Voltage variations due to wind power and solar power at time scales of 10 minutes and less

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SUMMARY

The production of wind and solar power varies over a range of time scales, causing variations in voltage magnitude. It is expected that the voltage variations will increase with an increase of renewable energy sources connected to the grid, especially at a time scale of 1 second to 10 minutes. Voltage variations in this time scale are not covered by any standard, and therefore require extra attention.

To estimate the variations in voltage magnitude at a time scale of 1 second to 10 minutes, measurements of active and reactive power from wind turbines and photovoltaic (PV) installations have been used. To quantify these variations, a novel voltage-quality index has been applied in this paper. Different network strengths have been evaluated, including the IEC reference impedance for testing of flicker due to low-voltage (LV) equipment. Both individual production units and aggregation of several production units has been studied, and the results have been compared with existing levels at a number of locations in the grid.

It has been concluded that the applied method is a good way of quantifying the voltage variations in the time scale of 1 second to 10 minutes. The results show that the voltage variations in this time scale will increase if more wind and solar power is connected to the grid, while also changing character. The increase in level is no reason for concern, but it is recommended to keep track of the levels in the grid.

KEYWORDS

Wind power, solar power, very short variations, VSV, voltage variations

1. INTRODUCTION

In the coming years, the amount of renewable energy sources in the grid is expected to increase, mainly in the form of wind and solar power. The produced power from wind and solar sources varies over a range of time scales and this causes variations in voltage magnitude at those time scales. As a consequence of an increase in wind and solar power it is expected that voltage variations in a time scale between 1 second and 10 minutes will increase.

The fastest variations in voltage magnitude (below 1 second) are covered by the flickermeter standard, IEC 61000-4-15. The power quality measuring standard, IEC 61000-4-30, defines both a 3-second and a 10-minute interval for aggregation, but power quality standards used for regulation, such as EN 50160, only consider the 10-minute values. There are currently no standards covering voltage variations in a time scale between 1 second and 10 minutes, with only limited ongoing research in that area. This paper is based on a study by STRI in conjunction with Luleå University of Technology in which this is investigated [1].

In this paper a novel method for quantifying voltage variations in time scales between 1 second and 10 minutes has been applied. It was developed by STRI as part of a large European project [2].

1.1 Very Short Variations

This section will provide an introduction to the approach used to quantify the voltage variations on a time scale between 1 second and 10 minutes, referred to as Very Short Variations, or VSV [3].

As mentioned above, IEC 61000-4-30 prescribes the use of 3-second and 10-minute values. The 10-minute values U_{sh} (short time) are calculated as the rms-value of the 3-second values, U_{vs} (very-short time), over the preceding 10-minute interval

$$U_{sh}(t_k) = \sqrt{\frac{1}{N} \sum_{i=k-N+1}^{k} U_{vs}^2(t_i)} \tag{1}$$

where N is the number of 3-second values in the 10-minute interval and t_k the time sample representing the end of the 10-minute interval.

The difference between the 3-second and 10-minute values is used to characterize the voltage variations. The 3-second VSV, ΔU_{vs}, is defined as

$$\Delta U_{vs}(t_k) = U_{vs}(t_k) - U_{sh}(t_k) \tag{2}$$

When calculating the 3-second VSV values, the 10-minute value U_{sh} is calculated as in (1), but the value is updated every sample (i.e. every 3-second value). From the 3-second VSV values a 10-minute VSV value is calculated for every 10-minute interval

$$\Delta U_{sh}(t_k) = \sqrt{\frac{1}{N} \sum_{i=k-N+1}^{k} \Delta U_{vs}^2(t_i)} \tag{3}$$

where t_k is the time sample representing the end of the 10-minute interval, as in (1).

Using this approach, every 10-minute interval can be quantified using three different indices

- The 10-minute average value (rms), U_{sh}
- The 10-minute VSV-value, ΔU_{sh}
- The short-time flicker value, P_{ST}.

2. MEASUREMENTS

As a part of the study, several measurements were obtained from different voltage levels in the grid and used to calculate the existing VSV-levels. In the LV grid measurements from around 10 different locations have been used. The measurements have a time resolution of 1-3 seconds and the locations include hotels, universities and apartments in different countries. Measurements in the medium-voltage (MV) grid have been acquired for one location, and measurements from the grid feeding the Swedish railway system have been acquired from four locations.

Figure 2-1 shows the 3-second and 10-minute VSV-levels in the MV grid, during one day.

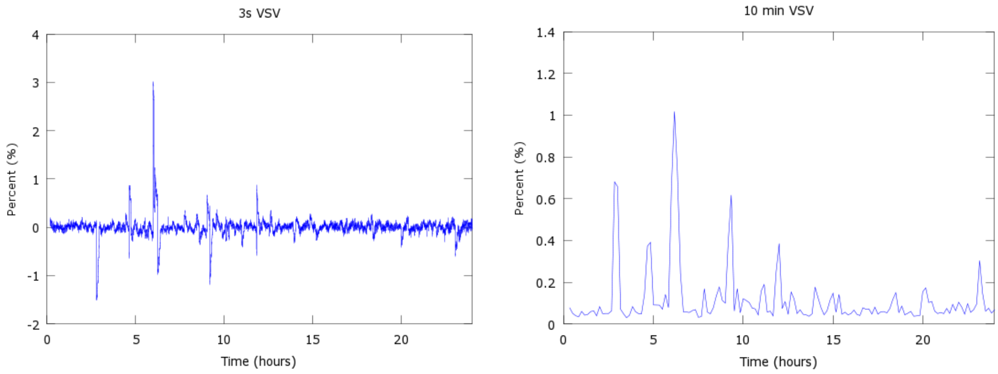

Figure 2-1: 3-second (left) and 10-minute (right) VSV-levels in the MV grid, during a day

The 3-second values can be characterized as noise with superimposed spikes. This holds true for all voltage levels, but there is less noise in the MV grid compared to the LV grid and the grid feeding the railway. The spikes in the 3-second values are reflected in the 10-minute values.

Table 2-1 shows a summary of typical VSV-levels for the different grids investigated in this report.

Table 2-1: Typical VSV-levels

Grid	Max 10-min	Average 10-min	95 %
LV	0.983-1.373	0.124-0.418	0.332-0.958
MV	0.306-1.344	0.094-0.154	0.176-0.522
Railway	0.594-2.125	0.086-0.620	0.231-1.142

3. SOLAR POWER

Data on solar power have been acquired for 5 different installations, ranging in capacity from 2 to 100 kW.

In order to calculate the relative change in voltage due to the active and reactive power provided by distributed generation the following simplified relation was used [3]:

$$\frac{\Delta U}{U} \approx \frac{RP + XQ}{U^2} \quad (4)$$

where U is the nominal voltage, R and X the resistance and reactance as seen from the generator terminals, and P and Q the active and reactive power provided. The calculated change in voltage was then added to the nominal voltage in order to calculate the VSV-values.

3.1 Study cases

In order to assess the voltage fluctuations from variations in production, several cases were studied. The first case considers a single PV unit with an LV customer. The PV unit is assumed to be connected to the grid via the IEC 60725 reference impedance for flicker testing, which represents a grid that is worse than 95 % of the grids in Europe. The voltage at the MV/LV transformer was assumed constant in magnitude to simplify the calculations. A comparison was also done between the reference impedance and cables common in the Swedish distribution network.

The second case considers effects of aggregated solar power in the LV grid. It is shown in Figure 3-1.

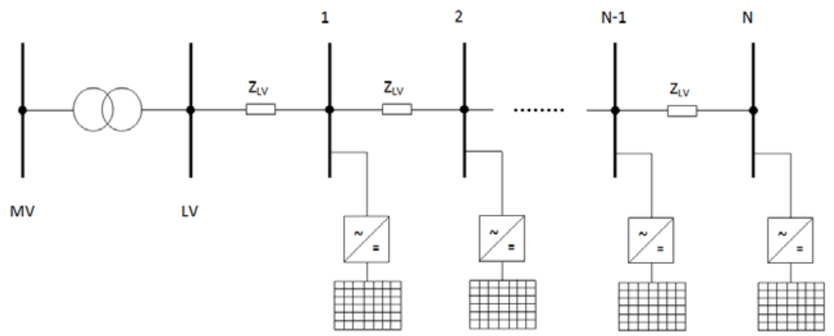

Figure 3-1: Aggregated PV model used in case 2

Different levels of PV penetration were evaluated, and in order to model a worst case it was assumed that houses with PV were located at the nodes furthest away from the MV/LV transformer. A distance of 100 m was assumed between the nodes; different cables and overhead lines were evaluated. All PV units have the same production pattern, but shifted in time to consider that they are some distance away from each other. References [4] and [5] investigate the variation in production of solar power from different houses during the passage of a cloud; based on their results it was decided to shift the measurements 10 seconds relative to each other.

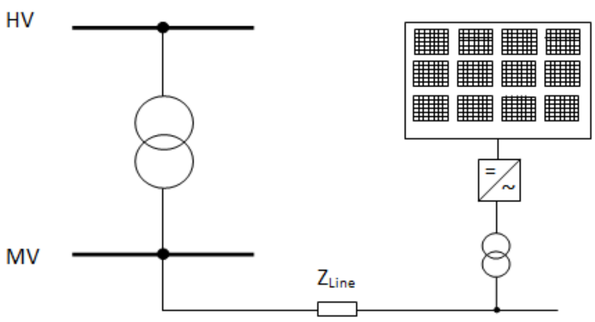

Figure 3-2: Large PV park model used in case 3

The third case considers a larger solar power plant connected to the MV grid. It is shown in Figure 3-2. Different cables and overhead lines were used while also varying the capacity of the plant. The voltage at the HV side of the HV/MV transformer was assumed constant in magnitude.

3.2 Results

Figure 3-3 show the 3-second and 10-minute VSV for a single PV unit connected to the reference impedance, during a day with partial cloud coverage. The PV unit was scaled to about 6 kW to represent a typical PV unit that can be found with a LV customer.

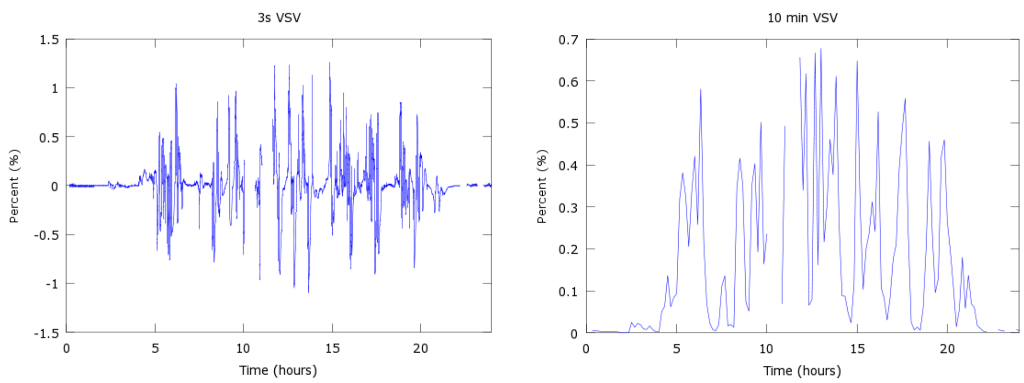

Figure 3-3: 3-second (left) and 10-minute (right) VSV-levels for a single PV unit during a day with partial cloud coverage

From the figure it can be seen that the characteristics of solar power differ from that of the grid, shown in Figure 2-1, in that there are more spikes, but much less noise. The 10-minute VSV-levels calculated when using the reference impedance are shown in Table 3-1, and they are around half of the highest levels found in the grid. It was found that very long cables or lines were required to reach the same VSV-levels as the reference impedance, and therefore a single PV unit is deemed no cause for concern considering the VSV-levels in the grid. It was also found that VSV-levels are higher if overhead lines are used instead of cables, due to that a smaller area, i.e. a higher resistance, can be used while transferring the same amount of power compared to cables.

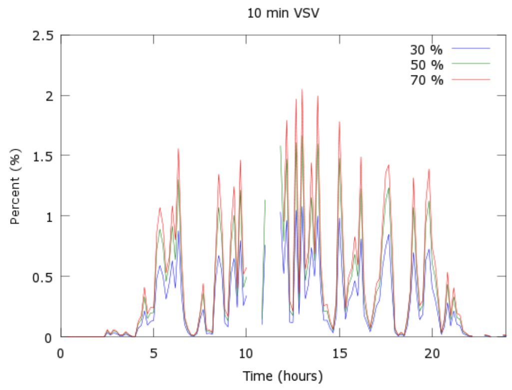

Figure 3-4: Different levels of PV penetration in the LV grid

In the second case, aggregation of several PV units was modeled according to Figure 3-1. Each PV unit was again scaled to 6 kW. Figure 3-4 shows the 10-minute VSV levels during a day for three levels of PV penetration. The cable used in this particular case is the AKKJ 240 mm^2, which is common in the Swedish LV grid. Despite being one of the most abundant cables used in this study, the 10-minute VSV-levels from aggregated PV were about the same as the highest levels found in the grid already at 30 % penetration. At 70 % penetration the VSV-levels were almost twice as high as the highest levels found in the grid. The 10-minute VSV-levels are summarized in Table 3-1. To see if the results were reasonable, the maximum increase in rms voltage was calculated. For 70 % penetration the voltage rise was 5.15 %, which could be acceptable depending on the voltage levels in the grid before the addition of the PV units to the grid.

In the third case, a PV park was modeled according to Figure 3-2 with different park capacities and cables or lines. The 10-minute VSV-levels are shown in Figure 3-5. In the case of a 0.5 MW park connected by overhead lines 10 km from the transformer at 10 kV, the 10-minute VSV-levels approached similar levels as the highest found in the MV grid, without exceeding other limits, such as the current carrying capability of cables or the maximum allowed voltage drop or rise in Swedish regulation. Considering the recent completion of a 1 MW-park in Sweden it is suggested to keep track of the levels in order to get a better understanding of the voltage variations caused by large solar power parks.

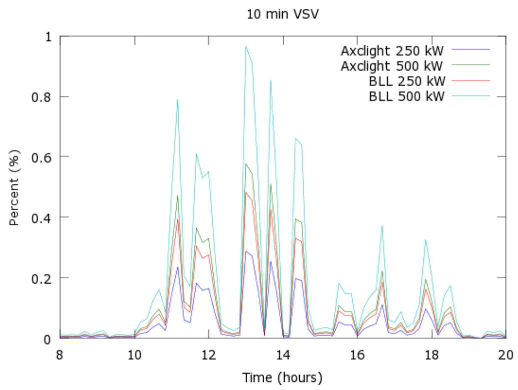

Figure 3-5: 10-minute VSV-levels for different PV park capacities and cables

From the results it can be seen that solar power, under some circumstances, can lead to VSV-levels of the same magnitude as those found in the grid, shown in Table 2-1.

Table 3-1: VSV-levels for different cases

Case	Max 10-min	Average 10-min	95 %
Single PV, reference impedance	0.677	0.168	0.580
Aggregated PV, 30 %	1.168	0.279	0.951
Aggregated PV, 50 %	1.823	0.424	1.423
Aggregated PV, 70 %	2.274	0.506	1.652
PV park 500 kW, BLL	0.964	0.089	0.551

4. WIND POWER

Data on wind power have been acquired for a 600 kW wind turbine and two wind farms with a capacity of 12 and 20 MW, respectively. The variations in voltage were calculated from the measured active and reactive power according to (4) in the same way as for solar power.

4.1 *Study cases*

Two cases were studied for wind power, the first being a single turbine connected to the MV grid. The voltage on the HV side of the HV/MV transformer was assumed constant in magnitude and the wind turbine was connected to the transformer using cables or overhead lines of different length.

The second case is similar to the first, the difference being that it considers the connection of a wind farm rather than a single turbine. It is shown in Figure 4-1. In order to assess the maximum possible VSV-levels from wind farms the hosting capacity was calculated based on the current carrying capability of the cables and the maximum allowed voltage drop as defined in Swedish regulation. From this the VSV-levels were calculated.

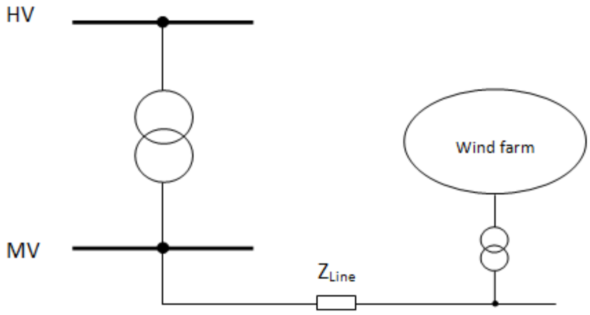

Figure 4-1: Wind farm model used in case 2

4.2 *Results*

Figure 4-2 shows the 3-second and 10-minute VSV-levels for a single 600 kW wind turbine connected 10 km from the HV/MV transformer in a 10 kV grid. In this case an ACXEL 95 mm^2 cable was used.

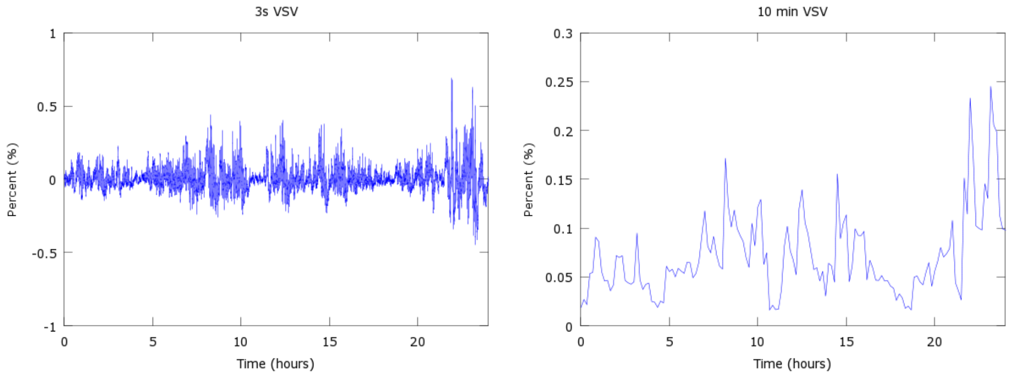

Figure 4-2: 3-second (left) and 10-minute (right) VSV-levels for a single wind turbine during one day

From the figure it can be seen that wind power has a characteristic more similar to that of the grid, shown in Figure 2-1, than that of solar power, shown in Figure 3-3. The 10-minute VSV-levels are shown in Table 4-1. Compared to the highest levels found in the MV grid, shown in Table 2-1, the VSV-levels from a single wind turbine are low.

In the second case, wind farms connected to the MV grid were evaluated. Figure 4-3 shows the VSV-levels for a wind farm connected to the 20 kV grid, 10 km from the HV/MV transformer. The cable used is the same as in the previous case and based on the selected cable the hosting capacity was calculated.

The wind farm shares the characteristics of the single wind turbine and the measurements from the grid, shown in Figure 2-1. The 10-minute VSV-levels are shown in Table 4-1. It can be seen that even for a wind farm equal in size to the hosting capacity, the values are lower than the highest found in the MV grid, shown in Table 2-1. The results indicate that wind power should be no cause for concern with regards to an increase in VSV-levels.

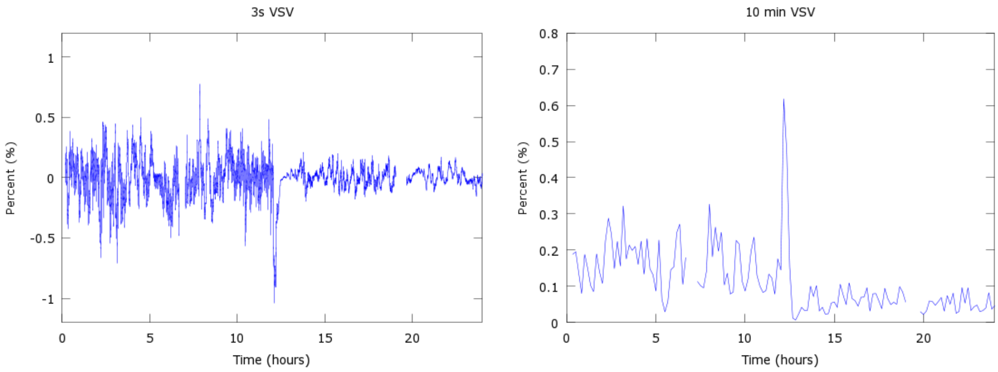

Figure 4-3: 3-second (left) and 10-minute (right) VSV-levels for a wind farm during a day

Table 4-1: VSV-levels for different cases

Case	Max 10-min	Average 10-min	95 %
Single wind turbine	0.239	0.073	0.148
Single wind turbine, max capacity	0.500	0.154	0.309
Wind farm	0.626	0.110	0.324

5. DISCUSSION

This study shows that wind and solar power under some circumstances may lead to an increase in the VSV-levels in the grid. The main concern is how such an increase will affect equipment. Several examples of consequences of rapid voltage changes (excluding flicker) can be found in [6] and [7]:

- Control actions for control systems that act on the voltage angle
- Braking or accelerating moments for motors
- Impairment of electronic equipment where the fluctuations in the supply voltage affects the electronic parts
- Small variations in the speed of motors, which in turn will give small, but unacceptable, variations in production. Specific examples include variations in diameter or colour

Any grid-connected motor will be affected by rapid voltage changes. It is not clear if continuous, small variations or temporary large variations affect motors more. Even electric drives can be affected as the voltage variations may be found also in the dc part that decides the speed of the motor.

There is also some uncertainty regarding how converters at wind and solar installations are affected by rapid voltage changes and voltage steps. Modern power electronics can be controlled quickly, following e.g. the voltage in the grid with a time resolution of milliseconds. However, in practice the control systems are usually slower in order to avoid instability.

The consequence of rapid voltage changes could be e.g. overvoltages in dc circuits, reducing the lifespan of components. There are indications from research conducted at a university in Australia that rapid voltage changes can damage equipment [8], [9], [10]. Further studies are required in order to establish acceptable VSV-levels.

6. CONCLUSIONS

Several cases have been studied of variations in voltage magnitude on the time scale between 1 second and 10 minutes. It has been found that the 3-second VSV calculated from the LV and MV grids, as well as the grid feeding the railway system, can be characterized as noise with superimposed spikes.

Wind power shows a similar characteristic whereas solar power can be characterized as having almost no noise, and a larger amount of spikes.

The results suggest that small scale distributed generation, such as a single solar panel in a residential area, should be no cause for concern regarding the VSV-levels in the grid. This is also true for individual wind turbines, as long as they are connected at suitable voltage levels.

Several solar power plants connected in the same LV grid may lead to a noticeable increase in the VSV-levels compared to when there is no solar power. It has been found that if 30 % of all customers in the evaluated LV grid have solar power, the VSV-levels (caused by solar power) will be as high as the highest levels already found in the grid.

Wind farms are not expected to lead to a significant increase in VSV-levels in the grid taking into account the current carrying capability of cables and acceptable increases in voltage. However, it has been found that the level of noise in the 3-second VSV-levels may increase slightly with the addition of wind farms.

It is concluded that an increase in wind and solar power is no immediate cause for concern with regards to increased voltage variations in the time scale between 1 second to 10 minutes. However, as it has been found that the voltage variations can increase under certain circumstances, while also changing its character, it is recommended to keep track of the levels.

It has been shown in this study that the concept of VSV is a good basis for indicators that can be used to assess the voltage variations in time scales between 1 second and 10 minutes.

7. ACKNOWLEDGEMENT

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