VERY SHORT VARIATIONS IN VOLTAGE (TIMESCALE LESS THAN 10 MINUTES) DUE TO VARIATIONS IN WIND AND SOLAR POWER

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ABSTRACT

This paper presents results from a study on variations in voltage magnitude at a timescale less than 10 minutes, due to measured variations in wind and solar production. The variations are compared with the measured variations at several low and medium-voltage sites. It is concluded that individual solar panels are not a concern but that several solar panels connected to the same low-voltage feeder may lead to a noticeable increase in voltage variations at this timescale. Individual wind turbines and wind farms are not expected to lead to a significant increase in voltage variations. The voltage variations do change in character by the introduction of wind and solar power.

INTRODUCTION

In the coming years, the amount of renewable electricity production 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. 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.

This paper presents results from a study on variations in voltage magnitude at a timescale less than 10 minutes, due to variations in wind and solar power production [1].

Very Short Variations

The voltage variations on a time scale between 1 second and 10 minutes are quantified using Very Short Variations, or VSV [2, 3]. The 3-second VSV, ΔU_{vs}, is defined as the difference between the 3-second and 10-minute values (as defined in IEC 61000-4-30):

$$\Delta U_{vs}(t_k) = U_{vs}(t_k) - U_{sh}(t_k) \qquad (1)$$

When calculating the 3-second VSV values, the 10-minute value U_{sh} 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

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

where t_k is the time sample representing the end of the 10-minute interval and N the number of samples during the 10-minute interval.

Using this approach, the voltage variations during every 10-min interval can be quantified using three indices

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

MEASUREMENTS

Measurements were obtained from different voltage levels in the grid and used to calculate the existing VSV-levels. In the low-voltage (LV) grid measurements from around ten different locations have been used. 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 1 shows the 3-s and 10-min VSV-levels in the MV grid, during one 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 1 shows typical VSV-levels in different grids based on the above-mentioned set of measurements.

Table 1. Typical VSV-levels (% of nominal voltage)

Grid	Max 10-min	Average 10-min	95 % 10-min
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%

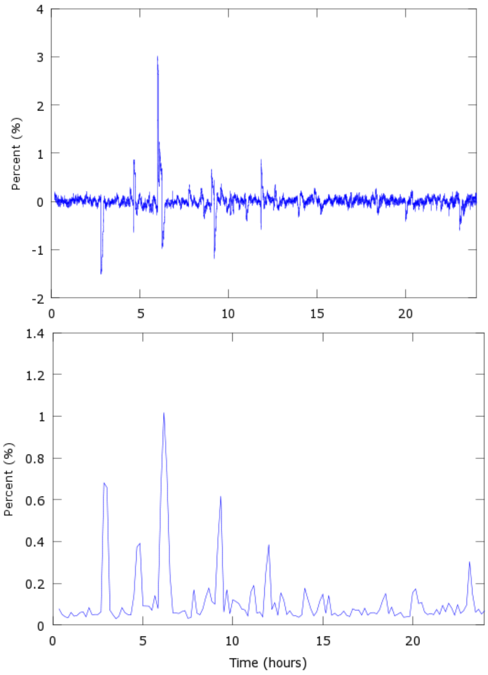

Figure 1. 3-sec (top) and 10-min (bottom) VSV-levels in the MV grid, during one day

SOLAR POWER

Data on solar power have been acquired for 5 different installations, ranging in capacity from 2 to 100 kW. Measured variations in active and reactive power were combined with a modeled source impedance, resulting in the voltage variations from which VSV was calculated.

Study cases

In order to assess the voltage fluctuations from variations in production, several cases were studied. The first case considers a single photovoltaic (PV) unit with an LV customer. The PV unit is assumed to be connected to 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 made 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 2

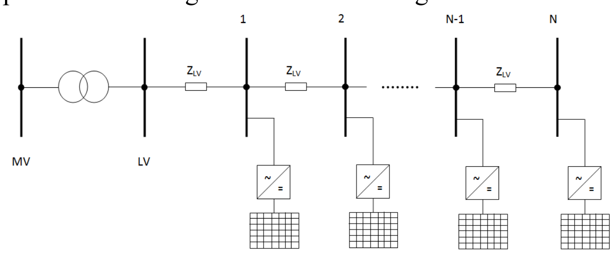

Figure 2. Aggregated PV model used in case 2

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.

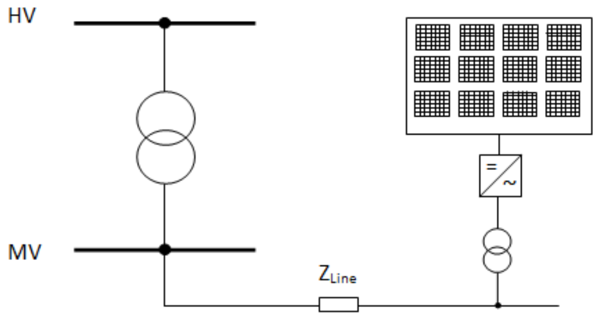

Figure 3. Large PV park model used in case 3

The third case considers a larger solar power plant connected to the MV grid (Figure 3). 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.

Results

Figure 4 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.

Table 2. VSV-levels for different cases

Case	Max 10-min	Average 10-min	95 % 10-min
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

The characteristics of VSV due to solar power differ from the existing ones (Figure 1): there are more spikes, but considerably less noise. The 10-minute VSV-levels calculated when using the reference impedance are shown in Table 2, and they are around half of the highest existing levels. Very long cables or lines are 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.

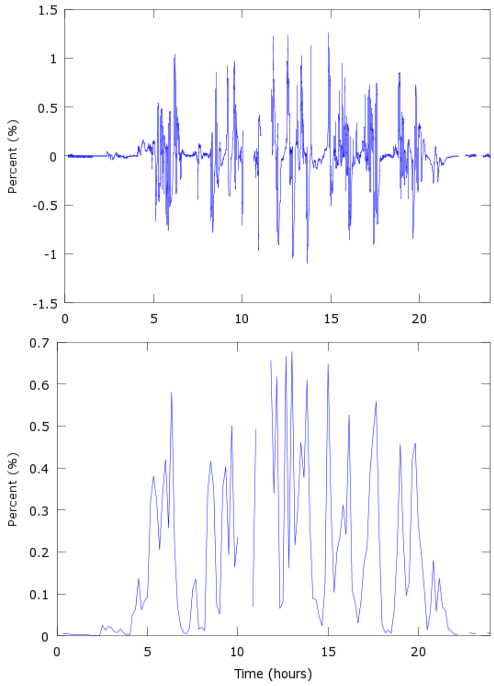

Figure 4. 3-second (top) and 10-minute (bottom) VSV-levels for a single PV unit during a day with partial cloud coverage

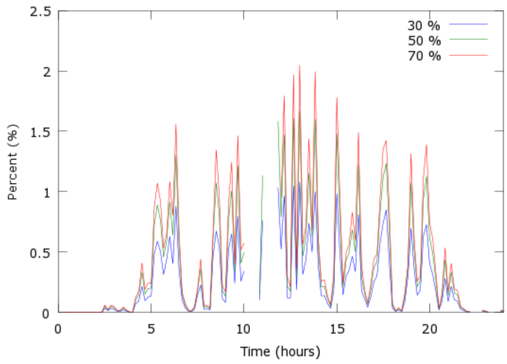

Figure 5. Very-short variations due to different levels of PV penetration in the LV grid

In the second case, aggregation of several 6-kW PV units was modeled according to Figure 2. Figure 5 shows the 10-minute VSV levels during a day for three levels of PV penetration. The cable used is the AKKJ 240 mm^2, common in the Swedish LV grid. The 10-minute VSV-levels from aggregated PV were about the same as the highest levels currently in the grid already at 30% penetration. At 70% penetration the VSV-levels were almost twice as high. The 10-minute VSV-levels are summarized in Table 2.

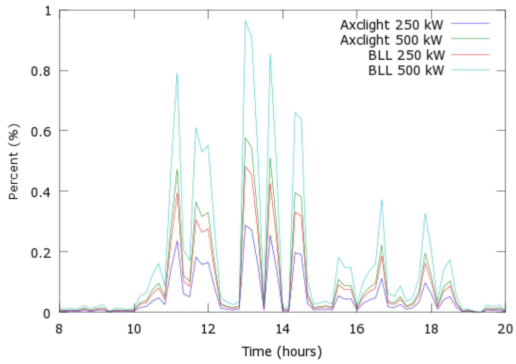

Figure 6. 10-minute VSV-levels for different PV park capacities and cables.

In the third case, a PV park was modeled according to Figure 3 with different park capacities and cables or lines. The 10-minute VSV-levels are shown in Figure 6. 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 permissable voltage rise. 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.

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

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.

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 7. 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.

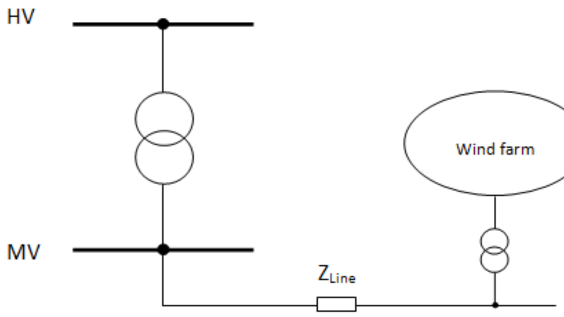

Figure 7. Wind farm model used in case 2

Results

Figure 8 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. Wind power has a VSV characteristic more similar to that of the grid, shown in Figure 1, than that of solar power, shown in Figure 4. The 10-minute VSV-levels are shown in Table 3. Compared with the highest levels found in the MV grid (Table 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 9 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 (Figure 1). The 10-minute VSV-levels are shown in Table 3. 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 (Table 1). The results indicate that wind power should be no cause for concern with regards to an increase in VSV-levels.

Table 3. VSV-levels for different cases

Case	Max 10-min	Average 10-min	95% 10-min
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

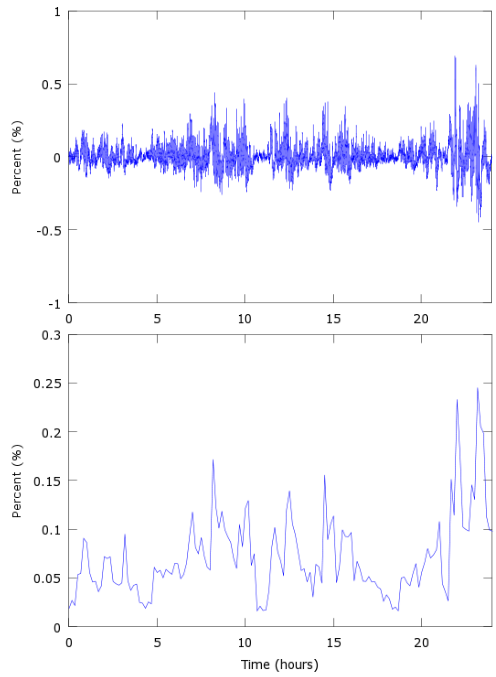

Figure 8. 3-second (top) and 10-minute (bottom) VSV-levels for a single wind turbine during one day

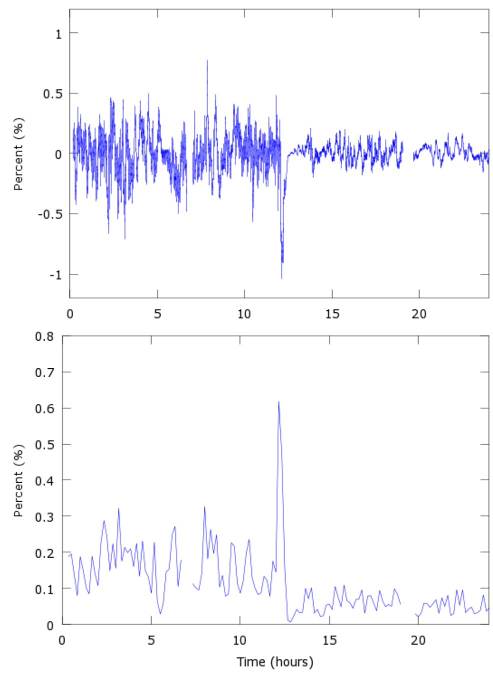

Figure 9. 3-second (top) and 10-minute (bottom) VSV-levels for a wind farm during a day

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 voltage that impacts the speed and torque 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]. Further studies are required in order to establish acceptable VSV-levels.

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.

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BIBLIOGRAPHY

[1] O. Lennerhag, M. Bollen, S. Ackeby and S. Rönnberg, “Spänningsvariationer och intermittent produktion,” Elforsk, 2014.

[2] M. Bollen, M. Häger and C. Schwaegerl, “Quantifying voltage variations on a time scale between 3 seconds and 10 minutes,” in 18th international conference on electricity distribution, 2005.

[3] M. Bollen and I. Gu, Signal Processing of Power Quality Disturbances.

[4] M. Bollen and F. Hassan, Integration of Distributed Generation in the Power System, 2011.

[5] E. C. Kern, E. M. Gulachenski and G. A. Kern, “Cloud effects on distributed photovoltaic generation: Slow transients ad the Gardner, Massachusetts photovoltaic experiment,” Energy Conversion, IEEE Transactions on, vol. 4, no. 2, pp. 184-190, 1989.

[6] J. Schlabbach, D. Blume and T. Stephanblome, Voltage Quality in Electrical Power Systems, IET, 2001.

[7] Guide to Quality of Electrical Supply for Industrial Installation. Part 5: Flicker and Voltage Fluctuations, Paris: International Union for Electricity Applications, 1999.

[8] K. Zhao, “Rectifier Capacitor Filter Stress Analysis When Subject to Regular Voltage Fluctuations,” IEEE Transactions on Power Electronics, Vol. 28, No. 7.