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Evaluation of Reliability of a Power Plant with the Aid of Boolean Function Expansion Algorithm

[1]D. Sarada Devi, [2]R. Bhuvana Vijaya and [1]A. Mallikarjuna Reddy

[1]Department of Mathematics, S.K. University, Anantapur, India
[2]Department of Mathematics, JNTUA College of Engg., Anantapur, India

Abstract

In this paper, investigation has been carried out for the evaluation of reliability behaviour of a power plant with the aid of Boolean function expansion algorithm. The complex system under consideration consists of four power generators in a power house. The object of the system is to supply power from a power house generated by generators to critical consumers fed from an output main switch and consequently, the reliability of the supply has been calculated by considering that failure times for various components i.e., cables, generators and main switch boards etc follow arbitrary distribution.

Introduction

Nowadays, reliability is far from an abstract concept and it ranks on the same level as the performance of an equipment. Moreover, evaluation of reliability is a basic requirement for all reliability studies. However, it is an open secret that reliability evaluation becomes more complicated when complexities increase in a system. Therefore, the derivation of a symbolic reliability expression in a simplified and compact form for a complex system is of the utmost importance.

The problem of ensuring the reliability of engineering systems is extremely complex and extends to all the stages of the service life of a system. Today, there exists a large number of problems which in designing marine power plants, for example, are still solved only on the basis of logical reasoning and experience and not with the aid of reliability calculations.

Keeping the above facts in view, we, therefore, consider a complex system consisting of four generators connected in parallel. The generators G_1,G_2,G_3 & G_4 are connected with two way main switches MSB_1,MSB_2,MSB_3 and MSB_4 respectively by perfectly reliable cables. A cable C_5 connects MSB_1, MSB_2, a cable C_6 connects

MSB_2, MSB_3 and a cable C_7 connects MSB_3, MSB_4. Further, cables C_1, C_2, C_3 & C_4 connect the two way main switch MSB_1 to output main two way switch MSB_2 to output main switch $OPMS_5$, two way switch MSB_3 to output main switch $OPMS_5$ and two way switch MSB_4 to output main switch $OPMS_5$ respectively. Thus, the complex system under consideration is nothing but a power plant. The object of the system is to supply power generated by G_1, G_2, G_3 & G_4 to critical consumers and consequently the reliability of the power supply fed from $OPMS_5$ has been estimated with the aid of Boolean Function Expansion Algorithm by considering that failure times for various components of the system follow arbitrary time distribution.

Assumptions

1. The reliabilities of all constituent components of the system are known in advance.
2. The state of all components is statistically independent.
3. The state of each component and of the whole system is either good (operating) or bad (failed).
4. There is no standby or switched redundancy.
5. The failure times for all the components are arbitrary.
6. There is no repair facility.
7. The system can fail i.e. The supply of power can fail only if

i. All the four generators fail.

ii. At least one component (switch or cable) in the routes of the power supply fails.

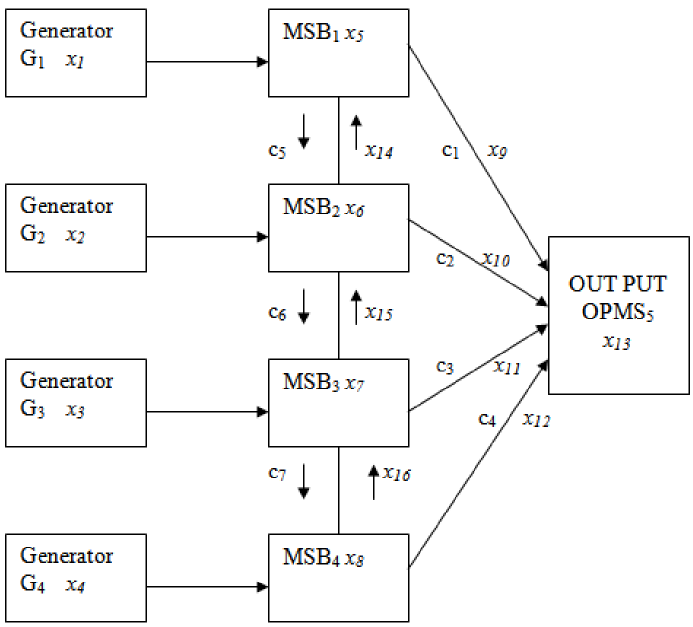


Figure 1: System Configuration.

Notations

x_1, x_2, x_3, x_4	States of generators G_1, G_2, G_3 & G_4
x_5, x_6, x_7, x_8	States of MSB_1, MSB_2, MSB_3 & MSB_4
$x_9, x_{10}, x_{11}, x_{12}, x_{14}, x_{15}, x_{16}$	States of the cables $C_1, C_2, C_3, C_4, C_5, C_6$ & C_7
x_{13}	State of $OPMS_4$
x_k'	Negation of x_k (k=1-16)
$\wedge$	Conjunction
$\vee$	Disjunction
x_i	$\begin{cases} 0 \text{ in bad state} \\ 1 \text{ in good state (i=1-16)} \end{cases}$
Pr (f=1)	The probability of the successful operation of the function f.

Formulation of Mathematical Model

By using Boolean Function Technique, the conditions of capability for the successful operation of the complex system in terms of logical matrix are expressed as

$$f(x_1 x_2 \ldots\ldots\ldots x_{16}) = \begin{vmatrix} x_1 & x_5 & x_9 & x_{13} \\ x_1 & x_5 & x_{14} & x_6 & x_{10} & x_{13} \\ x_1 & x_5 & x_{14} & x_6 & x_{15} & x_7 & x_{11} & x_{13} \\ x_1 & x_5 & x_{14} & x_6 & x_{15} & x_7 & x_{16} & x_8 & x_{12} & x_{13} \\ x_2 & x_6 & x_{10} & x_{13} \\ x_2 & x_6 & x_{14} & x_5 & x_9 & x_{13} \\ x_2 & x_6 & x_{15} & x_7 & x_{11} & x_{13} \\ x_2 & x_6 & x_{15} & x_7 & x_{16} & x_8 & x_{12} & x_{13} \\ x_3 & x_7 & x_{11} & x_{13} \\ x_3 & x_7 & x_{15} & x_6 & x_{10} & x_{13} \\ x_3 & x_7 & x_{15} & x_6 & x_{14} & x_5 & x_9 & x_{13} \\ x_3 & x_7 & x_{16} & x_8 & x_{12} & x_{13} \\ x_4 & x_8 & x_{12} & x_{13} \\ x_4 & x_8 & x_{16} & x_7 & x_{11} & x_{13} \\ x_4 & x_8 & x_{16} & x_7 & x_{15} & x_6 & x_{10} & x_{13} \\ x_4 & x_8 & x_{16} & x_7 & x_{15} & x_6 & x_{14} & x_5 & x_9 & x_{13} \end{vmatrix} \tag{1}$$

Solution of the Model

By the application of algebra of logic equation (1) may be written as

$$f(x_1\, x_2,\ldots\ldots,x_{16}) = x_{13} \wedge g\,(x_1, x_2, x_3\ldots\ldots x_{12}, x_{14}, x_{15}, x_{16}) \tag{2}$$

where

$$g(x_1 x_2, x_3, \ldots\ldots\ldots\ldots x_{12}, x_{14}, \ldots\ldots\ldots x_{16}) =$$

$$\left|\begin{array}{lllllll}
x_1 & x_5 & x_9 & & & & \\
 & & x_6 & x_{10} & x_{14} & & \\
 & & x_6 & x_7 & x_{11} & x_{14} & x_{15} \\
 & & x_6 & x_7 & x_8 & x_{12} & x_{14} \quad x_{15} \quad x_{16} \\
x_2 & x_6 & x_{10} & & & & \\
 & & x_5 & x_9 & x_{14} & & \\
 & & x_7 & x_{11} & x_{15} & & \\
 & & x_7 & x_8 & x_{12} & x_{15} & x_{16} \\
x_3 & x_7 & x_{11} & & & & \\
 & & x_6 & x_{10} & x_{15} & & \\
 & & x_5 & x_6 & x_9 & x_{14} & x_{15} \\
 & & x_8 & x_{12} & x_{16} & & \\
x_4 & x_8 & x_{12} & & & & \\
 & & x_7 & x_{11} & x_{16} & & \\
 & & x_6 & x_7 & x_{10} & x_{15} & x_{16} \\
 & & x_5 & x_6 & x_7 & x_9 & x_{14} \quad x_{15} \quad x_{16}
\end{array}\right| \tag{3}$$

Let us take x_{15} and break the complex event into incompatible events as follows:

$$g(x_1, x_2,\ldots\ldots..x_{12}, x_{14}, x_{15}, x_{16}) = x'_{15}\, y_0 \vee x_{15}\, y_1 \tag{4}$$

where

$$y_0 = \left|\begin{array}{lllll}
x_1 & x_5 & x_9 & & \\
 & & x_6 & x_{10} & x_{14} \\
x_2 & x_6 & x_{10} & & \\
 & & x_5 & x_9 & x_{14} \\
x_3 & x_7 & x_{11} & & \\
 & & x_8 & x_{12} & x_{16} \\
x_4 & x_8 & x_{12} & & \\
 & & x_7 & x_{11} & x_{16}
\end{array}\right| \tag{5}$$

$$y_1 = \left| \begin{array}{llllllll} x_1 & x_5 & x_9 & & & & & \\ & & x_6 & x_{10} & x_{14} & & & \\ & & x_6 & x_7 & x_{11} & x_{14} & & \\ & & x_6 & x_7 & x_8 & x_{12} & x_{14} & x_{16} \\ x_2 & x_6 & x_{10} & & & & & \\ & & x_5 & x_9 & x_{14} & & & \\ & & x_7 & x_{11} & & & & \\ & & x_7 & x_8 & x_{12} & x_{16} & & \\ x_3 & x_7 & x_{11} & & & & & \\ & & x_6 & x_{10} & & & & \\ & & x_5 & x_6 & x_9 & x_{14} & & \\ & & x_8 & x_{12} & x_{16} & & & \\ x_4 & x_8 & x_{12} & & & & & \\ & & x_7 & x_{11} & x_{16} & & & \\ & & x_6 & x_7 & x_{10} & x_{16} & & \\ & & x_5 & x_6 & x_7 & x_9 & x_{14} & x_{16} \end{array} \right| \qquad (6)$$

In y_0, ten arguments, ($x_5, x_6, x_7, x_8, x_9, x_{10}, x_{11}, x_{12}, x_{14}, x_{16}$) entering into equation (5) twice, therefore, any of them may be taken to perform the expansion. Let us take x_{16} and break the complex event into incompatible events as follows.

$y_0 = x'_{16}\, y_{00} \vee x_{16}\, y_{01}$ where

$$y_{00} = \left| \begin{array}{lllll} x_1 & x_5 & x_9 & & \\ & & x_6 & x_{10} & x_{14} \\ x_2 & x_6 & x_{10} & & \\ & & x_5 & x_9 & x_{14} \\ x_3 & x_7 & x_{11} & & \\ x_8 & x_8 & x_{12} & & \end{array} \right| \qquad (7)$$

$$y_{01} = \left| \begin{array}{lllll} x_1 & x_5 & x_9 & & \\ & & x_6 & x_{10} & x_{14} \\ x_2 & x_6 & x_{10} & & \\ & & x_5 & x_9 & x_{14} \\ x_3 & x_7 & x_{11} & & \\ & & x_8 & x_{12} & \\ x_4 & x_8 & x_{12} & & \\ & & x_7 & x_{11} & \end{array} \right| \qquad (8)$$

Now, expand the function y_{00} by argument x_{14} as follows.

$y_{00} = x'_{14} y_{000} \vee x_{14} y_{001}$ where

$$y_{000} = \left| \begin{array}{lll} x_1 & x_5 & x_9 \\ x_2 & x_6 & x_{10} \\ x_3 & x_7 & x_{11} \\ x_4 & x_8 & x_{12} \end{array} \right| \tag{9}$$

$$y_{001} = \left| \begin{array}{lll} x_1 & x_5 & \left| \begin{array}{ll} x_9 & \\ x_6 & x_{10} \end{array} \right. \\ x_2 & x_6 & \left| \begin{array}{ll} x_{10} & \\ x_5 & x_9 \end{array} \right. \\ x_3 & x_7 & x_{11} \\ x_4 & x_8 & x_{12} \end{array} \right| \tag{10}$$

Since all the letters occur is equation (9) only once, it implies that y_{000} is non-iterated.

Now, expand the function y_{001} by argument x_9 (say) as follows.

$y_{001} = x'_9 y_{0010} \vee x_9 y_{0011}$ where

$$y_{0010} = \left| \begin{array}{llll} x_1 & x_5 & x_6 & x_{10} \\ x_2 & x_6 & x_{10} & \\ x_3 & x_7 & x_{11} & \\ x_4 & x_8 & x_{12} & \end{array} \right| \tag{11}$$

$$y_{0011} = \left| \begin{array}{llll} x_1 & x_5 & x_6 & x_{10} \\ x_2 & x_6 & \left| \begin{array}{l} x_{10} \\ x_5 \end{array} \right. & \\ x_3 & x_7 & x_{11} & \\ x_4 & x_8 & x_{12} & \end{array} \right| \tag{12}$$

Now expand y_{0010} by argument x_{10} (say) as follows.

$y_{0010} = x'_{10} y_{00100} \vee x_{10} y_{00101}$ where

$$y_{00100} = \left| \begin{array}{lll} x_3 & x_7 & x_{11} \\ x_4 & x_8 & x_{12} \end{array} \right| \tag{13}$$

$$y_{00101} = \begin{vmatrix} x_1 & x_5 & x_6 \\ x_2 & x_6 & \\ x_3 & x_7 & x_{11} \\ x_4 & x_8 & x_{12} \end{vmatrix} \tag{14}$$

Since all the letters occur is y_{00100} only once, it implies that y_{00100} is non-iterated.

Now, expand the function y_{00101} by the argument x_6 (say) as follows.

$y_{00101} = x_6' y_{001010} \vee x_6 y_{001011}$ where

$$y_{001010} = \begin{vmatrix} x_3 & x_7 & x_{11} \\ x_4 & x_8 & x_{12} \end{vmatrix} \tag{15}$$

$$y_{001011} = \begin{vmatrix} x_1 & x_5 & \\ x_2 & & \\ x_3 & x_7 & x_{11} \\ x_4 & x_8 & x_{12} \end{vmatrix} \tag{16}$$

Since all the letters occur in equation (15) & (16) only once, it implies that y_{001010} and y_{001011} are non-iterated.

Now, we expand the function y_{0011} by argument x_{10} (say) as follows.

$y_{0011} = x_{10}' y_{00110} \vee x_{10} y_{00111}$ where

$$y_{00110} = \begin{vmatrix} x_2 & x_6 & x_5 \\ x_3 & x_7 & x_{11} \\ x_4 & x_8 & x_{12} \end{vmatrix} \tag{17}$$

$$y_{00111} = \begin{vmatrix} x_1 & x_5 & x_6 \\ x_2 & x_6 & x_5 \\ x_3 & x_7 & x_{11} \\ x_4 & x_8 & x_{12} \end{vmatrix} \tag{18}$$

Since all the letters occur in equation (17) only once, it implies that y_{00110} is non-iterated.

Now, we expand the function y_{00111} by argument x_6 (say) as follows.

$y_{00111} = x_6' y_{001110} \vee x_6 y_{001111}$ where

$$y_{00110} = \begin{vmatrix} x_3 & x_7 & x_{11} \\ x_4 & x_8 & x_{12} \end{vmatrix} \text{ which is non-iterated} \tag{19}$$

$$y_{001111} = \begin{vmatrix} x_1 & x_5 & \\ x_2 & x_5 & \\ x_3 & x_7 & x_{11} \\ x_4 & x_8 & x_{12} \end{vmatrix} \tag{20}$$

Since all the letters occur in equation (19) only once, it implies that y_{001110} is non-iterated.

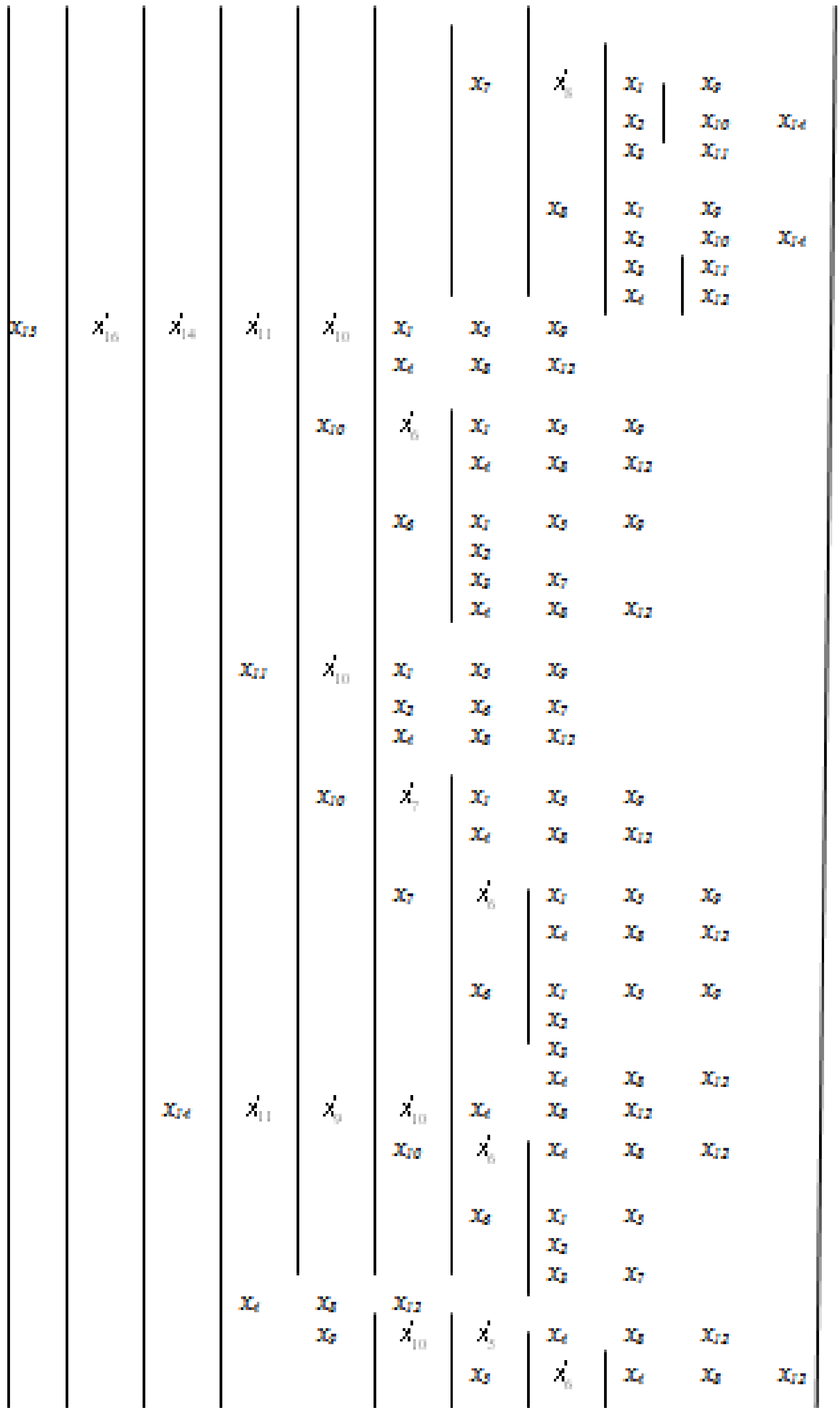
Proceeding in this way, finally it is observed that all the functions are non-iterated and also not subjected to further transformations.

So making use of equations, we get

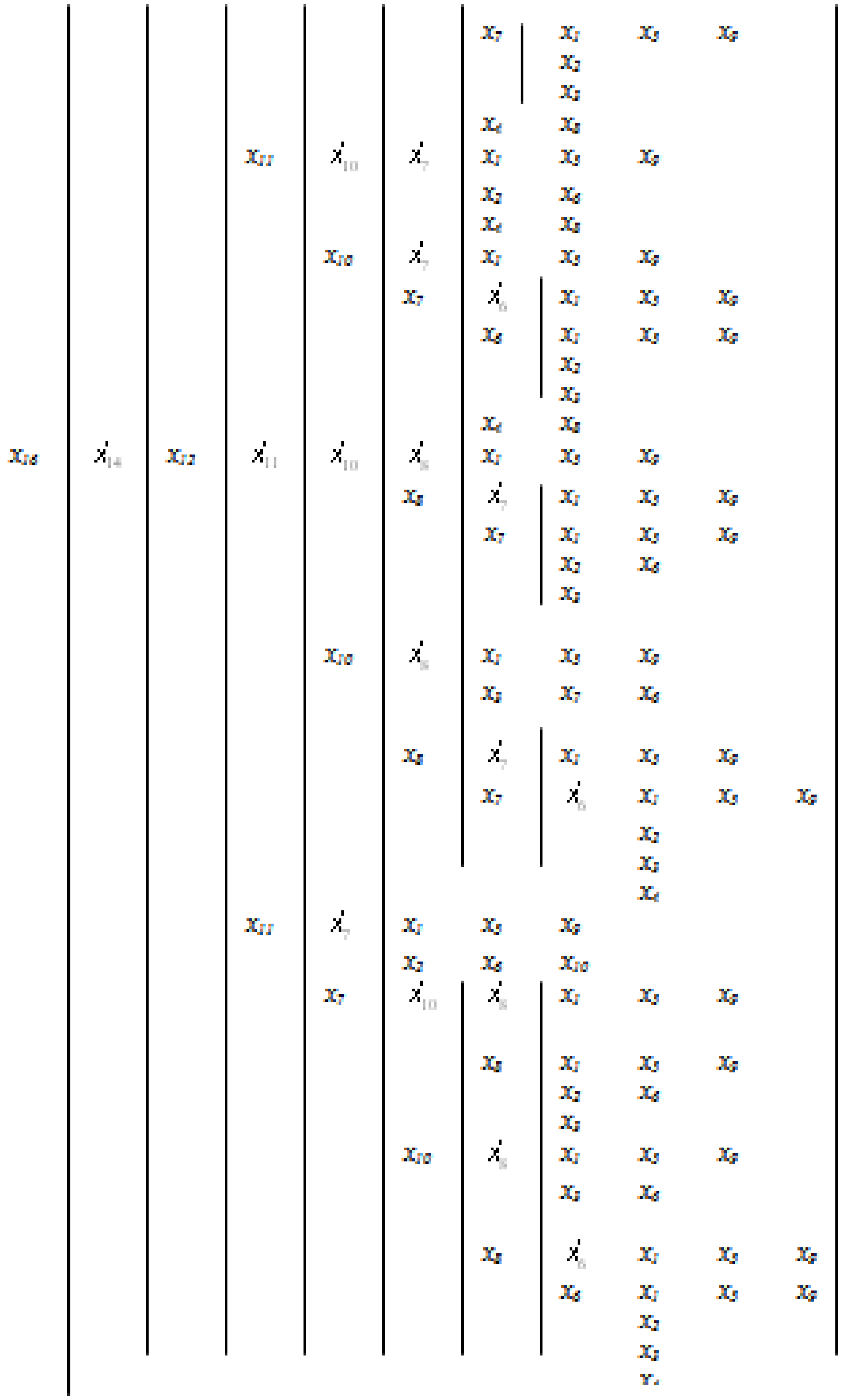
g ($x_1\ x_2 \ldots\ldots x_{12}, x_{14}, x_{15}, x_{16}$) =

$$\left|\begin{array}{l|l|l|lllllll}
x'_{15} & x'_{16} & x'_{14} & x_1 & x_5 & x_9 & & & & \\
 & & & x_2 & x_6 & x_{10} & & & & \\
 & & & x_3 & x_7 & x_{11} & & & & \\
 & & & x_4 & x_8 & x_{12} & & & & \\
 & & x_{14} & x'_9 & x'_{10} & x_3 & x_7 & x_{11} & & \\
 & & & & & x_4 & x_8 & x_{12} & & \\
 & & & & x_{10} & x'_6 & x_3 & x_7 & x_{11} & \\
 & & & & & & x_4 & x_8 & x_{12} & \\
 & & & & & x_6 & x_1 & x_5 & & \\
 & & & & & & x_2 & & & \\
 & & & & & & x_3 & x_7 & x_{11} & \\
 & & & & & & x_4 & x_8 & x_{12} & \\
 & & & x_9 & x'_{10} & x_2 & x_5 & x_6 & & \\
 & & & & & x_3 & x_7 & x_{11} & & \\
 & & & & & x_4 & x_8 & x_{11} & & \\
 & & & & x_{10} & x'_6 & x_3 & x_7 & x_{11} & \\
 & & & & & & x_4 & x_8 & x_{12} & \\
 & & & & & x_6 & x'_5 & x_3 & x_7 & x_{11} \\
 & & & & & & & x_4 & x_8 & x_{12} \\
 & & & & & & x_5 & x_1 & & \\
 & & & & & & & x_2 & & \\
 & & & & & & & x_3 & x_7 & x_{11} \\
 & & & & & & & x_4 & x_8 & x_{12}
\end{array}\right|$$

x'_{15}	x_{16}	x'_5	x'_7	x_2	x_6	x_{10}				
				x_4	x_8	x_{12}				
			x_7	x'_{11}	x'_8	x_2	x_6	x_{10}		
					x_8	x'_{12}	x_2	x_6	x_{10}	
						x_{12}	x_2	x_6	x_{10}	
							x_3			
							x_4			
				x_{11}	x'_8	x_2	x_6	x_{10}		
					x_8	x'_{12}	x_2	x_6	x_{10}	
						x_{12}	x_2	x_6	x_{10}	
							x_3			
							x_4			
		x_5	x'_6	x'_7	x_1	x_9				
					x_4	x_8	x_{12}			
				x_7	x'_8	x_1	x_9			
						x_3	x_{11}			
					x_8	x'_{11}	x'_{12}	x_1	x_9	
							x_{12}	x_1	x_9	
								x_3		
								x_4		
						x_{11}	x'_{12}	x_1	x_9	
							x_{12}	x_1	x_9	
								x_3		
								x_4		
			x_6	x'_7	x'_9	x'_{10}	x_4	x_8	x_{12}	
						x_{10}	x_4	x_{14}		
							x_2			
							x_4	x_8	x_{12}	
					x_9	x'_{14}	x_2	x_{10}		
							x_4	x_8	x_{12}	
						x_{14}	x'_{10}	x_4	x_8	x_{12}
							x_{10}	x_1		
								x_2		
								x_4	x_8	x_{12}



							x_8	x_2			
								x_3	x_7		
								x_4	x_8	x_{12}	
					x_{10}	x'_6	x_4	x_8	x_{10}		
						x_8	x'_5	x_4	x_8	x_{10}	
							x_5	x_1			
								x_2			
								x_3	x_7		
								x_4	x_8	x_{10}	
			x_{11}	x'_{10}	x'_9	x'_7	x_4	x_8	x_{12}		
						x_7	x'_6	x_4	x_8	x_{12}	
							x_8	x_1	x_5		
								x_2			
								x_4	x_8	x_{12}	
					x_9	x'_7	x_2	x_6	x_5		
							x_4	x_8	x_{12}		
						x_7	x'_6	x_2	x_6	x_5	
								x_4	x_8	x_{12}	
							x_8	x'_5	x_4	x_8	x_{12}
								x_5	x_1		
									x_2		
									x_3		
									x_4	x_8	x_{12}
				x_{10}	x'_9	x'_7	x_1	x_5	x_6		
							x_4	x_8	x_{12}		
						x_7	x'_6	x_4	x_8	x_{12}	
							x_8	x_1	x_5		
								x_2			
								x_3			
								x_4	x_8	x_{12}	
					x_9	x'_7	x'_6	x_4	x_8	x_{12}	
							x_8	x'_5	x_4	x_8	x_{12}
								x_5	x_1		
									x_2		
									x_4	x_8	x_{12}
x_{16}	x'_{14}	x'_{12}	x'_{11}	x'_{10}	x_1	x_5	x_9				
				x_{10}	x'_6	x_1	x_5	x_9			
					x_8	x'_7	x_1	x_5	x_9		
							[illegible]				



$$
\left|\begin{array}{c|c|c|c|c|cccccc}
X_{13} & X_{14} & x'_5 & x'_6 & x'_7 & X_4 & X_8 & X_{12} & & \\
 & & & & X_7 & x'_8 & X_3 & X_{11} & & \\
 & & & & & X_8 & X_3 & X_{11} & & \\
 & & & & & & X_4 & X_{12} & & \\
 & & & X_6 & x'_7 & X_2 & X_{10} & & & \\
 & & & & & X_4 & X_8 & X_{12} & & \\
 & & & & X_7 & x'_8 & X_2 & X_{10} & & \\
 & & & & & & X_3 & X_{11} & & \\
 & & & & & X_8 & X_2 & X_{10} & & \\
 & & & & & & X_3 & X_{11} & & \\
 & & & & & & X_4 & X_{12} & & \\
 & & X_5 & x'_6 & x'_{12} & x'_{11} & X_1 & X_9 & & \\
 & & & & & X_{11} & x'_7 & X_1 & X_9 & \\
 & & & & & & X_7 & X_1 & X_9 & \\
 & & & & & & & X_3 & & \\
 & & & & & & & X_4 & X_9 & \\
 & & & & X_{12} & x'_8 & X_1 & X_9 & & \\
 & & & & & & X_3 & X_7 & X_{11} & \\
 & & & & & X_8 & x'_{11} & X_1 & X_9 & \\
 & & & & & & X_{11} & x'_7 & X_1 & X_9 \\
 & & & & & & & X_7 & X_1 & X_9 \\
 & & & & & & & & X_3 & \\
 & & & & & & & & X_4 & \\
 & & & X_6 & x'_7 & X_1 & X_9 & & & \\
 & & & & & X_2 & X_{10} & & & \\
 & & & & & X_4 & X_8 & X_{12} & & \\
 & & & & X_7 & X_1 & X_9 & & & \\
 & & & & & X_2 & X_{10} & & & \\
 & & & & & X_3 & X_8 & X_{12} & &
\end{array}\right| \qquad (21)
$$

Now using Baye's formula, the probability of successful operation of the function g is given by

$$\Pr(g=1)=\sum_{i=1}^{94}\Pr(K_i)\Pr(g/K_i) \tag{22}$$

If R_i is the reliability of the component of the complex system corresponding to state x_i and Q_i is the corresponding unreliability, then from equation (22) finally, the probability of the successful operation (i.e., reliability) of the complex system is given by

$R_s = \Pr(f = 1) = \Pr(x_{13}).\Pr(g = 1)$

Particular Cases

If reliability of each component of the complex system is R, then

$R_s = 4R^4 - 12R^5 + 17R^6 - 20R^7 + 16R^8 + 10R^9 - 34R^{10} + 36R^{11} - 17R^{12} - 3R^{13} + 10R^{14} - 8R^{15} + 2R^{16}$.

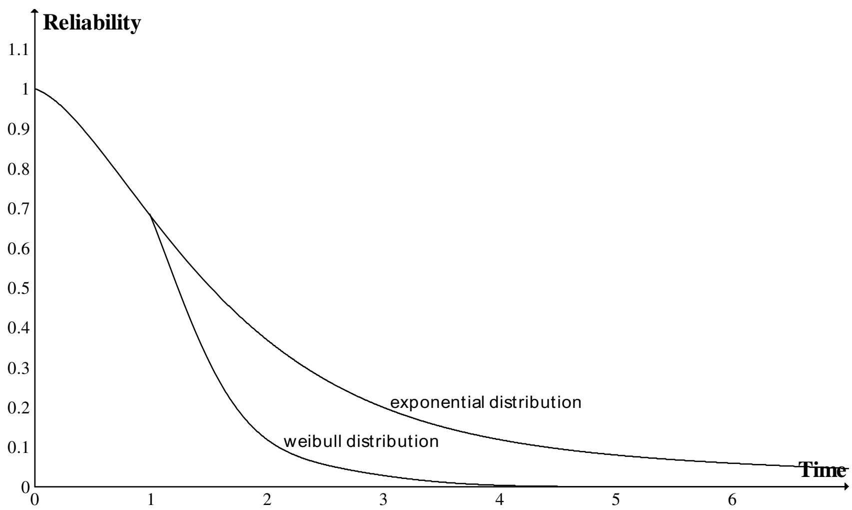
When failure rates follow Weibull distribution, let failure rate of each component of the complex system be λ, then reliability of the system at an instant t is given by

$$R_s(t) = 4e^{-4\lambda t^\alpha} - 12e^{-5\lambda t^\alpha} + 17e^{-6\lambda t^\alpha} - 20e^{-7\lambda t^\alpha} + 16e^{-8\lambda t^\alpha} + 10e^{-9\lambda t^\alpha} - 34e^{-10\lambda t^\alpha} + 36e^{-11\lambda t^\alpha} - 17e^{-12\lambda t^\alpha} - 3e^{-13\lambda t^\alpha} + 10e^{-14\lambda t^\alpha} - 8e^{-15\lambda t^\alpha} + 2e^{-16\lambda t^\alpha}$$

where α is a positive parameter.

When failure rates follow Exponential distribution, exponential distribution is a particular case of Weibull distribution for $\alpha = 1$. The reliability of the complex system in this case at an instant t is

$$R_s(t) = 4e^{-4\lambda t} - 12e^{-5\lambda t} + 17e^{-6\lambda t} - 20e^{-7\lambda t} + 16e^{-8\lambda t} + 10e^{-9\lambda t} - 34e^{-10\lambda t} + 36e^{-11\lambda t} - 17e^{-12\lambda t} - 3e^{-13\lambda t} + 10e^{-14\lambda t} - 8e^{-15\lambda t} + 2e^{-16\lambda t}$$



$\lambda = 0.1$, $\alpha = 2$.

Conclusion

This graph computes the variation of reliability with respect to time, when failure follows Exponential and Weibull distributions. A critical examination of Reliability Vs Time graph shows that the reliability of the complex system decreases approximately at a uniform rate in case of Exponential distribution, whereas it decreases very rapidly when failure follows Weibull distribution.

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