Operational Resilience of Hospital Power Systems in the Digital Age

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***Abstract*—An advanced guideline is required to support the design of power supply systems for the performances of service continuity and power outage resilience, which are vital for hospital power systems and strategic operational structures (SOSs). The supply sources, the power system topology, and its management are fundamental in guaranteeing the electrical resilience of the power system. There is still no standard to evaluate the adequacy of hospital power systems for natural calamities and human-made disasters and, subsequently, for the ordinary operation. The World Health Organization recognizes it as a basic problem and at this aim has to claim clearly the status of SOSs for the hospitals, recommending to safeguard and plan the full operability. The hospital power systems need a local fortified electrical structure, designed for service continuity during fault events and managed to ensure an adequate dynamic response to any emergency and maintenance needs. The importance of the business continuity management is highlighted; it has to be qualified for a permanent design with both the in-op approaches for the initial installation of the system and its life cycle operation.**

***Index Terms*—Concurrent maintenance, integrity levels and resilience, in-op approach, resilience to disaster, service continuity.**

I. Introduction

THE causes of outages in a power system are attributable to different levels of disturbance in an ordinary operation to the maintenance exigencies and to local failures, and in exceptional situations to natural and anthropic disasters. Appropriate solutions by design can face all of them.

The hospital power systems (HPSs) are structures at greater risk in the event of earthquakes, fires, floods, and hurricanes.

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The entity of the consequences in the case of disruptive events must save the structures of a building and guarantee the essential services, such as electricity, water, communication, transportation, and hospitals. It is well known that one of the most critical consequences is the loss of service continuity that, in hospital buildings, determines the interruption of a primary public service and the risk of the loss of human life and damage to public health.

After a disruptive event that generates a calamity, an extended electrical blackout can implicate many users supplied by the grid involved in the disaster especially for the HV lines; large areas of the neighboring territory can be left without the electric service and communication [1].

A tropical storm Leslie hit Portugal, France, and Spain, in 2018. Another storm was the Irma Hurricane in Florida, USA, in September 2017. Hurricane Sandy arrived on the US coast in October 2012 and caused floods to hit hospitals, causing power outages in New York, forcing to evacuate patients toward safer zones. Hurricane Katrina (August 2005) was one of the most serious hurricanes that hit the U.S. coast.

World Health Organization (WHO) identifies the adequacy of hospitals to cope with disasters as a basic problem to play an essential role in reducing disaster mortality rates [2], [3]. There are still no standard and useful tools to evaluate the adequacy for disasters and ordinary operation of hospitals [3]. The hospital safety index provides a snapshot of the probability that a hospital or health facility will continue to operate in emergencies, based on the structural, nonstructural, and functional factors, including the environment and the health services network to which it belongs [2]. In HPSs, it becomes essential to prevent the causes of danger/accident rather than to limit the consequences. The risk and assessment analysis must consider the prevention objective as primary.

II. Service Continuity Resilience of the HPS

The resilience level of a service is logically related to the density and importance of the users. Important structures and infrastructures, such as airports, data centers, financial districts, hospitals, and government buildings, are generally present in urban and industrial areas. In these kinds of areas, a usual high quality characterizes the electric power system of the public utilities. In order to improve the resilience of the services in case of disasters, it is necessary to organize a disaster recovery program.

Even if it is not possible to forecast a natural disruptive event, it is possible to prevent it in such a way as not to transform it into a disaster. The management of the risk, with a good planning activity, helps in mitigating the consequences deriving from an event. The utility distribution has to organize privileged lines as the preferential axes of energy transmission for special and strategical users.

In the HPS design, the seismic or flood resilience of the components has great importance and has to be considered during the selection and installation of equipment. The ways to stress the structures characterize these internal–external hazards as in the following.

1) Earthquakes increase the intensity of the lateral forces with the structure height.
2) River floods, flash floods, tsunamis, and hurricanes decrease their damages at the higher level of the structures.
3) Fires (e.g., building and forests), explosions, and terrorism decrease their actions with the compartmentations of the sensitive zones of the structures.

The service continuity resiliencies (SCRs) considered in the design process to resist during/after a disruption event, are as follows [4].

1) SCR1. Avoid and mitigate damages to persons and building during the event.
2) SCR2. Restore the service immediately after the disruption event, in case the event caused an out of service.
3) SCR3. Keep the service during and after the event, avoiding out of services.

Clearly, the SCR2 and SCR3 include the SCR1.

In order to meet the first level of resilience SCR1, the electrical components must be prevented from moving or falling during an event in order to avoid them from causing injury to people. Properly anchoring the equipment and preventing movement help to avoid the elongation and strain on the connection conductors, which could, therefore, cause short circuits. At this aim, it has to be used suitable installation requirements, adopting for earthquake joints, bracings, snubbers, etc.

In order to meet the second and third level of resiliencies SCR2 and SCR3, there are electrical and mechanical criteria both for the intrinsic characteristics and for the installation of equipment, both active and passive protections. An example of active protection is the use of accelerometers. In the case of seismic events, the sensor can interrupt all the rotating equipment (motors, elevators, etc.) and it can delay the starting of emergency generators. The purpose is to avoid mechanical and electrical problems during the seismic event, such as short circuits or blocks, and so to ease the restoration of the service after the disruption event.

Passive protections can facilitate the preservation of the service during and after the event if intrinsically adequate by the design to tolerate electrically and resist mechanically the expected forces. The examples of protective measures are as follows [4].

1) To select qualified components able to be repaired and restored and install them adequately.
2) To reduce the seismic accelerations by adopting the "brush-distribution systems" by localizing heavy and large equipment in the lower floors or below ground, while the lighter local distribution components are positioned on upper floors.
3) To reduce the floods damages by adopting an "up–down brush-distribution systems" by localizing the main equipment at a safe height in the structures.
4) To apply a compromise between the two approaches in presence of the two hazards.

TABLE I
INTEGRITY LEVELS ACCORDING TO THE KIND OF LOAD [8]

Loads		Integrity Level	IEC class	Supply
Critical	C-L	IL3	≤0.5 s	Automatic
Preferential	P-L	IL2	≤15 s	
Normal	N-L	IL1	> 15 s	No-Automatic
Shedable	S-L	IL0		

The efficacy of an HPS to guarantee service continuity is associated with the efficient operation of all subsystems and a supplying quality adequate to the medical loads [5].

Therefore, the HPS topology has to have an adequate grade of integrity resilience [topology integrity resilience (TIR) [6]] to the main causes of loss services in the ordinary operation, such as maintenance needs and blackouts of the supplying para-operational device (POD). An adequate TIR grade appears mandatory for relevant HPSs with a general medium-voltage (MV) system and many MV/low-voltage (LV) power stations (PSs).

The PODs at a LV of a hospital are surely of very low reliability because other users connected to the same medium/low-voltage transformer substation (TS) can affect interferences and, in any case, there is the limit of not being able to directly manage the substation under fault conditions.

The HPS must offer design performance for service continuity also with a resilient fault behavior of the triple integrity levels (integrity level resilience [6]) that is with adequate capacity of restoring in an assigned time the service to every level of distribution from maintenance needs, faults, and utility power outages [5]. So, local energy production systems, such as uninterruptible power system (UPS) and engine generators, are central for critical utilities to be guaranteed for disservices from 0 to 15 s but they cannot be of primary importance for an operative structure (see Table I) [7]–[10].

The suggested objective is to sustain the service continuity mainly by the utility grid, limiting the operation of engine generators and uninterruptible power supply at a small duration. In other words, in important structures, such as hospitals, the local energy production systems cannot replace completely the grid of the public service that must guarantee a preferential supply in a few hours of the outage.

Against a fault/disservice, UPSs provide the power supply continuity for the first few instants, the engine generator set in the time of its intervention. Finally, an HPS reconfiguration has to allow recovering the power supply from the network with operating procedures.

III. HPS: MV Topology and Management

A. Basic Topology

The necessity for a POD plurality, installed in different locations, in a hospital complex purposes to achieve greater reliability of service continuity under ordinary conditions and for exceptional catastrophic events, [9] such as, in particular, the earthquake and any other destructive and impedimental event of the availability of the points of delivery PODs.

It is important to underline that the solution prospected with at least two independent points of delivery is not contemplated in technical standards and thus they need a revision adequate to the current digital age. The standards must recommend solutions at least of two PODs, independent and active, instead of the usual practice of a single POD.

The solution of at least a dual-hot POD can support successfully the ordinary operation because the management will be more reliable, with less critical events that could create a total blackout; in fact, the contemporary blackout of two independent PODs is prospected a rare event and so the service is guaranteed with a level of continuity of 50% [6].

An important power outage may occur, unavoidable if it is caused by a combination of several serious faults, such as for a natural calamity. Among other causes, we could include the human factor. Sometimes, the failure of the power supply may be caused by a single technical fault, it can occur locally inside the power system, such as a transformer fire, or in the transmission and distribution system.

These preventable single faults can cause a long and dangerous power outage, such as catastrophic events, which are obviously unavoidable. In the case of two PODs, one active and the other one as an emergency source, each power outage is general and involves all the services not fed by UPS, such as preferential loads, elevators, refrigeration units, and complementary services. It should be underlined that the emergency setup with engine generators, prescribed to be taken in 15 s [8], is not always successful because in a hospital it is difficult to execute the periodical tests of the same engine generators on 100% of their load.

Multiple insidious anomalies, both electrical and mechanical, can stop engine generators (EGs) and UPSs, such as failures in the electronic control boards. Among the causes that can determine the stop of the EG are the generator parameters below the minimum or above the maximum threshold values, steady state not reached, energy inversions, and belt break. Among the causes that can determine the stop of the UPS are batteries breakdown, backfeed protection, static switch retransfer block, and inverter and/or booster shutdown.

Consequently, a secondary POD, at least in an emergency, it must always be provided for hospital users. In the event of a power outage of one POD, due to the maintenance or failure on the external network or on the internal network, it is possible to repower the area served by a POD that is still available, with an adequate procedure, which consists of reconfiguring the internal HPS. Fig. 1 shows a basic topology of two sections for a PS, each one with the LV distribution path. The reconfigurations are permitted operating on the tie switches (§⥃) that allow interconnecting the two sections at each level and on the bypass switches (&) that allow interconnecting the levels of the same section path [6].

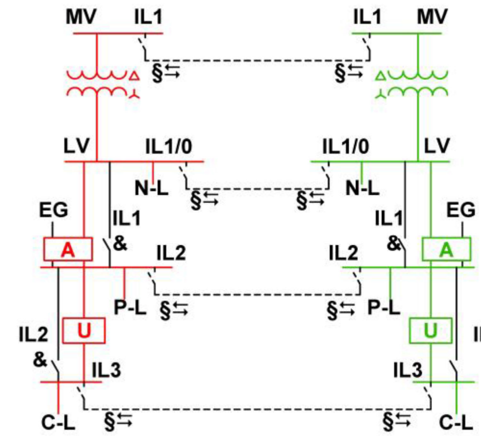

Fig. 1. Basic topology of two sections, each one with a path: §⥃: tie switch; &: level bypass switch; *A*: ATS; *U*: UPS; EG: engine generator; LV: low voltage; MV: medium voltage [6].

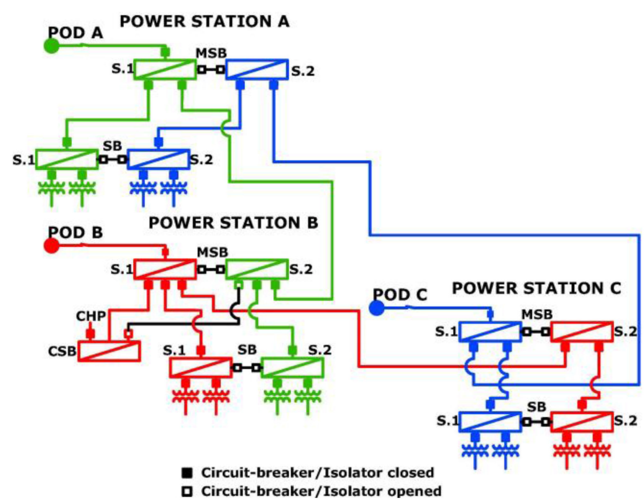

Fig. 2. MV scheme of a HPS with three independent PODs, three PSs, three TSs, and a power cogeneration (CHP) [3].

A suitable internal MV system allows operations on the interconnections, increasing the reliability of the hospital and avoiding general power outages. The de-energized area will be interested in short interruptions, assisted with engine generators, during the manual transfer to the re-energization by another active POD.

An efficient topology for a hospital with many TSs is constituted by the MV main distribution system that inteconnects and feeds them by MV main switchboards (MSBs) from multiple PODs.

Fig. 2 shows an example of topology with three PODs supplying three PSs, each one constituted of the MSB energizing the TSs. Each MV MSB consists of two sections, interconnected by means of two tie switches §⥃ as well as the local MV switchboard (SB) of each TS. The two sections offer a flexibility in managing a simultaneous double power supply.

In each PS, a POD from the distribution network energizes section 1 of the MV MSB, while section 2 is available to be energized by the tie switches §⇆ with section 1 of the same PS or with section 2 of the MSB. In Fig. 2, the scheme shows a possible ordinary setup, operating on the tie switches §⇆ with the sequence PS*A*: *A*-*C*; PS*B*: *B*-*A*; PS*C*: *C*-*B*. The division of the MV SBs into sections also makes it possible to cope with the power outage of a SB section for tests and maintenance, maintaining the service by means of the other section. It is recommendable to select MV units classified loss service 2 [9] because their structure allows a safe access inside one grounded unit, while the section common busbars can remain energized allowing the service of all the other functional units. An incorrect operating procedure could have serious consequences for the operator as well as for the strategic operational structure (SOS) power system. For this reason, it is reasonable to adopt MV units protected for the internal arc fault (even on all four sides).

B. Permanent Design and Business Continuity Management

The requirements of high availability and integrity are reached through an adequate system supplemented by the effective management of business continuity. For an efficient business continuity management (BCM), the design of the electrical system has to be aimed not only at the installation but also at the operational management of the system (In-Op design [12]) and so has to examine the system sets, guaranteeing normal and abnormal operations. The ISO 22313 standard applies the "plan-do-check-act" cycle to the complete design of the BCM system (permanent design) [13].

The management staff is a basic complement of the levels of integrity and resilience. This staff must be qualified, in fact, power supply systems can offer different performances depending on the competence and preparation of the operators.

C. Operating Rule Hospital Utility [3]

The need for multiple PODs aims to have them active for the best guarantee of ordinary operation that may involve the internal distribution network and the external (public) distribution network; in fact, multiple PODs allow the operation of the absorption areas in an ordinary way without concentrating in a single POD the total load of the whole hospital. Then, in these areas, as already noted, the power outage of a POD is limited only to the supplied sections, without impact on other areas.

The hospital electrical system and its equipment must comply with the safety regulations and with the prescriptions of the utility. It is necessary to establish an operating rule with the utility for the management of interconnection points in order to obey the following.

1) Agree on the composition of a unique electrical system that in ordinary conditions remains divided into utilization areas, served by medium-voltage/low-voltage substations with an internal interconnection electric network.

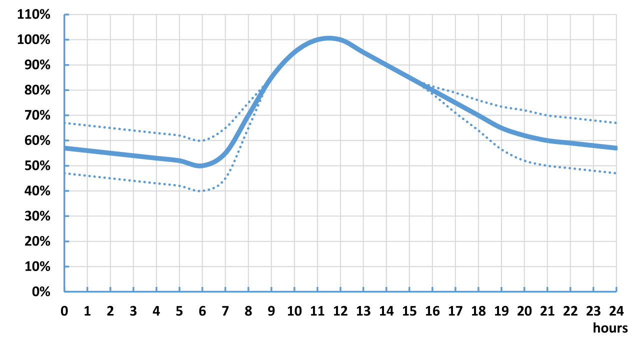

Fig. 3. Mean daily load diagram of Polyclinic Umberto I, Sapienza Hospital, with a power demand of 8 MW.

2) Agree on calibrations of the protective devices at the interface with the PODs, assuming a special classification for the hospital.
3) Define the total power demand, normally divided between the PODs in ordinary situations, while, in an emergency, plan the power transfer from a POD, out of service, to another POD, following a timely agreement.

The operating regulation is, therefore, necessary for the purpose of planning a controlled power for a simultaneous energization of the transformers. Suitable devices must de-energize the substations in the event of a power failure of more than a few seconds (such as 5 s) and provide for the re-energization of the transformers, according to the overall quantities not exceeding admitted limits and with an acceptable interval time (such as of at least 1 s).

IV. HPSs as Microgrids

Taking into account the aforementioned paragraphs, the electrical power system of a complex of hospital buildings has to constitute a microsystem that satisfies, in relation to its essentiality, adequate performances of service continuity and power quality. It has to present a proper topology of the distribution system and well-organized power supplies integrated by alternative sources as autonomous emergency and microgeneration sources. The options of supply sources can be between sources with the programmable availability and renewables without programmable availability. Sources with programmable availability are supplies from utility, standby generations, continuous on-site generations, combined heat and power generation (CHP) and combined cooling, heating, and power generation (CCHP), energy storages, and microgrids with redundancy and islanded operation capability. In an HPS, the behavior of the electric load diagram is generally suitable to guarantee a high efficiency for the CHP-CCHP, assuring a load basis higher than 40%–50% of the maximum demand power (see Fig. 3) [9].

If the minimum configuration appears to provide two PODs from the utility, the ideal configuration is to have three PODs coming from different substations and the cost can increase critically (see Fig. 2) [3].

In any case, at least one alternative emergency POD must always be provided for hospitals. In fact, it is unacceptable that the power outage of the single POD can have a longer duration than the maximum time to restore the supply operating on the second POD. For example, in Italy, the power outage can be prospected normally from 4 to 8 h. It is important to highlight that the UPS operating room autonomy is 3 h, reduced to 1 h, if engine generators are present, which as emergency groups may not enter service (IEC approach). In California, the hospital systems have to address planned power shut-OFF, which lasts for up to five days, and the system is being designed to connect temporary generators and other power sources. The current rule in Italy also provides that possible reimbursements for the failure to supply energy are not recognized in any case for outages that last for more than ten days [14].

Let us note that the Joint Commission (JC) requires hospitals to be able to run on generator backup for 72 h [15], [16]. The JC is an independent and not-for-profit organization that certifies and approves over 22 000 health care organizations and programs in the USA. However, many hospitals are not complying with this prerequisite; therefore, they are exposed to the risks of loss service for the impossibility of fueling the backup generators, during prolonged and extended power outages, such as those following a natural calamity or a human disaster.

Important sites of a hospital can require the willingness-to-accept greater financial costs against loss service risks. In any case, it is relevant to identify the weaknesses in the supplying system of the hospital and to value the remedies.

The financial analysis at the end could propose that spending the available funds on local generation systems is more convenient, such as to pursue the installation of a cogeneration-trigeneration (CHP-CCHP). At present, the general trend, such as in California, is of a net-zero mandate, even if the first purpose for a hospital is to save people's health and lives and to direct financial investments toward this goal.

It is important to note that instead if the main time between the failures of the supplying public grid confirms its role of electric energy bank, considered the availability of emergency engine generators and UPS inside an HPS, the type of CHP can be set as the priority thermal generation and electrical-type follow. Moreover, generally, the CHP is not provided for an islanded operation to support emergency conditions and this usual operating mode has to be changed to allow that the CHP can feed the hospital on the occasion of catastrophic events. The Texas Medical Center in Houston (the largest medical center in the world), during hurricane Harvey, was able to feed all its services (such as air conditioning, refrigeration, heating, sterilization, laundry, and hot water needs) throughout the hurricane event [17].

V. Regulatory Lacks Toward Strategic Users and in Particular HPSs

The buildings considered to be of strategic interest are those whose functionality during seismic events takes on the fundamental importance for the purposes of civil protection. The hospitals are buildings with important public and strategic functions, also with reference to the management of civil protection in the event of a seismic event. A hospital generally constitutes a single user, due to its strategic type of complex system, exclusively designed at the health care service and not at other activities. In particular, the type of hospital user must be declined with the following meanings.

1) The hospital user is more than a special user, which needs to guarantee a strategic performance, not only at the level of supporting structure but also the functional structure.
2) Some hospital users are located in sites in the zone with a high possibility of a natural calamity (hospital located in seismic areas, near volcanoes, or in areas prone to hurricanes).
3) The hospital is a coordinated electrical system that is made up of several departments, therefore, it is necessarily equipped with an internal electrical distribution and often equipped with the MV distribution system.

A hospital complex must have the safety requirement with respect to the limit state of immediate operability, i.e., it is part of the "buildings that must remain operational during and immediately after the earthquake" (SCR3) [4]. In the regulatory laws and electrical standards, it results that there are no explicit references of exception for the strategic infrastructures, also if subject to various antiseismic and civil protection legislation that prescribes to safeguard and plan the functionality, such as the service continuity of power supply. The general principle adopted by utilities is not to adopt a discriminatory behavior between users powered at the same voltage level and with a similar location without recognizing by rule the provision of multiple PODs for SOSs and so in particular for HPSs.

Instead, hospitals and other SOS are equated to common users. Only on request, the granting of alternative PODs refers to emergency connections authorized exclusively as a reserve for power outages and maintenance operations of the primary POD, admitted singularly active. This condition appears to be in contrast with a cost-benefit analysis since is expected that a reserve power system is generally to be kept unused, feeding the entire load by the active POD on only one branch of the upstream network. It appears singular to create a dedicated reserve connection with nonnegligible costs and maintain it unused in favor of the primary connection.

The WHO recognizes as an essential role in reducing the disaster mortality rates the capacity of hospitals to face disasters [2]. Therefore, the WHO has to claim the status of SOSs for the hospitals and together with international committees for electrical standardization that qualifies their power systems as very special users. It has to be highlighted the necessity that the supplying utilities plan adequate preferential axes of energy transmission, indispensable for SOSs, in case of catastrophic events, and also very useful for the ordinary operation, in case of faults.

VI. Conclusion

To enhance the resilience of hospitals, it is vital to provide an electrical power system able to guarantee the service even in case of catastrophic events. To limit the exposure of the service continuity to catastrophic events and to make the functionality more efficient and well-organized in emergency conditions, it is necessary by rule to classify the hospital and the strategic operating structures as special electrical users. They need peculiar characteristics that increase its resilience, the ordinary operation, and the maintainability: at least two contemporary PODs from independent PSs, an internal structure capable to guarantee an adequate level of redundancy; a cogeneration system with the islanded operation capability.

The cost of this system can increase remarkably, so it is necessary to underline that relevant sites of the hospital can require the willingness-to-accept greater financial costs against loss service risks. The apparent complexity of this power system is required because in SOSs, as hospitals or other strategic structures, the loss of service continuity determines the break of a primary public service and the risk of the loss of human life or damage to public health. It is important to note that the SOS has to work and be efficient even after a catastrophic event and even more so, it is not admissible for the SOS to suffer a long power outage that can be caused by a local single technical fault (such as a transformer fire). A resilient power system would be useless if not managed by skilled staff.

The staff must know the system and must be trained to operate safety and integrity procedures for the effective use of all power system performances with a secure service continuity.

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