M1 ELTI
Advanced power electronics

Chapter 6

Energy quality for static converter

1 Introduction

Network disturbances and power quality are issues of increasing importance, as the share of sensitive electronic equipment is steadily increasing in modern power systems. Due to their complex nature and the highest requirements for precision, power converters for particle accelerators are extremely sensitive to network disturbances. A large percentage of all unwanted accelerator stops, so-called major events, is related to such disturbances. Several cases of particle beam instabilities that were caused by power quality issues have been observed. This paper discusses the principal aspects of power quality, with a particular focus on power converters for particle accelerators.

The main objectives of this paper are to raise awareness amongst power converter specialists

about this subject, and to discuss the technologies and main engineering principles that can be applied to reduce the impact of power quality issues on particle accelerator operation.

2 Classification of disturbances

The most critical disturbances are discussed below .

2.1 Voltage dips

Voltage dips are two-dimensional phenomena, characterized by their amplitude and duration. They are typically caused by short-circuits in the electrical network upstream or downstream of the observation point. Voltage dips have a typical duration of 50–200 ms (in some cases up to 1000 ms), and an amplitude typically of −5% to −100%. Voltage dips are the principal cause of power quality issues related to particle accelerators, and for this reason it is essential to define the immunity levels of the electrical equipment in order to ‘survive’ most of these disturbances without tripping the particle accelerator.

2.2 Short supply interruptions

Short supply interruptions can be seen as voltage dips to zero. They are typically caused by short-circuits in overhead lines, which are cleared when the protection systems reclose. Short supply interruptions can last up to 180 s. For short supply interruptions, the concept of immunity of equipment is not applicable,

simply because most equipment will not be able to function without its energy supply even for short periods of time.

2.3 Flicker

Flicker is defined as the impression of unsteadiness of visual sensations induced by a light stimulus whose luminance fluctuates with time. A typical example is the visible change in the brightness of a lamp due to rapid and repetitive fluctuations of the network voltage. These voltage fluctuations are typically caused by variations in load current passing through the source impedance of the electrical network upstream.

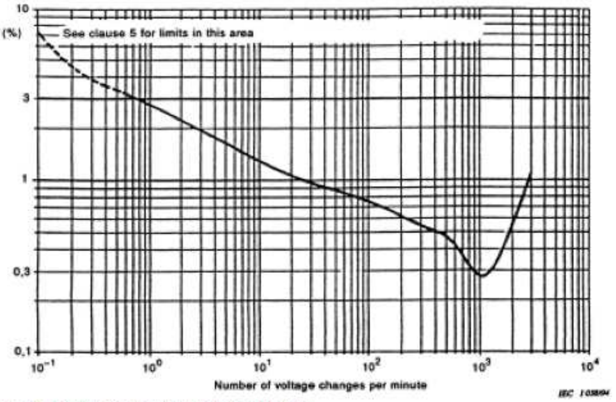
The repetitive active and reactive power cycles of the main power converters of a particle accelerator are a typical cause of flicker. The voltage drop caused by the load current flowing through the impedances of the upstream network has a major influence on the voltage amplitude and phase angle at a particular busbar. Depending on the network inductances and resistances upstream, as well as the amplitude of active and reactive power of the load, the voltage drop is calculated as follows:

$$\Delta U = RI\cos\phi + XI\sin\phi\,,$$

$$\frac{\Delta U}{U} = \frac{R.\Delta P + X.\Delta Q}{U^2}.$$

Equation (2) shows that any variation of load active and reactive power, as well as any change in network inductance or resistance, will result in a change in voltage drop and hence a variation of operating voltage at a given busbar. The most prominent example is the cycling power of thyristor converters for synchrotron accelerators.

The voltage fluctuations are defined as changes of r.m.s. voltage evaluated as a single value for each successive half-period of the network voltage. The short-term flicker indicator Pst specifies the severity of the flicker evaluated over a short period (e.g. 10 min); and Pst = 1 is the conventional threshold of irritability. The long-term flicker indicator Plt defines the flicker severity evaluated over a long period (typically 2 h) using the cubic average of successive Pst values. Typically, the admissible long-term flicker factor is 60% of its short-term equivalent. Figure 1 shows the limits for a short-term flicker factor of 1.



NOTE 1 200 voltage changes per minute give 10 Hz flicker.

Fig. 1: Flicker limits for short-term flicker factor $P_{st} = 1$ (source: IEC 61000-3-3, Fig. 4)

These flicker limits are based on the empiric definitions of the human eye's sensitivity to luminance fluctuations. At the point of connection with the external network, the flicker level represents a contractual constraint and needs to be strictly respected.

The irritating effects of flicker can be reduced by applying a combination of the following measures:

– strictly separate general services and power converter loads;

– reduce the network impedance (increase short-circuit power) at the load busbar;

– reduce the amplitude of the (active and) reactive power variation;

– install technologies for flicker mitigation.

2.4 Fast transient overvoltages

Fast transient overvoltages (surges) are typically caused by lightning strikes into overhead lines, hence having a much lower probability in buried cable networks. They can also be caused by network switching operations, such as switching off large or small inductive loads, as well as short-circuits. The amplitude of fast transient overvoltages can easily reach multiples of the nominal system voltage, and hence they need to be taken into consideration for insulation coordination of the electrical network. For the power equipment itself, an appropriate choice of component voltage rating combined with simple mains input filters are suitable measures to obtain immunity against fast transient overvoltages.

2.5 Temporary power frequency variations

Temporary power frequency variations are less critical for most electrical equipment, and there are no specific countermeasures required.

The fundamental frequency of an electrical network is an expression of balance between power generation and consumption:

$$\mathrm{d}E_k/\mathrm{d}t = P_g - P_c \ ,$$

where Ek is the kinetic energy of all rotating machines (= ½ J ω2); Pg is total generated power, Pc – total consumed power; J is the torque of the rotating machines; and ω is angular speed (rad/s).

The frequency of the European 400 kV network of the Union for the Co-ordination of Transmission of Electricity (UCTE) network is closely controlled, with typical fluctuations of only ±0.1 Hz around the nominal value of 50 Hz. The overall network power frequency characteristic of the 400 kV UCTE network is about 27 000 MW/Hz. As a simplified example (static point of view), an increase of power consumption by 270 MW would cause a drop in frequency of 10 mHz, if the power generation was not simultaneously increased.

Due to its three-level frequency control system, the large scale of generation systems, and the synchronous interconnection with other HV networks on a continental scale, the UCTE network has ample reserves to cope with load power variations under normal operating conditions.

However, in rare cases of breakdown of major interconnections and/or large groups of generation systems, the stability and continued operation of the entire network might be at risk. In such situations, the network operators could allow larger frequency variations in order to prevent runaways that would result in large-scale blackouts. In such exceptional situations the temporary frequency variations could be in the order of several hertz, being the result of larger imbalances between power generation and consumption.

2.6 Harmonics

Harmonics are conducted low-frequency disturbances of integer multiples of the system frequency.

According to IEC standards [3–9], the total harmonic distortion is calculated taking into account all harmonics up to the 50th harmonic order.

The principal causes of harmonics in electrical networks are non-linear loads such as large thyristor power converters or diode rectifiers. During transformer energization, the transformer magnetizing currents (inrush) also generate significant temporary harmonic distortion.

The generated harmonic spectrum of thyristor power converters on the AC input side is as follows:

Order of harmonics = $n \times p \pm 1$, (4)

where $n = 1, 2, 3\ldots$ and p = 6- or 12-pulse converters.

Harmonic distortion typically changes only slowly over time for stable loads; however, for fast cycling loads such as pulsating particle accelerators they change rapidly during each power cycle. For rapidly changing harmonics the conventional definitions according to the IEC are not meaningful, and smaller time windows (e.g. 100 ms) for the calculation of the harmonic distortion need to be defined.

These harmonic currents create harmonic voltage drops when passing through the upstream network impedances, which are then superimposed upon the fundamental frequency network voltage.

These are the most common techniques to reduce the harmonic levels in a network:

– strict separation of general services and power converter loads.

2.7 Temporary overvoltage

A temporary overvoltage has a typical duration of 10–500 ms, and can occur during a single-phase earth fault in the healthy phase(s) of a medium voltage network with non-effectively grounded neutral. The voltage increase is typically between +30% and +70%. Temporary overvoltages also occur during the energization of large capacitor banks, where the capacitive inrush current passing through the inductances of the upstream network causes a temporary voltage increase. These overvoltages have a much shorter duration of 10–20 ms, and typical amplitude of up to +50%.

2.8 Voltage imbalance

In the event of a voltage imbalance, the fundamental frequency voltage amplitude or angle between phases are not equal for all three phases. The imbalance is usually expressed as the ratio of egative to positive sequence components, using the following approximation:

$$\text{Voltage imbalance} = \sqrt{6\frac{U_{12}^2 + U_{23}^2 + U_{31}^2}{U_{12} + U_{23} + U_{31}} - 2} \,,$$

where U12, U23 and U31 are the fundamental frequency line–line voltages.

3 Power quality statistics

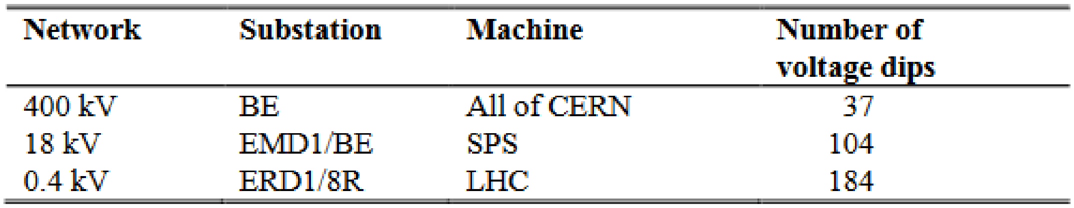
It is important to have a good understanding of the power quality of the electrical network. In particular, the duration and amplitude of voltage disturbances play a critical role in accelerator operating reliability.

Statistics for the CERN electrical networks are presented below as an example.

3.1 Voltage dips

Table 1 shows the number of voltage dips recorded during the reference period (mid June–mid November) at CERN.

Table 1: Number of voltage dips recorded at different voltage levels (period mid June–mid November)



Network	Substation	Machine	Number of voltage dips
400 kV	BE	All of CERN	37
18 kV	EMD1/BE	SPS	104
0.4 kV	ERD1/8R	LHC	184

Network disturbances at the 400 kV level are usually seen also in the 18 kV and 0.4 kV networks, while disturbances generated at the 0.4 kV level do not propagate upwards into the HV networks.

Network disturbances at CERN that cause one of the accelerators to stop are called ‘major events’, and are marked in red in Figs. 2–4. Although there are only limited statistical data available, it seems that the duration of network disturbances is not the critical parameter for accelerator trip; rather, it is the voltage amplitude. The data also indicate that most disturbances causing major events originate from the 400 kV network. Figures 2–4 show the statistics for network disturbances over a reference period (mid June–mid November):

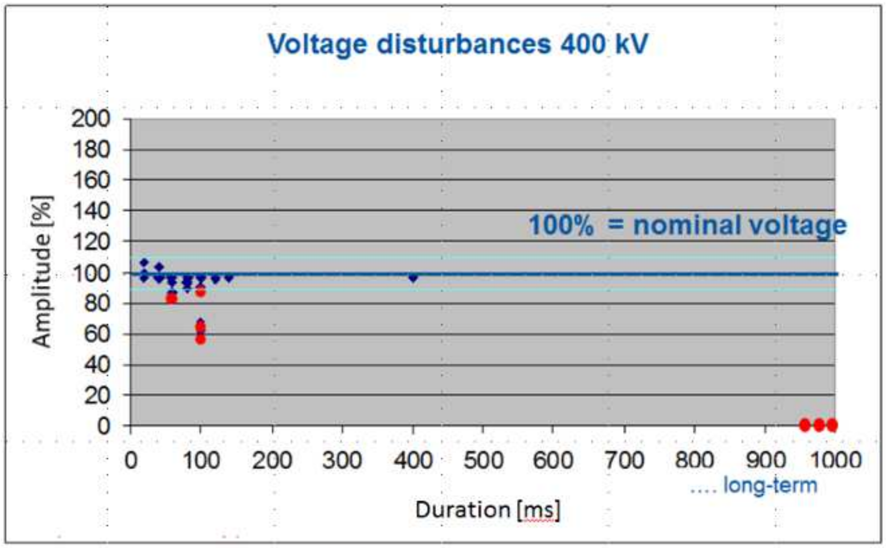


Fig. 2: Recorded disturbances in the 400 kV network. The events marked in red are major events, leading to a stoppage of an accelerator.