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REDUNDANT SYSTEMS SHUTDOWN DURING LOW CAPACITY OPERATION

Two possible operation modes of various pumps with redundancy in electric power generating units during low load periods (night) were analyzed. The first mode – two of three pumps work at night with 25% of nominal capacity, the third pump is a cold (passive) reserve. The second mode – one pump works at night with 50% of nominal capacity, two pumps are in cold reserve. A Markov reward model was built for the comparison analysis of these possible operation modes. The model takes into account all important factors – pumps power consumption, pumps failure rate, pumps starting availability, cost of alternative energy, and penalty cost of energy not supplied. It was shown that under current operation conditions the second operation mode is more effective one.

Keywords: *Auxiliary System, Markov Reward Model, Redundancy, Cold and Hot Reserve, Mean Accumulated Reward*

1. Introduction

Auxiliary systems such as condensing pumps, booster pumps etc are important equipment in primary coal firing generating unit. In present time the operation mode 1 for pumps is used at night during low load period: two of three pumps work at night with 25% of nominal capacity, the third pump is used as passive reserve. In order to decrease electric power consumption the following operation mode 2 was suggested: one pump works at night with 50% of nominal capacity, two pumps are used as passive reserve. The electric power consumption P_2 by the single pump in the suggested mode 2 is about 66% of the consumption in mode 1. So, the main advantage of mode 2 is the electric power consumption decreasing during low load period. On other hand the using of mode 2 leads to increasing of risk of power generation disturbances because of passive redundant pump may fail to start. The start of reserve pump when working pump failed is provided by control system. If reserve pump failed to start, then the generating power unit will be shut down after short time in order to prevent vacuum breaking. A comparison analysis in order to choice the best operation mode should be based on the measure $V = V^{(1)} - V^{(2)}$, where $V^{(1)}$, $V^{(2)}$ - expected annual cost for operation mode 1 and mode 2 respectively. In order to solve this problem a corresponding Markov reward model was suggested.

2. Description of system model

The method is based on the Markov reward model [Hillier and Lieberman, 1995]. This model considers the continuous-time Markov chain with a set of states $\{1, \ldots, K\}$ and transition intensity matrix $\boldsymbol{a} = |a_{ij}|$, $i, j = 1,\ldots,K$. It is suggested that if the process stays in any state i during the time unit, a certain cost r_{ii} should be paid. Each time that the process transits from state i to state j a cost r_{ij} should be paid. These costs r_{ii} and r_{ij} are called rewards (the reward may also be negative when it characterizes losses or penalties). For such processes, an additional matrix $r = | r_{ij} |$, $i, j = 1,\ldots,K$ of rewards is determined. The value that is of interest is the total expected reward accumulated up to time instant t under specified initial conditions. Let $V_i(t)$ be the total expected reward accumulated up to time t, given the initial state of the process at time instant $t = 0$ is state i. The following system of differential equations must be solved under specified initial conditions in order to find the total expected rewards:

$$\frac{dV_i(t)}{dt} = r_{ii} + \sum_{\substack{j=1 \\ j\neq i}}^{K} a_{ij} r_{ij} + \sum_{j=1}^{K} a_{ij} V_j(t) \quad i = 1,\ldots,K. \quad (1)$$

Usually the system (1) should be solved under initial conditions $V_i(0) = 0$, $i = 1,\ldots,K$.

State-space diagrams for the auxiliary system that operates using mode 1 and mode 2 are presented in fig. 1. At first we consider the operating mode 1. A state-space diagram for this mode is presented in fig. 1A.

In state 1 two pumps are working at night with capacity 25% from their nominal capacity and third pump is used as cold reserve. If the system will stay in state 1 during 1 day, the operation cost will be such as follows: $r_{11} = P_1 C_e T_N$, where r_{11} – operation cost during one day in the state

1; P_1 – electrical power consuming by pumps in the state 1, when each of two pumps works with capacity 25%; C_e – consumer's electrical energy price; T_N = 5 hours – low load period (night) during one day. If one of two pumps working in the state 1 will fail, the system will transit from state 1 to state 2 with intensity rate 2λ, where λ is a failure rate of one pump. In the state 2 one of reserve pump begins to work and begins a repair of failed pump. We designate by r_{22} the operation cost in state 2. Obviously, $r_{11} = r_{22}$. If a repair of failed pump will be completed before it will be a failure in working pump, the system will come back to state 1 with intensity μ. If an additional failure occurs before than failed pump will be repaired, the system will transit to the state 3 on diagram fig. 1A with transition intensity 2λ. In the state 3 only one pump works with capacity 50% of its nominal capacity and two pumps are under repair. If the system will stay in the state 3 during 1 day, the operation cost will be such as follows: $r_{33} = P_2 C_e T_N$, where r_{33} – operation cost during time unit in the state number 3; P_2 – electric power consumption by pump in the state 3, when only one pump works with capacity 50%. In the state 3 two repair teams are working in order to repair both two failed pumps. If repair of one pump will be completed before it will be a failure in the single working pump, than the system will come back to state 2 with intensity rate 2μ. If the single working pump fails before repair will be completed, than the system transits from state 3 to state 4 with transition rate λ. The system will be in the state 4 up to trip that prevents a vacuum breaking. In case of vacuum breaking the generating unit is switched off and a gas turbine starts up. Mean time T_L up to trip is about 30 min. for condensing pumps and about 8 min for booster pumps. Hence, with intensity $\lambda_L = 1/T_L$ the system will transit from the state 4 to critical state 5. We designate the cost of energy not supplied to consumers that associated with transition from state 4 to state 5 as r_{45}. This cost will be the following: $r_{45} = P_{unit} C_p T_{st}$, where P_{unit} - generating unit capacity at night (during low load period; C_p - penalty cost for energy not supplied; T_{st} - time duration of gas-turbines start. In state 5 gas-turbines begin to work and a cost of alternative energy during the time-unit that auxiliary system is in the state 5 can be obtained: $r_{55} = P_{unit} C_{gas}$, where C_{gas} is the cost of alternative energy. In the state 5 the system will be up to the time instant, when a repair of one of the pumps will be completed. In that instant of time the system transits from the state 5 to the state 3. The intensity of this transition is 3μ.

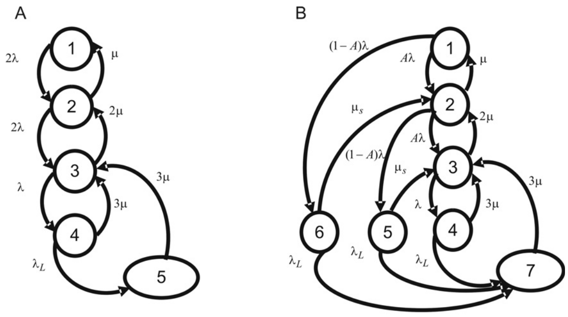

Fig. 1. State space diagram for auxiliary system operating in mode 1 (A) and in mode 2 (B).

Hence, the operating mode 1 the system of differential equation (1) can be written in the following form:

$$\begin{cases} \dfrac{dV_1(t)}{dt} = r_{11} - 2\lambda V_1(t) + 2\lambda V_2(t) \\ \dfrac{dV_2(t)}{dt} = r_{22} + \mu V_1(t) - (2\lambda + \mu) V_2(t) + 2\lambda V_3(t) \\ \dfrac{dV_3(t)}{dt} = r_{33} + 2\mu V_2(t) - (\lambda + 2\mu) V_3(t) + \lambda V_4(t) \\ \dfrac{dV_4(t)}{dt} = r_{45}\lambda_L + 3\mu V_3(t) - (\lambda_L + 3\mu) V_4(t) + \lambda_L V_5(t) \\ \dfrac{dV_5(t)}{dt} = r_{55} + 3\mu V_3(t) - 3\mu V_5(t) \end{cases} \tag{2}$$

This system should be solved under the following initial conditions:

$V_1(0)=V_2(0)=\ldots=V_5(0)=0.$

The expected annual cost for operation mode 1 can be obtained such as $V^{(1)} = V_1(t)$, $t = 1$ year.

In order to calculate $V^{(2)}$ the Markov reward model for operation mode 2 should be built by the same way. The state space diagram for auxiliary system using operation mode 2 is presented in fig. 1B. The main difference with the previous case is the following. If it will be the failure in the working pump, one of reserve pumps will start by control system. If a control system is available, than reserve pump will start and begins to work instead of failed pump. The system transits to state 2 with intensity rate $A\lambda$, where A - control system availability. If a control system is not available, than the system transits from state 1 to state 6 or in state 5 from state 2 with intensity rate $(1 - A)\lambda$. In states 5 and 6 operator begins to execute manually control operations in order to start a reserve pump. Mean time for manual pump starting is estimated as $T_s = 90$ sec. and therefore, transitions intensity from state 6 to state 2 and from state 5 to state 3 is $\mu = 1/T_s$. Hence, the following system of differential equations for finding the expected costs $V_i(t)$, $i=1, \ldots, 7$ for operation mode 2 can be written (3), where $r_{11} = P_2 C_e T_N$, P_2 – electrical power consuming by pumps in state 1, when only one pump works with capacity 50%. For booster and condensing pumps one has: $P_2 = 0.66\, P_1$.

$r_{33} = r_{22} = r_{11}$; $r_{47} = r_{57} = r_{67} = P_{unit} C_p T_{st}$; $r_{77} = P_{unit}\, G_{gas}$.

$$\begin{cases} \frac{dV_1(t)}{dt} = r_{11} - 2\lambda V_1(t) + A\lambda V_2(t) + (1-A)\lambda V_6(t) \\ \frac{dV_2(t)}{dt} = r_{22} + \mu V_1(t) - (2\lambda + \mu)V_2(t) + A\lambda V_3(t) + (1-A)\lambda V_5(t) \\ \frac{dV_3(t)}{dt} = r_{33} + 2\mu V_2(t) - (\lambda + 2\mu)V_3(t) + \lambda V_4(t) \\ \frac{dV_4(t)}{dt} = r_{45}\lambda_L + 3\mu V_3(t) - (\lambda_L + 3\mu)V_4(t) + \lambda_L V_7(t) \\ \frac{dV_5(t)}{dt} = r_{57}\lambda_L + \mu_s V_3(t) - (\lambda_L + \mu_s)V_5(t) + \lambda_L V_7(t) \\ \frac{dV_6(t)}{dt} = r_{67}\lambda_L + \mu_s V_2(t) - (\lambda_L + \mu_s)V_6(t) + \lambda_L V_7(t) \\ \frac{dV_7(t)}{dt} = r_{77} + 3\mu V_3(t) - 3\mu V_3(t) - 3\mu V_7(t) \end{cases} \quad (3)$$

As in the previous case the system (3) should be solved under the initial conditions: $V_1(0) = V_2(0) = \ldots = V_7(0) = 0$. The expected annual cost for operation mode 2 can be obtained such as $V^{(2)} = V_1(t)$, $t = 1$ year. According to current data $A \geq 0.99$, $\lambda = 1.4$ f/y the difference V between expected annual cost for operation mode 1 and mode 2 is estimated as $V \geq 9000$ \$ per for condensing pumps (for unit with nominal generating capacity 360 MWT) and $V \geq 4000$ \$ for booster pumps.

3. Conclusions

Operation mode 2 will be preferable and the income from its using instead of mode 1 in power unit with generating capacity 360 MWT will be at least 9000 USA $ per year for condensing pumps and 4000 $ for booster pumps.

4. References

[1] Hillier, F. and G. Lieberman (1995). *Operations Research*. NY, San-Francisco: McGraw-Hill.

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