Fire Risk in MTBF Evaluation for UPS System

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Abstract. *The reliability improvement of no-break redundant electrical systems is the first aim of the proposed strategy. The failure of some UPS (Uninterruptible Power Supply) system may lead to the fire occurrence. The most used electrical configurations are presented and discussed in the paper. The innovation of the proposed method consists of taking into account the fire risk to improve the accuracy of wiring configuration and components' failure rate. Thorough research on MTBF (Mean Time Between Failure) data has been performed for each wiring component and UPS. The fire risk is taken into account introducing an equivalent fire block in the Reliability Block Diagram scheme; it has an MTBF value calculated form yearly statistics of UPS fire events. The reliability of the most used UPS electrical configurations is evaluated by means of the RBD method. Different electrical systems have been investigated and compared based on MTBF. The importance of fire compartmentation between two or more UPS' connected in parallel is proved here.*

Keywords

Electrical installation, failure rate, fire risk, MTBF, no-break power system, RBD, redundant electrical system, reliability, UPS.

1.   Introduction

Ten years of maintenance activity in no-break electrical installations reveals a lot of design errors and a lack of reliability. Currently, it is common to evaluate the reliability only for the equipment and for electrical system' components. Today, it can be noticed that there is a defect in reliability evaluation of all project choices. Many real fire case occurrences on UPS were caused by power electronic or battery fail. The producers do not consider fire hazard significant for the UPS device and perform tests only in standard and good maintenance conditions. The UPS machines are very vulnerable and subjected to inadequate maintenance, overvoltages, high temperature, working conditions, and other electrical system malfunctions. Nowadays redundant UPS' are not isolated by a fire compartment. No-break systems are often designed following a wrong guideline. The standard procedure considered for reliability improvement consists of a simple installation of two UPS', which are connected in parallel. UPS power electronic, Control Unit, manual and static bypass, batteries and other system components are usually installed in the same room. All devices are, therefore, exposed to the same fire risk. Working UPS unit may be involved in fire event caused by the failure of another UPS unit in the same room, thus rendering the system redundancy ineffective. Moreover, an emergency manual bypass wired out of the UPS room is never installed. In those conditions a fire event entails certainly the complete failure of the no-break system. A short and contained fire is also sufficient to generate smoke and risk of toxic air; in this case nobody can access the UPS room and technicians are obliged to communicate immediately with the director to inform him of the imminent failure and recommend to stop all current operations. A lot of fire case studies have been investigated; the complete failure of the no break electrical system was often due to the lack of fire compartmentations between two UPS.

2.   Reliability Model

The reliability evaluation for each electrical configuration is based on the Reliability Block Diagram model (RBD) [1], [2]. By means of this method, the *MTBF* of UPS, Control Unit, batteries, switches, and other components are represented. Data on UPS fire occurrence frequency were obtained during ten years of consultant activity in the hospitals. In about a hundred of case studies the existence of two UPS' room fire events is

proved per year (2 % per year). Two hypotheses are necessary to evaluate the failure rate [3] by statistical data on fire risk. Firstly, the failure rate is constant in time. Secondly, break components are not repairable but quickly replaceable ($MTTR = 0$). The average fire failure rate is defined as the ratio between number of fires and number of studied events per time. It is shown in Eq. (1):

$$\lambda_{AVG} = \frac{N_F}{N_{TOT} \cdot T} \, , \qquad (1)$$

where N_F is the quantity of fire events, N_{TOT} is the number of observed systems and T is the observation time. Subsequently the $MTBF$ value is calculated [4] in Eq. (2):

$$MTBF_F = \frac{1}{\lambda_{AVG}} = \frac{N_{TOT} \cdot T}{N_F} = \frac{100 \cdot 8760}{2} =$$
$$= 438000 \text{ h.} \qquad (2)$$

Using the Eq. (2), the reliability calculation can be based on different fire statistics. Moreover, calculation can be developed implementing a parametric analysis varying the value of fire statistic. The reliability evaluation model is used based on these hypotheses. Firstly, UPS is only considered as a no break system that avoids voltage dips. Secondly, the continuous energy source is based only on power supplier's grid or emergency diesel generator.

3. MTBF Data

$MTBF$ data on studied components have been deduced by an accurate statistical survey. Used data were obtained from: Gold Book [5], some papers [1], [6], [7], [8], [9] and many datasheets. The UPS' $MTBF$ is evaluated including the presence of the on-board automatic static bypass and batteries. $MTBF$ value for the Fire Risk Factor block is pointed out by the maintenance activity experience, Eq. (2). The average values of $MTBF$ for all components are pointed out in Tab. 1.

Tab. 1: Average $MTBF$ of no-break system's components.

Components	Symbol	Failure rate [failure·h^{-1}]	MTBF [h]
Battery (lead acid)	BAT	$8.52086 \cdot 10^{-7}$	1173590
Circuit breaker	CB	$4.348 \cdot 10^{-6}$	229991
Complete UPS module (internal STS and batteries included)	UPS	$1.3779 \cdot 10^{-5}$	72574
Control Unit	CU	$1.33333 \cdot 10^{-6}$	750000
Fire Risk Factor	FRF	$2.28311 \cdot 10^{-6}$	438000
Inverter	INV	0.00002	50000
Rectifier	REC	0.00002	50000
Static Transfer Switch	STS	$9.79499 \cdot 10^{-6}$	102093
Switchgear Bus Bar	SBB	$1.08334 \cdot 10^{-6}$	923068

4. MTBF Evaluation of Various No-Break Electrical Systems

4.1. One UPS

The reliability of a base configuration with only one UPS is shown in this subsection.
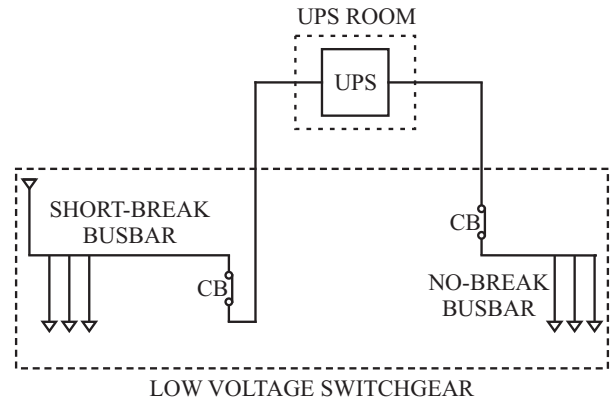

Fig. 1: No-break system with one UPS.

The Reliability Block Diagram of the one UPS configuration is shown in Fig. 2.

Fig. 2: RBD scheme of no-break system with one UPS.

The calculation shown in Eq. (3) reveals the total $MTBF$ for the system configuration with only one UPS.

$$MTBF_T =$$
$$\frac{1}{\dfrac{1}{MTBF_{SBB}} + \dfrac{1}{MTBF_{CB}} + \dfrac{1}{MTBF_{FRF}} + \cdots}$$
$$\overline{\cdots \dfrac{1}{MTBF_{UPS}} + \dfrac{1}{MTBF_{CB}} + \dfrac{1}{MTBF_{SBB}}} = \qquad (3)$$
$$= 37140 \text{ h} = 4.2 \text{ years.}$$

4.2. Two UPS Without Fire Compartmentations

The configuration with two UPS' connected in parallel is considered here. Each UPS has a rated power greater than the load demand. Machines are installed in the same room together with the batteries and without any fire compartmentations. The respective configuration scheme is shown in Fig. 3. The RBD scheme of that
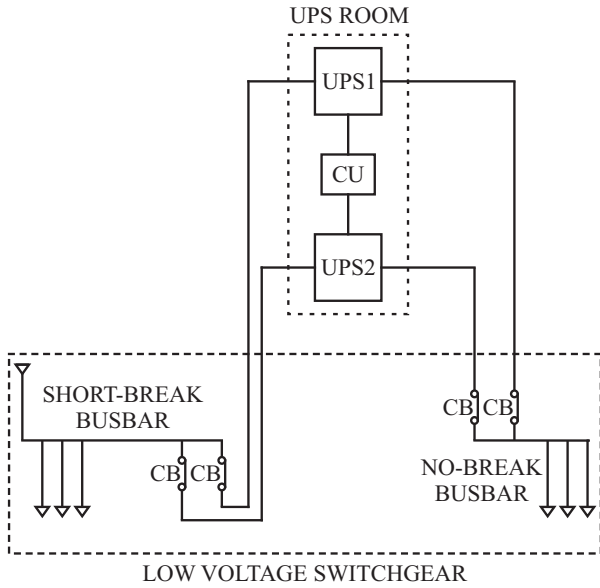
Fig. 3: No-break system with two UPS without fire compartmentations.

system is shown in Fig. 4, where it must be highlighted that the Fire Risk Factor of both UPS' influences the entire system.
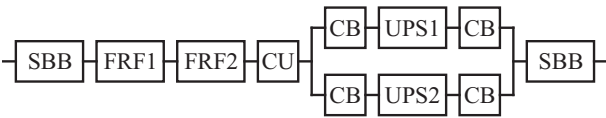

Fig. 4: RBD scheme of no-break system with two UPS without fire compartmentations.

The *MTBF* for that configurations is can be computed with the use of Eq. (4), Eq. (5), Eq. (6) and Eq. (7):

$$MTBF_{UPS} =$$

$$= \frac{1}{\frac{1}{MTBF_{CB}} + \frac{1}{MTBF_{UPS}} + \frac{1}{MTBF_{CB}}} = \quad (4)$$

$$= 44494 \text{ h.}$$

$$R_{UPS1UPS2} = R_{UPS1} + R_{UPS2} - R_{UPS1} \cdot R_{UPS2}, \quad (5)$$

where R [8] is the reliability and it is defined as $R = e^{-\frac{1}{MTBF} \cdot t}$.

$$MTBF_{UPS1UPS2} = \int_0^\infty R_{UPS1UPS2} \cdot dt =$$

$$= 66741 \text{ h.} \quad (6)$$

$$MTBF_T =$$

$$= \frac{1}{\frac{1}{MTBF_{SBB}} + \frac{1}{MTBF_{FRF1}} + \frac{1}{MTBF_{FRF2}} + \cdots}$$

$$\frac{1}{\cdots \frac{1}{MTBF_{CU}} + \frac{1}{MTBF_{UPS1UPS2}} + \frac{1}{MTBF_{SBB}}} =$$

$$= 43385 \text{ h} = 5 \text{ years.}$$

(7)

Only one Control Unit is usually installed for an emergency load switching between two UPS', that choice makes the *MTBF* worse.

4.3. Two UPS in Different Fire Compartments

The reliability of two fire compartmented UPS' is studied here. In Fig. 5 and Fig. 6, there are shown the system configuration and the RBD scheme respectively.
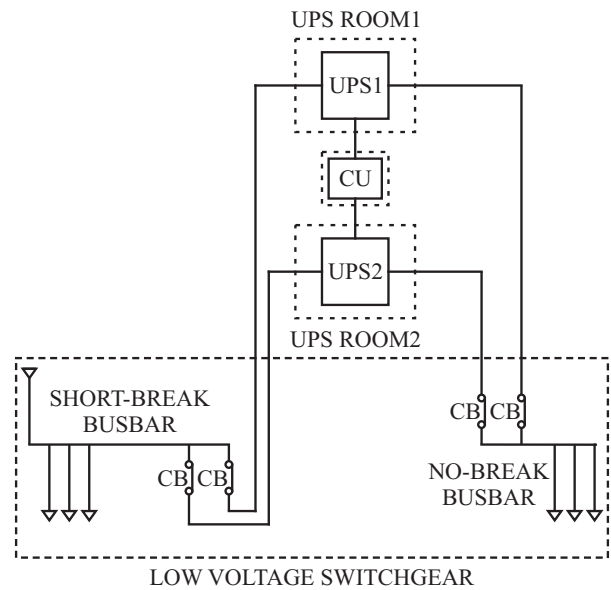

Fig. 5: No-break system composed of two UPS with fire compartmentations.
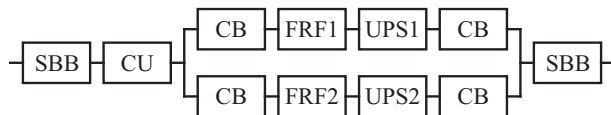

Fig. 6: RBD scheme of no-break system with two fire compartmented UPS.

In this case, each Fire Risk Factor is related exclusively to the respective UPS. Calculations to evaluate

the total $MTBF$ are represented in Eq. (8), Eq. (9), Eq. (10) and Eq. (11):

$$MTBF_{UPS} = \cfrac{1}{\cfrac{1}{MTBF_{CB}} + \cfrac{1}{MTBF_{FRF}} + \cdots}$$
$$\cfrac{1}{\cdots \cfrac{1}{MTBF_{UPS}} + \cfrac{1}{MTBF_{CB}}} = 40391 \text{ h.} \quad (8)$$

$$R_{UPS1UPS2} = R_{UPS1} + R_{UPS2} - R_{UPS1} \cdot R_{UPS2}. \quad (9)$$

$$MTBF_{UPS1UPS2} = \int_0^\infty R_{12} \cdot dt = 60587 \text{ h.} \quad (10)$$

$$MTBF_T = \cfrac{1}{\cfrac{1}{MTBF_{SBB}} + \cfrac{1}{MTBF_{CU}} + \cdots}$$
$$\cfrac{1}{\cdots \cfrac{1}{MTBF_{UPS1UPS2}} + \cfrac{1}{MTBF_{SBB}}} = \quad (11)$$

$$= 49987 \text{ h} = 5.7 \text{ years.}$$

4.4. Two UPS' and One STS with Fire Compartmentations

Another system improvement consists of installing a safety external bypass over two UPS'. All these devices must be installed in different fire compartmented rooms. In the Fig. 7 and Fig. 8 the configuration and the RBD scheme are shown respectively.

According to the proposed system scheme, calculations to evaluate total $MTBF$ are shown in Eq. (12), Eq. (13), Eq. (14), Eq. (15), Eq. (16), Eq. (17), Eq. (18) and Eq. (19).

$$MTBF_{UPS} = \cfrac{1}{\cfrac{1}{MTBF_{CB}} + \cfrac{1}{MTBF_{FRF}} + \cdots}$$
$$\cfrac{1}{\cdots \cfrac{1}{MTBF_{UPS}} + \cfrac{1}{MTBF_{CB}}} = 40391 \text{ h.} \quad (12)$$

$$R_{UPS1UPS2} = R_{UPS1} + R_{UPS2} - R_{UPS1} \cdot R_{UPS2}. \quad (13)$$

$$MTBF_{UPS1UPS2} = \int_0^\infty R_{12} \cdot dt = 60587 \text{ h.} \quad (14)$$

$$MTBF_{UPS1UPS2CU} =$$
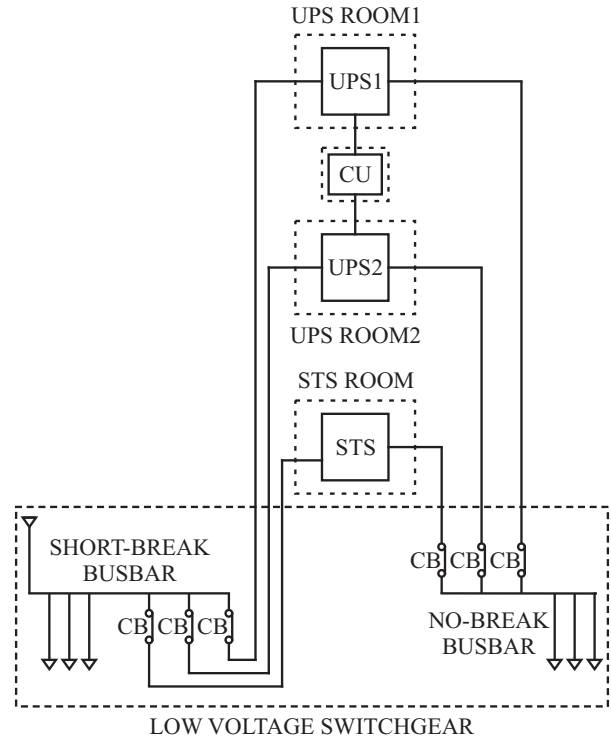$$= \cfrac{1}{\cfrac{1}{MTBF_{UPS1UPS2}} + \cfrac{1}{MTBF_{CU}}} = 56058 \text{ h.} \quad (15)$$

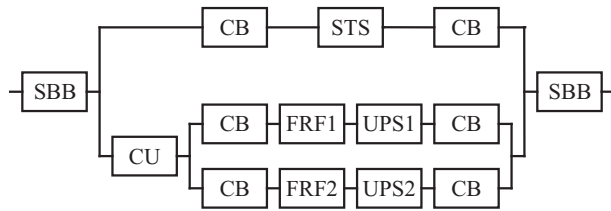**Fig. 7:** No-break system made up of two UPS and one STS with fire compartmentations.

Fig. 8: RBD scheme for no-break system with fire compartmented UPS and STS.

$$MTBF_{STS} =$$
$$= \cfrac{1}{\cfrac{1}{MTBF_{CB}} + \cfrac{1}{MTBF_{STS}} + \cfrac{1}{MTBF_{CB}}} = \quad (16)$$
$$= 54080 \text{ h.}$$

$$R_{UPS1UPS2CUSTS} = R_{UPS1UPS2CU} +$$
$$+ R_{STS} - R_{UPS1UPS1CU} \cdot R_{STS}. \quad (17)$$

$$MTBF_{UPS1UPS2CUSTS} =$$
$$= \int_0^\infty R_{UPS1UPS2CUSTS} \cdot dt = 82616 \text{ h.} \quad (18)$$

$$MTBF_T =$$

$$= \cfrac{1}{\cfrac{1}{MTBF_{SBB}} + \cfrac{1}{MTBF_{UPS1UPS2CUSTS}} + \cdots} \quad (19)$$

$$\cdots \cfrac{1}{\cfrac{1}{MTBF_{SBB}}} = 70070 \text{ h} = 8 \text{ years.}$$

The total $MTBF$ for compartmented system is 8 years. Calculations have been also performed for the case of absence of fire compartmentations. Installing two UPS' and one STS in the same room results in $MTBF$ of 6.4 years.

4.5. Three UPS' with Fire Compartmentations

The system configuration made of three UPS' installed in different rooms is studied here. The configuration scheme is shown in Fig. 9.
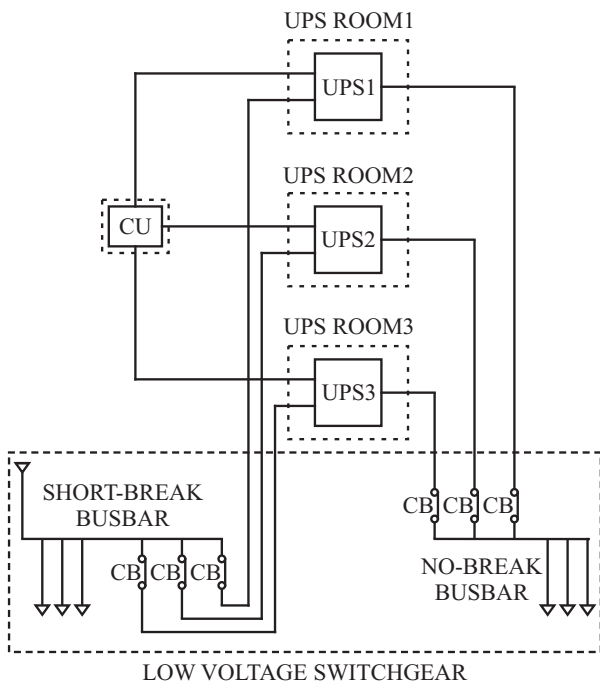
Fig. 9: No-break system made of three fire compartmented UPS.

The respective RBD scheme is shown in Fig. 10.

The total $MTBF$ of the three UPS' configuration is computed using the Eq. (20), Eq. (21), Eq. (22),
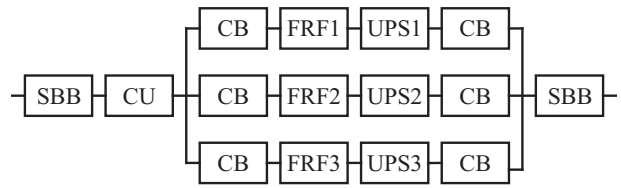
Fig. 10: RBD scheme for fire compartmented three UPS configuration.

Eq. (23), and Eq. (24).

$$MTBF_{UPS} =$$

$$= \cfrac{1}{\cfrac{1}{MTBF_{CB}} + \cfrac{1}{MTBF_{FRF}} + \cdots} \quad (20)$$

$$\cdots \cfrac{1}{\cfrac{1}{MTBF_{UPS}} + \cfrac{1}{MTBF_{CB}}} = 40391 \text{ h.}$$

$$R_{UPS1UPS2} = R_{UPS1} + R_{UPS2} - R_{UPS1} \cdot R_{UPS2}. \quad (21)$$

$$R_{UPS1UPS2UPS3} = R_{UPS1UPS2} + R_{UPS3} - \\ - R_{UPS1UPS2} \cdot R_{UPS3}. \quad (22)$$

$$MTBF_{UPS1UPS2UPS3} =$$

$$= \int_0^\infty R_{UPS1UPS2UPS3} \cdot dt = 76743 \text{ h.} \quad (23)$$

$$MTBF_T = \cfrac{1}{\cfrac{1}{MTBF_{SBB}} + \cfrac{1}{MTBF_{CU}} + \cdots}$$

$$\cdots \cfrac{1}{\cfrac{1}{MTBF_{UPS1UPS2UPS3}} + \cfrac{1}{MTBF_{SBB}}} = \quad (24)$$

$$= 60494 \text{ h} = 6.9 \text{ years.}$$

The total $MTBF$ for three compartmented UPS' is 6.9 years. In case of absence of fire compartments for the same configuration the reliability is studied; and $MTBF$ of 5.1 years is obtained for three UPS installed in the same room. With respect to the configuration with two UPS' and one STS, a little decrease of reliability is to be noticed. This is due to the better $MTBF$ of the STS compared to the UPS. On the opposite, this three system UPS permits all maintenance operations during working activities.

5. Conclusions

Revised statistical data on $MTBF$ components used in no-break systems have been summarized here. A

method to take into account the fire risk in a Reliability Block Diagram model has been performed. The reliability of seven different UPS configurations has been studied by means of the RBD method. The total *MTBF* has been computed for each configuration taking into account the effect of the devices' fire compartmentation. The results of this comparative analysis are shown in Fig. 11.
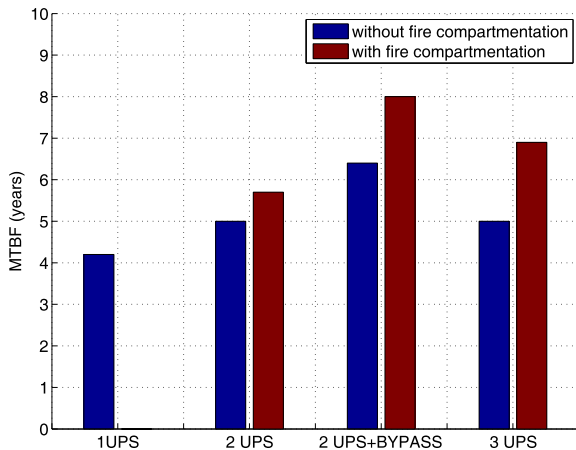

Fig. 11: *MTBF* for different no-break power systems by fire compartmentation.

These *MTBF* results can be also converted to yearly failure probability values by means of Eq. (25):

$$FP_\% = \frac{1}{MTBF} \cdot 100. \qquad (25)$$

These results demonstrate the importance of fire compartmentation for reliability improving in redundant UPS systems, especially for hospitals and safety systems. The more suitable configuration consists of two UPS and one STS fire compartmented, which achieves the best *MTBF*. Moreover, the three compartmented UPS' configuration and permits a complete maintenance during system's operation.

Acknowledgment

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