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Development of reliability index for combined cycle power plant using graph theoretic approach

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Abstract A systematic approach based on graph theory and matrix method is developed ingeniously for the evaluation of reliability index for a Combined Cycle Power Plant (CCPP). In present work CCPP system is divided into six subsystems. Consideration of all these subsystems and their interrelations are rudiment in evaluating the index. Reliability of CCPP is modeled in terms of a Reliability Attributes Digraph. Nodes in digraph represent system reliability and reliability of interrelations is represented by edges. The digraph is converted into one-to-one matrix called as Variable System Reliability Permanent Matrix (VPM-r). A procedure is defined to develop variable permanent function for reliability (VPF-r) from VPM-r. Reliability index of CCPP system is obtained from the permanent of the matrix by substituting numerical values of the attributes and their interrelations. A higher value of index implies better reliability of the system. The proposed methodology is illustrated step-by-step with the help of two examples.

1. Introduction

Reliability analysis is an innate aspect of combined cycle power plant design and plays considerable role throughout the plant operation in terms of expenses (operating and maintenance) and optimal maintenance scheduling of its equipments. Reliability may be defined as the ability of an equipment, component, product, system, etc., to function under designated operating state of affairs for a specified period of time or number of cycles [1]. For a large and complex electricity generating system such as CCPP, reliability is the probability of generating electricity under operational conditions for a definite period of time. Reliability of a CCPP is function of maintenance (scheduled or forced) cost, which in turns depends upon the Mean Time Between Failures (MTBF) and Mean Time To Repair (MTTR) of equipments or systems, and which are further dependent on complexity in design, state, age of the equipment or system and to some extent on the availability of spare parts.

Recurring failures that lead to complete power plant outage need repair and proactive maintenance to invigorate power

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plant performance and reduction monetary losses. Downtime losses and maintenance cost of a CCPP can be reduced by adopting a proper mix of maintenance and repair strategies. In the worst situation, unavailability of an equipment or system affects whole plant and plant trips in this case. But in general, the failure of an equipment or system may not affect the complete plant and therefore its criticality is at some intermediate value. In that case reliability of system comes down and its effect on reliability of other systems is also observed. The criticality level decides the importance of the equipment or system and choice of appropriate maintenance and repair strategy so that reliability may be maintained up to a mark.

In the literature both qualitative and quantitative methods for assessing the reliability of complex systems are available. The most commonly used qualitative methods are Fault Tree Analysis (FTA), Failure Modes, Effects and Criticality Analysis (FMECA), Failure Modes and Effects Analysis (FMEA), Root Cause Analysis (RCA), Root Cause Failure Analysis (RCFA), Fish Bone Analysis (FBA), Event Tree Analysis (ETA), and Predictive Failure Analysis (PFA). Block diagram analysis, Markov chain, and Monte Carlo simulation are some of the quantitative methods of reliability analysis available in the literature.

Various attempts have been made by researchers in developing procedures for the evaluation of the reliability of various systems [2–10]. The two-state Markov model is the mainly used outage model in power system reliability analysis [11].

Eti et al. [12] integrated reliability and risk analysis for maintenance policies of a thermal power plant. Need to integrate RAMS (reliability, availability, maintainability and supportability) centered maintenance along with risk analysis was stressed, although results expected or obtained with the application of those concepts were not explained.

A staircase function was introduced by Ji et al. [11] to approximate the aging failure rate in power systems and a component renewal process outage model based on a time-varying failure rate was proposed. The model reflected the effects of component aging and repair activities on the aging failure rate.

Markov method was used by Haghifam and Manbachi [13] to model reliability, availability and mean-time-to-failure indices of combined heat and power (CHP) systems based on interactions between electricity generation, fuel-distribution and heat-generation subsystems. The proposed model can be useful in feasibility studies of CHP systems and in determining their optimal design, placement and operational parameters.

Carpaneto et al. [14] carried out Monte Carlo simulation for identifying long, medium and short-term time frames by incorporating uncertainty at large-scale and small-scale for cogeneration system. Availability coefficient assumed to be independent of year, scenario and control strategy was defined for unavailability of the CHP units, due to scheduled maintenance and reliability aspects, taking into account. Large-scale uncertainty referred to the evolution of energy prices and loads and relevant to the long-term time frame was addressed within multi-year scenario analysis. Small-scale uncertainty relevant to both short-term and medium-term time frames was addressed through probabilistic models and Monte Carlo simulations [15].

Mohan et al. [2] calculated RTRI (real-time reliability index) for a SPP (steam power plant) using graph theory. Integration of systems and subsystems and interaction among them were considered for the reliability analysis and the proposed methodology can be applied for obtaining availability and maintainability; including optimum selection, bench marking, and sensitivity analysis of SPP. Tang [16] proposed a new method based on the combination of graph theory and Boolean function for assessing reliability of mechanical systems. Graph theory was used for modeling system level reliability and Boolean analysis for interactions. The combination of graph theory and Boolean function bring into being an effective way to evaluate the reliability of a large, complex mechanical system. Garg et al. [5] developed a graph theoretical model to compare various technical and economical features of wind, hydro and thermal power plants.

Performance analysis of coal based steam power plant boiler was carried out by Mohan et al. [3] using graph theory and step-by-step methodology for the evaluation was also proposed. Further graph theory was applied to calculate real-time efficiency index (RTEI) defined as the ratio of the values of variable permanent system structure function (VPF) in real-time (RT) situation to its achievable design value [4] and in this connection graph theory was used to recommend the an appropriate maintenance strategy for power plants [6].

The reliability and availability of a CCPP depend on the perfect operation of all its systems (e.g., gas turbine, heat recovery steam generator, steam turbine and cooling system) [17]. So far researchers evaluated combined cycle power plant system reliability only at system level without making an allowance for the interactions of systems, and subsystems. Therefore, there is a need for extending the compass of reliability analysis for combined cycle power plants by taking care of interaction among different systems and subsystems.

A number of approaches and methodologies developed by researchers are available in the literature to model the various systems and their elements. Graph theory is one of such methodologies. It synthesizes the inter-relationship among different parameters and systems to evaluate score for the entire system. Because of its inherent simplicity, graph theory and matrix method have wide range of applications in engineering, science and in numerous other areas [22]. Several examples of its use have appeared in the literature [2–6,21–24] to model the various systems.

This paper presents a mathematical model using graph theoretic systems approach that enables the prediction of CCPP reliability in terms of an index by taking into account various systems and interactions between them.

2. System structure graph of a combined cycle power plant

System structure development is imperative for understanding and analysis of its performance [25] and a combined cycle power plant is no exception. System structure is of two types: abstract and physical. Abstract structure involves performance contributing events and their interrelations or interdependencies. The physical structure of a system implies subsystems, assemblies, components and their interconnections. A CCPP is a combination of a Compressed Natural Gas (CNG) fired gas turbine with Heat Recovery Steam Generator (HRSG) and a steam powered turbine. These plants are very large, typically rated in the hundreds of mega-watts. Combined cycle power plant considered for the present analysis is shown in Fig. 1.