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DISTURBANCES AND POWER QUALITY OF CERN'S ELECTRICAL NETWORK

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Abstract

This paper gives an overview of the most common disturbances and power quality problems in CERN's electrical network and explains their consequences for accelerator operation. Based on detailed statistics, the quantitative parameters of network disturbances at CERN are presented and immunity levels for user's electrical equipment proposed in order to minimise the number of accelerator problems due to network disturbances. Several typical network disturbances recorded in 2003 are modelled in computer simulations, and their results are presented. Finally, the paper summarises the main parameters of CERN's low voltage distribution systems, their variations and power quality issues. Reference is made to the LHC Engineering Specification "Main Parameters of the LHC 400/230 V Distribution System" as a base for the specification of electrical equipment.

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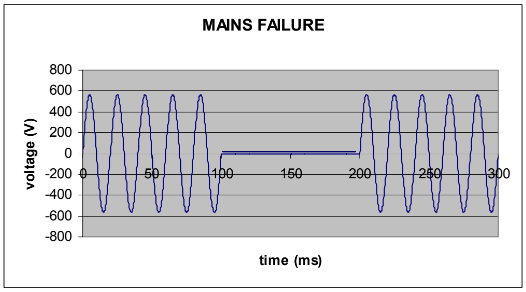
1 INTRODUCTION

Network disturbances and power quality are issues of increasing importance, as the share of sensitive electronic equipment is increasing steadily in modern power systems. Due to its complex nature, CERN's future LHC accelerator is expected to be extremely sensitive to network disturbances. The major types of disturbance are shown below:

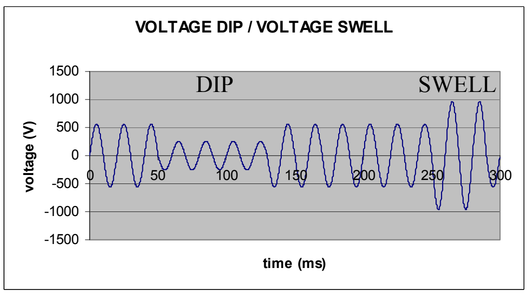


Causes:

- thunder-storms
- short-circuits
- emergency stop operation

Consequences:

- accelerator stop

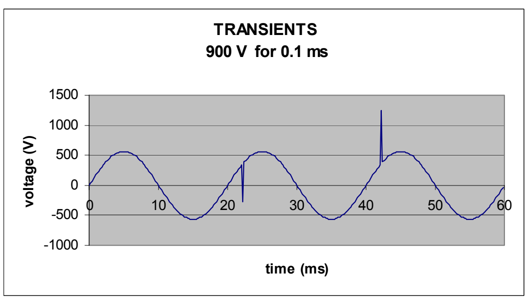


Causes:

- sudden change of load, inrush current of transformers
- short-circuits inside and outside CERN
- thunder-storms

Consequences:

- sometimes accelerator stop

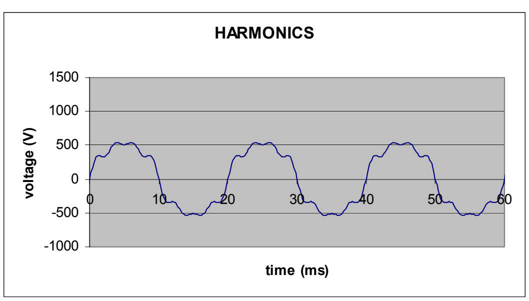


Causes:

- switching SVC's ON
- power converters
- thunder-storms

Consequences:

- failure of electronics



Causes:

- non-linear loads

(office PC's, power converters, etc.)

Consequences:

- malfunctioning of electronics

Fig. 1: Most common network disturbances

2 CERN NETWORK TOPOLOGY

With the 130 kV Meyrin and the 400 kV Prévessin network connections, CERN has two energy sources.

CERN's major supply and the only supply allowing LHC and SPS machine operation is the Prévessin 400 kV supply with its overhead line to the Génissiat HV station. Recently, a new additional 400 kV connection towards the Chamosson hydro power station (Valais, CH) was commissioned. Recent preliminary computer studies indicated that the LHC and SPS machines could temporarily be supplied via this connection, thus providing CERN with a 400 kV back-up supply.

The Meyrin 130 kV supply from Verbois (GE) is a back-up to maintain critical loads in case of 400 kV power failures. It also offers a high degree of flexibility in winter and gives some advantages and potential cost savings when negotiating CERN's energy contracts.

The 400 kV overhead lines supplying CERN are traversing the plane between the Geneva lake and the Jura, and are also crossing the Jura mountain chain at about 1500 m above sea level (direction Bellegarde). These geographical conditions make the lines particularly vulnerable to lightning strikes. The lines are equipped with earthing guard wires for lightning protection. In case of a single-phase short-circuit the line protection initiates a single-phase trip on both ends with subsequent autoreclosure after 1.5 s. Surge arresters are installed on the primary side of the 400 kV transformers, as a protection against overvoltages caused by lightning strikes.

Within CERN, the 18 kV level is the backbone for energy distribution. In case of a breakdown of one of the two sources 400 kV or 130 kV, CERN's decentralized Automatic Source Transfer (Autotransfer) system automatically detects this situation individually for each major substation, and changes over to the remaining source. The Autotransfer sequence takes about 20 s from the loss of power until the completion of the source transfer. The Autotransfer system is limited to 60 MVA in total, and therefore only used for general services and part of the LHC cryogenics.

There are a number of Static Var Compensators (SVC's) connected to the CERN 18 kV network. These SVC's are stabilising the bus voltage on the 18 kV level. However, they have a reaction time of about 50 ms, making them unsuitable to compensate for transient voltage disturbances.

There are a number of diesel generators connected to the 18 kV level, acting as a back-up supply for critical loads in case of mains failures. These generators have a start-up time of 45 s.

Table 1 and Fig. 1 summarise the main data of the transformers and the start point earthing scheme in CERN's electrical network.

Table 1: CERN network data

Transformer	Vector group	Impedance Ucc [%]	Earthing of prim. starpoint	Earthing of second. starpoint
400/66(20) kV, 110 MVA	YNyn0(d)	10.86 %	R = 0 Ohm	R_E = 80 Ohm
66/18 kV, 70 MVA	YNd11	7.8 %	None	artificial starpoint: Z = j 6 Ohm / phase R_E = 9 Ohm
18/0.4 kV, 2 MVA	Dyn11	6 %	None	R = 0 Ohm

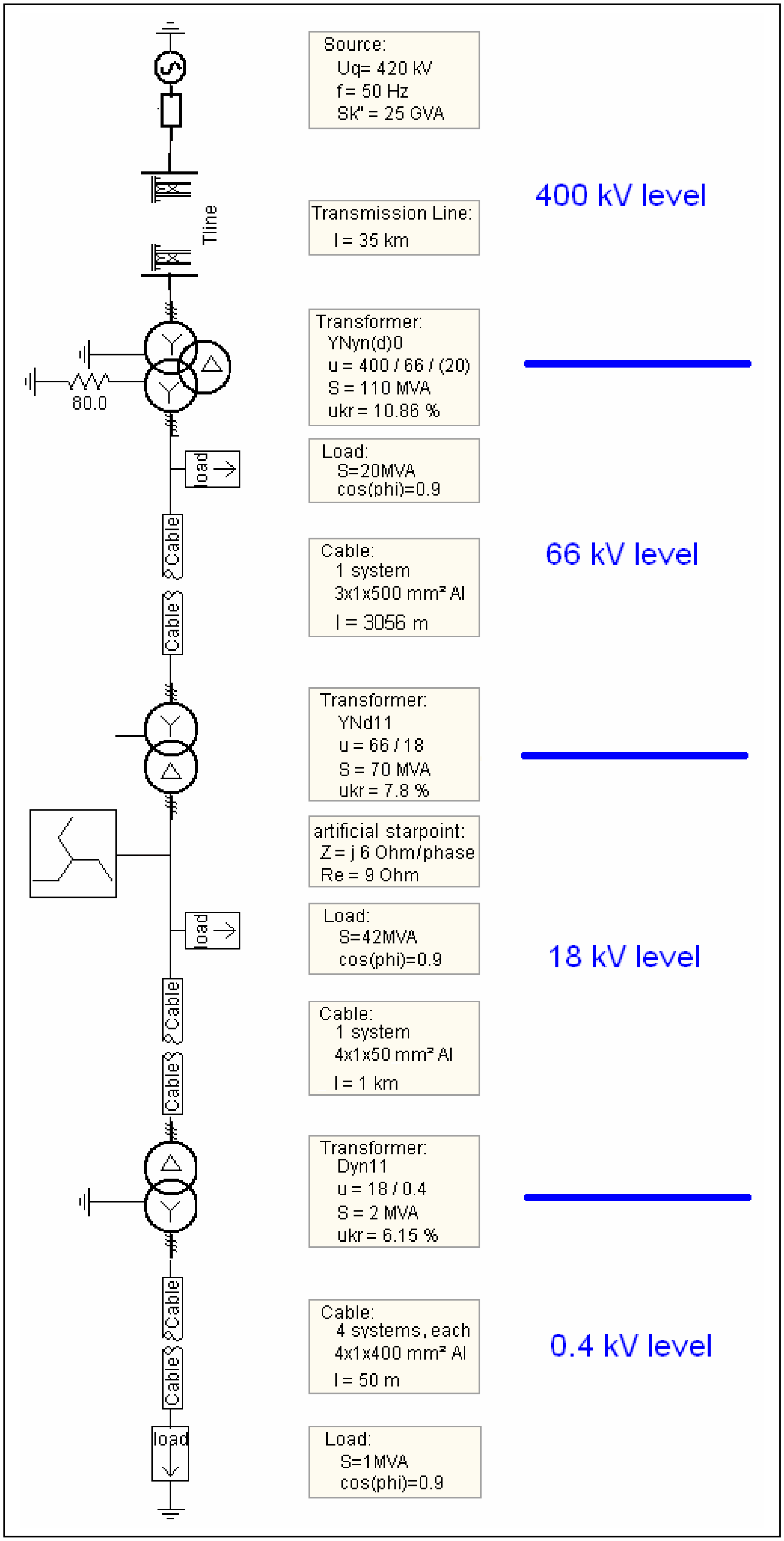


Fig. 2: Simplified CERN network

3 MONITORING OF POWER QUALITY AT CERN

3.1 Oscillostores for HV and MV network

Oscillostore devices are transient recorders for fixed installation, having large numbers of digital and analogue input channels, and an internal memory to record even avalanches of data. There are 7 oscillostores installed at CERN. The analogue channels are used to monitor currents and voltages, while the digital input channels record signals such as positions of circuit breakers and status of protection relays. The sampling frequency is 5 kHz, allowing the recording of voltage dips and swells but being too slow to detect fast transients or spikes.

In case of a disturbance or a short-circuit, there usually is an avalanche of data arriving at the oscillostore device, which are stored in the internal memory of the device. Subsequently, the data are transferred via Data Concentrator (DACON) to a central computer server where they can be analysed later on.

3.2 FLUKE voltage event recorders for the LV network

There are about 20 voltage event recorders of the type FLUKE VR101 installed across CERN. These devices are simply to be plugged into a 230 V single-phase socket. Network disturbances are stored locally within the device and can be read out locally using a portable PC. The device has sufficient memory for 4'000 events, allowing autonomous operation for at least one year.

4 STATISTICS 2003

4.1 Recording period

This paragraph covers the network disturbances recorded during the period mid June - mid November 2003.

4.2 Voltage variations (dips and swells)

Comprehensive recordings for all voltage levels at CERN are available for the period mid June – mid November 2003. The following number of events were recorded during this period:

Table 2: Number of voltage variations (mid June - mid Nov. 2003)

Network	Substation	Number of voltage variations
400 kV	BE	37
18 kV	EMD1/BE	104
0.4 kV	ERD1/8R	184

Network disturbances on 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 usually do not propagate into the HV networks.

Network disturbances at CERN, which cause one of the accelerators (PS or SPS) to stop, are called "major events", and marked in red colour in Figs. 3-5. Although there are only limited statistical data available today it seems that the duration of network disturbances is not, but voltage amplitude is indeed the critical parameter for accelerator operation. The data also indicate that most of the major events are caused in the 400 kV network. The following figures show the statistics of network disturbances in 2003:

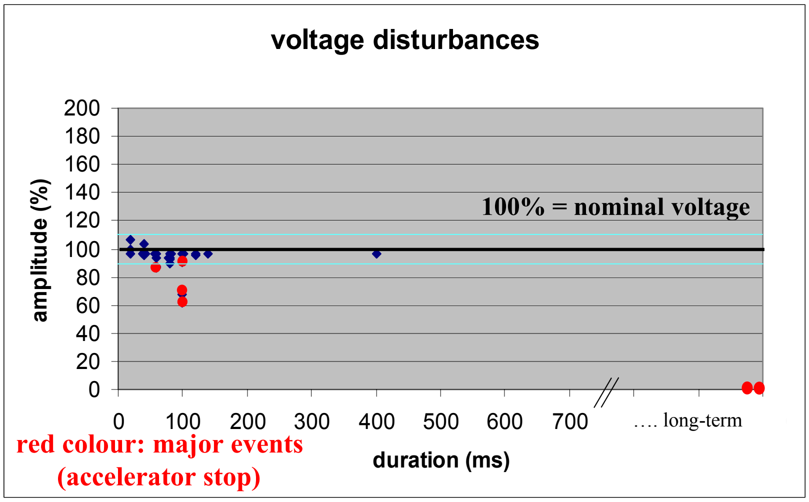


Fig. 3: Typical network disturbances in 2003 (BE substation, 400kV)

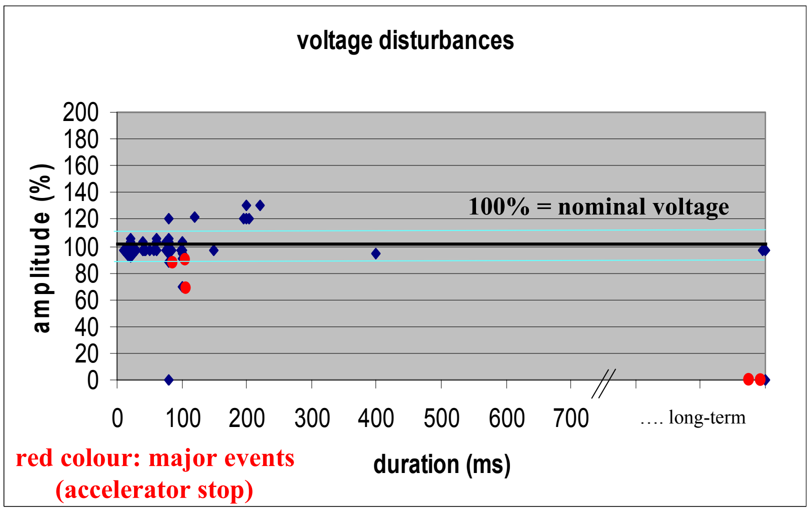


Fig. 4: Typical network disturbances in 2003 (EMD1/BE, 18kV)

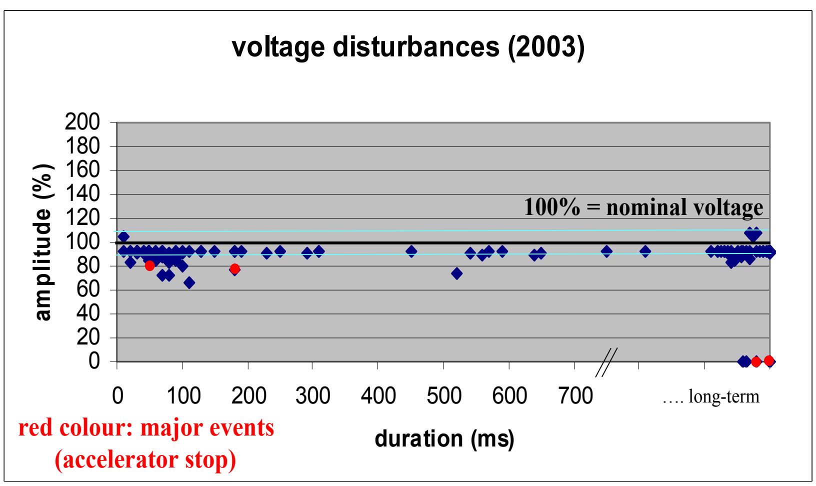


Fig. 5: Typical network disturbances in 2003 (ERD1/8R, 0.4kV)

Figs 6-11 represent the same data separately as a function of voltage amplitude and duration:

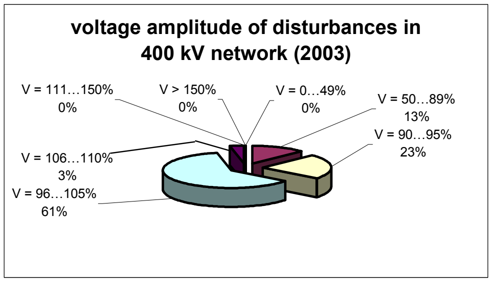


Fig. 6: Voltage amplitude of disturbances 400 kV

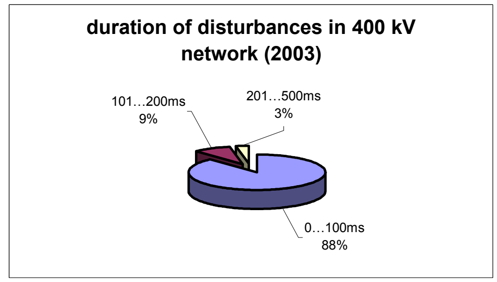


Fig. 7: Duration of disturbances 400 kV

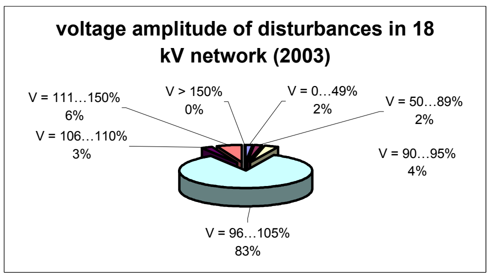


Fig. 8: Voltage amplitude of disturbances 18 kV

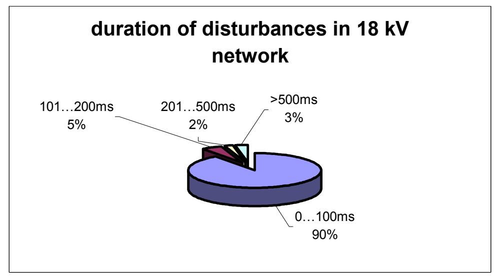


Fig. 9: Duration of disturbances 18 kV

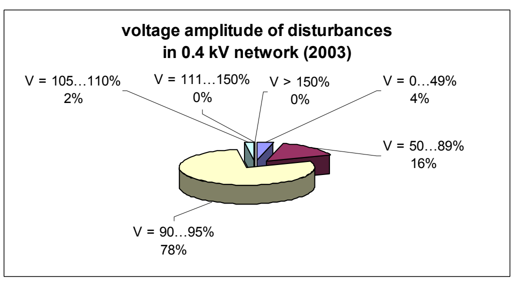


Fig. 10: Voltage amplitude of disturbances 0.4 kV

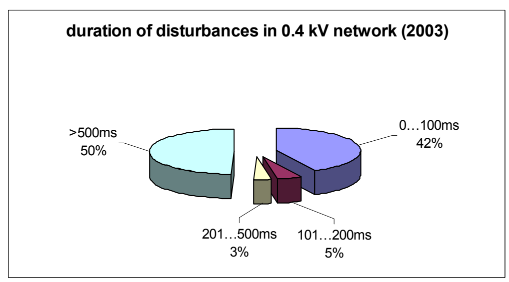


Fig. 11: Duration of disturbances 0.4 kV

The recordings show that the majority of network disturbances is in the range of 90 to 110 % of nominal voltage, most of them having a duration of 50 to 200 ms. The main causes of these events are sudden load changes, inrush currents of transformers, short-circuits and thunder-storms. In the 0.4 kV network there are in addition large numbers of events of longer duration (t > 500 ms) which are steady-state voltage variations due to changing load conditions.

Tables 3-5 show the worst-case voltage dips recorded in 2003, for each individual network:

Table 3: Worst-case voltage dips recorded in 2003 (entire CERN 400 kV network)

Dip	Duration	Location	Cause
- 38 %	100 ms	BE 400 kV	thunder-storm
- 32 %	100 ms	BE 400 kV	thunder-storm
- 13 %	60 ms	BE 400 kV	unknown
- 12 %	60 ms	BE 400 kV	thunder-storm
- 10 %	80 ms	BE 400 kV	unknown

Table 4: Worst-case voltage dips recorded in 2003 (entire CERN 18 kV network)

Dip	Duration	Location	Cause
- 86 %	180 ms	Station Jura	unknown
- 60 %	100 ms	Station Jura	unknown
- 58 %	140 ms	Station Jura	unknown
- 41 %	120 ms	Station BE	thunder-storm
- 38 %	100 ms	Station Jura	unknown

Table 5: Worst-case voltage dips recorded in 2003 (entire CERN 0.4 kV network)

Dip	Duration	Location	Cause
- 71 %	180 ms	Buildg. 2660, PA6	short circuit 18 kV
- 34 %	110 ms	Station ERD1/8R	thunder-storm
- 32 %	130 ms	Buildg. 2260, PA2	thunder-storm
- 30 %	110 ms	Booster SVC	thunder-storm
- 28 %	70 ms	Station ERD1/8R	thunder-storm

Tables 6-8 show the worst-case voltage swells, recorded in 2003, for each individual network:

Table 6: Voltage swells (entire CERN 400 kV network)

Swell	Duration	Location	Cause
+ 6 %	20 ms	BE 400 kV	unknown
+ 3 %	40 ms	BE 400 kV	switching

Table 7: Voltage swells (entire CERN 18 kV network)

Swell	Duration	Location	Cause
+ 78 %	220 ms	Jura 18 kV	unknown
+ 76 %	220 ms	Jura 18 kV	unknown
+ 30 %	220 ms	BE 18 kV	switch ON SVC1
+ 22 %	120 ms	BE 18 kV	switch ON
+ 20 %	200 ms	BE 18 kV	switch ON SVC1

Table 8: Voltage swells (entire CERN 0.4 kV network)

Swell	Duration	Location	Cause
+ 25 %	30 ms	ESD1/BK6	unknown
+ 20 %	30 ms	ESD1/BK6	unknown
+ 18 %	50 ms	EYS01/PA6	unknown
+ 16 %	50 ms	EYS01/PA6	unknown
+ 13 %	10 ms	EAD345/PA2	unknown

4.3 Fast transients (spikes)

There are no recordings available for the 400 kV and 18 kV networks as the 5 kHz sampling frequency of the oscillostore devices is not sufficient. Detailed data on the occurrence of transients in CERN's 0.4 kV networks are available, very strongly varying with the location. Some switchboards recorded no or very few transients in 2003, while in some places several thousands of them were observed.

The amplitude of the transients usually ranges from 50 to 250 V (added on top of the sinewave), although several transients up to 2500 V were recorded in some places. Due to the short duration of the spikes, the energy content is very small.

Table 9: Transients (entire CERN 0.4 kV network)

Spikes	Location	Cause
+ 2550 V	EAD345/PA2	unknown
- 2480 V	EAD345/PA2	unknown
+ 2480 V	EAD345/PA2	unknown
- 2190 V	ESD1/BK6	unknown
+ 2140 V	EAD345/PA2	unknown

4.4 Harmonic voltage distortion THD(U)

Repeated measurements of harmonic distortion were done in different 0.4 kV substations in CERN's electrical distribution network, showing that in all substations the harmonic distortion remained below the limits as specified in IEC61000-2-2 (class 2).

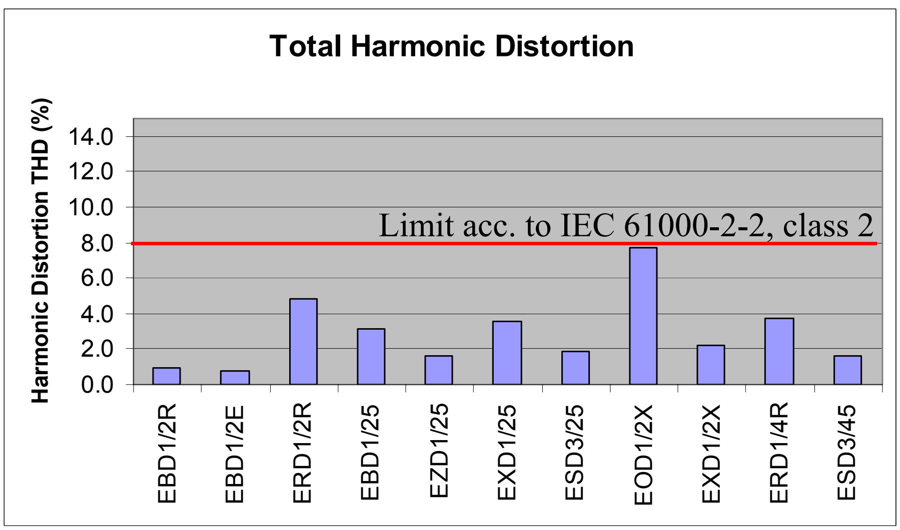


Fig. 12: Measured harmonic voltage distortion in CERN's 0.4 kV substations

Generally harmonics are lowest in switchboards for general services (called EBDxx/xx). Higher harmonic voltage distortion can be found in switchboards supplying rectified load (ERDxx/xx), and highest distortion was found on one switchboard supplied by a UPS (EODxx/xx).

5 COMPUTER SIMULATIONS

In order to better understand the consequences of network disturbances for accelerator operation, comprehensive computer studies were done using the software PSCAD. Fig. 13 shows the network model used for the computer simulations. Figs. 14-16 compare the recordings of a thunder-storm occurred on 29.08.2003 01:14h with the computer simulations. Recordings and computer simulations very closely correspond.

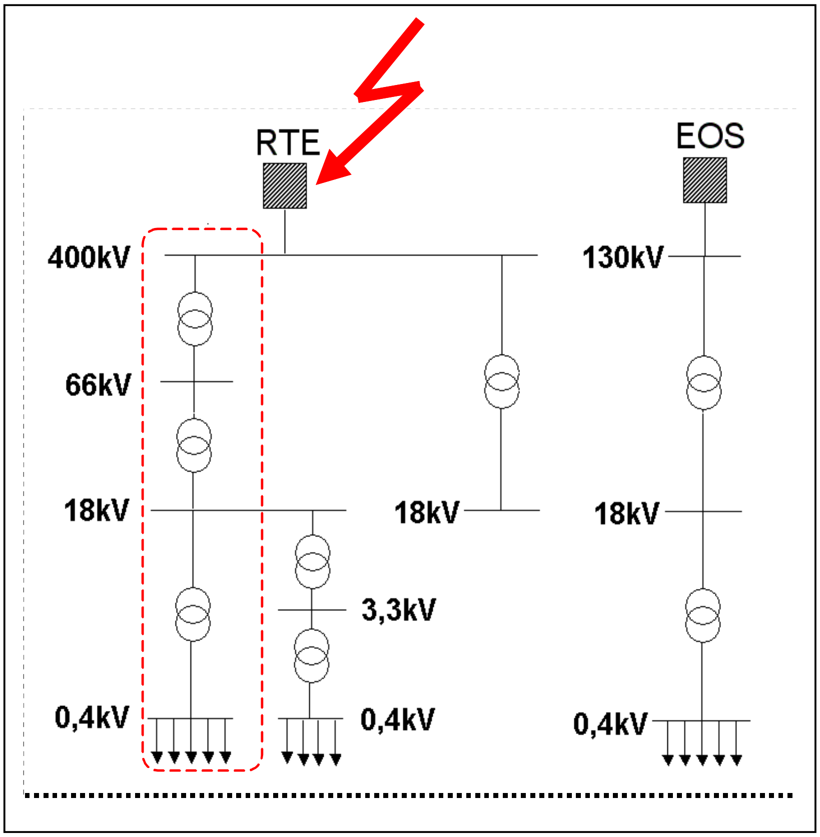


Fig. 13: Network model for computer simulations

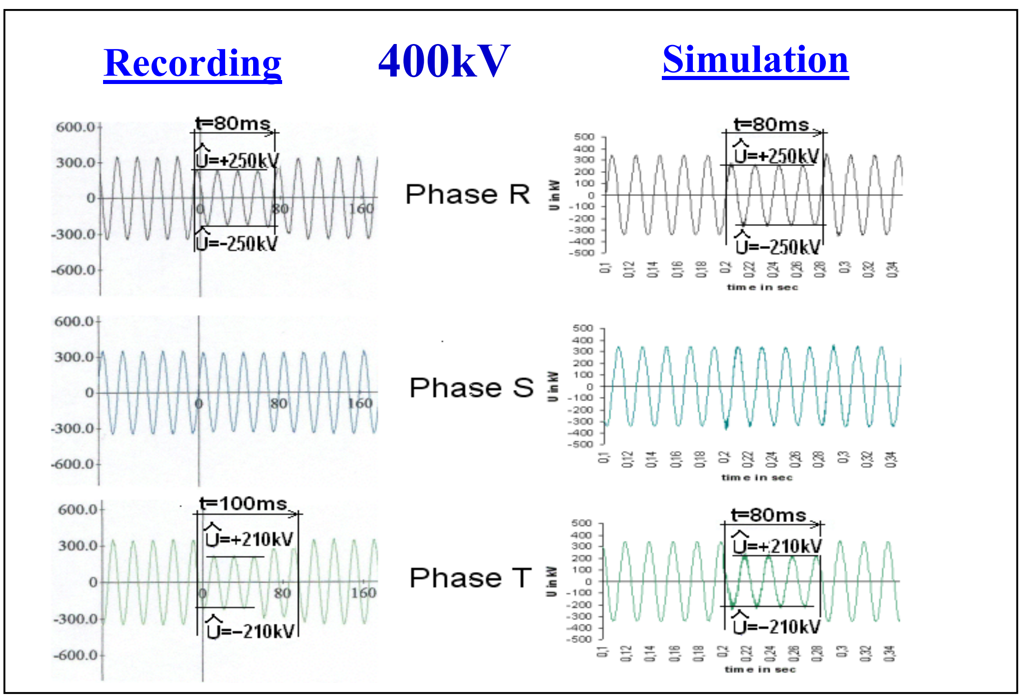


Fig. 14: 400 kV recordings and computer simulations of thunder-storm

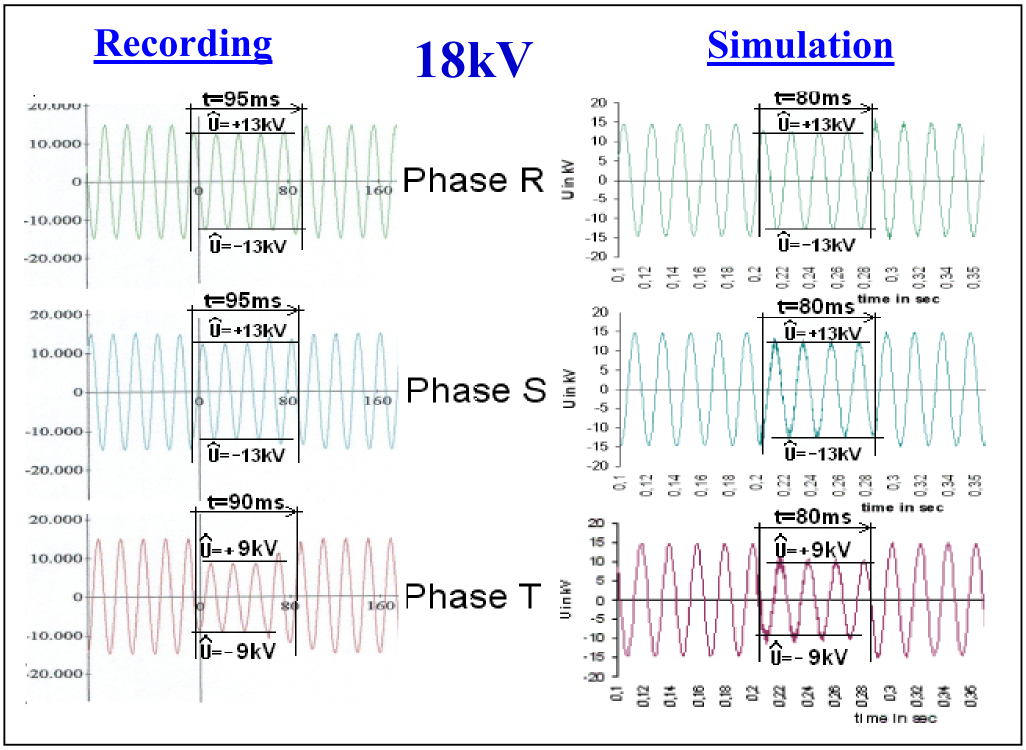


Fig. 15: 18 kV recordings and computer simulations of thunder-storm

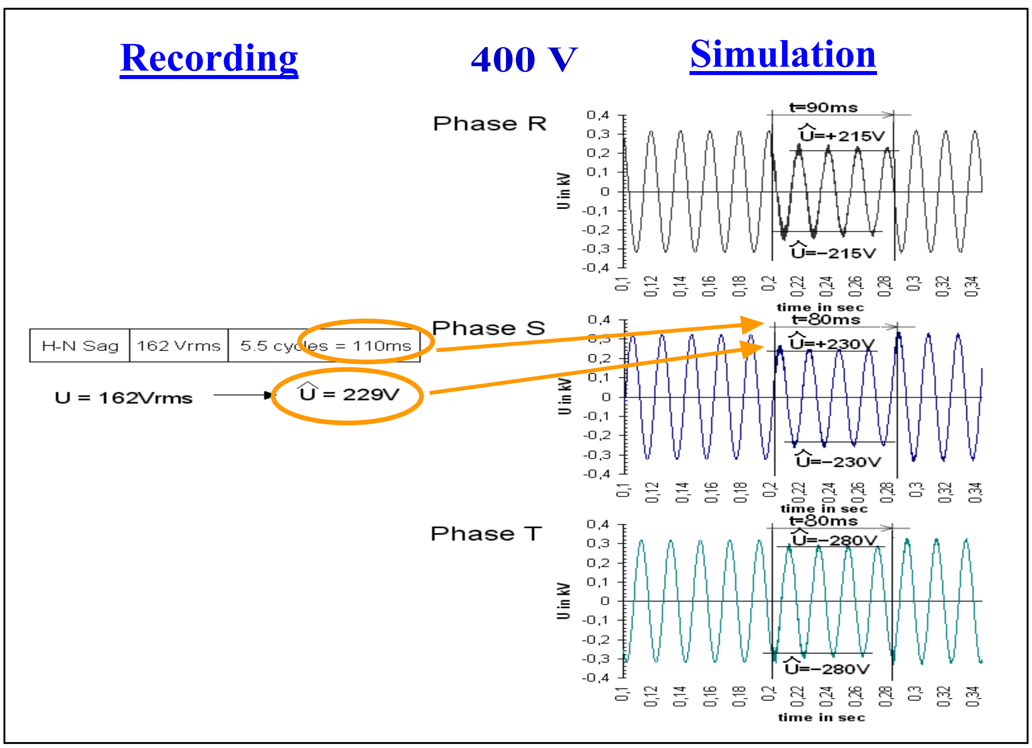


Fig. 16: 0.4 kV recordings and computer simulations of thunder-storm

Similar computer simulations were done for other thunder-storms recorded, they also show very close correspondence between recordings and simulations.

Tables 10-14 outline the propagation of unsymmetrical 400 kV network disturbances into the subsequent (lower) voltage levels, found by computer simulations.

Table 10: Propagation of single-phase voltage dip in 400 kV network, -50% in phase R

	R	S	T	R-S	S-T	R-T
400 kV	50%	100%	100%	75%	100%	75%
66 kV	62%	95%	93%	75%	100%	75%
18 kV	76%	76%	100%	65%	93%	93%
0.4 kV	91%	66%	91%	75%	75%	100%

Table 11: Propagation of double-phase voltage dip in 400 kV network, -50% in phases R and S

	R	S	T	R-S	S-T	R-T
400 kV	50%	50%	93%	50%	76%	76%
66 kV	57%	58%	87%	50%	76%	76%
18 kV	76%	50%	76%	60%	60%	83%
0.4 kV	81%	60%	60%	77%	50%	77%

Table 12: Single-phase interruption 400kV (after opening of circuit breaker, phase R)

	R	**S**	**T**	**R-S**	**S-T**	**R-T**
400 kV	(97%)	100%	100%	100%	100%	100%
66 kV	91%	95%	102%	89%	100%	100%
18 kV	99%	89%	100%	92%	93%	103%
0.4 kV	103%	91%	94%	98%	89%	100%

Table 13: Single-phase voltage dip -50% in phase R,
due to short-circuit midway (17.5 km) on 400 kV line Genissiat-Bois-Tollot

	R	**S**	**T**	**R-S**	**S-T**	**R-T**
400 kV	50%	111%	101%	62%	100%	87%
66 kV	62%	90%	98%	62%	100%	87%
18 kV	87%	63%	100%	66%	82%	102%
0.4 kV	100%	66%	82%	87%	62%	100%

Table 14: Double-phase voltage dip -50% in phases R and S,
due to short-circuit midway (17.5 km) on 400 kV line Genissiat-Bois-Tollot

	R	**S**	**T**	**R-S**	**S-T**	**R-T**
400 kV	50%	50%	111%	53%	55%	92%
66 kV	73%	37%	88%	53%	55%	92%
18 kV	92%	53%	56%	80%	33%	82%
0.4 kV	81%	81%	31%	93%	53%	56%

6 LHC ENGINEERING SPECIFICATION

Based on the statistics of past network disturbances, a certain minimum immunity of electrical equipment was defined in the Engineering Specification "Main Parameters of the LHC 400/230 V Distribution System"[1]. This document covers the main parameters of CERN's low voltage systems, their variations and power quality issues. User's equipment should be designed to normally function within the following limits:

- Nominal voltage 400 / 230 V
- Max. voltage variations ± 10 %
- Typical voltage variations ± 5 %
- Transients (spikes) 2500 V for 0.2 ms
- Voltage swells + 50 % of Un, 50 ms
- Voltage dips - 50 % of Un, 100 ms and - 20 % of Un, 200 ms
- Total harmonic distortion (THD) 5 %.

Equipment whose failure or malfunctioning would have more serious consequences might be specified having higher immunity against network disturbances. Fig. 17 visualises the limits as stated above. It is recommended to design or choose user's equipment such that it correctly operates within these limits.

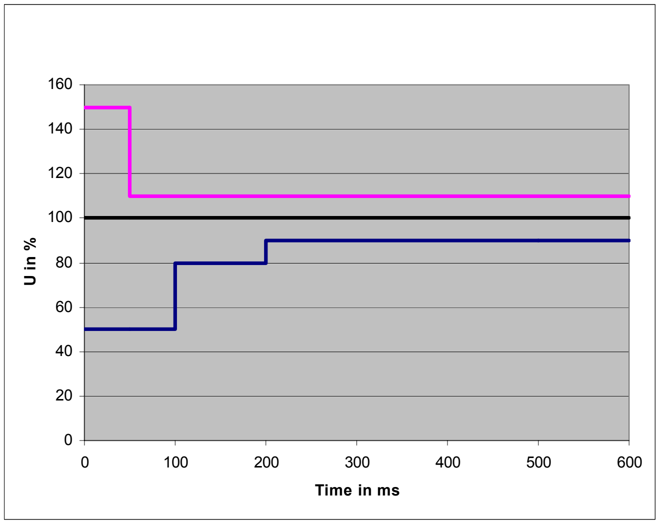


Fig. 17: Limits for voltage swells and voltage dips
as per Engineering Specification (for 0.4 kV LV networks)

7 CONCLUSIONS

This document explains the different types of network disturbances and outlines their impact on particle accelerator operation. It shows that the most critical network disturbances for the accelerators are voltage dips originating from the 400 kV network.

Based on detailed statistics, the quantitative parameters of network disturbances at CERN have been presented and immunity levels for user's electrical equipment proposed in order to minimise the number of accelerator problems due to network disturbances. Reference is made to the Engineering Specification [1].

Several typical network disturbances recorded in 2003 have been modeled in computer simulations. The results of the simulations very closely correspond to the recorded data, thus confirming the validity of the computer model. Based on this model, the propagation of 400 kV network disturbances into the CERN MV and LV networks have been studied and their impact on accelerator operation evaluated.

The statistics of 2003 have shown that power quality at CERN remains within the limits prescribed in the IEC standards [4].

8 REFERENCES

[1] G. Fernqvist, J. Pedersen, K. Kahle "Main Parameters of the LHC 400/230 V Distribution System" Rev.3, EDMS No. 113154, 29.9.2000.

[2] K. Kahle, LHC Performance Workshop 2003, "Disturbances and power quality of the 18 kV CERN electrical network and the 400/230 V UPS distribution system for LHC".

[3] EN50160 "Voltage characteristics of electricity supplied by public distribution systems".

[4] IEC61000 "Electromagnetic compatibility", Parts 2-2, 2-4, 2-12, 3-4, 3-6 and 4-7.