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Reliability Estimation of a Hybrid Geothermal Conventional Power Plant by Using Algebra of Logics

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Abstract

In this paper, the authors have considered a hybrid geothermal conventional power plant for its reliability estimation by using algebra of logics. Algebra of logics and Boolean function technique has been used to formulate and solve the mathematical model of geothermal power plant. Reliability and M.T.T.F. of the power plant have been computed in two different cases, as (i) when failures follow Weibull time distribution and (ii) when failures follow exponential time distribution. Graphical illustration of a numerical computation has also mentioned in the end to highlight important results of the study.

Keywords: Algebra of logics, Reliability estimation, Boolean function technique etc.

INTRODUCTION

This plant produces electric energy from geothermal energy. Geothermal energy is a proven resource for direct heat and power generation. The block-diagram of hybrid geothermal power plant has shown in fig-1. This power plant consists of six subsystems, connected in series. The first subsystem is geothermal fluid container and it contains the hot Braine at $100^{\cdot}C$ as geothermal fluid. The second subsystem is heat exchanger and it contains two identical units in parallel redundancy. The third subsystem is a coumbustor boiler, which produces the steam to rotate turbine. This subsystem contains two identical units in standby redundancy. On failure of main boiler, we can switch on the standby unit in to operation through an imperfect switching device. The fourth subsystem is a turbine, which produces electric energy. The fifth subsystem is an electric network and it is used to store the electric energy produced by the rotating turbine. The sixth subsystem is a controlling value and it controls the supply of electric energy to consumers. The sixth subsystem contains two identical units in parallel redundancy.

ASSUMPTIONS

The following assumptions have taken care throughout this study:

(i) Reliability of every subsystem of geothermal power plant is known in advance.

(ii) Supply between any two subsystems is hundred percent reliable.

(iii) There is no repair facility.

(iv) Failures are s-independent.

(v) Switching device used to online standby combustor boiler is imperfect.

(vi) Initially, the whole system is operable with its full efficiency.

NOTATIONS

The list of notations used in the study, is as follow:

x_1	:	State of geothermal fluid container.
x_2, x_3	:	States of heat exchangers.
x_4, x_6	:	States of combuster boilers.
x_5	:	State of switching device.
x_7	:	State of turbine.
x_8	:	State of electric network.
x_9, x_{10}	:	States of controlling valves.
x_i'	:	Negation of $x_i, \forall$ i .
x_i	:	$i = \begin{cases} 1, \ in \ \ good \ \ state \\ 0, \ in \ \ bad \ \ state, \ \forall \ i \end{cases}$.
$\wedge / \vee$	:	Conjunction/ Disjunction.
R_S	:	Reliability of whole system.
$R_{SE}(t)$	:	Reliability function for whole system, in case, failures follows exponential time distribution.
$R_{SW}(t)$	:	Reliability function for whole system, in case, failures follows weibull time distribution.

FORMULATION OF MATHEMATICAL MODEL

By using Boolean function technique, the conditions of capability of the successful operation of the considered power plant in terms of logical matrix are expressed as under:

$$F(x_1, x_2 - -x_{10}) = \begin{bmatrix} x_1 & x_2 & x_4 & x_7 & x_8 & x_9 & \\ x_1 & x_2 & x_5 & x_6 & x_7 & x_8 & x_9 \\ x_1 & x_2 & x_4 & x_7 & x_8 & x_{10} & \\ x_1 & x_2 & x_5 & x_6 & x_7 & x_8 & x_{10} \\ x_1 & x_3 & x_4 & x_7 & x_8 & x_9 & \\ x_1 & x_3 & x_5 & x_6 & x_7 & x_8 & x_9 \\ x_1 & x_3 & x_4 & x_7 & x_8 & x_{10} & \\ x_1 & x_3 & x_5 & x_6 & x_7 & x_8 & x_{10} \end{bmatrix} \qquad \ldots(1)$$

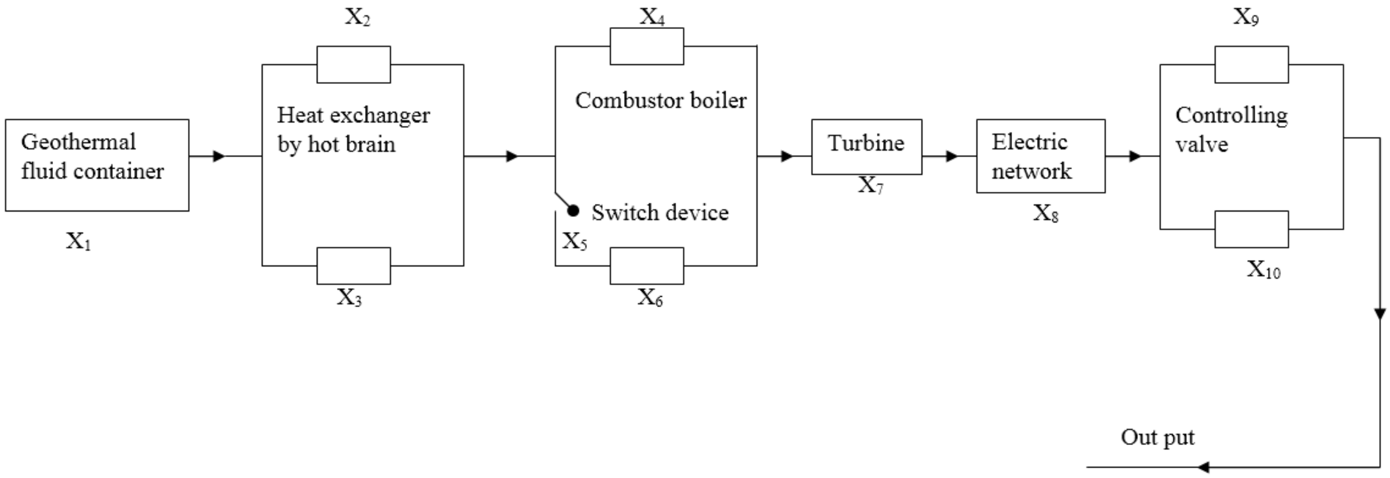

Figure 1: Block-diagram of geothermal power plant

SOLUTION OF THE MODEL

Using algebra of logic, we may write equation (1) as below:

$$F(x_1, x_2 - -x_{10}) = [x_1\ x_7\ x_8 \wedge \ f\,(x_2, x_3, x_4, x_5, x_6, x_9, x_{10})] \qquad \ldots.(2)$$

where,

$$f\,(x_2, x_3, x_4, x_5, x_6, x_9, x_{10}) = \begin{bmatrix} x_2 & x_4 & x_9 & \\ x_2 & x_5 & x_6 & x_9 \\ x_2 & x_4 & x_{10} & \\ x_2 & x_5 & x_6 & x_{10} \\ x_3 & x_4 & x_9 & \\ x_3 & x_5 & x_6 & x_9 \\ x_3 & x_4 & x_{10} & \\ x_3 & x_5 & x_6 & x_{10} \end{bmatrix} = \begin{bmatrix} P_1 \\ P_2 \\ P_3 \\ P_4 \\ P_5 \\ P_6 \\ P_7 \\ P_8 \end{bmatrix} (say) \qquad \ldots.(3)$$

where, $P_1 = [x_2 \quad x_4 \quad x_9]$ etc.

Using orthogonalisation algorithm, equation (3) can be written as:

$$f\left(x_2, x_3, x_4, x_5, x_6, x_9, x_{10}\right) = \begin{bmatrix} P_1 & & & & & & & \\ P_1' & P_2 & & & & & & \\ P_1' & P_2' & P_3 & & & & & \\ P_1' & P_2' & P_3' & P_4 & & & & \\ P_1' & P_2' & P_3' & P_4' & P_5 & & & \\ P_1' & P_2' & P_3' & P_4' & P_5' & P_6 & & \\ P_1' & P_2' & P_3' & P_4' & P_5' & P_6' & P_7 & \\ P_1' & P_2' & P_3' & P_4' & P_5' & P_6' & P_7' & P_8 \end{bmatrix} \quad \ldots(4)$$

Now, we have

$$P_1 = \left[x_2 \quad x_4 \quad x_9\right] \quad \ldots (5)$$

$$\therefore P_1' = \begin{bmatrix} x_2' & & \\ x_2 & x_4' & \\ x_2 & x_4 & x_9' \end{bmatrix}$$

$$\therefore P_1' P_2 = \begin{bmatrix} x_2' & & \\ x_2 & x_4' & \\ x_2 & x_4 & x_9' \end{bmatrix} \wedge \left[x_2 \quad x_5 \quad x_6 \quad x_9\right]$$

$$= \left[x_2 \quad x_4' \quad x_5 \quad x_6 \quad x_9\right] \quad \ldots(6)$$

Similarly,

$$P_1' \; P_2' \; P_3 = \begin{bmatrix} x_2 & x_4 & x_5' & x_9' & x_{10} & \\ x_2 & x_4 & x_5 & x_6' & x_9' & x_{10} \\ x_2 & x_4 & x_5 & x_6 & x_9' & x_{10} \end{bmatrix} \quad \ldots (7)$$

$$P_1' P_2' P_3' P_4 = \left[x_2 \quad x_4' \quad x_5 \quad x_6 \quad x_9' \quad x_{10}\right] \quad \ldots (8)$$

$$P_1' P_2' P_3' P_4' P_5 = \left[x_2' \quad x_3 \quad x_4 \quad x_9\right] \quad \ldots (9)$$

$$P_1' P_2' P_3' P_4' P_5' P_6 = \left[x_2' \quad x_3 \quad x_4' \quad x_5 \quad x_6 \quad x_9\right] \quad \ldots(10)$$

$$P_1' P_2' P_3' P_4' P_5' P_6' P_7 = \begin{bmatrix} x_2' & x_3 & x_4 & x_5' & x_9' & x_{10} & \\ x_2' & x_3 & x_4 & x_5 & x_6' & x_9' & x_{10} \\ x_2' & x_3 & x_4 & x_5 & x_6 & x_9' & x_{10} \end{bmatrix} \quad \ldots(11)$$

and

$$P_1' P_2' P_3' P_4' P_5' P_6' P_7' P_8 = \left[x_2' \quad x_3 \quad x_4' \quad x_5 \quad x_6 \quad x_9' \quad x_{10}\right] \quad \ldots(12)$$

By using expressions (5) through (12), equation (4) becomes:

$$f\left(x_2, x_3, x_4, x_5, x_6, x_9, x_{10}\right) = \begin{bmatrix} x_2 & x_4 & x_9 & & & & \\ x_2 & x_4' & x_5 & x_6 & x_9 & & \\ x_2 & x_4 & x_5' & x_9' & x_{10} & & \\ x_2 & x_4 & x_5 & x_6' & x_9' & x_{10} & \\ x_2 & x_4 & x_5 & x_6 & x_9' & x_{10} & \\ x_2 & x_4' & x_5 & x_6 & x_9' & x_{10} & \\ x_2' & x_3 & x_4 & x_9 & & & \\ x_2' & x_3 & x_4' & x_5 & x_6 & x_9 & \\ x_2' & x_3 & x_4 & x_5' & x_9' & x_{10} & \\ x_2' & x_3 & x_4 & x_5 & x_6' & x_9' & x_{10} \\ x_2' & x_3 & x_4 & x_5 & x_6 & x_9' & x_{10} \\ x_2' & x_3 & x_4' & x_5 & x_6 & x_9' & x_{10} \end{bmatrix} \quad \ldots(13)$$

Using this equation (13), equation (2) may be written as:

$$F\left(x_1, x_2 --, x_{10}\right) = \begin{bmatrix} x_1 & x_2 & x_4 & x_7 & x_8 & x_9 & & & & \\ x_1 & x_2 & x_4' & x_5 & x_6 & x_7 & x_8 & x_9 & & \\ x_1 & x_2 & x_4 & x_5' & x_7 & x_8 & x_9' & x_{10} & & \\ x_1 & x_2 & x_4 & x_5 & x_6' & x_7 & x_8 & x_9' & x_{10} & \\ x_1 & x_2 & x_4 & x_5 & x_6 & x_7 & x_8 & x_9' & x_{10} & \\ x_1 & x_2 & x_4' & x_5 & x_6 & x_7 & x_8 & x_9' & x_{10} & \\ x_1 & x_2' & x_3 & x_4 & x_7 & x_8 & x_9 & & & \\ x_1 & x_2' & x_3 & x_4' & x_5 & x_6 & x_7 & x_8 & x_9 & \\ x_1 & x_2' & x_3 & x_4 & x_5' & x_7 & x_8 & x_9' & x_{10} & \\ x_1 & x_2' & x_3 & x_4 & x_5 & x_6' & x_7 & x_8 & x_9' & x_{10} \\ x_1 & x_2' & x_3 & x_4 & x_5 & x_6 & x_7 & x_8 & x_9' & x_{10} \\ x_1 & x_2' & x_3 & x_4' & x_5 & x_6 & x_7 & x_8 & x_9' & x_{10} \end{bmatrix} \quad \ldots(14)$$

Since, R.H.S. of equation (14) is disjunction of pair-wise disjoint conjunctions, therefore, the reliability of power plant as a whole, is given by the following expression:

$$R_S = P_r\left\{F\left(x_2, x_2 --, x_{10}\right) = 1\right\}$$

$$= R_1 R_7 R_8 \left[R_2 R_4 R_9 + S_4 R_2 R_5 R_6 R_9 + S_5 S_9 R_2 R_4 R_{10} + S_6 S_9 R_2 R_4 R_5 R_{10} + S_9 R_2 R_4 R_5 R_6 R_{10}\right.$$

$$+ S_4 S_9 R_2 R_5 R_6 R_{10} + S_2 R_3 R_4 R_9 + S_2 S_4 R_3 R_5 R_6 R_9 + S_2 S_5 S_9 R_3 R_4 R_{10}$$

$$\left. + S_2 S_6 S_9 R_3 R_4 R_5 R_{10} + S_2 S_9 R_3 R_4 R_5 R_6 R_{10} + S_2 S_4 S_9 R_3 R_5 R_6 R_{10}\right]$$

where, $S_i = 1 - R_i, \forall i$ and R_i is the reliability of the i^{th} unit corresponding to state x_i.

Or,

$$R_S = R_1R_7R_8\big[R_2R_4R_9 + R_2R_5R_6R_9 + R_3R_4R_9 + R_2R_4R_{10} + R_2R_5R_6R_{10} + R_2R_4R_5R_6R_9R_{10} + R_3R_5R_6R_9 + R_2R_3R_4R_5R_6R_9 + R_3R_4R_{10} + R_2R_3R_4R_9R_{10} + R_3R_5R_6R_{10} + R_2R_3R_4R_5R_6R_{10} + R_3R_4R_5R_6R_9R_{10} + R_2R_3R_5R_6R_9R_{10} - R_2R_3R_4R_9 - R_2R_4R_5R_6R_9 - R_2R_4R_9R_{10} - R_2R_4R_5R_6R_{10} - R_2R_5R_6R_9R_{10} - R_2R_3R_5R_6R_9 - R_3R_4R_5R_6R_9 - R_2R_3R_4R_{10} - R_3R_4R_9R_{10} - R_2R_3R_5R_6R_{10} - R_3R_4R_5R_6R_{10} - R_3R_5R_6R_9R_{10} - R_2R_3R_4R_5R_6R_9R_{10}\big] \quad \text{....(15)}$$

SOME PARTICULAR CASES

CASE I: When the reliability of every unit of power plant is R

In this case, substituting $R_i(i = 1,2,--10) = R$ in equation (15), we get:

$$R_S = 4R^6 - 7R^8 + 5R^9 - R^{10} \quad \text{...(16)}$$

CASE II: When failure rates follow weibull time distribution

In this case, let $\lambda_i(i = 1,2,--,10) = \lambda$ be the failure rate of every unit of power plant, then, reliability of whole power plant at an instant 't', is given by:

$$R_{SW}(t) = 4\exp.\{-6\lambda t^\alpha\} - 7\exp.\{-8\lambda t^\alpha\} + 5\exp.\{-9\lambda t^\alpha\} - \exp.\{-10\lambda t^\alpha\} \quad \text{...(17)}$$

where, α is a positive parameter.

Also, mean time to failure of power plant in this case, is given by:

$$M.T.T.F.(w) = \frac{1}{\alpha}\Gamma\left(\frac{1}{\alpha}\right)\left[\frac{4}{(6\lambda)^{1/\alpha}} - \frac{7}{(8\lambda)^{1/\alpha}} + \frac{5}{(9\lambda)^{1/\alpha}} - \frac{1}{(10\lambda)^{1/\alpha}}\right] \quad \text{...(18)}$$

CASE III: When failure rates follow exponential distribution

Exponential time distribution is a particular case of weibull distribution for $\alpha = 1$. This distribution is very useful in various practical problems. Therefore, in this case, we can obtain the expressions for system's reliability and M.T.T.F. by putting $\alpha = 1$ in equations (17) and (18), respectively. So that

$$R_{SE}(t) = 4\exp.\{-6\lambda t\} - 7\exp.\{-8\lambda t\} + 5\exp.\{-9\lambda t\} - \exp.\{-10\lambda t\} \quad \text{...(19)}$$

and

$$M.T.T.F.(E) = \frac{1}{\lambda}\left(\frac{4}{6} - \frac{7}{8} + \frac{5}{9} - \frac{1}{10}\right)$$

$$= \frac{0.24722}{\lambda} \quad \text{...(20)}$$

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NUMERICAL COMPUTATION

For a numerical computation, let us consider the values:

(a) $\lambda = 0.002, \alpha = 2$ and $t = 0,1,2 --$ in equation (17);

(b) $\alpha = 2,$ and $\lambda = 0.04,\ 0.09,\ 0.16 ------$ in equation (18);

(c) $\lambda = 0.002$ and $t = 0,1,2 --$ in equation (19); and

(d) $\lambda = 0.04,\ 0.09,\ 0.16$ --- in equation (20).

By using these values, one can compute the table-1 and 2. Table-1 gives the reliability of the power plant as a whole for different values of time and for both the distributions. Table-2 gives the M.T.T.F. to the power plant for different values of failure rate λ. The corresponding graphs have been given through fig-2 and 3, respectively.

RESULTS AND DISUSSION

In this study, the author has tried to evaluate some reliability parameters of a hybrid geothermal conventional power plant. The author has been used algebra of logic and Boolean function technique to goal his aim. This technique avoids the tedious and time consuming calculations. The author has been used parallel and standby redundancies to obtain better results. The reliability and M.T.T.F. of the system have computed in two different cases, (i) when failures follow weibull time distribution and (ii) when failures follow exponential time distribution. A graphical illustration of considered numerical computation has also appended in last to highlight the important results of the study. As a concluding remark, we say that exponential time distribution gives better results as compared with the weibull time distribution.

Table-1

t	$R_{SW}(t)$	$R_{SE}(t)$
0	1	1
1	0.994002	0.994002
2	0.976038	0.988009
3	0.946232	0.982021
4	0.904893	0.976038
5	0.852643	0.970062
6	0.790543	0.964093
7	0.720176	0.958131
8	0.643655	0.952177
9	0.563541	0.946232
10	0.482660	0.940296

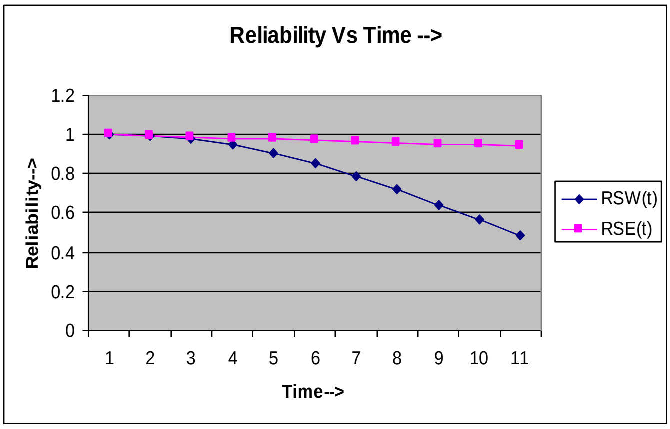

Figure 2.

Table-2

λ	M.T.T.F.(w)	M.T.T.F.(E)
0	∞	∞
0.04	3.99425	6.1805
0.09	2.662833	2.746889
0.16	1.997125	1.545125
0.25	1.597700	0.988880
0.36	1.331417	0.686722
0.49	1.141214	0.504531
0.64	0.998563	0.386281
0.81	0.887611	0.305210
1.00	0.79885	0.247220

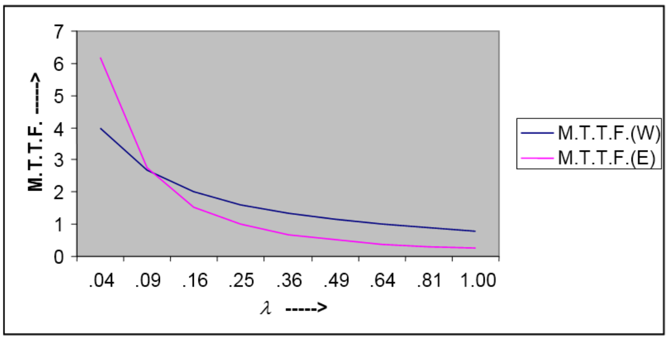

Figure 3

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