Resilience

Resilient Power Supply in a Modern Office Building

Copper Development Association
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Introduction

This application note presents a design approach to assure a resilient and reliable power supply in an electronics-intensive modern office building. It describes a case study of a 10-floor office building in Milan, Italy (hereafter referred to as ‘the building’ for confidentiality reasons). The building is the head office of a major financial institution and is occupied by 500 employees using information technology equipment intensively.

Following an assessment of the current status of the electrical installation in the building, accompanied by the results of power quality measurements, two design proposals are presented that assure a resilient and reliable power supply. A cost analysis completes this report.

Description of initial situation

Distribution scheme

The building is connected to a 23 kV grid. The medium voltage main power supply consists of two 800 kVA transformers, 23/0.4 kV, 50 Hz. The low voltage side of the installation is designed as a TN-S system.

The load is subdivided into standard, preferential, and privileged loads, according to requirements for continuity of supply (this is discussed in greater detail later in the section). There is a second point of common coupling (PCC) to feed a small portion of the standard load. The two PCCs are fed from the same grid point and so are not independent.

To assure continuity of the power supply, two UPSs (80 + 200 kVA) and a motor generator (250 kVA) are installed according to the scheme in Figure 1.

Note that in such a scheme it is imperative that the neutral conductor is connected to earth only once, at the main earthing terminal, and not at each transformer. Otherwise, the benefits of the TN-S wiring configuration – improved EMC and power quality - are lost.

The primary distribution is a compromise between radial and shunt schemes1. The installation has grown in a haphazard way, without a consistent structure. This is a direct result of the many changes in power requirements experienced during

1 Shunt scheme: a rising busbar or power line is shared for all floors; at each floor, a connection is made to the LV panel at the floor. Radial scheme: each LV panel at each floor has a dedicated connection with its corresponding switchgear at the main LV distribution panel in the basement.
the building's lifetime. Two distribution panels feed each floor. Each panel has two sections (standard and privileged) corresponding to the standard and privileged sections of the main LV power panel (Figure 2). Final distribution uses a single radial scheme.

**Lines**
The 3-phase distribution is made with multi-core copper cables. Where the phase conductor cross-sections were greater than 35 mm², half-sized neutral conductors had been used.

**Load**
The rated load for the office building is typical and consists of:
- Elevators (approx 80 kVA)
- Services (approx 100 kVA)
- Air-conditioning (approx 600 kVA)
- Horizontal distribution for lighting and power in the open office space (approx 35 kVA per floor).

**Power quality**
To evaluate the quality of the power supply, current harmonic content was measured at the main electrical lines feeding each floor and at the distribution panels for building services.

Figures 3 to 6 give examples of measured current and voltage waveforms and their harmonic content. The following points need to be highlighted:

Some phase conductors, particularly those for lighting circuits, have over 75% total harmonic current distortion (3\textsuperscript{rd}, 5\textsuperscript{th}, and 7\textsuperscript{th} harmonic) – see Figure 6. There is significant 3\textsuperscript{rd} harmonic current distortion in circuits serving IT and lighting equipment – see Figures 4, 5 (neutral conductor), and 6. In some neutral conductors, the harmonic currents are more than twice the phase current.

Both UPSs show current distortion in phase and neutral conductors – see Figures 4 and 5.

Even-order harmonics appear in more than one measurement (approx 30% in Figure 5). This means that the waveform of the current does not have the usual symmetry.

In some cases, the waveform produces more than two zero-crossings per cycle of the sine wave (Figure 5).
Rather high permanent currents are detected in the ground conductor. This is a typical indication that the TN-S configuration has not been preserved, i.e. that there are multiple connections between the neutral conductor and earth. It must be ensured that there is only one main earthing point with a connection between neutral and ground. On-site personnel need to be briefed to avoid making any connection between the neutral and ground in the LV distribution.

The instrument used to make these measurements was a Fluke 43 single phase, 0 - 600 V, CT 600 A/1 mV/A power quality analyser.

Events

The building occupant experienced a high and increasing number of events and faults, principally related to the overheating of lines and nuisance tripping of protection devices.

Analysis – initial situation

The current installation lacks organisation and rationality in its approach. This is not compatible with the resilient design the company adopted at the start (supply low-voltage distribution through multiple transformers, UPS, and generator).

Some elements do not conform to current standards. Even full compliance to standards does not guarantee adequate performance from a power quality and EMC viewpoint for a building with mission-critical functions.
Distribution scheme
The distribution scheme is neither systematic nor rational, probably due to the numerous modifications since the original installation. There are important limitations relating to reserve capacity and independence. Some bottlenecks are present, e.g. at the level of the main LV busbar (Figure 1). The two transformers are not independent.

Line overheating
The high density of information technology equipment such as PCs, servers, etc and electronic lighting produces high levels of harmonic current in many lines.
These phenomena result in neutral overheating (elevated currents in a downsized neutral – see Sections 3.1 and 3.5.1) as well as nuisance tripping of protective devices.

Co-ordination among protection devices and lines
The current capacities of some lines are not co-ordinated with their over-currents protection devices. The large number of lines running in the same trunking make the problem more critical because the operating temperature is higher.
Analysis of a faulty line showed that prolonged overheating was the cause of failure, due to overheating in the trunking. The grouping factors given in informative annexes of national and international wiring regulations should be observed.

Neutral Status
In case of such a multiple feed with TN-S configuration, the neutral current needs to be brought back right to the main earthing terminal. Procedures must be in place to avoid making any additional connection between neutral and ground. Such connections create alternative paths for the neutral current, thus eliminating all the benefits of having a TN-S system.

Design approach
The building occupant, operating in the financial sector, needs to upgrade the installation since reliable power quality is considered mission-critical. The problems shown by the analysis of the current situation and the PQ measurements suggest consideration of an update of the electrical system at different levels:

- rationalisation of mains distribution, and
- renewal of the electrical installation on the floors.

Load classification
To optimise the main distribution rationalisation, the first step is the classification of the loads. All loads are classified into 3 groups:

- standard
- preferential
- privileged.

Standard loads are used for daily business, but their non-availability does not result in risk of personal injury, damage to equipment or disruption of business processes. A simple radial circuit suffices for the supply and relatively long intervention times can be tolerated (Table 1).
Preferential loads need a redundant power supply, for example as provided by a dual radial scheme, starting either from the risers or at the level of intermediate connections (Table 2).
<table>
<thead>
<tr>
<th>Description of standard load</th>
<th>Type of power supply required</th>
<th>Timing needed for intervention</th>
</tr>
</thead>
<tbody>
<tr>
<td>Allows regular functioning of the building, but their unavailability does not result in</td>
<td>Standard radial circuits</td>
<td>None</td>
</tr>
<tr>
<td>risk to personnel or equipment:</td>
<td>Resumption of service can wait for some time without damage</td>
<td>Unavailability of service for relatively long time periods can be tolerated</td>
</tr>
<tr>
<td>General services, e.g. air conditioning (but not in server room)</td>
<td>Loads can be switched off</td>
<td></td>
</tr>
<tr>
<td>Normal lighting</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Heating</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Power sockets</td>
<td></td>
<td></td>
</tr>
<tr>
<td>General services, e.g. air conditioning (but not in server room)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Normal lighting</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Heating</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Power sockets</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Table 1 - Description, criteria, design, and intervention requirements for standard loads*

<table>
<thead>
<tr>
<th>Description of preferential load</th>
<th>Type of power supply required</th>
<th>Timing needed for intervention</th>
</tr>
</thead>
<tbody>
<tr>
<td>Regular functioning of the load is required for comfort and security of personnel and</td>
<td>Backup</td>
<td>According to the norm, a 20 second intervention time for the generator group is acceptable for</td>
</tr>
<tr>
<td>clients, as well as for ensuring smooth business operation. For example:</td>
<td>Dual radial primary supply, ensuring the functional and physical independence of the risers</td>
<td>long interruptions. Typical values for a diesel group:</td>
</tr>
<tr>
<td>Lighting of staircases, corridors, and certain rooms</td>
<td>Two separate risers can be employed, supported either by a generator or supplied from two</td>
<td></td>
</tr>
<tr>
<td>Minimum lighting conditions to avoid panic</td>
<td>independent grid points</td>
<td></td>
</tr>
<tr>
<td>Heating or air conditioning of certain rooms</td>
<td>Switching off the load is not acceptable</td>
<td></td>
</tr>
<tr>
<td>Elevators</td>
<td></td>
<td></td>
</tr>
<tr>
<td>UPS</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Regular functioning of the load is required for comfort and security of personnel and</td>
<td></td>
<td></td>
</tr>
<tr>
<td>clients, as well as for ensuring smooth business operation. For example:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lighting of staircases, corridors, and certain rooms</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Minimum lighting conditions to avoid panic</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Heating or air conditioning of certain rooms</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Elevators</td>
<td></td>
<td></td>
</tr>
<tr>
<td>UPS</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Table 2 - Description, criteria, design, and intervention requirements for preferential loads*

<table>
<thead>
<tr>
<th>Description of privileged load</th>
<th>Type of power supply required</th>
<th>Timing needed for intervention</th>
</tr>
</thead>
<tbody>
<tr>
<td>Essential services:</td>
<td>Secure</td>
<td>Loads with intervention within 15 seconds</td>
</tr>
<tr>
<td>Security lighting</td>
<td>Dual radial scheme, with independent risers</td>
<td>Short-interruption loads, within 0.15 seconds</td>
</tr>
<tr>
<td>Servers</td>
<td>At least one riser has to ensure high grid reliability</td>
<td>Some loads need continuous supply</td>
</tr>
<tr>
<td>Telecommunication systems</td>
<td>Use of UPS</td>
<td></td>
</tr>
<tr>
<td>Personnel retrieval</td>
<td>For certain loads, a dedicated UPS can be considered</td>
<td></td>
</tr>
<tr>
<td>Alarm &amp; security systems</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fire signalling and anti-fire systems</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Closed-loop TV circuits</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Certain auxiliary services</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Essential services:</td>
<td>Secure</td>
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</tr>
<tr>
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<td>Dual radial scheme, with independent risers</td>
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</tr>
<tr>
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<td>Use of UPS</td>
<td></td>
</tr>
<tr>
<td>Personnel retrieval</td>
<td>For certain loads, a dedicated UPS can be considered</td>
<td></td>
</tr>
<tr>
<td>Alarm &amp; security systems</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fire signalling and anti-fire systems</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Closed-loop TV circuits</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Certain auxiliary services</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Table 3 - Description, criteria, design, and intervention requirements for privileged loads*
Privileged loads are mission-critical. Loss of service means grave danger to personnel or severe damage to the organisation’s business processes. The level of independence needs to be determined for each load. At the very least, these loads must be supplied from two independent feeders with automatic switching (Table 3).

**Main distribution schemes**

To avoid the existing bottleneck at LV main busbar, the primary distribution must be modified as a dual radial distribution (Figure 7 left).

The rating of the transformers TR1 and TR2 must ensure that each can carry the full load. Considering that, because of the nature of the loads, the load current waveform will be highly distorted, the transformers must be sized to take account of the harmonic content. Rating transformers to cope with harmonic currents is discussed in Section 3.5.2.

To reduce short circuit currents, the system is normally managed with the main busbar-breaker open, but parallel operation between the two main transformers is possible for a short time.

To feed the thermal and HVAC services, the transformer section must be modified as shown in Figure 7 with a new 800 kVA transformer, TR3, in addition to the existing two.

Standard loads are supplied from a single grid point. The same grid power cable, riser, and radial distribution also supplies preferential and privileged loads.

Two generator groups supply preferential and privileged loads. Standard loads are switched off through the breakers at the extremity of the main busbar.
Two UPSs supply privileged loads in case of failure of normal and backup power supply.

Primary supply and backup supply are wired TN-S. UPS can be wired either TN-S or IT (meaning, here, isolated earth). Isolated earth systems are excellent for continuity of power supply, but cannot guarantee protection of personnel. Where an IT system is installed, proper security measures have to be taken to ensure that only authorised personnel can have access to the IT circuits.

The second LV PCC has been removed in Figure 7.

Each floor is still supplied by two distribution panels, each having three sections (standard, privileged and preferential) corresponding to the same sections of the main LV power panel.

Final distribution could be done using a shunt (Figure 8) or single radial (Figure 9) scheme.

The shunt scheme (shared line feeding all floors for each type of load) is cheaper and more flexible in the case of load growth. Unfortunately it is limited by poor resilience to faults in the main line and risers.

The single radial scheme (one line for each floor for each type of load) ensures:

- minimum interference and voltage drop caused by load
- in case of a fault, only loads supplied by the faulty line are out of service
- reduced maintenance problems.

The radial scheme is therefore the preferred scheme.

**Line sizing**

Table 5 shows the power-considered sizing of all of the main sections of the system.

The total installed load (Columns 2 and 3) is multiplied by utilisation and contemporary factors (Columns 4 and 5) to calculate the power requirements of the load (Columns 6 and 7). As a margin for future load growth, lines are sized (Columns 8 and 9) considering an additional factor equal to 130% and 115% for power and lighting circuits respectively.
Considering the measured waveform of the current, all the new lines have been sized to take into account the harmonic profile and resilience requirements:

- neutral cross-section equal to that of phase (Section 3.5.1)
- derated cables (Section 3.1 and 3.5.1).

Special attention should be paid to neutral and phase conductor sizing to avoid overheating and faulty tripping of protection devices. The adoption of a UPS or motor generator is not useful if a line fault occurs after it.

### Cost analysis

The cost of the existing installation is compared with two possible alternative solutions in Table 6. These alternatives differ only for risers, and hence for the cost of the main LV panel.

Solution 1 is the shunt scheme, and Solution 2 is the simple radial scheme, which is preferable for new buildings, but difficult to implement as an installation upgrade.

### Cost when selected at initial design stage

Regarding this situation, the following needs to be highlighted:

- the percentages refer to the cost of the existing installation
- the extra cost of the better solutions is low, if considered at the initial design stage
- the cost of the best technical solution (i.e. Solution 2 – single radial scheme at final distribution) differs only by 3% from Solution 1 if considered at initial design stage, but the difference is much greater if considered at refurbishment stage only
- cost basis 2001
- the cost for the UPS considers only purchase and installation. The additional costs of maintenance must be taken into account.

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**Resilient Power Supply in a Modern Office Building**

**Table 5 - Peak-rated and actual sizing of primary distribution system**

<table>
<thead>
<tr>
<th>Load</th>
<th>Installed load (kVA)</th>
<th>Utilisation &amp; Contemporary Factors</th>
<th>Power requirement (kVA)</th>
<th>Installed power (kVA)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Power (1)  Light (2)</td>
<td>Power (3)  Light (4)</td>
<td>Power (5)  Light (6)</td>
<td>Power (7)  Light (8)</td>
</tr>
<tr>
<td>Second underground</td>
<td>7 10</td>
<td>0.7 1</td>
<td>5 10</td>
<td>6.5 11.5</td>
</tr>
<tr>
<td>First underground</td>
<td>114 15</td>
<td>0.7 1</td>
<td>80 15</td>
<td>104 17.25</td>
</tr>
<tr>
<td>Ground and general services</td>
<td>43 15</td>
<td>0.7 1</td>
<td>30 15</td>
<td>39 17.25</td>
</tr>
<tr>
<td>First floor</td>
<td>50 17</td>
<td>0.7 1</td>
<td>35 17</td>
<td>45.5 19.55</td>
</tr>
<tr>
<td>Second floor</td>
<td>50 17</td>
<td>0.7 1</td>
<td>35 17</td>
<td>45.5 19.55</td>
</tr>
<tr>
<td>Third floor</td>
<td>50 17</td>
<td>0.7 1</td>
<td>35 17</td>
<td>45.5 19.55</td>
</tr>
<tr>
<td>Fourth floor</td>
<td>50 17</td>
<td>0.7 1</td>
<td>35 17</td>
<td>45.5 19.55</td>
</tr>
<tr>
<td>Fifth floor</td>
<td>50 17</td>
<td>0.7 1</td>
<td>35 17</td>
<td>45.5 19.55</td>
</tr>
<tr>
<td>Sixth floor</td>
<td>50 17</td>
<td>0.7 1</td>
<td>35 17</td>
<td>45.5 19.55</td>
</tr>
<tr>
<td>Seventh floor</td>
<td>50 17</td>
<td>0.7 1</td>
<td>35 17</td>
<td>45.5 19.55</td>
</tr>
<tr>
<td>Eighth floor</td>
<td>29 12</td>
<td>0.7 1</td>
<td>20 12</td>
<td>26 13.8</td>
</tr>
<tr>
<td>Ninth floor</td>
<td>3 2</td>
<td>0.7 1</td>
<td>2 2</td>
<td>2.6 2.3</td>
</tr>
<tr>
<td>Thermal Central</td>
<td>29 0</td>
<td>0.7 --</td>
<td>20 0</td>
<td>26 0</td>
</tr>
<tr>
<td>HVAC main station</td>
<td>843 0</td>
<td>0.7 --</td>
<td>590 0</td>
<td>767 0</td>
</tr>
<tr>
<td>Boxes</td>
<td>14 5</td>
<td>0.7 1</td>
<td>10 5</td>
<td>13 5.75</td>
</tr>
<tr>
<td>Elevators</td>
<td>114 0</td>
<td>0.7 1</td>
<td>80 0</td>
<td>104 0</td>
</tr>
<tr>
<td>TOTAL</td>
<td>1546 178</td>
<td>-- --</td>
<td>1082 178</td>
<td>1407 204.7</td>
</tr>
</tbody>
</table>
Even if the evaluation of average costs related to a system designed according to good PQ practice is difficult, it must be recognised that:

- the cost estimates include the costs related to the practical difficulties of installing and renewing a building in the centre of a major city
- the modification of the main distribution scheme is the most important and useful action to undertake
- the solution with unique riser lines is very difficult to install with the building operational.

## Conclusion

Initial low cost does not necessarily mean good value. A PQ compliant system, initially more expensive, can save a great deal of money during its life. The case study analysed in this paper shows that an electrical installation, designed without attention to PQ issues, results in a considerable amount of unnecessary expenditure. Decisions have to be made whether to resolve the issues or to simply live with the inconvenience and downtime they cause.

The cost/benefit analysis shows that resilience should be carefully considered at the design stage. A mere increase of 16% in the installation cost (1% of the building cost) provides:

- three lines of defence against power cuts for mission-critical loads (dual panels at each floor, generator, UPS)
- a highly resilient system, with each floor supplied by two distribution panels. Each panel is independent from the other, and from all panels on the other floors
- a highly flexible electrical system against future load growth.

Expensive though it may seem, the highly resilient solution would typically add only about 1% to the cost of the building. For commercial buildings, where the running costs amount to initial construction costs after 7-8 years, this initial investment will be paid back by a productivity increase of 10 minutes per week. All the rest is profit.

A design according to present standards does not guarantee optimum performance from power quality and EMC viewpoints and enhanced solutions have to be considered. At European level, better standards are at present under preparation.

<table>
<thead>
<tr>
<th>Item</th>
<th>Existing (€)</th>
<th>Solution 1 (€)</th>
<th>Solution 2 (€)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Cost at design stage</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Main LV panel</td>
<td>32 000</td>
<td>35 000</td>
<td>45 000</td>
</tr>
<tr>
<td>Risers</td>
<td>30 000</td>
<td>35 000</td>
<td>60 000</td>
</tr>
<tr>
<td>Horizontal distribution</td>
<td>107 000</td>
<td>135 000</td>
<td>135 000</td>
</tr>
<tr>
<td>Generator groups</td>
<td>87 000</td>
<td>107 000</td>
<td>107 000</td>
</tr>
<tr>
<td>UPS</td>
<td>55 000</td>
<td>105 000</td>
<td>105 000</td>
</tr>
<tr>
<td>Motive power</td>
<td>355 000</td>
<td>375 000</td>
<td>375 000</td>
</tr>
<tr>
<td>Lighting</td>
<td>500 000</td>
<td>525 000</td>
<td>525 000</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>1 166 000</td>
<td>1 317 000</td>
<td>1 352 000</td>
</tr>
<tr>
<td><strong>Differential cost</strong></td>
<td></td>
<td>151k (+13%)</td>
<td>186k (+16%)</td>
</tr>
<tr>
<td><strong>Cost for installation upgrade</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Additional cost</strong></td>
<td></td>
<td>422k (+36%)</td>
<td>543k (+46%)</td>
</tr>
</tbody>
</table>

*Table 6 - Cost Comparison*
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References


Reference & Founding Partners

European Copper Institute (ECI)
Web: www.eurocopper.org

Akademia Gorniczo-Hutnicza (AGH)
Web: www.agh.edu.pl

Centre d’Innovació Tecnològica en Convertidors Estàticos i Accionaments (CITCEA)
Web: www-citcea.upc.es

Comitato Elettrotecnico Italiano (CEI)
Web: www.ceiuni.it

Copper Benelux
Web: www.copperbenelux.org

Copper Development Association (CDA UK)
Web: www.cda.org.uk

Deutsches Kupferinstitut (DKI)
Web: www.kupferinstitut.de

Engineering Consulting & Design (ECD)
Web: www.ecd.it

Hochschule für Technik und Wirtschaft (HTW)
Web: www.htw-saarland.de

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