KW) |
| $\in$ | Effectiveness factor for heat exchanger |
| $\dot{Q}$ | Actual heat transfer rate (KW) |
| $C$ | ratio of min/max heat capacity rate |

Referring to Fig. 3, service water enters compressor via solenoid valve (SV854) and distributes in two lines, one line goes to cool Oil Cooler (heat exchanger, HX3012 and intercooler HX3009) and other cools after-cooler (heat exchanger, HX3015).

Service water often could contain silt particulates that could plug compressor internals and damage solenoid valves (SV) that open/close to supply water to cool compressor. Typical damage of solenoid valve involves plugging its internal assembly, interrupting its operation by failing in same position. For example, if solenoid valve is open (and supplying cooling water to compressor) plugging of silt will keep it stuck in open position. This would mean even if compressor downstream is not running, supply of silted water will keep flowing through and continue to plug its internals (i.e. oil cooler, intercooler and aftercooler) affecting its heat transfer efficiency in long run.

Failure of this type doesn't trip compressor in short-timeframe but reduces its lifespan due to equipment degradation that includes overcooling of compressor internals, increasing oil viscosity and causing condensation within compressor that could lead to corrosion problems requiring part replacements. It also leads to service water system impairments due to increase of flow diversion (with SV stuck open) that could otherwise be used to cool other equipment in the plant.

Second mode of solenoid valve failure involves plugging its internals in closed position and preventing it to open when signaled

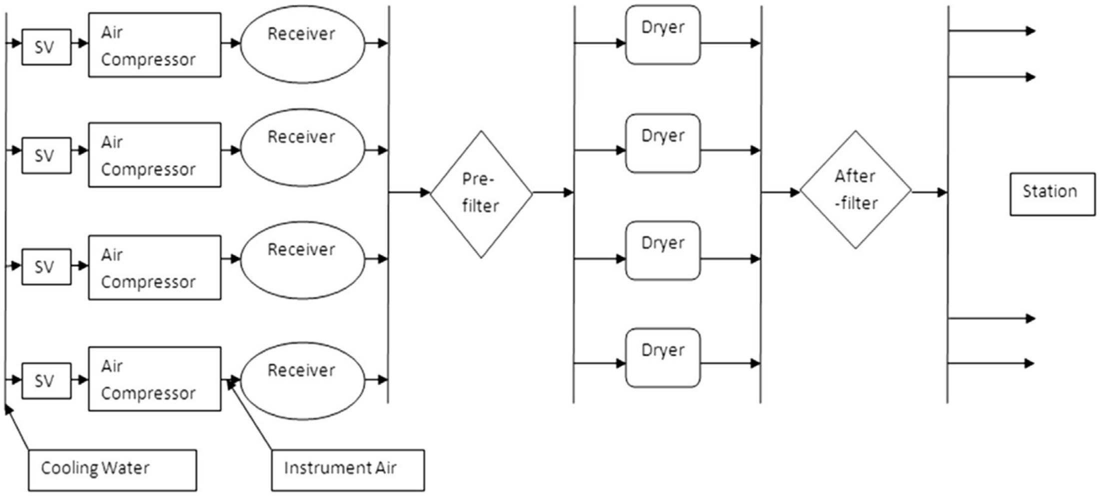

**Fig. 1.** Schematic system diagram.