PERFORMANCE MODELING OF POWER GENERATION SYSTEM OF A THERMAL PLANT

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Abstract The present paper discusses the development of a performance model of power generation system of a thermal plant for performance evaluation using Markov technique and probabilistic approach. The study covers two areas: development of a predictive model and evaluation of performance with the help of developed model. The present system of thermal plant under study consists of four subsystems with three possible states: full working, reduced capacity working and failed. Failure and repair rates for all the subsystems are assumed to be constant. A transition diagram represents the operational behavior of the system. A probabilistic model has been developed, considering some assumptions. Data in feasible range are selected from a survey of thermal plant and the effect of each subsystem on the system availability is tabulated in the form of availability matrix, which provides various performance/availability levels for different combinations of failure and repair rates of all subsystems. On the basis of this study, performance of power generation system is evaluated.

Keywords Markov Technique, Probabilistic Approach, Operational Behavior and Availability Matrix

چکیده مقاله حاضر توسعه مدل عملکرد یک سیستم تولید برق در یک نیروگاه حرارتی را برای ارزیابی عملکرد آن با استفاده از روش مارکوف و روش احتمالاتی مورد بحث قرار می‌دهد. این مطالعه دو زمینه را پوشش می دهد: توسعه یک مدل پیش بینی کننده و ارزیابی عملکرد به کمک مدل توسعه یافته. سیستم نیروگاه حرارتی مورد مطالعه شامل چهار زیر مجموعه با سه حالت ممکن است : کاملا در حال کار ، کار با ظرفیت کاهش یافته و متوقف است. طول مدت مرمت و زمانی که سیتم از مدار خارج باشد برای تمام زیر مجموعه‌ها به صورت ثابت فرض شده است. نمودار انتقال نشان دهنده رفتار عملیاتی سیستم می باشد. مدل احتمالاتی با توجه به برخی از مفروضات توسعه داده شده است. داده ها در محدوده امکان پذیر با توجه به بررسی صورت گرفته از نیروگاه حرارتی انتخاب شده و اثر هر زیر مجموعه بر روی دسترسی به سیستم به فرم ماتریس دسترسی فهرست شده است، که سطوح مختلف عملکرد / دسترسی برای ترکیب های مختلف ازنرخ شکست و تعمیر تمام زیر مجموعه‌ها را فراهم می کند. بر اساس این مطالعه، عملکرد سیستم تولید برق ارزیابی شده است.

1. INTRODUCTION

Managing industry in 21st century is a challenging task. Last few decades can be earmarked for the all round industrial development. Continuous improvement in the area of technology, productivity, maintenance standards and quality has resulted in a cut throat competition in the industries. Today, industries are striving to achieve improvement in efficiency in all the fronts (including production and maintenance) to have more competitive edge over other similar industries. Therefore, each equipment or operation in organization is critically examined to enhance the productivity/profitability. Improvement in product quality and productivity can be achieved by switching over to advanced technology and by increasing the equipment availability and reliability. However, if machine reliability and availability is increased, then production can be increased and then the nice prospects of finding new customers for the more products can be made, the price of manufacturing will be reduced and thus profitability will be increased. To ensure higher productivity and more consistent quality product; the efficiency of the production equipment must be maintained at the optimum level. A major challenge to process industries in this highly competitive global market is to produce high quality products with less energy and resources consumed. Due to economic globalization, industry is facing severe competition from foreign competitors. To success in this environment, the industries must significantly improve the productivity, quality, maintenance standards and minimize the scrap, during production.

The reliability prediction of engineering systems is becoming increasingly important because of factors such as cost, risk of hazard, competition, public demand and usage of new technology. High reliability level is desirable to reduce overall costs of production and risk of hazards for larger, more complex and sophisticated systems such as thermal power plant. Groote [1] concluded that maintenance plays a key role in an organization's long-term profitability and has increasingly become a part of a total performance approach, together with other topics such as productivity, quality, safety and environment. This has been reflected in the desire of organizations to improve maintenance performance. The maintenance of repairable systems has been widely studied by many authors, considering different focus of interest, such as the repair/replacement policy, periodic inspections, degrading, optimization problems, among other topics [2]. Gupta et al. [3] stated that it is necessary to maintain the thermal power plant to provide reliable and uninterrupted electrical supply for long time. In order to obtain regular and economical generation of electrical power, plant should be maintained at sufficiently high availability level corresponding to minimum overall cost. Barabady and Kumar [4] concluded that from an economic point of view, high reliability is desirable to reduce the maintenance costs of systems. Kumar et al. [5] stated that the rate of failure of the components/subsystems in the system depends upon the operating conditions and repair policies used. Since failure cannot be prevented entirely, it is important to minimize both its probability of occurrence and the impact of failures when they do occur. To maintain the designed reliability, availability and maintainability characteristics and to achieve expected performance, an effective maintenance program is a must and the effective maintenance is characterized by low maintenance cost [6]. A simplified steady state model was developed for the Riyadh sewage treatment plant by Al-Mozini et al. [7]. Khazaei et al. [8] presented some of the results of the modeling and simulation of an industrial furnace under the conventional combustion and the results were obtained using a computer program written FORTRAN language.

A lot of study was done by various authors for availability/decision support modeling and performance evaluation of some complex systems, eg. Gupta, et al [9 and 10] and Khanduja et al. [11 to 13]. Bhardwaj, et al [14] estimated the reliability of a fully connected network of some unreliable nodes and unreliable connections (edges) between them using the approach of Neuro optimization. Maintenance performance is generally hard to measure, as one should not only consider quantifiable parameters but also the quality of the performed maintenance and its organization [15-17]. The paper by Rabbani, et al [18] consists of development of a new state space stochastic model to make decision on the maintenance of a mechanical component subject to condition monitoring. Lim and Chang [19] studied a repairable system modeled by a Markov chain with two repair modes. A text of general interest for studying reliability systems and performance measures is that of Høyland and Rausand [20]. Performance modeling has a very important role in the power generation system of a thermal power plant. Performance modeling is an activity in which the performance of a system is characterized by a set of performance parameters whose quantitative values are used for evaluating the system's availability. An example of a performance evaluation effort is described in a case study by Clark and Estes [21] with a conclusion that data driven analysis leads to better solutions for performance improvement. The study described a computer hardware manufacturing company that was experiencing a decrease in productivity and an increase in assembly mistakes/damaged goods.

1.1. Architecture of the Paper

- The section 2 presents and discusses the configuration and nomenclature of power generation system for developing the transition diagram.
- Section 3 describes the development of a performance model, which is mathematical.
- Section 4 describes the performance evaluation made in this study.
- Section 5 and 6 describes the results and conclusions respectively of the study.

2. POWER GENERATION SYSTEM

A thermal power plant is a complex engineering system comprising of various systems: flue gas and air, coal handling, steam generation, cooling water, steam and water, coal crushing, ash handling, power generation and feed water system. These systems are connected in complex configuration [22]. Amongst the several systems power generation system constitutes most essential part of a thermal power plant. Power generation system, with whatever may be the operational intentions, i.e. continuous or intermittent, are expected to furnish excellent performance. The high performance of such power generation system can be achieved with highly reliable power plant and perfect maintenance [23].

2.1. Configuration of System The performance of the system depends on the configuration and performance of its subsystems. A typical system consists of subsystems connected to each other either in series or in parallel or in combination of both. The Power generation systems comprise the four subsystems with following description:

1. Subsystem Fi (i=1, 2): This subsystem consists of generator cooling unit and seal oil unit, failure of any unit reduces the capacity of plant and loss in production.
2. Subsystem F2: This subsystem consists of turbine lubrication unit, failure of which reduces the capacity of plant and loss in production.
3. Subsystem Fj (j=1, 2): This subsystem consists of condensate evacuation unit and regenerative unit. Failure of any unit reduces the capacity of plant and loss in production.
4. Subsystem F4: This subsystem consists of turbine governing unit, arranged in series with other subsystems. Failure of this subsystem causes the complete failure of the system.

2.2. Assumptions

The following assumptions [24] are made during the development of probabilistic availability model:

1. There are no simultaneous failures among system. However, simultaneous failures may occur among various subsystems in a system.
2. A repaired system is as good as new, performance wise, for a specified duration.
3. Service includes repair and/or replacement.
4. System failure/repair follows the exponential distribution.
5. Standby subsystems are of the same nature and capacity as that of active subsystems.
6. At any given time, the system is either in operating state or in the failed state.
7. Failure/repair rates are constant over time and statistically independent.
8. Sufficient repair facilities are available, as and when required.
9. System may work at a reduced capacity.

3. PERFORMANCE MODELING

The probabilistic model for the system under study has been developed on the basis of an actual study conducted in a coal based thermal power plant (Unit no. 5) located in Panipat (North India). The plant is well equipped with eight individual units with total installed capacity of 1360 MW (4*110MW+2*210MW+2*250MW).

Modeling starts with preparation of a transition diagram, which is helpful in analyzing the availability/performance of a repairable system. The transition diagram is logical representation of all possible states' probabilities encountered during the failure analysis and describes the flow of states of the power generation system. With the help of transition diagram (Figure 1), the differential equations are generated using Markov approach (as discussed in section 3.1) and then using normalizing conditions steady state availability model for power generation system of thermal power plant is formulated. The failure and repair rates of the different subsystems are used as standard input information to the developed availability model. Formulation is carried out using the joint probability functions based on the transition diagram [25].

3.1. Modeling Approach According to Markov if $P_0(t)$ represent the probability of zero occurrences in time t, then the probability of zero occurrences in time (t + Δt) is given by equation (eq.) 1; i.e.

$$P_0(t+\Delta t) = (1-\lambda t).P_0(t) \tag{1}$$

Similarly

$$P_1(t+\Delta t) = (\phi.\Delta t).P_0(t) + (1-\lambda.\Delta t).P_1(t) \tag{2}$$

The Equation 2 depicts the probability of one occurrence in time (t + Δt) and is composed of two parts, namely, (a) probability of zero occurrences in time t multiplied by the probability of one occurrence in the interval Δt and (b) the probability of one occurrence in time t multiplied by the probability of no occurrences in the interval Δt, as stated by Srinath [26]. Then simplifying and putting $\Delta t \rightarrow 0$, one gets

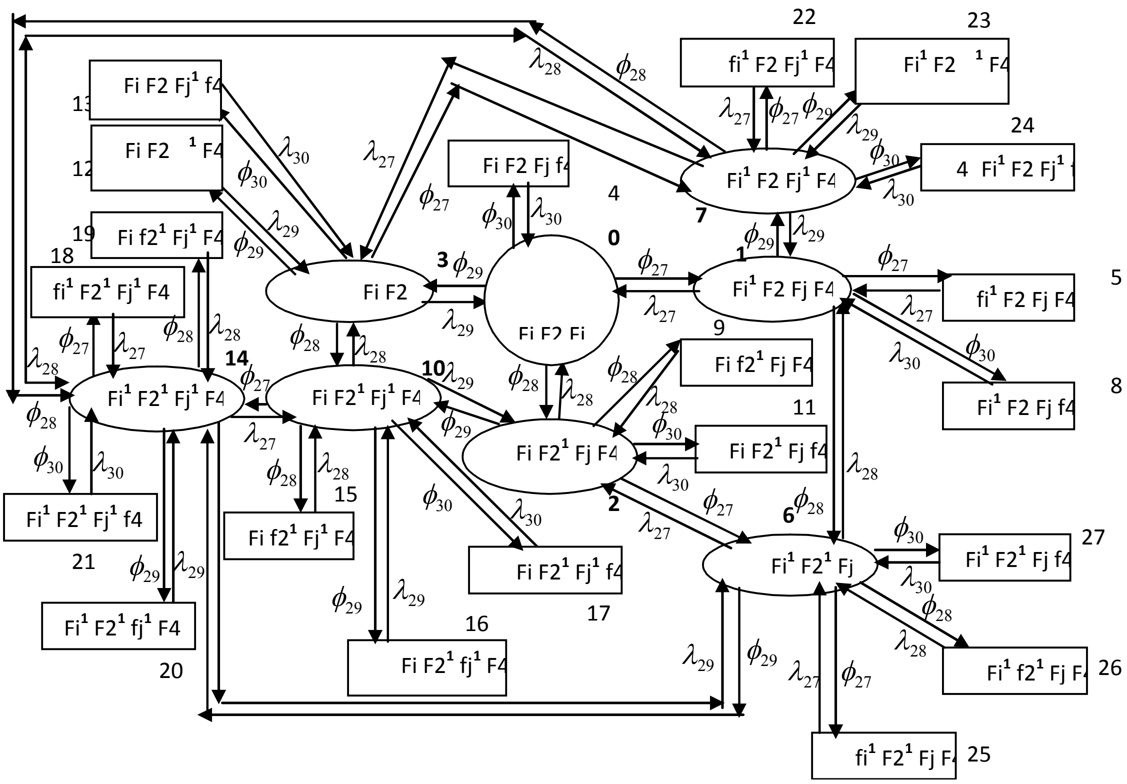

Figure 1. Transition diagram of power generation system.

$$P'(t)+\phi.P_1(t)=\lambda.P_0(t) \quad (3)$$

The transition diagram of Power generation system is shown in Figure 1, which consists of following 28 possible states.

State 0: Full capacity working without standby unit.

State 1-3, 6,7,10 and 14: Full capacity working with standby unit.

State 4,5,8,9, 11-13, 15-27 shows that system is in failed state due to complete failure of one or the other unit of the system.

Using the concept used in equation 3 and various probability considerations, the following differential equations associated with the transition diagram of power generation system are formed [27].

$$P_0'(t)+\sum_{i=27}^{30}\phi_i P_0(t)=\sum_{i=27}^{30}\lambda_i P_{i-26}(t) \quad (4)$$

$$P_1'(t)+\sum_{i=27}^{30}(\phi_i+\lambda_{27})P_1(t)= \sum_{i=27}^{30}\lambda_i P_{i-22}(t)+\phi_{27}P_0(t) \quad (5)$$

$$P_2'(t)+\sum_{i=27}^{30}(\phi_i+\lambda_{28})P_2(t)= \sum_{i=28}^{30}\lambda_i P_{i-19}(t)+\phi_{28}P_0(t)+\lambda_{27}P_6(t) \quad (6)$$

$$P_3'(t)+\sum_{i=27}^{30}(\phi_i+\lambda_{29})P_3(t)= \sum_{i=29}^{30}\lambda_i P_{i-17}(t)+\phi_{29}P_0(t)+\lambda_{27}P_7(t)+\lambda_{28}P_{10}(t) \quad (7)$$

$$P_6'(t)+\sum_{i=27}^{30}(\phi_i+\lambda_{27}+\lambda_{28})P_6(t)= \sum_{i=27}^{28}\lambda_i P_{i-2}(t)+\phi_{28}P_1(t)+\phi_{27}P_2(t)+\lambda_{29}P_{14}(t)+\lambda_{30}P_{27}(t) \quad (8)$$

$$P_7'(t)+\sum_{i=27}^{30}(\phi_i+\lambda_{27}+\lambda_{29})P_7(t)= \sum_{i=29}^{30}\lambda_i P_{i-6}(t)+\phi_{27}P_3(t)+\phi_{29}P_1(t)+\lambda_{28}P_{14}(t)+\lambda_{27}P_{22}(t) \quad (9)$$

$$P_{10}'(t)+\sum_{i=27}^{30}(\phi_i+\lambda_{29}+\lambda_{28})P_{10}(t)= \sum_{i=27}^{30}\lambda_i P_{i-13}(t)+\phi_{28}P_3(t)+\phi_{29}P_2(t) \quad (10)$$

$$P_{14}'(t)+\sum_{i=27}^{30}(\phi_i+\lambda_{27}+\lambda_{28}+\lambda_{29})P_{14}(t)= \sum_{i=27}^{30}\lambda_i P_{i-9}(t)+\phi_{27}P_{10}(t)+\phi_{28}P_7(t)+\phi_{29}P_6(t) \quad (11)$$

$$P_i'(t)+\lambda_m P_i(t)=\phi_m P_j(t) \quad (12)$$

Where as in Equation 12, when

$m=27, then\ \mathrm{i}=5, \mathrm{j}=1; \mathrm{i}=18,$
$\mathrm{j}=14, \mathrm{i}=22, \mathrm{j}=7; \mathrm{i}=25, \mathrm{j}=6$

$m=28, then\ \mathrm{i}=9, \mathrm{j}=2; \mathrm{i}=15, \mathrm{j}=10;$
$\mathrm{i}=19, \mathrm{j}=14; \mathrm{i}=26, \mathrm{j}=6$

$m=29, then\ \mathrm{i}=12, \mathrm{j}=3; \mathrm{i}=16, \mathrm{j}=10,$
$\mathrm{i}=20, \mathrm{j}=14; \mathrm{i}=23, \mathrm{j}=7$

$m=30, then\ \mathrm{i}=4, \mathrm{j}=0; \mathrm{i}=8, \mathrm{j}=1, \mathrm{i}=11,$
$\mathrm{j}=2; \mathrm{i}=13, \mathrm{j}=3; \mathrm{i}=17, \mathrm{j}=10, \mathrm{i}=21,$
$\mathrm{j}=14; \mathrm{i}=24, \mathrm{j}=7; \mathrm{i}=27, \mathrm{j}=6;$

Since any thermal plant is a process industry, where raw material is processed through various subsystems continuously, till the final product is obtained. Thus, putting derivatives of all probabilities equal to zero, gives the long run availability of the power generation system of a thermal plant [28]. Solving these equations recursively, the following are the values of all state probabilities in terms of full working state probability i.e. P_0.

$P_1=C_{37}P_0$
$P_2=C_{39}P_0$
$P_3=C_{38}P_0$
$P_4=\frac{\phi_4}{\lambda_4}P_0$
$P_5=\frac{\phi_1}{\lambda_1}P_1$

$P_6 = C_{40}P_0$

$P_7 = C_{42}P_0$

$P_8 = \frac{\phi_4}{\lambda_4} P_1$

$P_9 = \frac{\phi_2}{\lambda_2} .P_2$

$P_{10} = C_{43}P_0$

$P_{11} = \frac{\phi_4}{\lambda_4} P_2$

$P_{12} = \frac{\phi_3}{\lambda_3} P_3$

$P_{13} = \frac{\phi_4}{\lambda_4} P_3$

$P_{14} = C_{41}P_0$

$P_{15} = \frac{\phi_2}{\lambda_2} P_{10}$

$P_{16} = \frac{\phi_3}{\lambda_3} P_{10}$

$P_{17} = \frac{\phi_4}{\lambda_4} P_{10}$

$P_{18} = \frac{\phi_1}{\lambda_1} P_{14}$

$P_{19} = \frac{\phi_2}{\lambda_2} P_{14}$

$P_{20} = \frac{\phi_3}{\lambda_3} P_{14}$

$P_{21} = \frac{\phi_4}{\lambda_4} P_{14}$

$P_{22} = \frac{\phi_1}{\lambda_1} P_7$

$P_{23} = \frac{\phi_3}{\lambda_3} P_7$

$P_{24} = \frac{\phi_4}{\lambda_4} P_7$

$P_{25} = \frac{\phi_1}{\lambda_1} P_6$

$P_{26} = \frac{\phi_2}{\lambda_2} P_6$

$P_{27} = \frac{\phi_4}{\lambda_4} P_6$

where C_{37} to C_{43} are constant values.

3.2. Normalizing Condition The probability of full working capacity, without standby units (P_0) is determined by using normalizing condition [28]: (i.e. Sum of the probabilities of all full working, reduced capacity working and failed states is equal to 1).

i.e $\sum_{i=0}^{27} P_i = 1$, therefore

$$P_0 = \frac{1}{\left[\begin{array}{l} (1+\frac{\phi_4}{\lambda_4}).(1+C_{37}+C_{38}+C_{39}+C_{40}+C_{41}+C_{42}+C_{43}) \\ +\frac{\phi_1}{\lambda_1}\left(C_{37}+C_{40}+C_{41}+C_{42}\right) \\ +\frac{\phi_2}{\lambda_2}\left(C_{39}+C_{40}+C_{41}+C_{43}\right)+ \\ \frac{\phi_3}{\lambda_3}\left(C_{38}+C_{40}+C_{41}+C_{42}+C_{43}\right) \end{array} \right]}$$

3.3. Steady State Availability The steady state availability of power generation system may be obtained as summation of all full working and reduced capacity working states probabilities [29].

Hence

$$A_V = P_0 + P_1 + P_2 + P_3 + P_6 + P_7 + P_{10} + P_{14}$$

or

$$Av. = P_0\left(1 + C_{37} + C_{38} + C_{39} + C_{40} + C_{41} + C_{42} + C_{43}\right) \quad (13)$$

Therefore, Equation 13 represents the predictive model of the power generation system.

4. PERFORMANCE EVALUATION OF POWER GENERATION SYSTEM

Performance evaluation forms the foundation for all other performance improvement activities (e.g. solution design and development, implementation, and evaluation) [30]. Companies are interested in monitoring and assessing the performance of production and maintenance techniques/standards of their organization. Poor systems' performance means low availability, which causes low productivity and hence a loss to the industry. The performance measures generally adopted in a manufacturing system are; (i) Manufacturing lead time (ii) Work in process (iii) Machine Utilization (iv) Through put (v) Capacity (vi) Flexibility (vii) Quality (viii) Performability. The availability and maintenance effectiveness assessment, work as basis of evaluation of maintenance performance. The developed availability model is used to predict the availability/performance of power generation system of thermal power plant for known input values of failure and repair rates of its subsystems. The performance of the system is mainly affected by the failure and repair rates of its subsystem. For the computation purpose, the appropriate values of states of nature (failure rates) and courses of action (repair rates) are taken after a long stay, deep study and long discussions with highly skilled and experienced plant personnel. During stay, continuous monitoring of failure/repair patterns, consultation of maintenance log sheets and history cards and recording of maintenance strategies in different situations are made. Then availability matrix (availability values) is prepared for each subsystem of power generation system of thermal power plant, by putting these failures and repair rates values in expression for the availability model (A_v.) as given in Equation 13. The developed availability model forms the foundation for all other performance improvement activities (e.g. solution design and development, implementation and analysis). These unit parameters ensure the high availability/performance of the all subsystems of various systems.

4.1. Significance of Availability Matrix Tables 1 represent the availability matrix for various subsystems of power generation system of thermal power plant. This matrix simply reveals the various availability levels for different combinations of corresponding failure and repair rates/priorities. On the basis of evaluation made, the best possible combinations (ϕ, λ) for each system may be selected. The availability values in availability matrix further help in identifying the subsystems which ensures the maximum availability of the system. The optimum vales of failure/repair rates of each subsystem of concerned system can easily be taken from availability matrix.

5. RESULTS AND DISCUSSION

The performance of Power generation system is analyzed with the developed availability model. On the basis of availability values, as given in Table 1, the following observations are made, which reveals the effect of failure and repair rates of various subsystems on the availability of Power generation system.

- The effect of failure and repair rates of generator cooling and seal oil subsystem (Fi) on the availability of Power generation system is shown in Table 1. It is observed that for some known constant values of failure / repair rates of other three subsystems (F2, Fj, and F4), as failure rate of subsystem Fi (ϕ_{27}) increases from 0.0005 (five failures in 10000 hrs) to 0.00082 (82 failures in 100000 hrs), the availability decreases slightly (0.02 %). Similarly as repair rate of subsystem Fi (λ_{27}) increases from 0.01 (once in 100 hrs) to 0.02 (once in 50 hrs), the availability increases slightly (0.04 %).
- The effect of failure and repair rates of turbine lubrication subsystem (F2) on the availability of Power generation system is also depicted in Table 1. It is evident that for some known constant values of failure / repair rates of other three subsystems (Fi, Fj and F4), as failure rate of subsystem F2 (ϕ_{28}) increases from 0.006 (06 failures in 1000 hrs) to 0.008 (08 failures in 1000 hrs), the availability decreases slightly (0.09 %), but shows decreasing trend. Similarly as repair rate of subsystem F2 (λ_{28}) increases from 0.068 (68 times in 1000 hrs) to 0.1 (once in 10 hrs), the availability increases slightly (0.75 %), but shows increasing trend.
- The effect of failure and repair rates of condensate evacuation and regenerative subsystem (Fj) on the availability of Power generation system is depicted in Table 1. It is clear that for some known constant values of failure/repair rates of other three subsystems (Fi, F2 and F4), as failure rate of subsystem Fj (ϕ_{29}) increases from 0.0008 (08 failures in 10000 hrs) to 0.001 (once in 1000 hrs), the availability shows decreasing

TABLE 1. Availability Matrix of Various Subsystems of Power Generation System.

Subsystem Fi

λ_{27} / ϕ_{27}	0.0100	0.0125	0.0150	0.0175	0.0200	Constant values
0.00050	0.978834	0.979044	0.979155	0.979217	0.979250	
0.00058	0.978767	0.978985	0.979096	0.979154	0.979181	$\phi_{28} = 0.007, \lambda_{28} = 0.084$
0.00066	0.978715	0.978939	0.979049	0.979102	0.979123	$\phi_{29} = 0.0009, \lambda_{29} = 0.0075$
0.00074	0.978679	0.978907	0.979014	0.979061	0.979075	$\phi_{30} = 0.00112, \lambda_{30} = 0.0075$
0.00082	0.978658	0.978890	0.978992	0.979032	0.979037	

Subsystem F2

λ_{28} / ϕ_{28}	0.068	0.076	0.084	0.092	0.100	Constant Values
0.0060	0.977326	0.980125	0.982199	0.983747	0.984898	
0.0065	0.975189	0.978315	0.980648	0.982408	0.983738	$\phi_{27} = 0.00066, \lambda_{27} = 0.015$
0.0070	0.972996	0.976453	0.979049	0.981023	0.982533	$\phi_{29} = 0.0009, \lambda_{29} = 0.0075$
0.0075	0.970749	0.974543	0.977405	0.979597	0.981287	$\phi_{30} = 0.00112, \lambda_{30} = 0.0075$
0.0080	0.968450	0.972586	0.975719	0.978130	0.980003	

Subsystem Fj

λ_{29} / ϕ_{29}	0.00500	0.00625	0.00750	0.00875	0.01000	Constant Values
0.00080	0.979310	0.979339	0.979356	0.979368	0.979376	
0.00085	0.979150	0.979183	0.979203	0.979217	0.979226	$\phi_{27} = 0.00066, \lambda_{27} = 0.015$
0.00090	0.978988	0.979025	0.979049	0.979065	0.979076	$\phi_{28} = 0.007, \lambda_{28} = 0.084$
0.00095	0.978825	0.978867	0.978894	0.978911	0.978924	$\phi_{30} = 0.00112, \lambda_{30} = 0.0075$
0.00100	0.978661	0.978707	0.978737	0.978758	0.978772	

Subsystem F4

λ_{30} / ϕ_{30}	0.00500	0.00625	0.00750	0.00875	0.01000	Constant Values
0.00100	0.974671	0.978124	0.980440	0.982100	0.983350	
0.00106	0.973640	0.977293	0.979744	0.981502	0.982825	$\phi_{27} = 0.00066, \lambda_{27} = 0.015$
0.00112	0.972611	0.976463	0.979049	0.980904	0.982300	$\phi_{28} = 0.007, \lambda_{28} = 0.084$
0.00118	0.971584	0.975635	0.978355	0.980307	0.981776	$\phi_{29} = 0.0009, \lambda_{29} = 0.0075$
0.00124	0.970559	0.974809	0.977662	0.97971	0.981253	

trend (decreased by 0.07 %). Similarly as repair rate of subsystem Fj (λ_{29}) increases from 0.005 (once in 200 hrs) to 0.01 (once in 100 hrs), the availability shows increasing trend.

- The effect of failure and repair rates of turbine governing subsystem (F4) on the availability of Power generation system is shown in Table 1. It is observed that for some known constant values of failure / repair rates of other three subsystems (Fi, F2 and Fj), as failure rate of subsystem F4 (ϕ_{30}) increases from 0.00100 (100 failures in 100000 hrs) to 0.00124 (124 failures in 100000 hrs), the availability decreases by about 0.41 %. Similarly as repair rate of subsystem F4 (λ_{30}) increases from 0.005 (once in 200 hrs) to 0.01 (once in 100 hrs), the availability increases by about 1 %.

6. CONCLUSION

Performance model is successfully developed for making performance evaluation/analysis of power generation system of thermal power plant under study. The model analyzed and presented here provides a useful tool in making maintenance planning and decisions. The system availability has been excellent, mainly because of the low failure rates, supported by the state of the art repair facilities. It can thus be concluded that this model provides the various availability levels for different combinations of failure and repair rates for every subsystem of power generation system. It is evident from Tables 1, that as failure rate of various subsystems of power generation system increases, the availability decreases and as repair rate increases, the availability goes on increasing. One may select the best possible combination of failure events and repair priorities for each subsystem. The developed model helps in determining the optimal maintenance strategies, which will ensure the maximum overall availability of power generation system. Such results are found highly beneficial to the plant management for making futuristic maintenance decisions.

7. NOTATIONS AND NOMENCLATURE

The symbols and notations used in the present paper are as follows:

Indicate the subsystems in full capacity working state.

Indicate the subsystems in reduced capacity working state.

Indicate the subsystems in failed state.

Fi, F2, Fj, F4:	Denotes the full capacity working states of subsystems Fi, F2, Fj, F4 respectively.
$Fi^1, F2^1, Fj^1$:	Denotes that the subsystem Fi, F2 and Fj are working with reduced capacity.
fi, f2, fj, f4:	Denotes the failed states of subsystems Fi, F2, Fj, F4 respectively.
P_0 (t):	Indicate the probability that at time 't' the subsystems are working in full capacity.
$P_i(t)$	i=1-3, 6,7,10 and 14 : Indicate the probabilities that at time 't', the subsystems are working in reduced capacity.
$P_i(t)$	i=4,5,8,9, 11-13, 15-27 : Indicate the probabilities that at time 't' the subsystems are in failed states.
ϕ_i and λ_i,	i=27-30: Indicate the mean failure rates and repair rates of subsystems Fi, F2, Fj, F4 respectively.
$P'(t)$:	Indicate the derivative w.r.t. time (t).
Av.:	Steady state availability of the system

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