WHITE PAPER

The impact of a power module's MTBF value on the modular UPS system

Modular UPS: reliability and internal failure rate

By Leo Saro, Clemente Zanettin and Vinko Božič

socomec
Innovative Power Solutions

Introduction

APPLI 647 A

Modular UPS systems are usually presented as having an extremely low failure rate when considering the UPS output.
In fact, the best modular UPS systems are designed to increase the global system's reliability and availability with minimum downtime due to their hot-swappable parts and cost-effective redundancy, the complete independence of each module and no fault propagation if one of the modules fails.
However, the biggest concern is their internal reliability: having a high number of modules increases the failure rate of the UPS system.
Consequently, to avoid this problem, the module's MTBF value should be much higher than the typical MTBF of a standard UPS.
The aim of this guide is to help users understand and quantify the strong impact of the power module's MTBF value on the internal reliability of the Modular UPS System, as well as the associated costs of substituting the failed modules, and the possible impact on the supplied equipment's downtime.

Glossary

Modular UPS	A UPS system with scalability and redundancy in which UPS power modules can be added (replaced) while in normal operation
Monolithic UPS	A “standard“ stand-alone UPS
MTBF	Mean Time Between Failures of repairable systems
MTTR	Mean Time To Repair
VFI	The Voltage and Frequency Independent output of a UPS
TCO	Total Cost of Ownership

Contents

Failure of modular UPS dystems

Modular UPS structures

A modular UPS structure is composed of several power modules in parallel. Each power module contains the hardware necessary to operate in VFI (Double Conversion) mode. Modular systems can have a hybrid bypass structure with distributed inverter bypasses and a robust mains bypass (Fig. 1), a distributed bypass structure like that of a parallel monolithic UPS system (Fig. 2), or a structure with a centralised bypass (Fig. 3).

Modular systems are generally designed to have one more module than is required for the UPS system's rated capacity, making them inherently "N+1" redundant. All modules are active and share the load equally. Should one module fail, the remaining modules will keep supplying the load in VFI mode without interruption. Due to this internal redundancy, modular systems are more reliable than monolithic UPS systems, but to fully profit from this advantage, an appropriate design and topology must be integrated into the modular system. Modular UPS systems have emerged as the result of technological advancements developed to address end users' primary concerns such as seamless scalability, concurrent maintenance and availability.

The availability of modular systems is recognised as extremely high: much higher than that of a stand-alone UPS and higher than that of a UPS system with a parallel configuration. There are two main reasons for this.

Firstly, the modular system's high availability is due to its modularity and resilience, and the power modules' N+x redundancy. This means that in the event of a module failure, the probability that the global system will be affected is low. However, this can only be true if the UPS modular system has been designed to detect failed modules and to disconnect them safely, minimising the risk of a failure propagation. Only the best modular systems can achieve this, using features such as completely independent and self-sufficient power modules (each one with its own independent control), real active and selective disconnection of a failed module with input and output galvanic disconnection from a common output, no centralised control for parallel management, etc.
Secondly, the low MTTR achieved thanks to hot-swapping, combined with a simple, risk-free plug-in replacement, greatly improves the availability.

The detailed analysis and calculations of the modular UPS system availability is not within the scope of this paper.

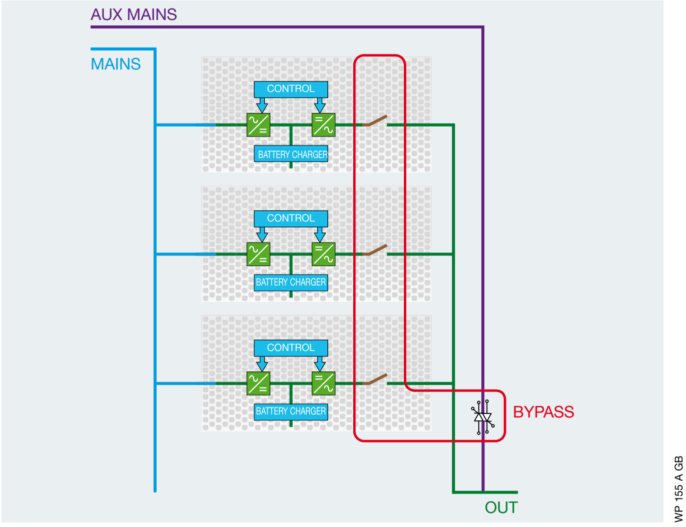


Fig. 1 - Modular UPS architecture - hybrid bypass structure (distributed inverter bypass and common auxiliary mains bypass).

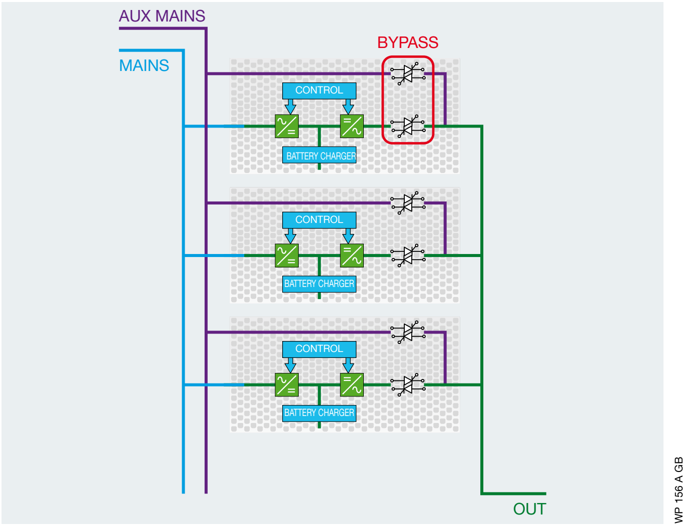


Fig. 2 - Modular UPS architecture - distributed bypass structure.

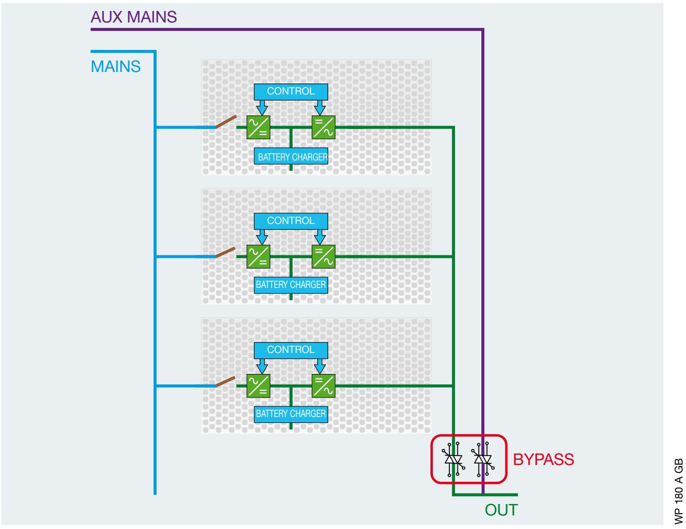
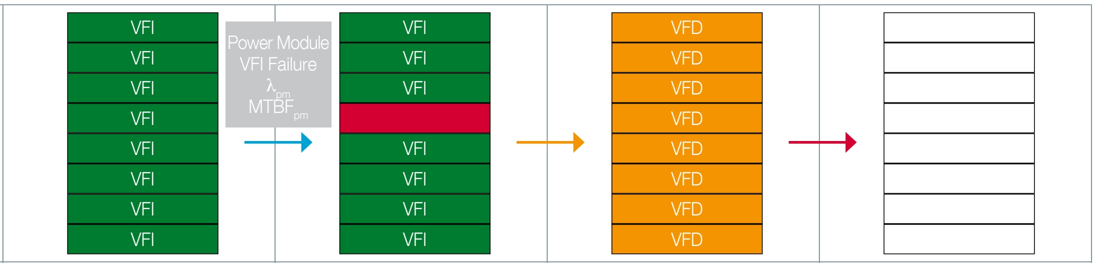


Fig. 3 - Modular UPS architecture - power modules connected to a centralised bypass.

Failure definition of modular UPS

The full analysis and definitions of the various types of failures possible a Monolithic UPS and in a Modular System UPS are the subject of a dedicated whitepaper [1].
The visual summary of the Modular System UPS failure modes are shown in tab. 1 and this failure structure is valid for all the modular UPS architectures described in Fig. 1, Fig. 2 and Fig. 3.

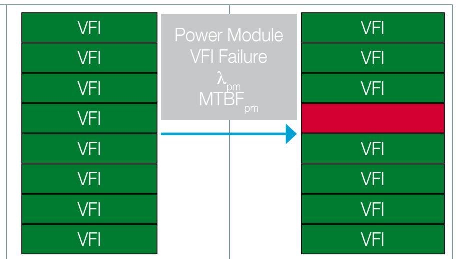


UPS SYSTEM FAILURE MODE		INTERNAL Failure	VFI Failure	UPS Failure
RELIABILITY PARAMETERS		λ_{INT} $MTBF_{INT}$	λ_{VFI} $MTBF_{VFI}$	λ_{UPS} $MTBF_{UPS}$
UPS INPUT				
UPS OUTPUT				
UPS CONDITION	VFI (double conversion) N+R	N+(R-1)	Permanent VFD (bypass mode)	UPS off
LOAD CONDITION	Supplied & protected		Supplied & very low protection	Load cut
LOAD PROTECTION LEVEL ON MAINS DISTURBANCE / CUT				

Table 1 - Modular UPS system conditions, failure modes and load protection levels.

Power module "failure" is defined as any event that damages one of the power modules within the system, ending the power module's capability to function in double conversion mode (VFI).
Such a definition is logical as it requires the power module to be replaced and, while the UPS system still functions in VFI mode, the system's redundancy is reduced (Tab. 1).
The failure rate of the power module is also fairly independent from the architecture of both the UPS system and the module itself: it is valid for modules with or without an internal auxiliary mains static bypass switch [1], or for modules with a centralised common bypass solution and no internal bypass switch. There are in fact some differences between different module types: the more complex modules with a complete internal bypass have a higher failure rate than the modules with no internal bypass. For the purpose of this WP, these differences are not significant.

The power module's failure mode has an associated failure rate λ_{pm}, its inverse providing the value $MTBF_{pm} = 1/\lambda_{pm}$ [Note 1].
It has been proved [1] that the MTBF value of a single power module MTBFpm is very similar (although slightly lower) to the MTBFVFI of a state of the art monolithic UPS, namely around 200,000 ÷ 300,000h.
This is also confirmed by on-site data gathered from power module failure rates for different types of modular UPS systems, whatever the bypass architecture of the power module.



UPS SYSTEM FAILURE MODE		INTERNAL Failure
RELIABILITY PARAMETERS		λ_{INT} $MTBF_{INT}$
UPS SYSTEM CONFIGURATION	N+R	N+(R-1)
UPS CONDITION	VFI (double conversion)	
LOAD CONDITION	Supplied & protected	

Table 2 - Power Module failure mode and Modular UPS failure mode.

Consequences of power module failures (internal failure rate)

As explained above, the failure of one power module within a modular UPS system can be considered as a simple “internal failure” that will not affect the double conversion mode of a state of the art UPS (with the selective disconnection of the failed module only, and no failure propagation). Consequently, the load is kept fully protected.
However, the biggest concern in a Modular UPS is its internal failure rate λ_{INT}, caused by the failure of the power modules [2]. In fact, the bigger the number of modules, the higher the probability of failure.
Over time, this can be a real problem as it has an important impact on maintenance and other associated costs, leading to a substantial increase of the Total Cost of Ownership.

System internal failure due to power module failures

As λ_{pm} is the failure rate of a single module, in a modular system with K_{pm} modules in parallel, considering the modules as being totally independent, the internal failure rate of the system is:

$$\lambda_{Sint} = K_{pm}\lambda_{pm} \qquad (1)$$

or, considering the internal MTBF of the system:

$$MTBF_{Sint} = \frac{MTBF_{pm}}{K_{pm}} \qquad (2)$$

The statistical number of modules F_{pm} that will fail during the lifetime of the system T_s is:

$$F_{pm} = K_{pm}\lambda_{pm}T_S = \frac{K_{pm}}{MTBF_{pm}}\,T_S \qquad (3)$$

The conclusion is that, given the number of modules and the supposed lifetime of the system, the number of power module failures depends on the modules’ MTBF value.
Another approach to evaluate the importance of a very high $MTBF_{pm}$ value in modular systems is to calculate the frequency of the power module failure inside the UPS system.
Starting from (3), the statistical average time between the modules’ failure TF_{pm} is:

$$TF_{pm} = \frac{T_S}{F_{pm}} = \frac{MTBF_{pm}}{K_{pm}} \qquad (4)$$

The total cost of replacing a power module includes the repair costs or the cost of a new module, but also the logistics necessary to cope with the failed module (module swap, internal management, back-and-forth shipments, service costs, etc.).
Defining $Cost_{purch}$ as the purchasing cost of a single power module and $Cost_{repl}$ as the global cost to replace a failed power module, the contribution of the power module replacement cost to the TCO is:

$$\Delta TCO_{pm} = \left(\frac{Cost_{repl}}{Cost_{purch}}\right)\frac{F_{pm}}{K_{pm}} \qquad (5)$$

As a practical example of the effects of a power module's MTBF value, a system comprising of 24 modules is considered, with a realistic lifetime of 15 years and a currently very high $MTFB_{pm}$ of 300,000h.
Applying (3) and (4) statistically, there are 11 module failures, which is almost equivalent to 1 failure per year! This global internal failure rate is considered excessive, as the number and frequency of failures experienced during the modular UPS system's lifetime will be an important burden to the end user. The associated costs of the substitution or the repair of the failed modules will have a big impact on the Total Cost of Ownership (TCO). Assuming a purchasing cost with a value of 100 when the modular UPS system is installed, the global cost associated with the full repair process of a damaged module can be estimated as 150 (6), as it also includes the logistics necessary to cope with the failed module (module swap, internal management, back-and-forth shipments, service costs, etc.).

$$\frac{Cost_{repl}}{Cost_{purch}} = 1.5 \qquad (6)$$

Following this assumption, the overall TCO increase is close to 70 % for a system with 24 modules. The data is represented visually in Table 3, in the column "300,000h best standard MTBF".
The next parameter, considered as even more important in DTC, is the system availability. A common simplification is to consider the modules to be completely independent (uncorrelated), therefore, through redundancy, a failure in one module will never affect the other modules. The best modular UPS have high levels of redundancy or resiliency in an attempt to reach maximum independence of the modules, but it is recognised that this subject must also be treated with a probabilistic approach. Such an analysis is outside the scope of this paper; however, it is intuitive that the more power module failures there are during the system's lifetime, the higher the risk of a cascading failure, and consequently, of a reduction in the global availability of the system.

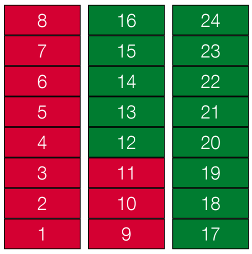
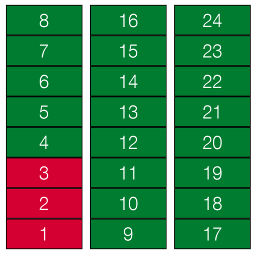
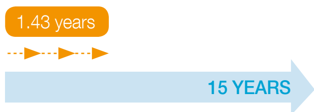
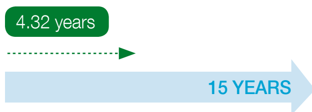
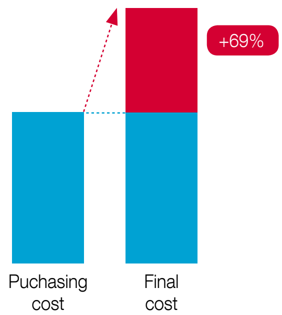
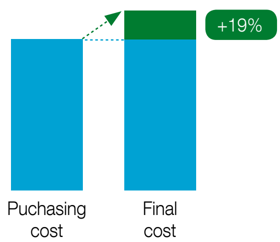
<table>
<tr><td>NUMBER OF POWER MODULES</td><td>K_{pm}</td><td colspan="2">24</td></tr>
<tr><td>SYSTEM LIFETIME</td><td>T_S</td><td colspan="2">15y</td></tr>
<tr><td>POWER MODULE'S MTBF</td><td>$MTBF_{pm}$</td><td>300,000h
BEST STANDARD MTBF</td><td>1,000,000h
ENHANCED MTBF</td></tr>
<tr><td>NUMBER OF POWER MODULE FAILURES DURING SYSTEM LIFETIME</td><td>$F_{pm} = \frac{K_{pm}}{MTBF_{pm}} T_S$</td><td>
</td><td>
</td></tr>
<tr><td>AVERAGE POWER MODULE FAILURE FREQUENCY</td><td>$TF_{pm} = \frac{MTBF_{pm}}{K_{pm}}$</td><td>
</td><td>
</td></tr>
<tr><td>TCO INCREASE DUE TO POWER MODULE REPLACEMENT</td><td>$\Delta TCO_{pm} = \left(\frac{Cost_{repl}}{Cost_{purch}}\right)\frac{F_{pm}}{K_{pm}}$
$\frac{Cost_{repl}}{Cost_{purch}} = 150\%$</td><td>
</td><td>
</td></tr>
</table>

Table 3 - Statistical analysis of the number of failures including the cost of replacement caused by the module's MTBF (failure frequency).

It is clear that the MTBF value of the individual power modules of a modular system must be greater than today's best MTBF value of 300,000h to avoid frequent internal system failures and related drawbacks.
This conclusion is not intuitive, as for monolithic UPS systems, an $MTBF_{VFI}$ value of around 300,000h is known to be suitable to ensure an acceptable UPS system reliability.
This apparent contradiction can be explained by considering a monolithic UPS as a modular UPS system with only one module [note 2]. It becomes clear that the number of power modules operating in parallel in a modular system alters the results.

It can therefore be concluded that a modular UPS system with standard 300,000h MTBF power modules presents some downsides:

- high internal failure rate,
- high TCO,
- affected system availability.

These points confirm that the end user's biggest concern regarding a modular UPS system with a large number of modules is its internal reliability. This remains a strong restraining factor which still limits the growth of the Modular UPS market [2].
To reach an acceptable system failure rate in a modular UPS system, the power module's MTBF value should be increased to at least 1,000,000h.
Such an MTBF value would allow the number of failed power modules to drop from 11 to 3 modules over 15 years for a system containing 24 power modules, which is equivalent to an increase in the average time without failure from 1.4 to 4.3 years.
This would also lead, using (6), to an increase in the TCO of just 19 % due to module replacement, instead of almost 70 %.
The data is represented visually in Table 3, in the column "1,000,000 h enhanced MTBF".

An MTBF value of 1,000,000h may seem challenging to reach, but it is of crucial importance for an end-user, consultant, engineer, etc. conscious of the extreme importance of having high MTBF values for power modules in modular systems.
It is therefore necessary to have a reliable way of providing the MTBF value.

There are basically two methods to obtain the MTBF value:

- the predicted MTBF, for which various standards, such as MIL-HDBK-217F, Telcordia (Bellcore) SR-332, IEC TR 61709 or FIDES can be used,
- the empirical MTBF, based on real data gathered regularly from the field (cumulated hours worked of installed power modules and number of failures).

Each method presents advantages and disadvantages, as described on Tab. 4.

	PREDICTED MTBF	**EMPIRICAL MTBF CALCULATED FROM FIELD DATA**
MTBF DATA AVAILABILITY	AVAILABLE FROM THE START OF PRODUCTION	REQUIRES SUFFICIENT INSTALLED EQUIPMENT AND SUFFICIENT CUMULATED TIME WORKED, ONLY AVAILABLE SOME YEARS AFTER THE START OF PRODUCTION
MTBF DATA CONSINSTENCY	COMPLEX ESTIMATION BASED ON CALCULATIONS, STATISTICAL ANALYSES AND TESTS DONE ON PRE-SAMPLES. PREDICTIVE VALUE	CALCULATION BASED ON REAL DATA AND COMPRISING ALL FAILURE TYPES
MTBF DATA CREDIBILITY	MTBF ESTIMATION CAN BE DONE BY A THIRD PARTY, OFFICIAL CERTIFICATION	MTBF IS BASED ON FIELD DATA DECLARED BY THE UPS PRODUCER, NOT VERIFIED BY A THIRD PARTY
CUSTOMER BENEFITS	- AVAILABLE FROM THE PRODUCT LAUNCH ON THE MARKET - IMPARTIALITY WHEN CERTIFIED BY A THIRD PARTY	- REAL VALUE STEMMING FROM REAL DATA, REAL APPLICATIONS AND REAL ENVIRONMENT

Table 4 - Characteristics of a predicted MTBF versus an empirical MTBF calculated from field data.

Using just one of the two methods might not be considered reliable enough due to the limitations of each described in Table 4.
To provide an accurate and indisputable MTBF value, both the predicted MTBF value certified by a third party and the measured MTBF value based on field data must be made available [7].

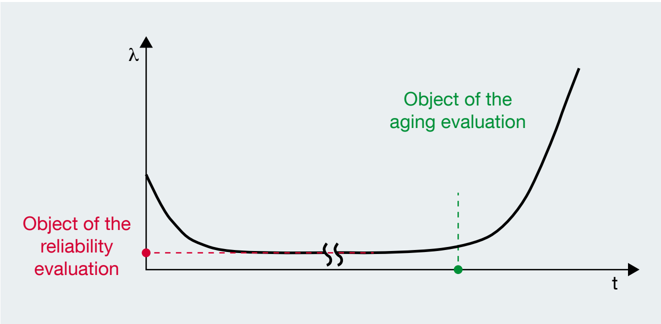
Conclusion

This WP investigates the reliability (MTBF value) of the UPS power module, which is a building element of the modular UPS system. For the purpose of this study, there is no distinction between the different types of modular UPS system architectures: the distributed bypass architecture, the centralised bypass or the hybrid architecture.
It presents the impact of a power module's MTBF value on a modular UPS system and demonstrates its influence on the internal reliability of the system and the associated costs for the substitution of the failed modules.
It demonstrates that the use of numerous standard power modules with a typical 300,000h MTBF value causes a high internal failure rate over the modular UPS system's lifetime. This reduces the global reliability of the UPS system and, moreover, has a big impact on maintenance and other associated costs, causing a dramatic increase of the Total Cost of Ownership.
Finally, it establishes that the power module's MTBF value should be enhanced to at least 1,000,000h to obtain an acceptable system failure rate.
Both the predicted MTBF value calculation, preferably certified by a third party, and the empirical MTBF value based on field data should be obtained to build confidence in the declared MTBF value.

Notes

[Note 1]

This analysis focusses on the constant failure rate period represented on the classic bathtub curve, based on the assumption that over this period, the statistical distribution of failure is exponential: this corresponds to the useful life of the equipment (left). The Reliability and Aging evaluation is illustrated on the bathtub curve (right).



WP 177 A GB

With the above assumptions, failure occurs with a failure rate λ that is linked to the MTBF value: MTBF = 1/λ.

[Note 2]

To evaluate the number of failures over a 15-year lifespan for a monolithic UPS system, (3) and (4) may be calculated using K_1 = 1 as the monolithic UPS system is equivalent to a modular UPS system with one module, with $MTBF_{VFI}$ = 320,000h (assumed to be slightly higher for the monolithic UPS system as it does not operate in parallel).
The number of failures F_1 = 0,41 over 15 years for a monolithic UPS system, which is considered an excellent result.

Bibliography

[1] White Paper: Failure mode definitions for UPS systems – Saro Leo, Clemente Zanettin – Vinko Božič – Socomec.
[2] Modular UPS Market, Global Forecast to 2020 - Markets & Markets 2015.
[3] The impact of a single module's MTBF value in Modular UPS Systems: technique for its assessment, improvement and final validation – Leo Saro, Clemente Zanettin – 2016 IEEE International Telecommunications Energy Conference (INTELEC).
[4] Design high availability system - Zachary Tailor- Wiley, 2013.
[5] Design for Reliability - Dana Crowe, Alec Feinberg - CRC press, 2001.
[6] IEC TR 62380 - Reliability data handbook - Universal model for reliability prediction of electronics components, PCBs and equipment, 2004.
[7] White Paper: High reliability design approach for UPS Power Modules and methodology to determine the true MTBF value – Saro Leo, Clemente Zanettin – Vinko Božič – Socomec.

About the authors

Leo Saro

Leo Saro received an MSc degree in Electronic Engineering from the University of Padova, Italy, in 1987.
After 7 years of experience in FIAR (Finmeccanica) designing avionic radars, he has been working for Sicon s.r.l. (Socomec group) since 1994, where he currently is the Market and Product Manager for Modular UPS and Industrial UPS (after 10 years spent in the R&D department designing telecom rectifiers and modular UPS). He is also involved in the development of new products.
His major research interests are related to the development of innovative solutions for critical power applications and to product marketing strategy and communication.

Vinko Božič

Vinko Božič received an MSc degree in Electronic Engineering from the University of Ljubljana, Slovenia, in 1985.
He worked at ISKRA Microelectronics for 8 years as a reliability engineer, dealing with failure analysis, design and production issues influencing the reliability of custom-made integrated circuits. He then joined Socomec Sicon, in Ljubljana, first handling technology transfers, then technical sales support, as well as managing sales in Central and Eastern Europe. He is currently acting as a business developer for Germany, Central and Eastern Europe.
His major research interests are related to the strategic definition of innovative solutions for critical power applications, as well as their promotion and implementation in significant projects.

Clemente Zanettin

Clemente Zanettin received an MSc degree in Electrical Engineering from the University of Padova, Italy, in 1997.
His thesis was on the subject of harmonic filtering and power factor correction in electrical networks. He worked for Siemens in 1998 and has been working for Sicon s.r.l. (Socomec group) since 1999, where he currently is the Power Electronic Professional Leader.
His job activities include the design of converters for UPS, PV and storage applications.
His major research interests are related to power semiconductors, magnetic components and system reliability and availability. He is a fellow of the IEEE.

Socomec: our innovations supporting your energy performance

1 independent manufacturer

3,200 employees worldwide

10 % of sales revenue dedicated to R&D

400 experts dedicated to service provision

Your power management expert

POWER SWITCHING

POWER MONITORING

POWER CONVERSION

EXPERT SERVICES

The specialist for critical applications

- Control, command of LV facilities
- Safety of persons and assets

- Measurement of electrical parameters
- Energy management

- Energy quality
- Energy availability
- Energy storage

- Prevention and repairs
- Measurement and analysis
- Optimisation
- Consultancy, commissioning and training

A worldwide presence

8 production sites
- France (x3)
- Italy
- Tunisia
- India
- China (x2)

27 subsidiaries
- Australia • Belgium • China • France
- Germany • India • Italy • Netherlands
- Poland • Romania • Singapore
- Slovenia • Spain • Switzerland • Thailand
- Tunisia • Turkey • UK • USA

80 countries
where our brand is distributed

HEAD OFFICE

SOCOMEC GROUP
SAS SOCOMEC capital 10 633 100 €
R.C.S. Strasbourg B 548 500 149
B.P. 60010 - 1, rue de Westhouse
F-67235 Benfeld Cedex
Tel. +33 3 88 57 41 41 - Fax -33 3 88 57 78 78
info.scp.isd@socomec.com

www.socomec.com

YOUR DISTRIBUTOR / PARTNER

ENERGY SPECIALIST SINCE 1922

socomec
Innovative Power Solutions

DOT 24013i - 03/18 - Réalisation: Socomec