VOLTAGE QUALITY REGULATION IN SWEDEN

Lars STRÖM Math H.J. BOLLEN Rémy KOLESSAR
Energy Markets Inspectorate – Sweden
lars.strom@ei.se math.bollen@ei.se remy.kolessar@ei.se

ABSTRACT

This paper presents the voltage-quality requirements set by the Swedish energy regulator. Requirements have been set for harmonics, unbalance, slow voltage variations, voltage dips, voltage swells and rapid voltage changes, which are all discussed in this paper. This paper further discusses recommended measurement methods for verification of compliance with the requirements and the way in which voltage-quality regulation takes place in practice.

INTRODUCTION

According to the Swedish Electricity Act the "transport of electrical energy shall be of good quality", in other words: the voltage should be of sufficient quality.

The relevant article of the electricity law came in force in 2001. In 2006 the Swedish energy regulator, the Energy Markets Inspectorate ("Energimarknadsinspektionen") was given the authority to issue specific requirements. At present, no such requirements have yet been set. Instead, upon receipt of a complaint from a customer, it is decided on a case-by-case basis whether the voltage quality is sufficient. The limits set in the European voltage-characteristics standard, EN 50160 [1], are used as a basis for making that decision.

There are a number of disadvantages with maintaining this situation:

- ✓ The 95% limits in the EN 50160 standard introduce an uncertainty towards the customer on the highest disturbance levels that can be expected.
- ✓ No limits exist for number of voltage dips or voltage swells that can be expected. The "indicative values" in the EN 50160 standard are of no practical use.
- ✓ The absence of well-defined limits makes it difficult for network operators to set planning levels, for example towards disturbing loads.

To remedy this situation a project was started by the Energy Markets Inspectorate with the aim to issue a national regulation defining limits for voltage-quality variations and events.

Several rounds of discussions with the stakeholders have taken place during 2010. The final version of the new regulation [2] will be available by summer 2011 and is subject to feedback by the stakeholders. This paper presents the most likely outcome, but details might not correspond with the actual regulation.

VOLTAGE-QUALITY VARIATIONS

The voltage-quality regulation gives a number of conditions that the voltage characteristics have to fulfil for the voltage quality to be of sufficient. Limits are being proposed for the following voltage-quality variations: harmonics; unbalance and voltage fluctuations.

Reference voltage

Like in EN 50160, a reference voltage is used to relate the size of voltage-quality disturbances to. For low-voltage networks (with nominal voltage up to 1000 V), the reference voltage is equal to the nominal voltage (in most cases 230 V phase-to-neutral). For higher voltage levels, another voltage than the nominal voltage may be agreed upon.

Harmonics

For harmonics and unbalance the objective values are the ones given in EN 50160. But instead of not being exceeded during 95% of the time, these limits shall not be exceeded at all for the voltage quality to be considered sufficient.
Different limits are used for voltage levels up to 36 kV (shown in Table 1) and for voltage levels above 36 kV (shown in Table 2).

Table 1. Harmonic limits for voltage levels up to 36 kV

Odd harmonics				Even harmonics	
Non-multiple of 3		Multiple of 3			
Harm	Limit	Harm	Limit	Harm	Limit
5	6.0%	3	5.0%	2	2.0%
7	5.0%	9	1.5%	4	1.0%
11	3.5%	15	0.5%	6 .. 24	0.5%
13	3.0%	21	0.5%		
17	2.0%				
19	1.5%				
23	1.5%				
25	1.5%				

Table 2. Harmonic limits for voltage levels above 36 kV

Odd harmonics				Even harmonics	
Non-multiple of 3		Multiple of 3			
Harm	Limit	Harm	Limit	Harm	Limit
5	5.0%	3	3.0%	2	1.9%
7	4.0%	9	1.3%	4	1.0%
11	3.0%	15	0.5%	6 .. 24	0.5%
13	2.5%	21	0.5%		
17					
19					
23					
25					

As we will see later, measurements for verification of the requirement have to be performed in accordance with IEC 61000-4-30. The values shown in the table thus correspond to harmonic subgroups. No limits are defined for interharmonics, nor for harmonics above order 25 (1250 Hz).

Unbalance

All ten-minute values of the voltage unbalance (ratio of negative and positive-sequence voltage) shall be at most 2%. This holds for all voltage levels.

Flicker

No specific limits are given for the short-term or long-term flicker severity. Instead the limits according to EN 50160 hold: 95% of the long-term flicker severity (Plt) values during one week shall be below 1.0.
The reason for not defining any further limits for flicker is the ongoing replacement of incandescent lamps by more energy-efficient lamps. The flicker severity indices (Pst and Plt) have been developed for incandescent lamps; their practical use in a world without incandescent lamps remains unclear. The Energy Markets Inspectorate has decided to wait for developments in international standardization before setting specific limits here.

Slow voltage variations

All 10-minute values of the rms voltage shall be at least 90% and at most 110% of the reference voltage. This holds for all voltage levels.

VOLTAGE-QUALITY EVENTS

Voltage-quality events are sudden, large deviations from the ideal voltage waveform. The main practical difference between variations and events is in the measurement method used. Voltage-quality events require a triggering method. Once an event is detected, using the triggering method, its characteristics can be determined.
Limits have been defined for voltage dips, voltage swells and rapid-voltage changes, as part of the voltage-quality regulation. Limits for interruptions are part of the continuity of supply regulation; they are discussed below for completeness. No limits have been defined for voltage transients. Also here, it was decided to wait for progress in research, development and standardization.
Limits for voltage quality come in two forms:

- ✓ A maximum number of events with characteristics exceeding a certain value (i.e. more severe than a given threshold);
- ✓ A maximum value for the event characteristics (i.e. the event shall not be more severe than a given threshold).

Voltage dips

A voltage dip is defined as an event during which the one-cycle rms voltage drops below 90% of the reference voltage. Voltage dips are divided in three groups based on their residual voltage and duration, as shown in Figure 1 and Figure 2.
A) Mild dips that are not supposed to have any adverse impact on end-user equipment or installations. These dips are considered as a normal part of the operation of the power system. Equipment and installations are expected to be immune to this, and no limits are set on the number of voltage dips in this group. Dips in this group are added to the statistics on rapid voltage changes.
B) Dips with a duration and residual voltage in between the two limits. The number of dips in this group should not be more than what can be achieved with state of the art technology and against reasonable costs. No absolute limits on number and duration of dips are set in this region of the magnitude-duration plane. What should be seen as sufficient quality depends strongly on local circumstances. It is further recognized that a distinction should be made between voltage drops in one, two and three phase-to-phase or phase-to-neutral voltages.
C) Very severe dips that point to serious problems with the operation of the power system. When a voltage dip occurs in this group, the voltage is considered to be of insufficient quality.

The definition of the three groups is different for voltage levels below and above 45 kV, as shown in Figure 1 (up to 45 kV) and Figure 2 (above 45 kV). The choice of 45 kV as a border is related to specific voltage levels used in Sweden and the way in which they are operated.

U (%)	Duration t (ms)				
	10≤t≤200	200<t≤500	500<t≤1000	1000<t≤5000	5000<t≤60000
90>U≥80					
80>U≥70	A				
70>U≥40			B		
40>U≥5					C
U<5					

Figure 1. The three groups of dips for voltage levels up to 45 kV.

U (%)	Duration t (ms)				
	10≤t≤100	100<t≤150	150<t≤600	600<t≤5000	5000<t≤60000
90>U≥80					
80>U≥70	A				
70>U≥40			B		
40>U≥5					C
U<5					

Figure 2. The three groups of dips for voltage levels above 45 kV.

From the figures one can conclude for example that voltage dips with duration longer than 600 ms and residual voltage below 80% are not acceptable for voltage levels above 45 kV. For voltage levels up to 45 kV, the borders between the groups are based on recommendations by CIGRE/CIRED/UIE JWG C4.110 [3]. For voltage levels above 45 kV, the borders have been discussed with the major stakeholders; in particular with network operators and large industrial consumers.
Note that this approach goes a step beyond the ”responsiblity sharing curve” as proposed by the European energy regulators [6]. Instead on one curve, two curves are used. The left-hand curve corresponds to the responsibility sharing curve in the original proposal.
To prevent double counting of dips and interruptions, all events included in the continuity of supply statistics do not have to be included in the voltage-dip statistics. The continuity of supply statistics are the subject of a companion paper [7].

Voltage swells

A voltage swell is an event for which the rms voltage exceeds 110% of the reference voltage. The approach for voltage swells is the same as for voltage dips; with three groups being defined based on the maximum swell voltage and the duration of an event. The three groups are shown in Figure 3 for low-voltage networks (up to 1 kV). No requirements are set for voltage swells in networks with nominal voltage above 1 kV.

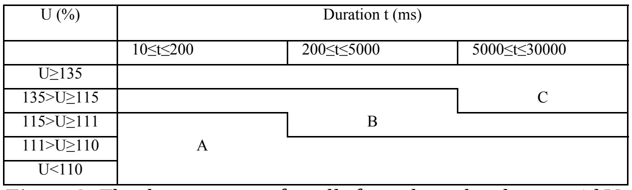

Figure 3. The three groups of swells for voltage levels up to 1 kV.

The border between region A and B is based on the requirements for overvoltage protection of microproduction [9]; the border between region B and C is based on experiments after equipment damage due to overvoltages [8] and an estimation of what can be expected in Swedish distribution networks.

In some cases a voltage dip in one of the phase-to-ground voltages coincides with a swell in another phase-to-ground voltage. Such an event should be counted both as a voltage dip and as a voltage swell, as they impact different types of equipment and different types of customers.

Rapid voltage changes

The rules for rapid voltage changes are based on the Norwegian regulation [5]. A rapid voltage change is defined as a change in rms voltage faster than 0.5% of the reference voltage per second. A rapid voltage change is quantified through the "steady-state change" ΔU_{ss} and the "maximum change" ΔU_{max}. The steady-state change is the difference between the rms voltage before and after the change. The maximum change is the highest difference between the rms voltage during the rapid voltage change and the rms voltage before or after the change.

The requirements for rapid voltage changes are shown in Table 3. When both the steady-state voltage and the maximum change exceed the limit (3% and 5%, respectively), the event is counted towards both criteria.

Table 3, maximum number of rapid voltage changes

	Maximal number per day	
	Un ≤ 45 kV	Un > 45 kV
$\Delta U_{ss} \geq 3\%$	24	12
$\Delta U_{max} \geq 5\%$	24	12

For voltage levels up to 45 kV, 24 events per day are acceptable; for voltage levels above 45 kV, the limit is 12 events per day.

Note that these numbers include voltage dips and voltage swells in region A, as indicated in Figure 1, Figure 2, and Figure 3.

Interruptions

The Swedish electricity law states that no interruption shall last longer than 24 hours. Shorter upper limits for the duration of interruptions are set when larger customers or groups of customers are impacted. The requirements that have to be fulfilled are shown in Table 4.

Table 4, maximum duration of interruption for different load size

	Maximum interruption duration	
Load size (Megawatt)	Normal conditions	Abnormal conditions
≤ 2	24 hours	24 hours
> 2	12 hours	24 hours
> 5 ≤ 20	8 hours	24 hours
> 20 ≤ 50	2 hours	24 hours
> 50	2 hours	12 hours

The maximum interruption duration depends on the conditions for restoring the supply. Under normal circumstances, the supply has to be restored significantly faster when the interruption impacts a larger amount of load. Normal conditions are defined as such operational and weather conditions that do not prevent the restoration of the supply to start immediately after the start of the interruption. Abnormal conditions are conditions during which restoration of the supply cannot reasonably be expected to start immediately.

In all cases, even during abnormal conditions, the supply shall be restored within 24 hours.

No limits are in place for the number of short or long interruptions experienced by a customer.

MEASUREMENTS

The Energy Markets Inspectorate does not have the authority to define or prescribe a measurement method for voltage quality. However, a number of measurement issues are strongly related to verification of compliance with the requirements and are therefore included in the regulation.

The verification for harmonics, slow voltage variations, and unbalance is based on measurements during a period of at least one week. For voltage dips and voltage swells a much longer period is needed. A measurement period of at least one year is recommended by a number of sources including CIGRE/CIRED/UIE JWG C4.110 [3]. It is also recognized that measurement is not always the most suitable method, in which case a stochastic prediction method could be considered.

For low-voltage networks (nominal voltage up to 1000 V), the voltage characteristics should be calculated from the phase-to-neutral voltages. For higher voltages, the phase-to-phase voltages should be used.

The measurements should be in accordance with Class A of EN 61000-4-30. Flagging is introduced in this standard to prevent double counting and to be able to remove unrealistic values. The standard does however not give any recommendations on how to treat flagged values.

The following recommendation is made as part of the voltage-quality regulation. If, during a 10-minute period as in EN 61000-4-30, a voltage dip, a voltage swell or a rapid voltage change occurs, the corresponding 10-minute values for harmonics, flicker and unbalance are not considered for the verification. If the 10-minute period coincides partly or completely with an interruption, the 10-minute values for harmonics, unbalance, flicker and slow voltage variations are not considered for the verification.

REGULATION IN PRACTICE

It belongs to the responsibility of the network operator that the voltage is of sufficient quality for all customers (or, "network users"). Currently, no reporting of voltage quality by the network operator is in place and no such reporting is planned either. Several Swedish network operators perform voltage-quality measurements for their internal use, but none of this data is published.

The Energy Markets Inspectorate only becomes involved in voltage quality once a customer files a complaint about negative impacts of insufficient voltage quality. This triggers the regulatory process, the first step of which is communication between the network operator and the customer to reach an agreement, for example because the network operator takes suitable measures. Once such an agreement is reached, no further action from the regulator is needed.

When no agreement can be reached, the case is investigated further, for example by performing measurements. Important questions addressed in this investigation are:

- ✓ Is the voltage quality sufficient?
- ✓ Is there a link between the insufficient quality and the complaints by the customer?
- ✓ Where lays the origin of the disturbance that results in insufficient voltage quality?

If the voltage quality is insufficient and the complaints are related to this, the further course of action depends on the origin of the disturbance resulting in insufficient quality.

When the origin is with another network operator, a communication is started between this network operator, the network operator supplying the customer, and the customer. When the origin is with the network operator supplying the customer, the Energy Markets Inspectorate can enforce measures in the network to improve the voltage quality. This will only happen when network operator and customer cannot reach an agreement and when the costs for the measure are reasonable in relation to the inconvenience and costs experienced by the customer.

The regulation lays down what level of voltage quality a network owner must provide to customers, i.e. the basic rights of a customer connected to a public network. If the origin of the disturbance is with another network user it is up to the network owner to communicate with that user and see to that the disturbances are remedied. In this case the matter is transferred to the national electricity safety board ("elsäkerhetsverket"), the Swedish government agency responsible for electromagnetic compatibility.

CONCLUSIONS

The Swedish energy regulator has defined a number of requirements that have to be fulfilled for the voltage to be considered of sufficient quality.

For harmonics, unbalance and slow voltage variations the limits in EN 50160 have to be fulfilled during 100% of the time. No limits are defined for interharmonics or for harmonics above order 25. Requirements for flicker are the same as in EN 50160, awaiting new developments in standardizations.

For voltage dips and voltage swells, two requirements are defined: a maximum-permissible event severity (in terms of voltage and duration); and a maximum number of events. The number of events of medium severity (defined by two curves in the voltage-duration-plane) shall not be more than what can be achieved with state-of-the-art technology against reasonable costs. For rapid voltage changes a maximum number of events is set when their severity exceeds a certain threshold. Interruptions are limited in duration; no limits exist for the number of interruptions. No requirements are set for voltage transients, awaiting further developments in research and standardization.

More experience with the interpretation of the requirements is expected to be gained during the coming years. This especially concerns dips, swells and rapid voltage changes. The regulatory process for voltage quality is only triggered when a complaint is received from a network user. As a final resort the Energy Markets Inspectorate can enforce improvements in the network. This will only happen when the voltage is found to be of insufficient quality, when the complaints are related to this, when network operator and network user cannot reach an agreement, and when the costs of the improvement in the network are reasonable in relation to the inconvenience and costs experienced by the customer.

REFERENCES

[1] EN 50160, Voltage characteristics in public distribution systems.

[2] Energimarknadsinspektionens föreskrifter och allmänna råd om krav som ska vara uppfyllda för att överföringen av el ska vara av god kvalitet (in Swedish), to be published during 2011.

[3] CIGRE/CIRED/UIE JWG C4.110, Voltage dip immunity of equipment and installations, CIGRE TB 412, April 2010.

[4] EN 61000-4-30, Electromagnetic compatibility (EMC) - Part 4-30: Testing and measurement techniques - Power quality measurement methods.

[5] Forskrift om leveringskvalitet i kraftsystemet (in Norwegian), NVE, FOR 2004-11-30 nr 1557.

[6] Towards voltage quality regulation in Europe - An ERGEG public consultation paper, ERGEG Ref: E06-EQS-09-03, 6 December 2006.

[7] D. Torstensson, M.H.J. Bollen, R. Kolessar, The Swedish benchmarking report on continuity of supply, this conference.

[8] H. Seljeseth K. Sand, K.E. Fossen, Laboratory tests of electrical appliances immunity to voltage swells, CIRED 2009.

[9] EN 50438:2007 – Requirements for the protection of micro-generators in parallel with public low-voltage distribution networks.