POWER QUALITY MEASUREMENTS AND DIP CALCULATIONS IN FINNISH ELECRICITY NETWORKS

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SUMMARY

Two power quality projects from Finland are introduced. ***Part 1:*** *PQ measurements were carried out in 1997 and 1998 at the low voltage networks of 15 utilities at 78 different sites. The number of weeks measured was about 250. The requirements of EN 50160 were exceeded at the flicker, fifth harmonic, total harmonic distortion and negative sequence unbalance.* ***Part 2:*** *An AM/FM-GIS modification for analyzing voltage sags caused by line-to-line and 3-phase faults has been completed. Also a simplified model of a voltage restorer is introduced.*

PART 1: OBJECTIVES AND REALIZATION

The goal of the power quality (PQ) measurement project was to measure the voltage characteristics and to collect some other parameters of distribution networks and loads, mainly in low voltage networks [1]. The participants, rural as well as urban distribution network companies, measured with their own meters at their own distribution networks as many PQ quantities as the meters at their disposal were able to. Because the loads and the networks have influence on the voltage characteristics we tried to gather following explaining site information:

- active and reactive powers and/or currents
- short circuit current at the measurement location
- lengths of the overhead lines and cable lines
- main customer groups and
- compensation (capacitors)

The different measurement principles and output data presentations of the utilities' meters had to be justified to measure the desired PQ quantities. The raw data had to be emptied from the meters and to be sent to the processing centre. Then the data had to be processed to a compatibility form (standard form). Finally the conclusions were made.

15 participating utilities measured totally 248 weeks. In addition the utilities measured with parallel meters during 18 weeks, so the total number of weeks rose to 266. When the customer groups were determined as the greatest customer group of a feeder measured we had the site distribution as presented in table 1.

Table 1. The number of sites per customer group classified according to the biggest customer group at a site or feeder.

CUSTOMER GROUP	Number of sites
Industry and service	
• Small industry	10
• Public service	23
• Private service	11
Private sector and farm houses	
• Blocks of flats without electric heating	15
• Small houses without electric heating	2
• Small houses with electric heating	14
• Farm houses with electric heating	3
SITES TOTALLY	**78**

Following meters were used to pick up the measurement information; the right number column indicates the number of the participating utilities which had this kind of meter:

Meter	Utilities
• MXPQKML (product name "Quality Guard"), Mittrix Oy nowadays MX Electrix Oy (Finland)	7
• Memobox 686, Lem Elmes Ag (Switzerland)	6
• Vip System 3, Elcontrol Energy S.p.A. (Italy)	2
• PA-7, Metrosonics, Inc. (USA)	2
• Linecorder LC-836i, Telog Instruments, Inc. (USA)	2
• MELKO system, Enermet Oy (Finland)	2
• Dranetz 8000-2, Dranetz Technologies, Inc. (USA)	1
• Vip System 20, Elcontrol Energy S.p.A. (Italy)	1

The measurements were intended to be carried out according to the valid PQ standard EN 50160 [2].

The meter output results (raw data) were transmitted to the processing centre through e-mail and 3.5 inch 1.44 MB diskettes. All the files received were easily readable, thus the both transmitting means were considered adequate and reliable. Raw data (except the event quantities) from the different meters were conformed to cumulated probability curves. The most important values of the PQ quantities were at the percentages of 95 % and 100 % (= maximum value).

RESULTS

Summary of the values at 95 % cumulated probability

The values at the 95 % cumulated probability of three phase PQ quantities were united and handled as single phase values. Memobox 686 gave the results of the two tailed quantities, namely supply voltage variation (voltage level) and frequency, as an odd difference way by proposing e.g. for the voltage level that the number of the mean values greater than the upper limit of 1.10 x 230 V is equal to the number of the mean values lower than the lower limit of 0.90 x 230 V, although there were no mean values greater than 230 V. Only then Memobox 686 declares the voltage level out of allowed limits when there is the difference expression given greater than 10 % of 230 V; the percentage provided with the sign of ±.

Table 2 presents the PQ quantities exceeding the standard limit, the allowed limits, the 10 min mean values at 95 % cumulated probability and in addition the maximum 10 min mean values. The results are from all the measurements carried out, about 250 weeks and 78 sites. At the bottom of the table there are the numbers of the event quantities. The events have no requirements in EN 50160. The bolded values exceeded the allowed limits at 95 % cumulated probability in EN 50160 or in the suggested limits in table.

No values of the frequency and signal voltage measured exceeded the allowed limit of EN 50160. In tables 2 and 3 the event case of the number of 950 dips a week occurred in winter at a line-to-ground voltage of a small house with electric heating. Mostly there was such dip that lasted less than 20 ms and ranged 195.5 V … 207 V. At this site the short circuit current was informed to be about 300 A. The great number of the dips was mostly due to the changing line-to-ground voltage which varied over and under the limit value of 207 V. The amount of the voltage change was very many times only of the order of 1 V.

Duration curve of the low voltage level

The duration curve of the low voltage level was calculated from the 252 measurement weeks. The duration is given in a single-phase presentation. The interruptions (all the 10 min mean values smaller than or equal to 1 % of 230 V = 2.3 V) were removed from the total number of the 10 min mean values measured, the total number being 735’042. (The number of the 10 min values which were interpreted as interruptions was 1’009.)

The duration curve as a single-phase presentation was depicted (not shown here). This curve was considered as “a duration curve of the line-to-ground voltage in Finnish low voltage distribution networks” by the controlling group of the measurement project.

Only a single 10 min mean value of a phase voltage level was greater than 1.10 x 230 V, namely 258 V, and it occurred within the customer group of public service.

Table 2. The10 min mean values at 95 % cumulated probability and the maximum10 min mean values of the PQ quantities at low voltage + some numbers of event quantities.

PQ QUANTITY	**Allowed limits from EN 50160**	**10 min mean values at 95 % cumulated probability**	**Maximum 10 min mean values**
Voltage level / V, no interruptions included	207 V … 253 V	Changing range: 2,3 … 258	**258**
Memobox way; difference expression	±10 % of 230 V	±1,0 % … ±6,0 %	
Flicker	1,0	0,18 … **2,1**	0,21 … **5,3**
Harmonic voltage that mostly exceeded the limit of the table in the standard EN 50160			
5. harmonic / % of 230V	6,00	… **6,75**	**9,6**
7. harmonic / % of 230V	5,00		**6,75**
9. harmonic / % of 230V	1,50		**1,5**
15. harmonic / % of 230V	0,50		**0,70**
21. harmonic / % of 230V	0,50		**1,5**
THD in % of 230V	8,00	0,62 … 6,8	0,87 … **9,6**
- Quality Guard / % of $U_{measured}$		1,0 … **8,5**	1,2 … **9,4**
Negative sequence unbalance U^-/U^+ in %	2,00	0,13 … **2,0**	0,19 … **4,5**
- Dranetz 8000-2 (calculated from line-to-line-voltages)	2,00	0,46 … **2,5**	0,70 … **5,3**
PQ QUANTITY outside the scope of EN 50160	**Suggested limit:**	**10 min mean values at 95 % cumulated probability**	**Maximum 10 min mean value**
DC voltage component / % of the voltage measured	[2 % $U_{measured}$]	0,08 … 1,1	0,10 … **2,5**
Zero sequence unbalance U^0/U^+ in %	[4 % $U_{measured}$]	0,14 … 1,8	0,17 … **4,7**
EVENT QUANTITIES	**Number**		
Interruptions / phase / week	0 … 5		
Overvoltages and dips / phase/ week	0 ... 290 ... 354 … *950*		
- Overvoltages / phase/week	1 … 8		
- Dips / phase/week	0 … *950*		
- Transients (over 300V) / phase / week	0 …		

Table 3 presents the greatest values measured at 95 % cumulated probability of the PQ quantities with the corresponding customer groups. The bolded values exceeded the allowed limits of the standard EN 50160.

Table 3. The highest values of the PQ quantities at 95 % cumulated probability and the corresponding customer groups.

PQ QUANTITY & CUSTOMER GROUP	**Values at 95 % probability**
Supply voltage variation (level)/V	
Memobox; difference in % of 230 V -small houses with electric heating	±1.0 … ±6.0
Flicker	
-small houses with electric heating	0.18 … **2.1**
- small industry	0.29 … **1.8**
- farm houses	0.56 … **1.3**
Harmonic voltage that mostly exceeded the limit of the table in the standard EN 50160	
5. harm. in % of 230V -public service	2.0 … **6.75**
7. harm. in % of 230V -public service	1.6 … 4.5
THD in % of 230V - public service	1.4 … 6.8 …**8.5**
- small houses without el heating	1.6 … **8.2**
Negative sequence unbalance U^-/U^+ in %	
- private service	0.19 … **2.5**
- blocks of flats	0.19 … **2.5**
- farm houses	0.51 … **2.0**
DC voltage component in % of the voltage measured	Suggested limit = 2 %
- private service	0.1 … 1.1
- small houses with electric heating	0.13 … 1.1
Zero sequence unbalance U^0/U^+ in %	Suggested: 4 %
- private service	0.18 … 1.8
- small houses with electric heating	0.21 … 1.8
EVENT QUANTITIES	Number
Interruptions / phase / week - farm houses	0 … 5
Overvoltages & dips / phase/ week	0...290...354… *950*
- small houses with electric heating	0 … 950
- public service	0 … 290
- small industry	0 … 110
- farm houses	1 … 60

About 70 % of all the mean 10 min values measured were greater than the nominal voltage 230 V. The explanation may occur in measurement sites which were many times near the distribution transformer, thus the voltages were there higher than at the end of a feeder.

The voltage level of the duration curve was 213 V at 0.2 % cumulated probability and 122 V at 0.1 % probability.

Same kind of duration curves can be presented for the total harmonic distortion (thd) and the DC voltage component, the latter being outside the scope of the standard EN 50160. The thd value at 95 % cumulated probability was 4.9 % of 230 V and the maximum mean value was about 9.6 % of 230 V.

The DC component 10 min mean value at 95 % cumulated probability was 1.0 % of the voltages measured instead of 230 V, and the maximum 10 min mean value was about 2.5 % of the voltages measured. When these voltages measured were sufficiently close to the nominal voltage of 230 V, the expressed measurement percentages can be compared directly with 230 V without any remarkable inaccuracy.
The meter of DC voltage component was Quality Guard.

CONCLUSIONS (PART 1)

The power quality (PQ) in Finland was according the project measurements good when evaluated in comparison with the requirements mentioned in EN 50160. There were some occurrences where the standard limits were exceeded namely at the flicker (small houses with electric heating, small industry and farm houses), at the fifth harmonic (public service), at the total harmonic distortion (public service and small houses without electric heating) and at the negative sequence unbalance (private service and blocks of flats).

The most PQ quantities were measured as the 10 min mean values. Thus a great PQ quantity value (greater than the limit value at 95 % cumulated probability in the table of EN 50160) tells that there may occur in the future, if not during the measurement, problems within this kind of PQ quantity. For instance harms caused by too strong harmonics, especially harmonics of order 5 or 7.

During the result processing we had to point out some inconsistencies in the standard EN 50160 e.g. the supply voltage should be determined as the RMS value for the averaging time of 10 min and the supply voltage variation (level) should have both the maximum and minimum values during the whole measurement week as well as the interruptions also should have more requirements than those definitions mentioned in EN 50160.

REFERENCES (PART 1)

[1] J. Farin & M. Siirola, *Study about the power quality of the Finnish distribution networks*, Electricity Energy Association registered society Sener, Publication series 1/98, Product number 1093, Helsinki 1998, 58 pages + 19 attachments (in Finnish).

[2] EN 50160. *Voltage characteristics of electricity supplied by public distribution systems*. CENELEC, Brussels, Belgium, November 1994. 53 p.

PART 2: ANALYSING VOLTAGE SAGS

Voltage sags are considered as the most frequent disturbances for industrial consumers. Their adverse effects on various types of loads can cause remarkable losses in production. These reasons have made voltage sags worth studying.

Basic idea

Commercial network information systems (AM/FM-GIS) usually calculate voltages only in steady state. Furthermore the system is often assumed to be a symmetrical three-phase network with symmetrical voltages and currents. Voltage sags are unsymmetrical and transient in nature. They can, however, be analysed by means of an AM/FM-GIS system. Some simplifications had to be made, though.

First, the sagged voltage is assumed to be sinusoidal and thus have the fundamental frequency component only. Secondly, it is divided into sections each having certain duration with a constant rms value. (See figure 1.) These sections of the remaining voltage during the sag can be calculated in steady state, i.e. as momentarily constant values. The sag penetration into the network, especially the sound feeders, is then analysed.

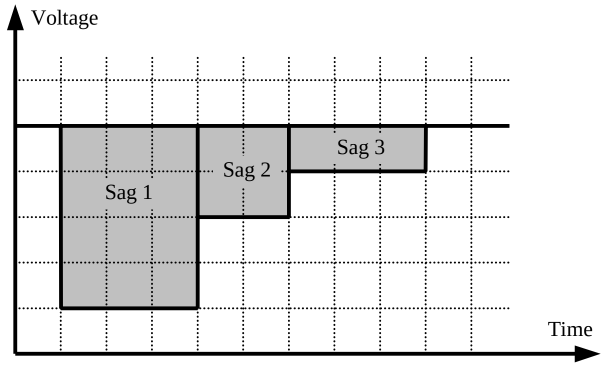


Fig. 1. Dividing a voltage sag into sections with constant rms magnitude.

In a radially operated medium voltage distribution network the voltage sag caused by a fault is most severe at the fault site itself. The remaining line voltages increase along the faulted feeder towards the substation busbar, i.e. the PCC (point of common coupling). The sound feeders will then have line voltages equal to the bus voltages during the sag, assuming the load currents to be zero. (See figure 2.)

Fault types considered

In Finland the medium voltage (20 kV) networks have usually isolated or, in some cases, coil earthed star-point. Thus earth faults do not cause actual voltage sags. The line-to-ground voltages do change but the line-to-line voltage triangle remains unaltered.

The deepest voltage sags occur due to faults between the lines. Line-to-line and three-phase faults are the fault types considered in this study. The fault impedance between the lines was taken into account.

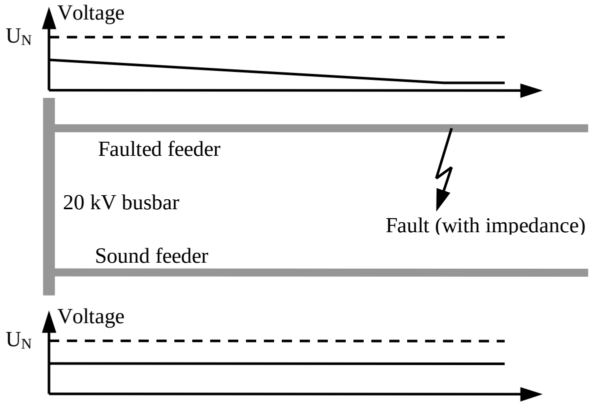


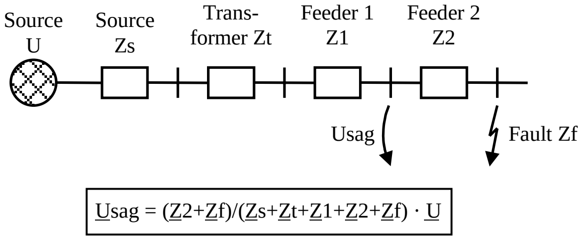
Fig. 2. Sagged voltages on two adjacent feeders during a fault with impedance. Load currents are neglected.

Fault simulator

A fault simulator was added to the software used for modelling. Here the user defines the fault type (2-phase, 3-phase), fault impedance between the lines and the duration of the fault. Also the node of the network to which the fault will be applied has to be determined. The simulator then delivers the input data for the voltage sag calculation.

Three-phase faults

For symmetrical 3-phase faults the single-phase equivalent of the network can be used. The sagged voltages are then calculated for each node by using the network impedances and the source e.m.f. The ratio of the downstream impedance (from the monitored node to the fault including the fault impedance) and the total fault current path impedance gives the percentage of the source voltage that remains in the node during the sag. (See fig. 3.)



$$\underline{U}sag = (\underline{Z}2+\underline{Z}f)/(\underline{Z}s+\underline{Z}t+\underline{Z}1+\underline{Z}2+\underline{Z}f) \cdot \underline{U}$$

Fig. 3. Calculating the sagged voltage caused by a 3-phase fault.

One of three line-to-ground voltages is calculated (both magnitude and angle) and after that the phase angles for the two other voltages are retrieved. Assuming the situation to be symmetrical the voltages are equal in magnitude and have phase angle shift of ± 120 degrees.

Line-to-line faults

Line-to-line faults cause unsymmetrical voltages to the network and thus each phase has to be calculated separately. The method is applicable to symmetrical faults as well.

Applying the symmetrical components and assuming the positive and negative sequence networks to be equal the line-to-ground voltages in the faulted node can be calculated. The line currents have to be calculated as well.

Finally, knowing the line-to-ground voltages in the faulted node and the phase currents the sagged voltages throughout the faulted feeder can be calculated. (See fig. 4.) The adjacent feeders have voltages equal to the substation bus voltages when neglecting the load currents.

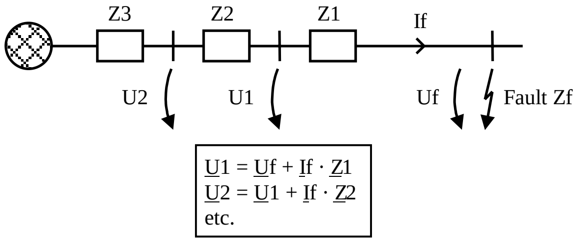


Fig. 4. Calculating voltages on a faulted feeder. Only one phase presented.

Using this kind of simplification for the phenomenon gives rather rough results. It still gives the software user some idea about the severity and penetration of the sags caused by short-circuit faults, which the conventional programs are not able to do.

Output formats

Three output formats were developed for viewing the sag calculation results in the software. Two of them are graphic in addition to one alphanumeric way of presentation.

The graphic output viewing the sagged voltages in the network looks very much like the traditional way of representing the voltage drop on the feeders caused by the load currents. Each feeder is coloured with certain tone according to the remaining voltage magnitude. This gives an illustrative idea of the sag penetration into the network.

The other type of output is called the area of vulnerability. [3] A certain node having sag sensitive load is selected to be the reference. The user defines the fault type and impedance. Each feeder is then coloured according to the sag severity on the reference load assuming that the fault occurs on that particular feeder. This shows the critical area on which faults of selected type will be fatal to a sensitive load.

The text output was modified so that the sag analysis results can be represented properly. E.g. a precise numerical value for sagged voltage on each node can be shown on the list. The total impedance from the node to the source e.m.f. is available as well.

MODELLING A DYNAMIC VOLTAGE RESTORER

Background

After adding the sag calculation to the software it is also possible to simulate the performance of a dynamic voltage restorer, DVR. DVRs are widely used for voltage sag mitigation. The device restores the sagged voltages to the level required by a sensitive load. Connected in series with the protected load each phase of a DVR can independently inject the needed voltage with appropriate magnitude and phase angle. Harmonic frequency components can also be added to the injected voltage.

DVRs are in many cases equipped with an external energy storage, e.g. capacitor, flywheel or SMES, that delivers the active power needed for voltage restoration. Typically the stored capacity is rated for mitigating a sag of 50 % with duration of approximately 10 cycles.

Equipment model

Due to the simplifications applied to the voltage sag simulation and the steady state nature of the used software also the DVR model had to be modelled in a reduced way. The sags restored were thought to be steady state and consist of the power frequency component only. This gives the possibility to consider the voltages, both sagged and injected, as phasors with a constant magnitude and phase angle. As mentioned above the sag can, however, be divided into several sections each having a specific magnitude and angle and thus representing a voltage sag with dynamic properties.

Input data

The software user defines the ratings for the device: maximum apparent power, maximum voltage injection, energy storage capacity and charge/discharge time ratio.

Additionally, information about the protected load is needed. The sag ride-thru level (i.e. the minimum voltage required by the sensitive load in order not to trip off) is given as a percentage of the nominal voltage. The DVR is controlled to inject only the voltage that is needed to maintain the ride-thru level, not more. This helps the device to carry on the load as long as possible. (See fig. 5.)

When the load voltage decreases to the ride-thru level also the current changes and furthermore the active and reactive power taken by the load. Certain parameters are given to describe how the power depends on the voltage. The load can then be modelled as constant impedance, constant current, constant power or a combination of them.

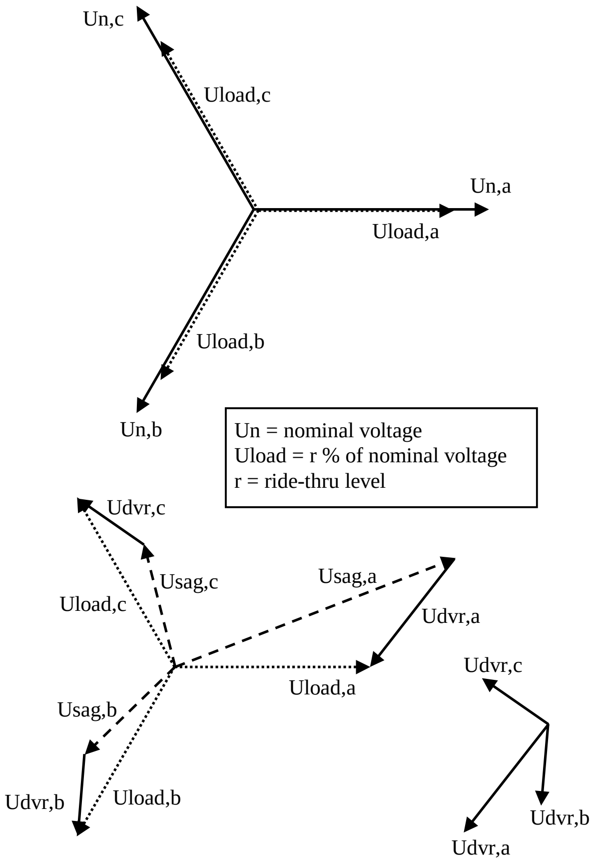


Fig. 5. Restoring sagged voltages up to the ride-thru level.

Restoring a voltage sag

Sagged voltages in the DVR node can be retrieved from the fault simulator described above. Currents flowing through the restorer are calculated from the given load parameters. DVR injects to each phase a voltage that is needed to restore the sagged voltage up to the ride-thru level. It also corrects the eventual phase angle jump caused by an unsymmetrical sag. Knowing the injected voltages and the currents flowing through DVR the injected active and reactive power can be calculated. The PWM converter of the restorer produces the reactive power needed. Active power is taken from the energy storage. It may also be swapped from one line to another in case of an unsymmetrical fault, which causes voltage increase on the sound line(s).

Charging the energy storage

The storage is charged after the fault being cleared or during the dead times of the reclosing sequences in case the DVR is located on a sound feeder. During the dead time on the faulted feeder the pre-fault voltage is seen on the adjacent feeders. This time is typically 200-500 ms for the first reclosure attempt and 1-2 min for the second one. This is enough for charging the DVR storage in most cases.

Reclosure time sequence data for each relay can be retrieved from the application database. The modelled DVR takes these into account and forms corresponding charge/discharge sequences for the storage. These sequences follow each other until the fault is cleared or the faulted feeder disconnected permanently for repair.

Device capability monitoring

During the DVR operation the injection is controlled in order to prevent exceeding the given ratings. Also the energy storage status is monitored. If the limits are exceeded or the storage fails, report on unsuccessful protection appears on the screen. If the DVR ratings are not exceeded and the storage is capable of delivering the required active power throughout the sag, the protection is appropriate.

CONCLUSIONS (PART 2)

A simplified method for calculating voltage sags was added to an AM/FM-GIS software. The original database was used for retrieving the information about the network. Illustrative output formats were added to the application as well.

Also the performance of a sag mitigation device, DVR, was modelled. DVR restores the voltages up to a preferred level. The active power required is delivered from an external energy storage. The storage charge and discharge sequences are connected to the reclosure time sequences retrieved from the software database.

The models introduced in this paper are applicable to any AM/FM-GIS software. They are developed for getting a rough analysis of a voltage sag caused by a fault penetrating into the network and the performance of the equipment that is used for the mitigation. Future studies with practical experiences will show the accuracy and usefulness of these methods.

REFERENCES (PART 2)

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[4] E. Lakervi, M. Nurmi, “Present status in applying mathematical planning methods in AM/FM-GIS systems”, *CIRED 97, 14th International Conference and Exhibition on Electricity Distribution*, Birmingham, UK, 1997. pp. 6.24.1-6.24.5.