CUSTOMIZED ELECTRICAL SYSTEMS: THE SPECIAL CASE OF THE COLOSSEUM

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Abstract. The design of the electric system "architecture" purposes to accomplish performances of operation, maintenance and safety. The paper discusses about the criteria in designing special cases that need a structured architecture complying with electrical loads extensively distributed. Historical or innovative architectural buildings outside of the typical and classical configurations require tailored solutions for the electrical systems.
The general criterion of designing power distributions is to structure the system in two or more levels from the utility up to the terminal equipment adopting a number equal or lower of voltages. The paper deals with a proposal of customized power systems to be applied to the Colosseum, the most important monument of Roman archeology.

Keywords*: Electrical system design, power systems for historical buildings, safety by design, reliability by design, brush-distribution .*

I. INTRODUCTION.

The paper deals with the restructuring design of the lighting and power systems of the Colosseum in Rome (Italy); it provided a case study to analize special problems and constraints correlated with this particular kind of structures [1].
In *typical structures*, the architecture of the power system is naturally defined by internal configuration, as floors, rooms, locals that identify load areas. In *special structures* characterized by large geometrical dimensions, the system architecture needs more accurate modeling criteria. In fact, in these cases the electrical loads are extensively distributed in a large area or “open” volume, with one or more of the following characteristics: - modular and repetitive loads, - higher risk for elevated presence of persons and/or fire ignition, - subject to weather.
As sample cases of special structures that need a *structured electrical distribution* they can be recognized [2]:
- innovative architectural buildings, outside of the typical volumes and classical structures, that require custom-made configurations;
- historical, archeological, museum areas ;
- large open space buildings, for commercial, sport, expositive activities, natural and amusement parks, etc.
- roadway tunnels, photovoltaic fields that present loads/PV distributed in a particular large area and a globally power demand/production that could be considerable.

II. POWER AND CONTROL SYSTEMS RELIABLE BY DESIGN

In the *special structures* considered in this paper, the power and control system must adapt its architecture to its special and complex characteristics, in particular taking into account the relevant geometric, architectural and other constraints.
The requirements of the power system in the structures with historical and/or artistic importance have to take into account very many special characteristics, such as [3]:
- the large number of visitors with the related safety requirements against electric shock and fire ignition,
- the non-invasiveness, adequate mechanical withstand and relative installation stability of the various elements that require non conventional components and adequate installation kinds,
- the resilience of the system itself to any action of tampering or sabotage with the related security and service continuity requirements.

To comply these requirements, an essential approach is to apply an adequate zoning of the technical distributed systems for the whole structure. The goal is to create service islands for a reduced influence zone that is characterized by an independent operation from the other islands.
The island favorites the failures confinement inside the zone, with an high immunity for the whole system. For the power system the reduced load demand for each island allows to install an isolation local transformer that permits:
- to adopt the TN-S system, confining the ground faults (islanded immunity) inside the zone;
- to reduce short circuit currents (s.c.c.) at a prospected value and limiting the related let through energy (components size reduction in the zone); for transformer rate up to 15 kVA the prospected s.c.c. maximum value is limited generally lower than 1 kA;
- to reduce the secondary voltage nominal value with high benefits for safety.

The design of each zone can apply a “Darwinian” approach in sizing the components and in drawing the layout. This approach allows to optimize the electrical behavior of the system and to minimize the operation time during the installation and in the maintenance. A criterion to structure the load groups in each zone is to determine, as much as possible, a homogeneous and repetitive branch distribution system. Each one zone can be served by a *local satellite center* (LSC), both for power and for data services (Figure 1).

The zoning of the technical systems distributed in the structure, determines an architecture subdivided at least in two sections:

- the Backbone Network BN as primary distribution that supply all the *LSCs*;
- the Satellite Networks SNs as branch distribution in each zone starting from the *LSC*.

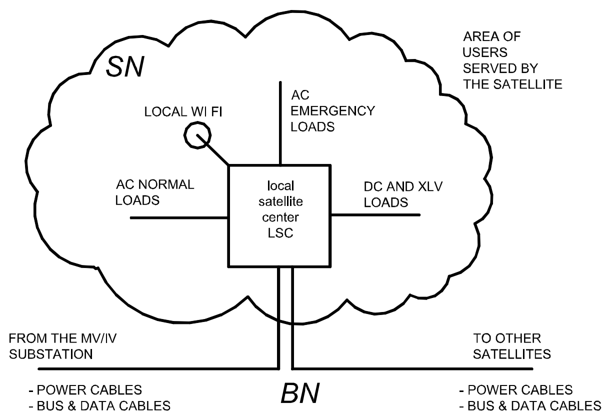

Figure 1. Satellite Center.

Backbone Network BN. BN generally consists of electrical and data networks, from the connections with public networks, up to the LSCs.
Considering the presence of local transformers for each zone, the long distance of the main circuits, the primary electrical distribution of the BN can be operated at an Intermediate Voltage IV (i.e. 1 kV that is the limit value of the low voltage in IEC in order to optimize the cross section and to reduce the voltage drops, and can be operated in radial or loop architecture.
The Italian National Standard CEI 64-15 “Electrical Installation of valuable buildings having historical and/or artistic importance” prescribes the maximum nominal value for the voltage equal to 400 V, considering the presence of artistic goods, historical furnishes and other flammable materials. In the cases of absence of these conditions, especially in external or open structures, it seems appropriate to adopt the 1 kV nominal voltage, gaining the related benefits.
The BUS Control and Data BN transmission system, most suitably is wired by optical fiber.
Satellite Networks SNs. SN consists in the distribution from the LSCs up to the individual distributed loads, light points and sockets, including the system of control and regulation. It is operated at low voltage (LV). The LSC can include a local transformer IV/LV, an UPS for emergency loads, a DC bus, and a extra low voltage transformer for loads at non-conventional voltages (like extra low voltage for BUS and Data systems) as shown in Figure 2. The power system from the panels to the load can be operated in a radial architecture by adopting special multipolar cables with the grounding equipment conductor incorporated, and with a special taping against rats, and a special sheath against water and other atmospheric actions.
For Data SNs, the transmission system most suitable is wireless.
For BUS control networks (for lighting system), the transmission system most suitable is a secure wireless mesh network.

The general Control and Data system is shown in Figure 3.
Many features of various services can be installed, such as communications systems, monitoring and control, security and emergency, utilities for electrical, audio, video and multimedia, utilities for working premises, set preparation and museum permanent and temporary.
In particular, the Figure 3 shows the lighting control architecture.

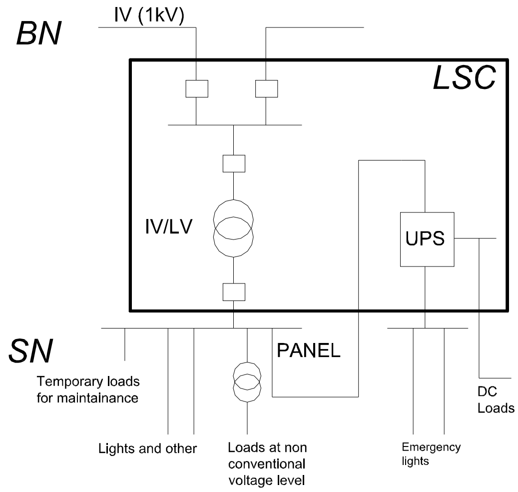

Figure 2. LSC scheme

The lamps can be controlled by:
- an analogic wired system (AWS) (1-10V);
- a digital wireless system (DWS).

The choice of the wiring of the wireless connection is done according to the architectural constraints.
Both the subsystems AWS and DWS are connected with a main BUS system (MBS) that adopts, for example, the Konnex KNX protocol: the analogic by an actuator SA KNX/1-10V, the digital by a gateway MG KNX/mesh system. The sensors can be wired directly on the KNX BUS or connected by the MESH network.
The MBS is connected to the BN by a gateway KNX/IP.
For the DWS, a wireless mesh network is suggested. This is a communications wireless network made up of radio nodes with a mesh topology. This kind of network consists of mesh clients (the lamps) and mesh routers (the gateways KNX/MESH, called MG in Figure 3). The MG devices forward traffic to and from the KNX BUS and so to and from the KNX/IP gateways connect to the BN. The coverage area of the radio nodes represents a mesh cloud. The main characteristics of a mesh network is the reliability and the redundancy [4]. In the case of failure of one node, the rest of the nodes can still communicate with each other, directly or through one or more intermediate nodes.
In conclusion, the suggested infrastructure organized in many modular satellites allows obtaining several goals:
- to provide a reliable service with a level of quality adequate to the importance of the structure (reliable by design system),
- to simplify the management and maintenance, even if equipped with high technology solutions (maintainable by design system),
- to improve the performance from the energy point of view, providing solutions with high efficiency and with a system of control and supervision which drastically reduce annual energy expenditures (efficient by design system),

- to support a temporary need for more electrical load, such as external lighting, temporary job sites, special equipment, shows, etc (flexible by design system),
- to provide the ability to deploy new multimedia and internet services (multimedia designed system);
- to cope with any future needs for expansion of services, avoiding useless redundancies and temporary solutions (scalable by design system);
- to improve the safety of users, visitors, maintenance personnel and all users operating in the Special Structure (safe by design system).

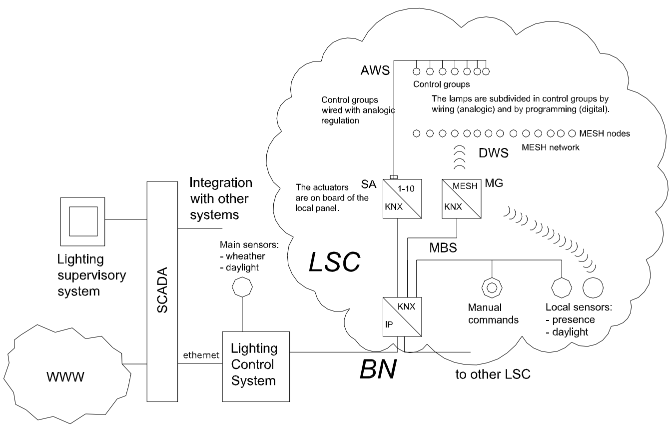

Figure 3 General layout of Data and Lighting Control System

LV Modular distributions. As already mentioned, the modeling of electrical distribution promotes the modularity of components and facilitates the installation and maintenance structuring the equipment, as much as possible, in repetitive groups with a standardized local distribution system (unified cross section of the cables and characteristic parameters) [5,6].

Modeling the power and control systems architecture has to achieve many objectives and appears suitable to apply logic that facilitates the understanding of the structures, promotes the modularity of components to help installation, maintenance operation and efficient control.

Therefore, all the components should have adequate ratings, and be installed in a proper manner.

III. THE SPECIAL CASE OF THE COLOSSEUM

The Colosseum is the most important monument of Roman archeology for the architectural design, for the suggestions that evokes, for its location that is the center of Rome, near the Roman Forum and the Triumphal Arch.

Its architectural design reflects the excellent Roman logic of the organizational capacity of each activity. The Colosseum is an example of kalòs kagathòs (the beautiful and the good), where the architectural aesthetics and the best result in the use of the structure are a dipole indissoluble. With the elliptical shape and accessibility to 360 degrees, it offered the practicability of the structure for an audience of 50,000 to 75,000 people.

The arena is an ellipse of 527 m perimeter, with aces that measure 187.5 and 156.5 m (Figure 4). The arena inside size are 86×54 m, with a surface area of about 3,500 m². The actual height reaches 48.5 m, but originally it came at 52 m.

A whole range of sectors, in which it was divided, allowing a smooth flow and placement of such a large audience with a flock logic high efficiency, comparable to a framework of military troops, of which the Romans were unparalleled directors.

The type of the most famous shows was not using the art of simulation, but was based on actual fighting, unrepeatable events. Therefore, the visit of the Colosseum can evoke suggestions in each visitor.

The new technology of electrical systems and communication technologies (ICT) can add values of modern features for the best use of this wonder of the world.

Adequate lighting system makes obtaining a new dimension to the structure, which enhances the spatial dynamics in all its arches, creating unique suggestions with the language of lights, modulated by a system of control and supervision and completed with sounds and images by audio-visual and multimedia (Figure 5).

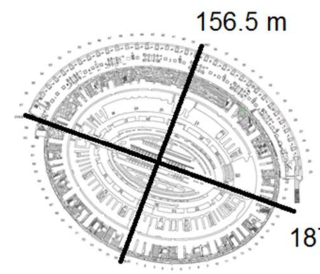

Figure 4. Dimensions in meters of the Colosseum ellipse.

Lighting system The integral remaking of functional and architectural Colosseum could provide a complex of systems of lights of different type which require a power supply system and adequate control. The lighting concept is based on a “surface interpretation” which highlights solids and a “grid interpretation” which focuses on voids, thereby deciding against any form of lighting which invites a vertical or horizontal interpretation of the monument.

The design underlines the different nature of the “front walls” along the perimeter: the northern wall, still intact, maintains its original function as a facade whereas on the southern front the innermost ring has become a facade following the collapse of the other two rings.

This design concept is implemented by two lighting systems for each front wall: a projected external light and an internal lambent light within each of the arches. Each of the four systems will have to be controlled separately owing to differences in their luminous flux and color temperatures. The adjustable calibrations of each system, set in predefined cycles which can be altered in case of special events, will grant the monument different levels of interpretation.

Given the internal architecture’s complexity, the design goals are to realize a lighting system that offers an interpretation hierarchy of the structure and develop many scenarios and interpretative hypotheses, which can be adapted to suit the numerous needs of the monument. Primary detectable morphological elements aim to offer different scenarios for the interpretation of (Figures 5 and 6):

- the horizontal planes, given by the arena's perimeter and the second and third level of rings; - the vertical planes, given by the first and second levels and the attic; - the inclined planes, which follow the geometric layout of the 'cavea'; - the main axes.
Common to all these scenarios is the general criteria of a hierarchy of light, which foresees a gradual decrease in light intensity from the inside going outwards and from the bottom to the top to underline the plastic properties of the Colosseum.

The actual average demand in normal service is about 60 kW during the night and 80 kW during the day with peaks up to 170 kW. The electric power estimated after the remaking is:

Table I

Distributed lighting and sockets	PL	100 kW
Offices and services	PS	30 kW
Elevators and techincal systems	PT	70 kW
Available for events	PA	100 kW
Global	PG	300 kW

Figure 5. Lighting system: primary scenario which highlights a vertical interpretation.

Figure 6. Lighting system: total scenario which highlights vertical, horizontal and inclined elements.

Power system. Besides the above mentioned main requirements of the power system (number of visitors, non invasiveness, resilience to sabotages), the Colosseum have to take into account very many special characteristics, such as:

- the exposure of the components to atmospheric agents, providing an adequate degree of protection provided against intrusion (body parts such as hands and fingers), dust, accidental contact, and water by mechanical casings and electrical enclosures (international protection marking IP code [IEC]),
- the feature of TV broadcast worldwide that have some events, considering an additional specific distribution system sized for the prospected load demand.

In fact, the Colosseum is a special structure that can accommodate events with high electrical loads and considerable presence of the public, of a strategic also subject to terrorist attacks and where power and technical systems can be at hand.
From the point of view of the electrical and lighting systems, the Colosseum is currently connected via a low voltage supply point with contractual power of 200 kW. The electric power system serves the lighting and other services located inside the amphitheater.

This makeover is not possible without a complete restructuring of the supporting structure and electrical systems by the implementation of a data network for control and communication.
The distributed power PL is 100 kW. It can be considered distributed along the ring of the Colosseum.
The suggested layout of the electric system consists in (Figures 7 and 8):

- a point of delivery at the voltage of 20 kV;
- a main medium voltage switchboard (MVSB);
- a distribution system at the voltage of 400V for the Offices, Services, Elevators and, Technical Systems;
- a main loop distribution (BN) operated at an intermediate voltage of 1 kV for the distributed lighting systems;
- local panels (LP) for each zone, equipped with local transformers (LTs) 1/0,23 kV (i.e. of 15 kVA rating power) with the neutral point grounded and the neutral conductor not distributed, supplying each zone subdivided in two subsectors;
- subpanels supplied by the LPs, for the subsectors;
- a secondary distribution (SN) starting from the LTs at the voltage of 230V phase to phase and 115 V phase to ground with high benefits for safety.

- a special feeder operated at the voltage of 1 kV for the panel available for special events (100 kW) with an adequate LT.

The LTs installed in each satellite guarantee a natural compensation of the voltage drop on the main feeder and the equalization of the prospected maximum value of the short circuit current. The power PL can be subdivided in 8 zones. Each zone is subdivided in two subsectors supplied by a proper panel.

All the Colosseum will be "wired" as well as with an electric power system even with a ICT system control. The wiring can be of a low visual impact, adopting minimally invasive solutions.

ICT System. The ICT considered services are:

- the BUS Control systems for lighting and other regulations,
- DATA systems for all the other data communications.

For the data systems it can be introduced where possible a wireless solution.

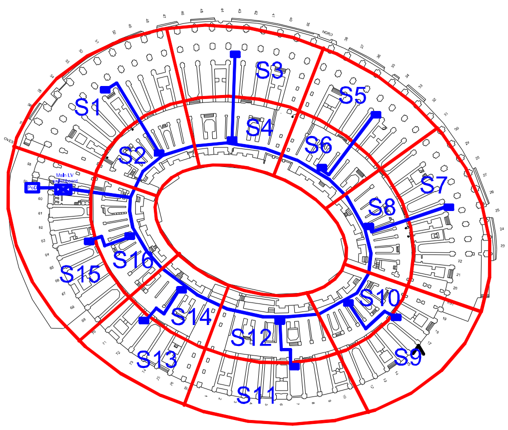

Figure 8 Power system architecture with 16 satellites

A logic of a customized power system, applied to the Colosseum, has to be essentially able to withstand and survive the local types of stress.

Transformer, generator sets and same low-voltage distribution can be located in proper internal local. The internal distribution has to be designed complying with the special power distribution that must locate, as much as possible, the backbone primary distribution at the level basement, because it needs the best protection from external actions and the lowest vulnerability to flooding, rodents and people actions. This main distribution, also if with minimum exposure to the fire and higher temperatures, can be characterized by components of fire non-propagating cables, low smoke and very low level of toxicity.

IV. Protection Against Faults

In these special structures a timely protection against faults derived by mechanical deteriorations, damages, sabotages, etc. is a crucial goal considering critical aspects presented by the branch circuits. A long length (up to 50-80 meters) and cables with a small size (for architectural constraint) characterize these circuits. The presence of local transformers determines low values (<1500 A) for the faults with a power factor near to the unity and the short circuit currents are generally with arcing and rarely bolted.

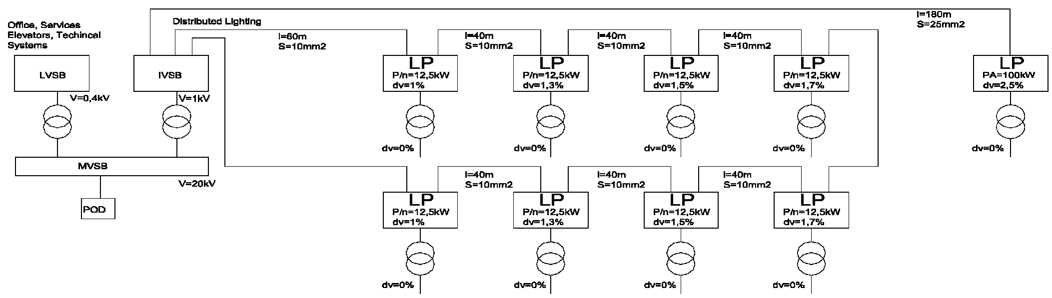

Figure 7. Colosseum power system architecture

Short circuits. In these cases of power factor near to unity, the arc current is intrinsically discontinuous and the fault current is extinguishing itself in few cycles (for reference as mean time, t_{arc} =0.04s).

The arcing fault I_F can be characterized by means of a probabilistic factor h=0.7, equal to the value of the arcing fault in per unit of the bolted fault $I_{kbolted}$. It is suggested to assume a value h=0.7 in correspondence of which the arc-fault has the 50% probability to reach a peak value not less than 70% of bolted short circuit value [7]. The value 0.7 $I_{kbolted}$. evaluated at the end of the circuit (minimum prospected value) has to be considered in selecting the instantaneous trip I_m of a CB and to guarantee $I_m \leq .0.7\ I_{kbolted}$

International Standard IEC/EN 60898-1 [8] classifies the circuit breakers by the letters "B", "C" or "D" for the instantaneous tripping current I_m. It is the minimum value of current that causes the circuit-breaker to trip without intentional time delay (i.e., in less than 30 ms), expressed in terms of I_n: - B above 3 I_n up to 5 I_n - C above 5 I_n up to 10 I_n - D above 10 I_n up to 20 I_n.

An easy and immediate criterion consists in using a very high-speed protection trip (few half-cycles), able to prevent the natural fault evolution and a CB correctly sized according to the cable with a B curve and a low value of rated current I_n (i.e. 6 or 10 A).

Ground faults. A complete protection of a circuit against the sputtering arcs, of any types, can be assured:

- by the special device, recognizing characteristics unique to arcing (the well known Arc-fault Circuit Interrupter AFCI),

- by an ordinary Ground Fault Protective Device (GFPD), when the circuits are wired with the PE protective conductor even if supplying double insulated equipment or with Ground Faults - Forced Cable, GFFC-type [9].

The GFFC-type cables convert the line-to-line fault into a line-to-ground fault or into a mixed-type case. This measure is recommended in the cases of circuits exposed to mechanical damage or other insulation stresses. The special design for single-core or multicore power cables is such that each insulated core has a concentric conductor shield. By adopting GFFC-type cables coordinated with a residual current breaker RCB, the fault can be easily detected, because the shield connected to ground provides a conductive path for the damaged cable. The RCB type A ensures that its tripping is triggered, by normal ac (alternating current) and also by residual pulsating direct current, as in the sputtering arc ac reduced to a half-cycle duration like the case of electronic components. The standard IEC 60755 [10] defines the types AC, A, and B of RCDs depending on the characteristics of the fault current. RCD type AC guarantees the tripping for residual sinusoidal ac, while RCD type A ensures also the tripping for residual pulsating dc also if superimposed by a smooth dc. RCD type B ensures in addition the tripping for sinusoidal residual currents up to 1 kHz or superimposed by a pure dc or which may result from rectifying circuits, and for pulsating dc superimposed by a pure dc.

V. CONCLUSIONS

The restructuring design of the lighting and power systems of the Colosseum in Rome (Italy) provided a case study to analyze special problems and constraints correlated with this particular kind of structures. The requirements of the power system in the structures with historical and/or artistic importance have to take into account very many special characteristics, such as the large number of visitors, the non-invasiveness, adequate mechanical withstand, installation stability of the equipment, the resilience of the system, the service continuity.

The power system suggested for this special case is an electrical system with evolved adequate characteristics:

- installation of components the less invasive and contained dimensions,
- controlled electrical parameters (voltage drop and short-circuit),
- balance of the electrical loads,
- an effective protection against electric shock by adopting redundant systems,
- special versions of the various components and installation types.

References

[1]. Bowers, Brian, Roman engineering [overhead power line history], Proceedings of the IEEE, 2003, Volume: 91, Issue: 2

[2]. G. Parise, L.Martirano, L.Parise, "The Architecture Of Electric Power Systems: Some Special Cases" IEEE-IAS ICPS Technical Conference, 20 May - 23 May 2014 Worthington Renaissance Forth Worth Hotel Fort Worth, TX, USA

[3]. CEI 64-15 Italian Standard, Electrical Installation of valuable buildings having historical and/or artistic importance

[4]. Bruno, R.; Conti, M.; Gregori, Enrico, Mesh networks: commodity multihop ad hoc networks, IEEE Communications Magazine, 2005, Vol. 43, Issue 3

[5]. G. Parise, L. Martirano, P. E. Sutherland, V. Saporita, D. Neeser "Natural and prospective parameters modeling architecture of electric power systems ", IAS Annual Meeting 2002 October – Pittsburgh

[6]. G. Parise, L. Parise "Microsystem Criteria In Branch Circuits Design" IEEE-IAS ICPS Tech. Conference, May 1-5, 2011 New Port Beach, California (USA) 2010 PSEC 565

[7]. Parise, G.; Grasselli, U.; Di Luozzo, V., Arcing fault in sub-distribution branch-circuits, IEEE Transactions on Power Delivery, 1993, Vol. 8, Is: 2

[8]. IEC/EN 60898-1 Electrical accessories Circuit-breakers for overcurrent protection for household and similar installations Part 1: Circuit-breakers for a.c. operation Edition 1.2 2003-07

[9]. Parise, G.; Martirano, L.; Nabours, R.E., Arc-fault protection of branch circuits, cords, and connected equipment, IEEE Transactions on Industry Applications, 2004, Vol. 40, Issue: 3

[10]. IEC 60755, General Requirements for Residual Current Operated Protective Devices Jan. 30, 2008.

BIOGRAPHIES

Giuseppe Parise (M'82-SM'03-F'10-LF'15)) received his M.S. degree in Electrical Engineering from the Sapienza University, Rome Italy in 1972. Since 1973, he has been with the Department of Electrical Engineering, Faculty of Engineering, Sapienza University of Rome, where he is currently a Full Professor of Electrical Power Systems. He has been Designer of power electrical systems in buildings complexes as in: the Sapienza University City, the Engineering Faculty, the Polyclinic Umberto I, the Italian Parliament and the Campus Biomedical Research Center. He has authored about 300 papers and he is the holder of two patents and three Prize Paper Awards by IEEE/IAS PSD. Prof. Parise has been a Member of Superior Council of Ministry of Public Works since 1983. He is active in the IEEE Industry Applications Society (past Member at Large of Executive Board), chair of the committee I&CPS Forensics and of the committee I&CPS Ports. He is past coordinator of the Electrical Engineering Area of Sapienza University, chair of Italy Section Chapter IA34, Member of subcommittees of the Italian Electrical Commission (CEI) and of the Electrical Italian Association (AEIT), the vice President of Association Safety Technology Research for Industry (ASTRI), past President of AEIT Rome's Section. Since 1975, he has been a Registered Professional Engineer in Italy. parise@ieee.org

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Luigi Parise (StM'06-M'10) received the B.S. degree (three years), the M.S. degree (two years) and Ph.D. degree (three years) in Electrical Engineering from the Sapienza University of Rome, Rome Italy, in 2007, 2009 and 2014 respectively. He was Research Fellow at University of Calabria (UNICAL) and he is currently Voluntary Research at Sapienza University of Rome and Tutor in electrical power systems in hospitals in the University Biomedical Campus of Rome. Mr. Parise was a recipient of the 2010 Italian Electrotechnical Committee (CEI) Award for the Best Thesis titled: Electrical Service Continuity in Critical Buildings - Protection of Hospitals against Lightning. He is a member of the Electrical Italian Association (AEIT), the R8/Europe Area Chair of IEEE Industry Applications Society SBCs and the Secretary of Italy Section IAS Chapter. Since 2008, he has been a Registered Professional Engineer in Italy.

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