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continuous power availability

Evaluating Availability of Centiel UPS Architecture

White paper

Igor Kaitovic [1], Gerardo Lecuona [2]

[1] Advanced Learning and Research Institute,
Università della Svizzera Italiana, Lugano, Switzerland
[2] Centiel S.A. Lugano, Switzerland

[1] igor.kaitovic@usi.ch, [2] gerardo.lecuona@centiel.com

Head Office:
Centiel UK
Faraday House
Caker Stream Road
Alton, GU34 2QF, UK

Global HQ:
Centiel SA,
Via alla Stampa 5a
Cadro, Lugano
CH6965, Switzerland

Phone:
01420 82031

Mail:
sales@centiel.co.uk

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With increasing dependency on various types of electrically powered devices in all walks of life, ensuring continuous power supply is ever-more important particularly in safety-critical environments. An Uninterruptible Power Supply (UPS) provides power even when the main power source is not available. Unfortunately, as any other device, a UPS may fail. Typically, redundancy is used to decrease the failure rate and to improve availability but different architectural designs with a same level of redundancy may have significantly different availability.

We model, evaluate and compare availability of a typical UPS architectures and Centiel one. In our conclusion availability with Centiel modular architecture with 160kVA output power has availability of even nine nines that translates to annual downtime of order of 10-2. When compared to typical architectures, availability is improved by multiple orders of magnitude.

Introduction

Continuous supply of electric power is often taken as granted despite frequent interruptions and disturbances as also summarized in [1]. Power-quality sensitive devices such as computer servers, medical devices and lab equipment are frequently connected to Uninterruptible Power Supplies (UPS'es) that provide power when the main source fails and also ensure high-level of power quality. However, UPS'es are not failure-proof and may also, even though very rarely, fail. Failures are particularly dangerous in safety-critical environments, such as hospitals, server farms and banks, where they may cause significant financial losses or even endanger lives. As for that, ensuring high availability of UPS'es is of paramount importance.

This is task that must be performed through the entire lifecycle of a UPS. Redundancy is the most common way to improve availability (and reliability) of a UPS at design time but different architectural solutions, with the same number of redundant components, may result in significantly different values of availability indices. At exploitation time, it is important to maintain the device properly. The main strategies are periodic (scheduled) and preventive maintenance (that may be based on online failure prediction). In this white paper we focus on architectural solutions to endure dependability at design time whereas maintenance is being addressed in our previous publication [2].

We present analysis of different UPS architectures ranging from a single UPS to complex structures with high power outputs. We model, evaluate and compare availability of typical UPS architectures and Centiel modular architecture. Following the industrial practice in white papers and reports similar to this one, we introduce simplifications to easy calculations and results comparison. For example, we do not include failure rates for control and logical components but assume that they never fail. However, these simplifications are applied to all the considered architectures. Whenever appropriate, reliability indices of individual components are adopted from [3]. In other cases we use typical values or rely on our experience. Modelling and evaluation is performed with Reliability Block Diagrams (RBDs) and Markov chains using Symbolic Hierarchical Automated Reliability and Performance Evaluator (SHARPE) [4].

The rest of the document is organized as follows. In the next section we give a brief overview of availability modelling and evaluation methods that we use. In Section III availability of typical architectures are analyzed starting with a single UPS module to n+1 configuration. Centiel modular architecture is analyzed in Section IV whereas availability with different architectures is compared in Section V. Section VI concludes the paper and briefly describes the ongoing and future work.

Background

We give definition of availability and other basic dependability concepts that are necessary for understanding the conducted analysis.
For a comprehensive overview of dependability concepts and terminology we refer interested readers to [5] whereas more details including descriptions of dependability methods and tools may be found in [6].

Dependability is the ability of a system to perform a required service under stated conditions for a specified period of time. It is a composite property that includes availability, reliability, maintainability, safety, and integrity [5]. Availability is defined as readiness of a system to provide a correct service. Steady-state availability is the most commonly used metric for availability quantification. It is defined as the fraction of time a system is operational during its expected lifetime. Equation (1) is the most commonly used for calculating steady-state availability.

$$A = \frac{MTTF}{MTTF + MTTR} \qquad (1)$$

The equation may be applied at different levels, from atomic components to composite systems. Mean-Time-To-Failure (MTTF) is a mean time between two consecutive failures whereas Mean-Time-To-Repaid (MTTR) is a mean time needed for the repair. In other words MTTF is average time during which the system is up after it has been repaired and before it fails again and MTTR is average time need to repaid the system after any failure. Failure and repair rates, which we will also use in the analysis, are usually denoted by λ and μ and are defined as inverses of MTTF and MTTR, respectively. In practice, to easy the comparison, steady-state availability is usually expressed with a number of nines. For example, “five nines” availability means that steady-state availability is 0.99999 or 99.999%.

Dependability models are used for modelling and evaluating dependability properties of complex systems when indices of its building blocks are known. In general, dependability models may be classified as component based and state based.

The first ones, that include Reliability Block Diagrams (RBDs) and Fault Trees (FTs) focus on system building blocks and assume that failures and repairs of components are stochastically independent. They are also more frequently used in industry as they are more intuitive to make and simpler to update and maintain. On the other hand they also provide sufficiently accurate results. In state-based models, that include Markov Chains and Petri Nets, system states and transitions are considered. These models provide more comprehensive results as interdependencies between the components are also included in the analysis. However they are more complex and are difficult to apply for large systems as number of states may grow exponentially.

We use RBDs in our analysis and Markov Chains. An RBD reflects the structure of a system and each component is described with its MTTF and MTTR. Using an RBD one may calculate system’s MTTF, MTTR, λ, μ, steady-state availability and other indices when indices of components (building blocks) are known. For more accurate analysis of individual UPS modules we use Markov Chains. The analysis is performed in SHARPE [1]. It is a general hierarchical modeling tool widely used in industry and academia to analyze stochastic models of reliability, availability, performance, and performability.

Availability of typical architectures

A. Availability of a single UPS

An RBD of a single UPS unit is presented in Fig. 1. Typical values of component reliability indices are given in TABLE I and are adapted from [3]. Only electrical components are considered whereas logic and control units are assumed to be perfectly reliable following the assumptions introduced in [3]. A more detailed model will be developed in the latter version of the document.

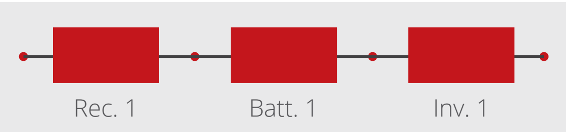

Fig. 1 A simplified RBD of a UPS module

Table 1
Reliability indices of ups module electrical components.

Component	Rectifier	Battery	Inverter
MTTH [h]	50000	1000000	50000
Failure rate (λ) [h-1]	20*10-6	10*10-6	20*10-6

For the given values of component's reliability, Mean-Time-To-Failure of a UPS unit is MTTFUPS = 20000 h. Assuming that Meat-Time-To-Repair is MTTRUPS = 6 h availability of one UPS is 0.9997. In other words, the expected downtime per year is 2h 37min.

To improve availability of a single UPS unit, the unit may be placed in parallel with the main power source using a Static Bypass Switch (SBS). That way, if a failure of any of UPS components occurs, online switching to the main power source is performed so that the user experiences no power interruption. As a simplification, we will assume that the same main power source is used to power the SBS and to provide power to the device when UPS fails. An RBD model of a UPS with the main power source and an SBS is presented in Fig. 2. Reliability indices of components are given in TABLE II.

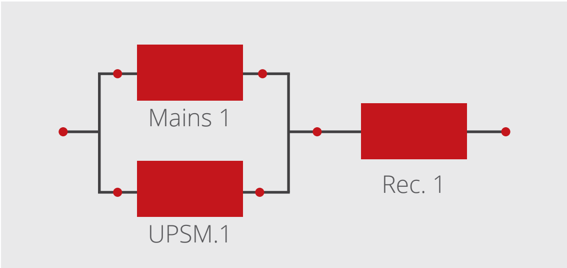

Fig. 2 An RBD of a UPS with the main source

Table 2
Reliability indices of a ups module, main power supply and a static bypass switch.

Component	MAINS	UPS Module	SBS
MTTH (h)	50	20000	500000
Failure rate (λ) [h-1]	2*10-2	50*10-6	2*10-6
MTTR [h]	0.1	6	0.5
Repair rate (μ) [h-1]	10	16*10-2	2
Availability	0.998	0.9997	0.999999

It is worth repeating that failures do not include only complete interruptions of the power delivery but also decreases in the power quality that are not acceptable for the customer.

Following the values presented in the table, availability of a single UPS is still by the order of magnitude higher that of the main power source. This means that, without a UPS module a customer will experience even 17.5 h of power interruption per year, whereas with a single UPS module the interruptions is decreased to 2.6 h.

Availability is significantly improved with a system from Fig. 2 as it reaches the value of 0.999998. This translates to only 51 seconds of annual downtime. Unfortunately, the output power of such a system is limited to one singe UPS unit. To get higher power output, several UPS units must be combined. Some of these architectures are analyzed next.

B. Availability of a non-redundant UPS system

Building a system with higher power output requires a number of single UPS units each connected in parallel to the main power over an SBS. In this architecture, UPS'es must also be connected to each other to ensure synchronous operation. Communication is established via a parallel bus (PBUS). Following our empirical experience and considering [3] we may assume that MTTFPBUS equals 2500000h and that MTTRPBUS is 30min. For a configuration where the number of UPS'es is n, also n PBUS'es must be used. In a typical configuration, a failure of any of the busses causes the entire system to fail. This significantly decreases system's availability despite that a PBUS is a highly reliable component.

Let us consider a case of a system with 160kVA output. Following [3] we assume that each UPS element has a power output of 40kVA. We introduce optimistic simplification that each UPS element may be modeled as the one from Fig. 2. The simplification assumes that every UPS is combined with a different main power source, whereas in reality they are all connected to one power source only. This gives a simplified RBD model where 4 UPS'es with independent main power sources are connected in series. Solving the model we evaluate that availability of such configuration drops down to 0.999993 (MTTF = 3*104h) that is equivalent to downtime of 3 minutes and 40 seconds per year.

C. Availability of a typical n+1 architecture

To boost dependability of a UPS system a redundant UPS unit may be introduced. A configuration with n UPS'es coupled with one redundant is known as n+1 configuration. Such a system may tolerate a failure of a single UPS unit.

In a typical configuration n+1 UPS'es are connected with n+1 PBUS'es. The system may tolerate failure of one UPS unit but a failure of any of PBUS'es makes the entire system to fail. In [3], a simplified analysis is performed so that system's MTTF is evaluated considering a series of PBUS'es only. In this paper, we perform a more accurate evaluation.

First, equivalent MTTF and MTTR of a subsystem composed only of n+1 UPS units are calculated using ((2) and ((3). Availability may be calculated with (4). In the equations, MTTFUPS and MTTRUPS are availability indices of a single UPS unit. Equations are derived following generic ones for reliability indices of a system with n equivalent components out of which k are required for system operation (k-of-n configuration) [6]. An RBD of the entire system is composed of a series of (n+1) UPS'es subsystem and a series of n+1 PBUS'es. An example for n=4 is given in Fig. 3.

$$MTTF_{SS} = \frac{1 \quad MTTF_{UPS}^2}{n(n+1)\ MTTF_{UPS}} \qquad (2)$$

$$MTTR_{SS} = \frac{MTTR_{UPS}}{2} \qquad (3)$$

$$A_{SS} = \frac{2MTTF_{UPS}^2}{2MTTF_{UPS}^2+n(n+1)MTTR_{UPS}^2} \qquad (4)$$

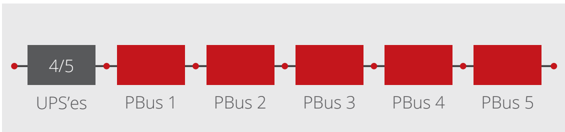

Fig. 3 An RBD of a typical 4+1 configuration

The equivalent MTTF and MTTR of the entire (n+1) system composed if a series of elements is given with (5) – (7). Resuts derived by solving the equations for a range of n are presented in Section V.

$$MTTF_{n+1} = \frac{MTTF_{UPS}^2\ MTTF_{PBUS}}{(n+1)(MTTF_{UPS}^2+ {}^{n}MTTR_{UPS}MTTF_{PBUS})} \qquad (5)$$

$$A_{n+1} = \frac{2MTTF_{UPS}\left(\frac{MTTF_{PBUS}}{MTTF_{PBUS}+MTTR_{PBUS}}\right)^{n+1}}{2MTTF_{UPS}^3+n(n+1)MTTR_{UPS}^2} \qquad (6)$$

$$MTTR_{n+1} = \frac{1 - A_{n+1}}{A_{n+1}}\ MTTF_{n+1} \qquad (7)$$

Centiel n+1 modular architecture

In the Centiel n+1 architecture that is presented in Fig. 4, numerous changes are introduced to improve the overall dependability. In this paper we analyze only the major ones.

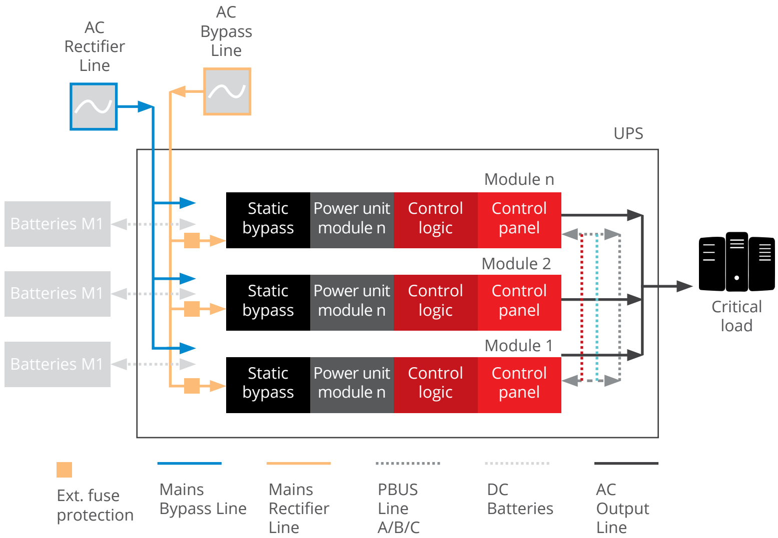

Fig. 4 Centiel architecture (Block diagram)

Specifically, the control logic allows to keep the communication between the UPS units even when one of the PBUS'es has failed. Thus, instead of a series of (n+1) PBUS'es the communication subsystem may be modeled as an (n+1) configuration.

MTTF, MTTR and availability of the communication subsystem may be evaluated using (2) to (4) with the difference that a subscript UPS needs to be substituted with PBUS. Equations of the entire (n+1) Centiel modular architecture are given in (8) – (10).

$$MTTF_{c,n+1} = \frac{MTTF_{UPS}^2 MTTF_{PBUS}^2}{n(n+1)(MTTF_{UPS}^2 MTTR_{PBUS} + MTTF_{PBUS}^2\, MTTR_{UPS})} \quad (8)$$

$$A_{c,n+1} = \frac{4MTTF_{UPS}^2 MTTF_{PBUS}^2}{(2MTTF_{UPS}^2 + n(n+1)MTTR_{UPS}^2)(2MTTF_{PBUS}^2 + n(n+1)\, MTTR_{PBUS}^2)} \quad (9)$$

$$MTTR_{c,\,n+1} = \frac{1 - A_{n+1}}{A_{n+1}} MTTF_{n+1} \quad (10)$$

With the Centiel architecture, MTTR of a single UPS module is additionally decreased by placing the SBS fuse of each module at the frame level, out of the module. That way, the fuse may be replaced without a need of pulling-out nor opening the entire module. We perform the analysis for a range of failure rate values of the fuse. The failure rate is expressed as a percentage of the failure rate of the entire system. Assuming that a fuse causes c% of the total module failures (we assume that c is between 5 and 10) module's MTTR will be reduced to MTTRUPSC. Evaluation has been performed by modeling a UPS module with the Markov chain depicted in Fig. 5. The model has been solved in SHARPE [4]. A method to solving the model analytically may be found in [6]. Results are presented in the next section.

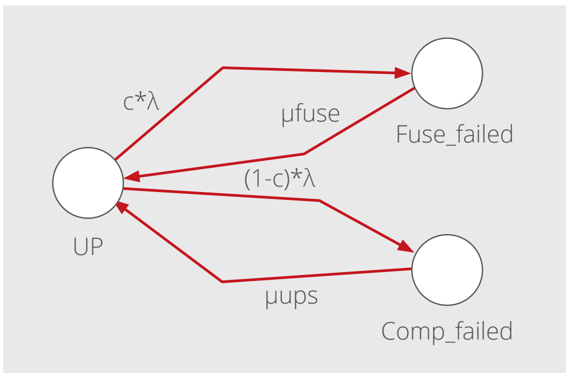

Fig. 5 A Markov chain for evaluating MTTR of a Centiel UPS module

Comparing different architectures

As a summary, we compare availability and annual downtime of n+1 architectures for different output powers. In a typical n+1 architecture, standalone UPS units are used. This affects MTTR significantly as repairing a UPS units requires the entire USP system to be offline for about 6 hours.

In a modular architecture, as the one described in [3], UPS modules may be exchanged independently so that, in the case of n+1 configuration, the system may continue operation with the remaining n modules. As for that MTTR of a modular architecture decreases to only 0.5 h.

In Centiel architecture in Fig. 4, there are manifold changes that increase system's MTTF and decrease MTTR. In the current version of the paper we consider only the two that were described in Subsection IV, namely increasing MTTF with (n+1) PBUS configuration and decreasing MTTR by isolating the SBS module fuse.

We assume that mean time to repair the fuse is 5 minutes and that the fuse causes 5% of the overall module failures. As Centiel architecture is modular a failure of any other part of an UPS module requires 0.5h of downtime for the repair. Solving Markov model from Fig. 5, MTTF of a single Centiel UPS module becomes MTTFCUPS = 0.48h. Applying the set of Equations (8) – (10) we calculate dependability indices for different configurations and compare them in TABLE III.

Table 1

Comparing MTTF, MTTR, availability, and downtime per year for different architectures.

N+1	Power output (kVA)	Steady-state availability	Downtine per year
Typical modular architecture			
1+1	40	0.9999996	12
2+1	80	0.9999994	19
3+1	120	0.9999992	25
4+1	160	0.99999	32
Centiel modular architecture			
1+1	40	0.99999999998	$6*10^{-4}$
2+1	80	0.99999999995	$1*10^{-3}$
3+1	120	0.99999999991	$3*10^{-3}$
4+1	160	0.999999999	$4*10^{-2}$

As it may be observed, even for the 1+1 configuration (full redundancy), availability with the Centiel architecture significantly outperforms the one with typical n+1 architecture, as it increases from six and a half to even ten and a half nines. This means that the annual downtime is decreased from 12 s to 6*10-4. However, the 1+1 configuration also has a limited output of 40kVA. As the output increases, availability of both architectures slightly decreases, but the level of availability improvement with the Centiel architecture (when compared to a typical one with the same level of redundancy) gets even higher. For example, when the output is 160kVA (4+1 configuration), a typical architecture has availability of six nines (annual downtime is 32 s), whereas availability with the Centiel architecture is nine nines (annual downtime of 3*10-2).

Conclusions and ongoing work

We have modeled and evaluated availability of typical and Centiel UPS architectures. As we demonstrated, a novel approach by Centiel that combines innovative features and with modular architectures achieves extremely high level of availability that, even for high-output configurations with 160kVA reaches the level of even nine nines where typical architecture with the same power output and same level of redundancy has availability of six nines. Thus, with an advance architecture it is possible to improve availability by multiple orders of magnitude almost at the same price. The future work includes the analysis of different sets of UPS frames and configurations as well as sensitivity analysis. Also, a detailed cost analysis will be performed.

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Head Office:
Centiel UK
Faraday House
Caker Stream Road
Alton, GU34 2QF, UK

Global HQ:
Centiel SA,
Via alla Stampa 5a
Cadro, Lugano
CH6965, Switzerland

Phone:
01420 82031

Mail:
sales@centiel.co.uk

www.centiel.co.uk
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