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Fault diagnosis based on Petri Nets: the case study of a hydropower plant

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Abstract: Identification and fault diagnosis of industrial discrete event system has been used Petri Nets models in classical Place/Transition approach or even high level nets. A very important issue in this approach is the system monitoring and the integration of structural and behavioral models observed while the system is working, which is captured in the net system. In 2004 a ISO/IEC Petri Nets standard was launched where classic and high level net could be synthesized by folding/unfolding processes. The new standard approximated Petri Nets formal representation to both requirements and fault diagnosis methods. On the other hand, in what concerns the risk analysis of hazardous operations, some new methods appear that approximate diagnostic to the design process or to functional analysis, all requiring discrete process representation. In this paper a fault diagnosis method is proposed, where a HAZOP model is used as input requirement that is transformed in a Goal Oriented Requirements Engineering(GORE) representation called KAOS, which are further analyzed in Petri Nets. KAOS diagrams are translated to Petri Nets, using the classic P/T (place/transition) approach. Such approach is scalable and suitable to be applied to large and critical systems as hydroelectric plants. A case study is presented just to this to show applicability to this kind of application.

Keywords: Fault diagnosis, Petri nets, hydropower plant, formal modeling, intelligent maintenance.

1. INTRODUCTION

Hydropower is already one of the cleanest and most efficient forms of electricity generation available. However, improvements still could be made at a hydroelectric plant in order to make the process even more efficient. One of the main sources of power loss in the generator string can be traced to the thrust bearing used to support the rotating assemblage. Energy dissipated as a result of fluid shear, friction and increased temperatures within the bearing and lubricant have the combined effect of reducing efficiency and limiting generation capacity.

The loss of the lubricating film in the bearings can induce extreme localized rises in temperature, and stress, which consequently contribute to material damage, increased rates and volumes of wear and a general reduction in system operating efficiency and can also cause the unavailability of hydropower.

As well as any fluid-film bearing, temperature is arguably the most important factor in determining the limits of performance. This applies to both the bearing itself as well as the lubricating fluid. Temperature influences lubricant viscosity which in turn has an effect on pressure within the oil film. This pressure affects bearing load carrying capacity. Therefore, in order to develop a full picture of bearing and lubricant performance, all these factors must be monitored.

The cooling and lubrication system of thrust bearing is responsible for formation of fluid-film and it is essential for the hydropower plant operations, so it becomes necessary the development of not only a good maintenance plan, but a failure diagnostic system as well. Fault diagnosis, according to Papadopoulos (2001), is the process of identifying the origin of a fault by analyzing a series of effects that it causes in the system to which it belongs. Moreover, a fault diagnosis system can, through modeling techniques, predict or at least indicate the causes of certain failure (Lampis, 2010).

Hence, by pinpointing one or more root causes of a given system failure, fault diagnosis allows both operations and maintenance teams to take corrective actions. Moreover, a fault diagnosis system can also be used to identify critical components, enabling the development of an appropriate preventive maintenance plan.

To develop a fault diagnosis program, a broad overview of the subject matter is needed. Risk analysis techniques such as Hazard and Operability Study (HAZOP) are important tools for the complete understanding of the functioning of a particular system as well as a broad understanding of causes and risks of possible failures it presents.

Hu et. al. (2015) developed an intelligent fault diagnosis system for process plant using a functional HAZOP alongside with Dynamic Bayesian Networks (DBN). In this study, HAZOP was used in order to acquire knowledge about the system in a structured way. According to (Cheng et al., 2015), Petri nets have attracted much attention in fault diagnosis because, besides having rigorous math-

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ematical definitions, they also have intuitive reasoning processes that are consistent with the occurrence of faults. Cavalheiro (2013) applied the HAZOP technique alongside with Bayesian Networks and Petri Nets in order to develop a control and diagnosis system for a ventricle assist device.

Mansour et. al. (2013) showed that Petri nets can be applied for fault diagnosis of large power generation station using information acquired by SCADA system. Rueda et. al. (2015), Liu et. al. (2013) and Fanti et. al. (2015) also applied Petri nets for diagnostics purposes.

The development of a fault diagnosis methodology using the HAZOP technique and Petri nets in case of thrust bearings contributes to greater safety in operations of a hydraulic turbine. Additionally, fault diagnosis method will allow the hydropower plant operations team to quickly mitigate a failure, reducing downtime of the system.

The objective of this paper is to develop a model-based fault diagnosis for the cooling and lubrication system of thrust bearing through the use of Petri nets, alongside with risk analysis techniques such as HAZOP, in order to automate the process of identification of the source of a given fault in the system. By analyzing sensor readings, the developed Petri net should identify which system components can be responsible for the failure of the system.

Therefore, the Petri net design must be carefully developed in order to optimize its results. In order to do so, the Petri net will be obtained through the conversion of a previously obtained KAOS (Keep All Objectives Satisfied) model of the diagnostic system. The KAOS model is a goal oriented requirements engineering method which defines, among other things, the goals that the system should meet (Van Lamsweerde, 2001). To validate the method, all possible sensor readings combinations will be introduced in the Petri net and the results will be analyzed.

The main advantage of the proposed method is the systematic way of obtaining the Petri net. In a fault diagnosis expert system, it is very difficult to determine how the inference engine design must be like. So, by using the KAOS model to obtain the Petri net, which is the inference engine (the one which will do the reasoning, the identification of possible faulty components), the process of developing a diagnosis system is partially automated.

2. METHODOLOGY

The objective of this paper is to develop a model-based fault diagnosis for the cooling and lubrication system of thrust bearing. The proposed method is given by five steps, shown in Fig.1.

The first step of the proposed method is defined by a study of the cooling and lubrication system of thrust bearing, in which a description of its operation is made. To carry out operational description, it is necessary to examine the technical characteristics of the components through the study of plans, catalogs, manufacturer manuals, etc. This step may present some difficulties in the industry since this information may not be available.

In the second step, it is developed a Hazard and Operability Study. The purpose of the HAZOP is to investigate

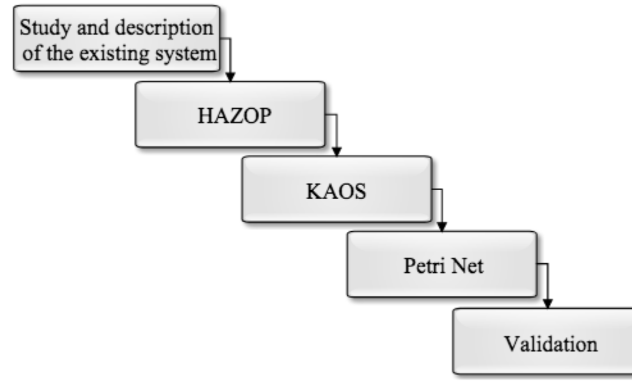

Fig. 1. The proposed method divided in five steps

how the system can deviate from design intent, creating operability problems or even risk for personnel. So, by using HAZOP, it will be possible to analyze what are the faults that the system can present and, by doing that, it allows an analysis of whether the sensors used are able to identify those faults.

In the third step, it is developed a goal-driven requirements engineering method called Knowledge Acquisition in Automated Specification (KAOS). The use of this method in this research aims to define the goals of the fault diagnosis process to be developed. The results of HAZOP will be used to improve the development of the KAOS model, since it will help identify the requirements of the fault diagnosis system.

The fourth step is to develop a Petri Net that should indicate which component or components of the system can be the responsible for the fault showed by the system. The Petri net will be developed based on the KAOS goal diagram obtained in the previous step. In order to do so, the KAOS diagram will be translated to a Petri net through a transference algorithm called ReKPlan, proposed by Silva, J.M. and Silva, J.R. (2015). By analyzing sensor readings, the developed Petri net should identify the components that can be responsible for the failure of the system.

The final step is to validate the model and, in order to do so, all possible sensor readings combinations will be introduced in the Petri net and the results will be analyzed.

3. APPLYING THE METHOD TO THE MAINTENANCE OF HYDROELECTRICS PLANTS

The system to be analyzed is the lubricating and cooling systems of hydraulic turbine thrust bearing used in hydroelectric power plant localized in São Paulo state in Brazil. The hydroelectric power plant has a generation capacity of 120 MW.

3.1 Cooling and Lubrication System of Thrust Bearing at a Hydraulic Turbine

The thrust bearing, or hydrodynamic bearing, operates on the principle of hydrodynamic lubrication and is used to carry loads in applications where roller bearings are unsuitable due to dimensional limitations, demands for operational lifespan or high loading requirements. In it, the load carrying surfaces are completely separated by an oil film, eliminating the risk of surface wear as long as a film of sufficient thickness is maintained.

The main purpose of the oil circulation and lubrication circuit is to dissipate the heat generated by the bearing and to lubricate its components. Fig. 2 shows the Lubricating and cooling systems of hydraulic turbine thrust bearing, which is composed by an oil reservoir and three other sub-systems: the oil injection system, the oil pressuring power unit and the cooling system.

The oil injection system has the primary objective to ensure the formation of the oil film during starting and stopping of the generating unit, avoiding the bearing metal to metal contact anchor. Since this system operates only when the hydraulic turbine have low rotation speed, it injects the lubricating oil in the thrust bearing at very high pressure.

The oil pressuring power unit ensures the formation of the oil film between stator and rotor during all the operation of the turbine. It injects the lubricating oil in the thrust bearing at a lower pressure compared with the oil injection system.

Finally, the cooling system is responsible for refrigerating the oil that circulates in the system through the use of heat exchangers. It guarantees an optimal lubricating oil working temperature and prevents oil viscosity changes.

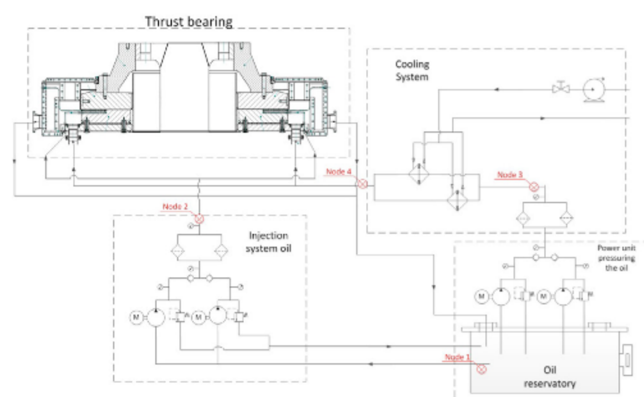

Fig. 2. Lubricating and cooling systems of hydraulic turbine thrust bearing

3.2 HAZOP

The HAZOP is characterized by being a qualitative analysis and is mainly used in the identification of operational problems and inefficiencies of a process to thereby identify deviations that turn to be dangerous events. The danger is defined as any accidental event that can potentially cause damage to people, plants or the environment. This method aims to eliminate, mitigate or control such deviations(Ericson II , 2016).

The system to be analyzed can be divided into local nodes, which will be submitted to a group of experts. These experts will use keywords to systematically cover all possible malfunctions and operational deviations of a plant. Some keywords most frequently used are: not, low, over and others. When these keywords are applied to process variables such as pressure, temperature, etc., deviations of the corresponding process variables are obtained, and nominated as over pressure, over temperature, no flow , among others. Once a deviation is identified by its cause and consequences, an action is proposed to eliminate, mitigate or control the hazard or to solve the system operational problem (Ericson II , 2016).

The main goal in developing a HAZOP technique is to acquire knowledge for the fault diagnosis process by identifying, for instance, in the cooling and lubricating subsystem which nodes and corresponding parameters must be monitored. At the end it is possible to elicit all requirements that implies in necessary (sufficient) condition (s) to a diagnostic system. As such, all these requirements must be considered in the requirements model, which will be represented by a specific diagram based on Goal Oriented Requirements Engineering: KAOS (Keep all Objects Satisfied) diagrams (Lamsweerde , 2009) (Lamsweerde , 2001).

Table 1 shows a parametric relation that emerges from HAZOP where the terminology described above is use to identify a deviation its cause and consequences. Nodes identified as those to be monitored should be highlighted, as in Figure 2, and the parameters analyzed depend of the node: Node 1 is associated with the Oil Level, while Nodes 2, 3 and 4 are associated with Pressure and Flow.

Node	Parameter	Keyword	Deviation	Causes	Consequences
3	Pressure	Low	Low pressure	1) Clogged Filter 2) Clogged Pipeline 3) Pipeline Leakage 4) Tank Leakage 5) No Oil in Tank 6) Motor Failure 7) Pump Failure 8) Relief Valve Failure	1) Thrust Bearing poorly lubricated 2) Thrust Bearing heats up and stop working 3) Possibly damaged rotor and stator

Table 1. Example of obtained HAZOP results

3.3 Recovering requirements in KAOS

KAOS approach is an goal-oriented implementation of GORE method which involves a rich set of formal analysis techniques based on Linear Time Logic (LTL). Indeed, KAOS stands for *Keep All Objectives Satisfied* (Lamsweerde, 2009)

It was used the Objectiver (Objectiver, 2015) tool to apply the KAOS methodology, which can be used to identify project requirements, create models that take user agents and the system environment into account or represent user scenarios, producing structured requirements documents (Graa et al, 2012).

Based on the results obtained in the HAZOP, the KAOS model is developed. Fig.5 shows a part of the generated model. It is possible to see, by analyzing the model, the system sensors, represented in the HAZOP table by nodes, turned out to be an agent in the KAOS model.

3.4 Converting requirements to High Level Petri Nets

From the developed KAOS model, a Petri Net is synthesized using a transference algorithm proposed by Silva et al. (2009), called GHENeSys.

The elements used in the GHENeSys net are illustrated in Fig. 3. Likewise, Fig. 4a illustrate how basic elements from the KAOS model are translated to the GHENeSys net and Fig. 4b shows how the AND/OR refinement from the goal oriented model are translated to structural net components.

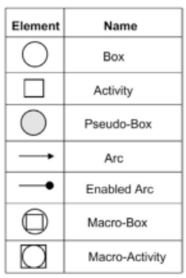

Fig. 3. GHENeSys basic elements

In order to obtain the Petri net, it was used the RekPlan (Requirement Engineering for Planning Problems) tool, which automatically transforms KAOS diagrams into Petri nets. The obtained Petri net is able identify a faulty component in the system, which is responsible for the deviating sensors reading.

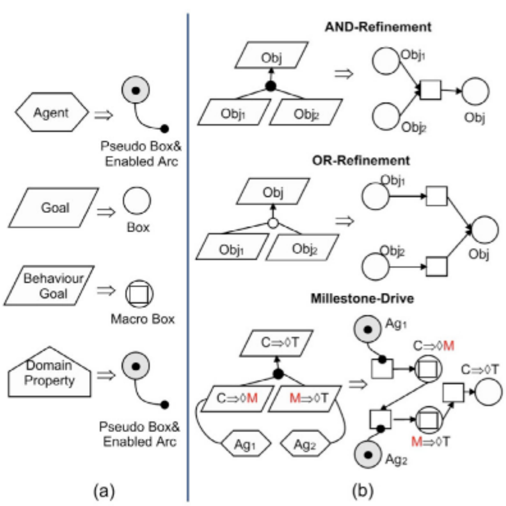

Fig. 4. Translation from KAOS to GHENeSys (SILVA JR and SILVA JM, 2015)

3.5 Validation of the Petri Nets

The obtained Petri [1] net can indicate which components can be faulty given sensors readings. In the Petri net, input boxes (or input places) are represented by sensors nodes, which represent a detected system deviation. The box "Sensor 1" represents low oil level identified in Node 1 (shown in Fig. 2). "Sensor 2", "Sensor 3" and "Sensor 4" represent low oil pressure at nodes 2, 3 and 4, respectively.

Fault diagnosis is done by analyzing the tokens reachability, i. e., given a certain combination of tokens in the input places (deviations identified by the sensors), a component can be in a faulty condition only if this tokens can reach the box representing this fault in the Petri net.

In order to have a failure at motor 3, for example, Sensor 2 must have a token, i. e., a low oil pressure must be identified at Node 2. In order to have a failure at motor 1, however, sensors 3 and 4 must have tokens.

By adding more sensors in the system, it is possible to improve the fault diagnosis done by the Petri net, since a failure in a given component will produce different sensors readings.

4. CONCLUSIONS

The introduction of HAZOP technique as input requirement was a new feature in the proposed method. A KAOS model was derived from that which was translated to Petri Net where fault diagnosis was programmed. Information obtained in risk analysis can be very useful during the development of a goal oriented model which, in turn, will be used to assist the automation of fault diagnosis. Monitoring spots were then identified from cause-effect relations derived from HAZOP and to the relational representation in the state space formal representation of Petri Net turning out to be a very reliable process.

One of the difficulties to implement a model-based fault diagnosis system is the validation, that is, to make sure that a developed model really represents the actual system behavior. Such behavior is embedded in KAOS model which also uses Petri Nets to perform requirements analysis and validation (Silva, 2015). Therefore, the use of Petri Net can be a dual benefit, first identifying the monitoring points (which can combine different sensor signals) and also relating the monitoring with the general behavior of the system. On the other hand the correctness of the process relies on the accuracy of the conversion from KAOS diagrams to Petri Nets.

The conversion algorithm was formally derived and further implemented by ReqPlan, a computer environment based on a meta-model of both KAOS diagram and the Petri Net formalism. However it is also important to stress that ReqPlan can also work with a unified net called GHENeSys Petri Net which includes several extensions. One of those extensions is hierarchy, and that makes the process scalable and therefore suitable to be applied to large systems.

All preliminary results presented on this paper were obtained using a classic Place/Transition Petri net that is purely deterministic, i. e., it only identifies all possible fault components responsible for a given set of sensors. Future steps on this research point to the possibility is to use a Petri net that can identify a faulty component given by sensors readings and also some probabilistic information about the components. Besides being a normal extension

[1] In fact ReKPlan translate KAOS diagram to an unified Petri Net called GHENeSys (General Hierarchical Enhanced Net system, proposed by Silva et al. (2009). A unified net is the one that can fit the ISO/IEC 15.909 standard and reproduce a classic P/T net a high level net (HLPN) and some specific extensions, such as hierarchy, special pseudo-places and time.

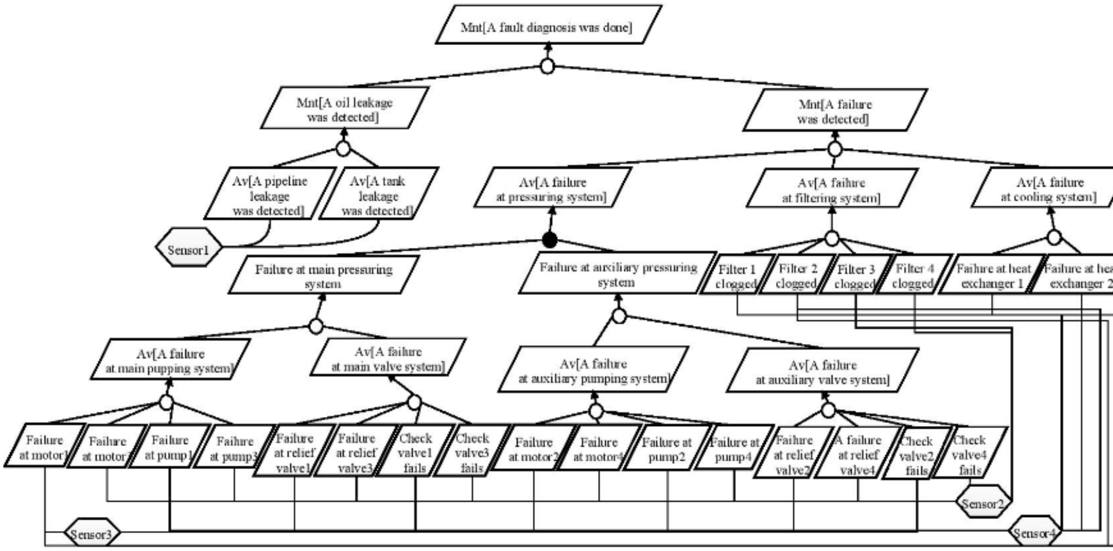

Fig. 5. KAOS diagram of the diagnostic system

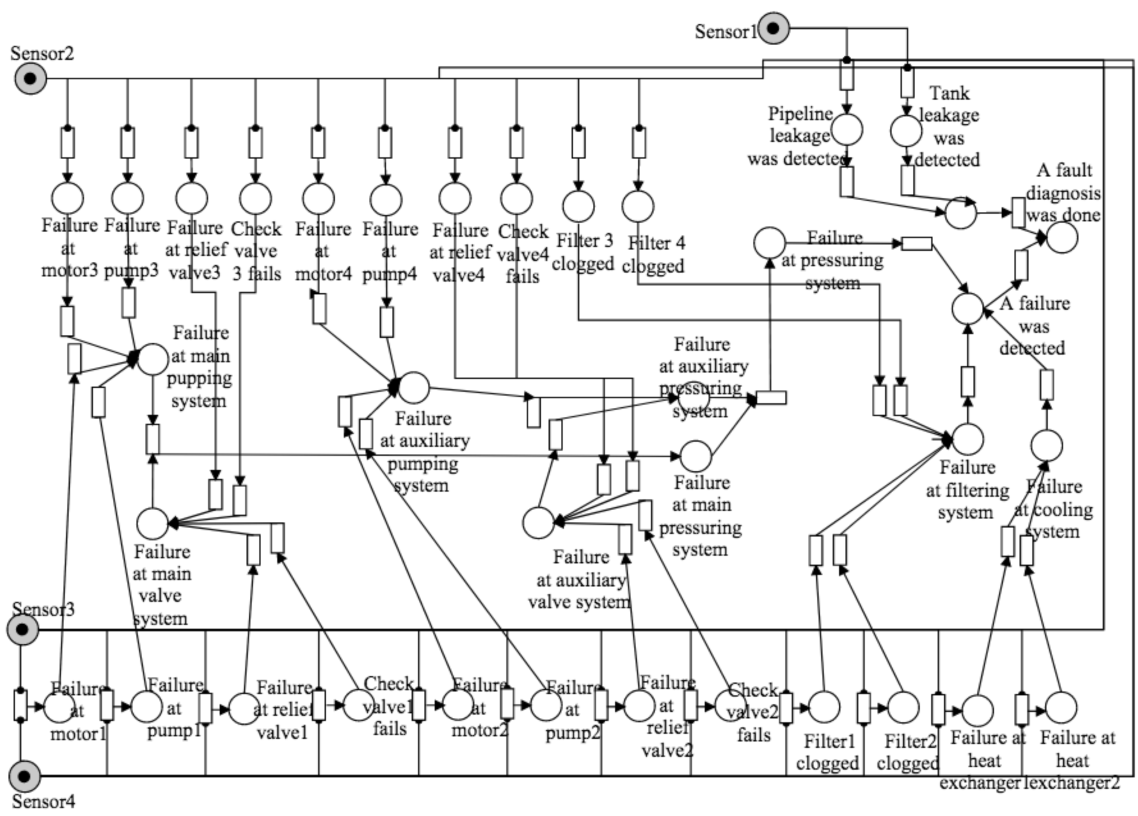

Fig. 6. GHENeSys net of the diagnostic system

to the current work that would introduce new features such as reliability and probability of failure, to enhance the precision of the diagnosis.

Although it was presented just one practical application, it is easy to notice that there a generic discipline that does not dependent on the application domain. In a further work we intended to test this method on systems with different operational characteristics to put in checkd its generality and effectiveness. The use of property analysis in the analysis and validation of KAOS models are also a challenge.

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