Reliability Forecast for UPS (Uninterruptible Power Supply) by Employing Boolean Truth Table Method

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This paper investigates the application of the Boolean Truth Table modeling method in estimating the reliability parameters such as the system's failure rate and Mean Time Between Failures (MTBF), for the uninterruptible Power Supply (UPS) systems. The term "uninterruptible" in the UPS implies that the system never fails. However, like any electrical system, failure will occur at some point in time. The reliability of the system is a function of the component selection, the environment of the UPS and the proper operation and maintenance of the UPS. The reliability estimation of the UPS enables the system designers, manufacturers and lastly the end-user to ensure that the UPS will be able to support the critical loads for a specified time during unforeseen circumstances. This paper proposed the Boolean Truth Table method in predicting the failure rates, (λ) and mean time between failures (MTBF), of the three types of UPS configurations.

Keywords: Boolean Truth Table modeling method, Mean Time Between Failures (MTBF), Reliability parameters, Uninterruptible Power Supply (UPS).

1. INTRODUCTION

In application such as medical equipment, air and ground traffic control systems, electrical data processing systems, telecommunication equipment and process plant instrumentation; the continuous availability of electricity is critical. An uninterruptible power supply (UPS) operates in conjunction with the utility power supply to ensure a continuous supply of electric energy to these critical loads. All possible state combinations (operating and failed states) of the major components in the UPS systems were listed and their effects on overall system were studied. The method was applied to three UPS configurations and the results obtained were such as the Reliability Block Diagram (RBD) method and field data estimation method.

There were several papers [1,2] discussing on the reliability analysis of the UPS systems. Markov chains method was used to analyze the availability and reliability performance of the UPS systems. Component redundancy, supervision systems to detect failures and common mode failure sources in the UPS system were recommended by this study to increase system reliability. The state space approach was also used for the reliability modeling and analysis of emergency and standby power systems. The models were able to compute quantitative reliability indices such as number of failures per year, downtime hours per year and the mean downtime. Above studies compare the reliability of four UPS configurations: single module, parallel redundant, static bypass, and static bypass redundant [3] based on the components failure rates. The equations for calculating the MTBF's [4] of these configurations are presented along with component reliability estimates.

Reliability indices of the major components that made up the UPS were calculated. Finally, comparisons between the UPS system can be distinguished in several ways:

(a) The reliability models [5] of the UPS systems were simple to construct as it is quite close the system single-line diagram/ layout.

(b) The truth tables are relatively easy to understand, as they do not involve any formulae.

(c) The reliability model can clearly show the interdependencies of the components in the system as they will be arranged in series or parallel between the system input and output nodes.

(d) The Boolean variables can have only two distinct values, TRUE or FALSE; which is taken as SUCCESS or FAILURE in this study.

However, there are some drawbacks in this method:

(a) The truth table for a large system can be very complex and impracticable.

(b) For the reliability analysis of UPS system application, understanding of the system operation is required to determine the state of the system (system Up/ Success or Down /Fail).

(c) The number of events are 2^n, where *n* is the number of components in the system. Thus, for system with high number of components, the truth table will be long and tedious.

2. BOOLEAN TRUTH TABLE METHOD

The Boolean truth table approach involves the following steps:

(a) Identify all the major components in the system which failure will leads to system failure (i.e. load collapsed).

(b) Construct the reliability model for the system to show how the components/ modules are connected.

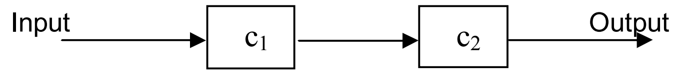
(c) Determine the probability of operation/ success, P(Success) and probability of failure, P(Fail) of the component / module from its failure rates, (λ).

(d) Identify the state of the system (i.e. system SUCCESS – means system up, or system FAIL- means system down) with respect to the states of the component (i.e. component working or component fails).

This method consists in listing all possible state combinations (operating state and failed state) for the major components in the UPS one after the other and in studying their effects. The failure modes of the components and their failed states should be identified and listed.

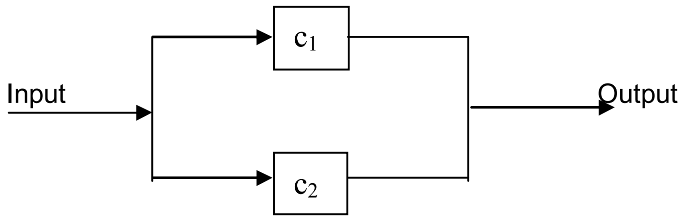
As shown in Figure 1, two simple systems that are connected in series and parallel. Two components (c_1 and c_2) were considered, and its possible states (operating -1, or failed-0) determined the resultant output or states of the overall system.

Series Selection



c_1	c_2	Output
0	0	0
0	1	0
1	0	0
1	1	1

Parallel Connection



c_1	c_2	**Output**
0	0	0
0	1	1
1	0	1
1	1	1

Figure 1: Truth table for simple systems

3. RESULTS AND DISCUSSIONS

The Boolean Truth table method has been applied to three types of UPS to determine their reliability parameters. The failure rates (λ) of each UPS configuration can be used to calculate the reliability (R) or the probability of operation / success, P (Success), of a UPS system with respect to time (t), using the equation:

$$\mathrm{Re}\,liability\,,\mathrm{R} = \exp^{-\lambda.t} \quad (1)$$

The three types of UPS considered were

(a) Online UPS with bypass

(b) Online UPS without bypass

(c) Line-Interactive UPS (Buck/Boost)

(a) Online UPS with Bypass

Figure 2 shows that the bypass line will provide another path of input Ac supply to the critical loads. The reliability model of the UPS shows that the system comprises of two parallel-connected blocks, i.e. block 1 and 2. The static bypass switch enables the bypass Ac power to feed the critical load during UPS failure. In this paper, we assumed that the bypass line is connected to the utility input line.

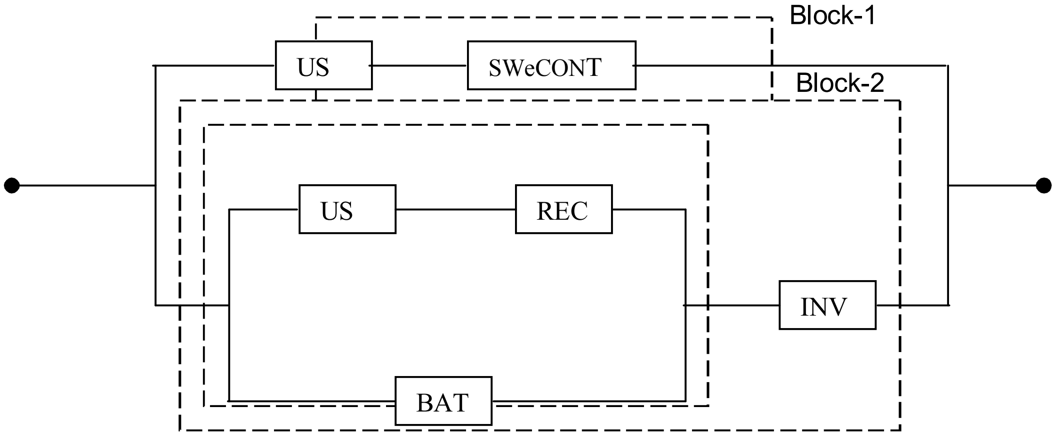


Figure 2: On-line UPS (with bypass) – Reliability Model

Each UPS component probabilities (i.e. probability of success and probability of failure) are require to obtain the probability of all the system events. These probabilities can be calculated using equation (1). Reliability design handbooks and datasheets from UPS manufacturing can provide some estimated reliability values such as the failure rates for electrical equipment and components based on measured field data. Table 1 shows the failure rates of the major components in the UPS systems; which can leads to probability of operation, P(Success) and probability of failure, P(Fail) of each component.

Table1: P(Success) and P(Fail) for online UPS (with bypass) component.

Components	Sign	Failure rate	P(Success)	P(Fail)
Utility	A	1.000E-03	0.000157	0.999843
Static Switch	B	3.700E-06	0.968108	0.031892
Rect/ Char	C	4.3480E-06	0.962628	0.037372
Battery AC	D	7.143E-07	0.993762	0.006238
Inverter	E	2.000E-05	0.839289	0.160711

With P(Success) and P(Fail) of all the major components in the UPS, the probability of the system's event can be calculated, as shown in Table 2.

Table 2: Boolean Truth Table for online UPS (with bypass)

No.	A	B	C	D	E	S or F	Success	Failure
1	0	0	0	0	0	F		1.1946E-06
2	0	0	0	0	1	F		6.2389E-06
3	0	0	0	1	0	F		1.9032E-04
4	0	0	0	1	1	S	9.9394E-04	
5	0	0	1	0	0	F		3.0772E-05
6	0	0	1	0	1	F		1.6070E-04
7	0	0	1	1	0	F		4.9024E-03
8	0	0	1	1	1	S	2.5602E-02	
9	0	1	0	0	0	F		3.6264E-05
10	0	1	0	0	1	F		1.8938E-04
11	0	1	0	1	0	F		5.7774E-03
12	0	1	0	1	1	S	3.0172 E-02	
13	0	1	1	0	0	F		9.3408E-04
14	0	1	1	0	1	F		4.8781E-03
15	0	1	1	1	0	F		1.4881E-01
16	0	1	1	1	1	S	7.7716E-01	
17	1	0	0	0	0	F		1.8745E-10
18	1	0	0	0	1	F		9.7894E-10
19	1	0	0	1	0	F		2.9864E-08
20	1	0	0	1	1	S	1.5596E-07	
21	1	0	1	0	0	F		4.8283E-09
22	1	0	1	0	1	S	2.5215E-08	
23	1	0	1	1	0	F		7.6922E-07
24	1	0	1	1	1	S	4.0172E-06	
25	1	1	0	0	0	S	5.6902E-09	
26	1	1	0	0	1	S	2.9716E-08	
27	1	1	0	1	0	S	9.0653E-07	
28	1	1	0	1	1	S	4.7342E-06	
29	1	1	1	0	0	S	1.4657E-07	
30	1	1	1	0	1	S	7.6542E-07	
31	1	1	1	1	0	S	2.3350E-05	

32	1	1	1	1	1	S	1.2194E-04	
Total							8.3408E-01	1.6592E-01

Calculation for event no. 1 can be simplifies as:

$$P(Event\,1) = \mathrm{P}\left(\overline{\mathrm{A}}\right)\mathrm{P}\left(\overline{\mathrm{B}}\right)\mathrm{P}\left(\overline{\mathrm{C}}\right)\mathrm{P}\left(\overline{\mathrm{D}}\right)\mathrm{P}\left(\overline{\mathrm{E}}\right)$$

= (0.999843) (0.031892) (0.037372) (0.006238) (0.160711)

= 1.1946E-06

Referring to the rule of probability, the summation of P(Success) and P(Fail) for all the events must equal to 1 i.e.

$$\mathrm{P(Success) + P(Fail) = 1} \quad (2)$$

Since we assumed the reliability of the system with respect to time, R(t) to be equal to the probability of success of the system, P(Success), we can attain the failure rate of the system, using following relation

$$Failure\ \mathrm{rate}, \lambda = \frac{-\ln(\mathrm{R})}{\mathrm{t}} \quad (3)$$

The mean time between failure (MTBF) of the system can be calculated as

$$MTBF = \frac{1}{Failure\ \mathrm{rate}, \lambda} \quad (4)$$

Thus, using equation (3) and (4), the failure rate and MTBF of the system can be calculated as

Failure rate = 2.0711E-05

MTBF = 48283.878 Hrs

= 5.512 Years

(b) Online UPS without Bypass

For online UPS without bypass line, the battery supply is connected in parallel to the utility supply and rectifier. As shown in the reliability model in Figure 3, the inverter will be receiving power from either the rectifier (normal operation) or battery power (back-up operation).

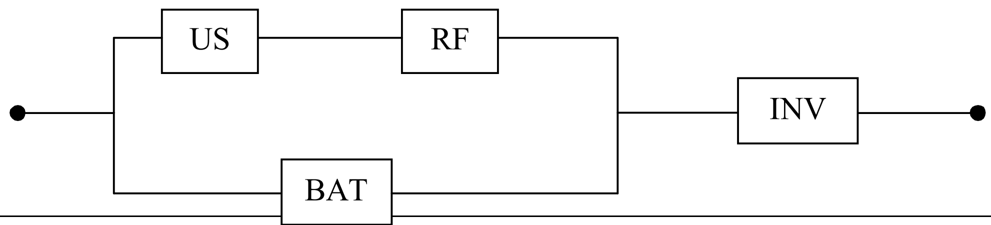


Figure 3: Online UPS (without Bypass) – Reliability Model

Table 3 and Table 4 show the probabilities of success and failure for the components in the UPS, and state probabilities of the system respectively.

Table 3: P(Success) and P(Fail) for online UPS (without bypass) components

Components	Sign	Failure rate	P(Success)	P(Failure)
Utility	A	1.000E-03	0.000157	0.999843
Rect/ Char	B	4.348E-06	0.962628	0.037372
Battery AC	C	7.143E-07	0.993762	0.006238
Inverter	D	2.000E-05	0.839289	0.160711

Table 4: Boolean Truth Table for Online UPS (without bypass)

No.	A	B	C	D	S or F	Success	Failure
1	0	0	0	0	F		3.7459E-05
2	0	0	0	1	F		1.9562E-04
3	0	0	1	0	F		5.9677E-03
4	0	0	1	1	S	3.1166E-02	
5	0	1	0	0	F		9.6486E-04
6	0	1	0	1	F		5.0388E-03
7	0	1	1	0	F		1.5372E-01
8	0	1	1	1	S	8.0276E-01	
9	1	0	0	0	F		5.8776E-09
10	1	0	0	1	F		3.0695E-08
11	1	0	1	0	F		9.3639E-07
12	1	0	1	1	S	4.8902E-06	
13	1	1	0	0	F		1.5139E-07
14	1	1	0	1	S	7.9064E-07	
15	1	1	1	0	F		2.4119E-05
16	1	1	1	1	S	1.2596E-04	
Total						0.83405	0.16595

Now, using equation (3) and (4), the failure rate and MTBF of the system can be calculated as

Failure rate = 2.0715E-05

MTBF = 48273.83242 Hrs

= 5.5107 Years

(c) Line-Interactive UPS (Buck/Boost)

The reliability model for the line-interactive UPS with buck/boost transformer is shown in Figure 4. The buck/boost transformer is connected to the bypass line to provide a wider variation of the bypass voltage before the output voltage reaches its limit and initiates a load transfer to inverter. The reliability model of the system comprises of two blocks, Block 1 and Block 2, connected in parallel.

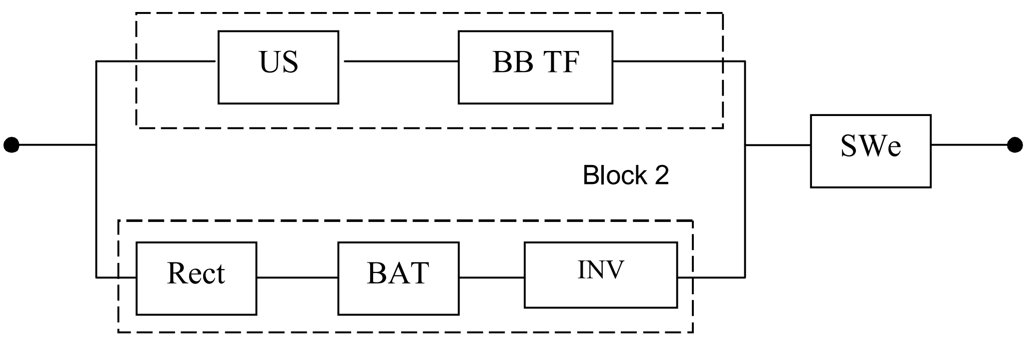


Figure 4: Line-interactive (Buck/Boost) UPS - Reliability Model

Table 5 and Table 6 show the probabilities of success and failure for the major components in the line-interactive (buck/boost) UPS, and state probabilities of the system respectively.

Table 5: P(Success) and P(Fail) for line-interactive (buck/boost) UPS components

Components	Sign	Failure rate	P(Success)	P(Failure)
Utility	A	1.000E-03	0.000157	0.999843
Buck/Boost TF	B	7.407E-05	0.522645	0.477355
Rect.	C	4.348E-06	0.962628	0.037372
Battery AC	D	7.143E-07	0.993762	0.0006238
Inverter	E	2.000E-05	0.839289	0.160711
SW_{eCONT}	F	1.000E-05	0.916127	0.083873

Table 6: Boolean Truth Table for line-Interactive (buck/boost) UPS components

No.	A	B	C	D	E	F	S or F	Success	Failure
1	0	0	0	0	0	0	F		1.500E-06
2	0	0	0	0	1	1	F		1.638E-05
3	0	0	0	1	0	0	F		7.832E-06
4	0	0	0	1	1	1	F		8.555E-05
5	0	0	1	0	0	0	F		2.389E-04
6	0	0	1	0	1	1	F		2.610E-03
7	0	0	1	1	0	0	F		1.248E-03
8	0	0	1	1	1	1	S	1.363E-02	
.	.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.	.
57	1	1	0	0	0	0	F		6.636E-09
58	1	1	0	0	1	1	S	7.249E-08	
59	1	1	0	1	0	0	F		3.466E-08
60	1	1	0	1	1	1	S	3.786E-07	
61	1	1	1	0	0	0	F		1.057E-06
62	1	1	1	0	1	1	S	1.155E-05	
63	1	1	1	1	0	0	F		5.522E-06
64	1	1	1	1	1	1	S	6.031E-05	
	Total							0.7641	0.2359

Now, using equation (3) and (4), the failure rate and MTBF of the system can be calculated as

Failure rate = 3.071E-05

MTBF = 32557.180 Hrs

= 3.717 Years

Table 7 shows the results obtained from Boolean truth table reliability estimation method for each UPS types considered. From the results, few findings were attained as

(1) Bypass line that are taken from the same source as the utility line has no effect on the reliability of the UPS system.

(2) Line-interactive UPS with buck/boost transformer configuration has a lower reliability as compared to others.

Table 7: Summary of results obtained from Boolean Truth Table method

	P(Success)	P(Fail)	Failure Rate	MTBF (Years)
Online with	0.8341	0.1659	2.071E-05	5.512
Online without	0.8341	0.1659	2.071E-05	5.511
Line-Int	0.871878	0.128122	3.071E-05	3.717

4. RESULT COMPARISONS

In order to verify the results obtained from the Boolean Truth Table reliability modeling method, results from the reliability block diagram (RBD) and field data reliability estimation methods were compared, as in Table 8.

Table 8: Result Comparisons

UPS Configuration	MTBF (Years)		
	Boolean Truth Table	RBD	Field Data
Online with bypass	5.512	5.623 (+2.01%)	5.708 (+3.56%)
Online without Bypass	5.511	5.512 (+0.02%)	5.365 (-2.65%)
Line-Int (Buck/Boost)	3.717	4.055 (+9.09%)	3.613 (-2.80%)

The number in the brackets indicates the percentage of the increment of the result obtained from the two other methods compared to results from Boolean Truth Table method. Results for all the UPS type lie between -2.80% to +9.09%, which is quite close. However, considering that these figures are estimated numbers, the percentages of increment for the Online without bypass UPS MTBF results are acceptable.

5. CONCLUSIONS

The important of reliability estimation of the Uninterruptible Power Supply (UPS) system has been stated. The Boolean Truth Table method has been proposed. It is based on considering all the possible state combinations (operating state and failed state) for the major components in the UPS one after the other and studying their effects on the UPS system. The probabilities of operating and failure states for the system were then calculated. Eventually, reliability parameters such as failure rates and mean time between failures (MTBF) can be determined. The objective of the proposed methodology is to provide an uncomplicated and convenient procedure for reliability estimation that based on state probabilities.

The results from Boolean Truth Table method suggest that the bi-directional converter in the line-interactive UPS that acts as a rectifier (charge battery) during normal operation and as an inverter (supply AC supply to loads) during power failure, increase the system reliability. It was also noted from this study, in order to increase UPS system's reliability, the bypass line that is connected to the system must be taken from other source that the utility line that supplying the UPS system. If it is taken from the same source as the utility, the reliability will be unchanged.

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