Influence of grid configuration on current conducting behaviour in PV installations

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***Abstract* - On the roof of an industrial site a 385 kWp PhotoVoltaic installation is operational. When production of this system reaches 60% of the installed power, the circuit breaker trips. At sufficient production, measurements show a high distortion of phase voltage and variable waveform of both phase voltage and current. Analysis of the installation showed that a Yy_0 transformer is used introducing a high zero sequence impedance. Unbalance in the injected current combined with a high zero sequence impedance leads to a high neutral-ground voltage and distorted phase-neutral voltages. In this paper it will be shown that the tripping of the circuit breaker is caused by the measurement method of the device. This paper analyses the practical measurement results, causes of errors and the solution to the stated problem.**

Keywords* - *Solar power, transformer, tripping circuit breaker, measurement method,* *zero sequence impedance

I. INTRODUCTION

The 20/20/20 targets of the European Union lead to the massive implementation of dispersed renewable energy. By 2020, Belgium has to produce 13% of its electrical energy out of renewable energy [1]. Photo Voltaic (PV) installations are therefore heavily promoted by government funding, in a system of so-called green current certificates [3]. The large funding has led to an exponential growth and situations of technically unconsidered investments, as shown in the analysed case.

On the roof of an industrial site a 385 kiloWatt peak (kWp) PV installation is integrated in the existing low voltage grid (Figure 1). The PV installation is divided on two roofs. On one roof, closest to the transformer, 230 kWp is installed using 41 single phase invertors. Here the cable length to the General Low Voltage Distribution Board (GLVDB) is the shortest. On the second roof 155 kWp is installed using 21 single phase invertors. In both cases the distribution of the single phase inverters is nearly balanced over the three phases.

The majority of the load in the company consist of symmetrical three phase loads, mainly Variable Speed Drives (VSD) and Direct OnLine induction motors (DOL). Single phase loads, mostly lighting and IT equipment, are negligible with respect to the total load.

At low irradiation, (< 1000W/invertor), no problems are reported. When irradiation increases to more than 1000W/invertor a light flickering is observed in the fluorescent lamps in the factory. After a period of ±5 minutes the main electronic circuit breaker trips, with a total production loss of the PV installation as a consequence. As a temporary solution, only the half of the installed capacity is used. The limited use of the PV installation, to prevent shutdown, leads to large production losses and increase of payback time [2].

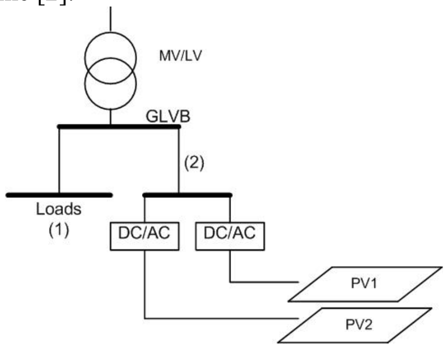

Figure 1: general situation

II. MEASUREMENTS

A. General

Measurements were performed on a sunny day, with and without PV production. Three phase measurements were performed using a Fluke 435 Power quality analyzer.

Since the RMS values of voltage and current are obtained by using Eq. (1) and Eq.(2) with $i_{(t)}$ and $u_{(t)}$ the instantaneous values of current and voltage, T is needed. It will be shown that measurement errors occur due to period variation of both voltage and current [9].

$$U_{RMS} = \sqrt{\frac{1}{T}\int_0^T u^2(t)dt} \qquad (1)$$

$$I_{RMS} = \sqrt{\frac{1}{T}\int_0^T i^2(t)dt} \qquad (2)$$

The Total Harmonic Distortion (THD) is one of the most common used parameters to evaluate the quality of voltage or current. The mathematical equation of the THD of the voltage (THD(U)) is given in Eq. (3). The dual expression can be made for the THD of the current (THD(I)). Where V_1 is the value of the fundamental RMS voltage, V_h the RMS value of the voltage of harmonic order h.

$$THD(U) = \sqrt{\sum_{h \neq 1} \left(\frac{V_h}{V_1}\right)^2} \qquad (3)$$

Measurements were also done on the quality parameters of the phase voltage and current at the GLVDB and at the lighting circuits.

B. *Measurement on the GLVDB*

On the GLVDB measurements of THD(U), THD(I) and waveforms of voltage and current were performed during production with both installations active. Figure 2 and Figure 3 give the THD(U) of the phase voltage and THD(I) of the current.

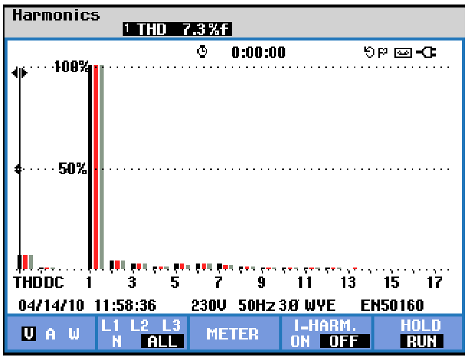

Figure 2: harmonic spectrum of the voltage on GLVDB with production

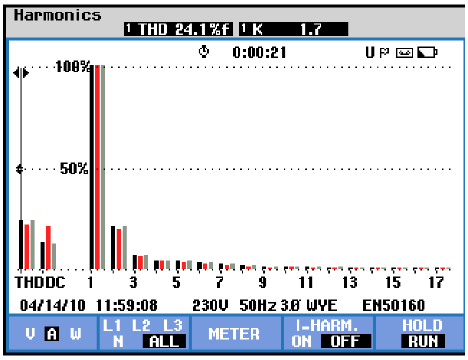

Figure 3: harmonic spectrum of the current on GLVDB with production

Figure 4 gives the waveform of both voltage and current on one phase and Figure 5 gives the waveform of the phase currents in the three phases and the neutral conductor. Table 1 gives the numerical values of voltage and current.

Table 1: Measurement values

Voltage	L1	L2	L3	N
V_{RMS}	229.5	225.4	232.9	1.1
Current	L1	L2	L3	N
A_{RMS}	297	298	253	407

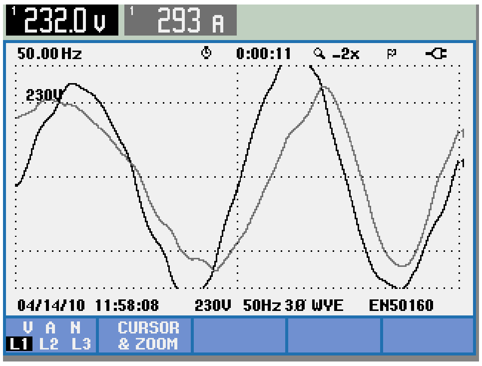

Figure 4: waveform of phase voltage on phase 1 with production

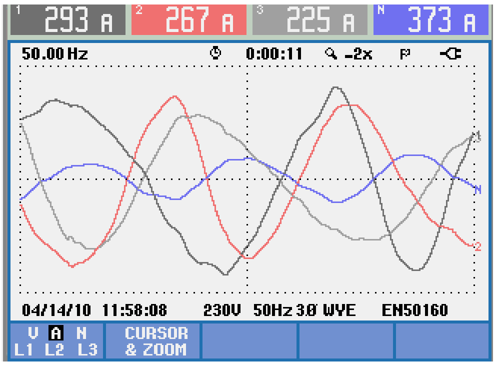

Figure 5: waveform of phase current with production

C. *Measurement on the lighting circuits*

First a measurement was done on the lighting circuits without the PV installation connected. The harmonic spectrum of the phase voltage is given in Figure 6. The THD(U) is 3%, which can be considered as normal taking into account background pollution and load conditions. Figure 7 gives the waveform of the voltage.

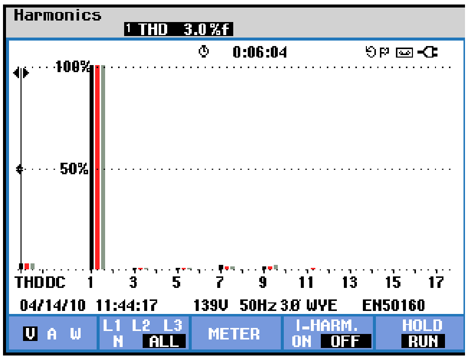

Figure 6: harmonic spectrum voltage without production

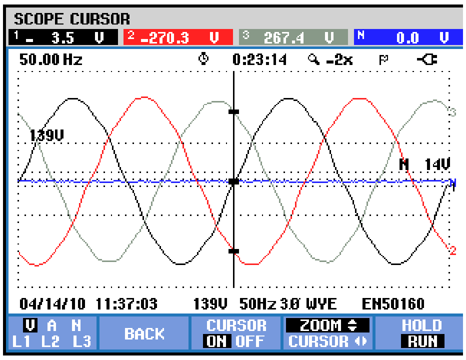

Figure 7: waveform phase voltage without production

A second measurement was done with the PV installation connected. The voltage harmonic spectrum is shown in Figure 8, the THD(U) of the phase voltage is 9,5%. Figure 9 gives the waveform of the voltage.

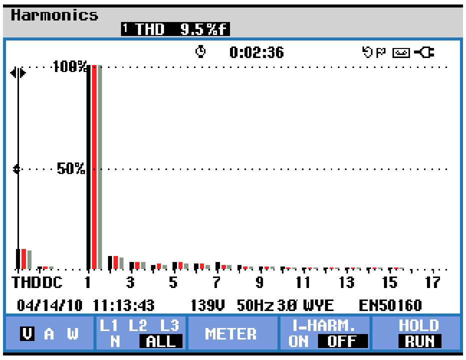

Figure 8: harmonic spectrum voltage with production

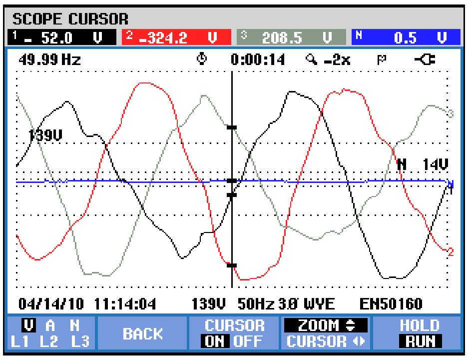

Figure 9: waveform phase voltage with production

III. EVALUATION OF THE MEASUREMENT RESULTS

The measurements show for both measurement locations a high voltage distortion of phase voltage when PV production is high. At the time the invertors produce more than 60% of the installed capacity the THD(U) of the phase voltages varies between 7,3% to 9,5%. A THD(U) of more than 8% is not allowed according to the EN50160 standard [6], although these values fluctuate very quickly in time.

Based on the data shown in Figure 3 it could also be assumed that due to a THD(I) of 24,1%, a relatively large current distortion is present.

IV. CAUSE

A. Cause of phase voltage distortion

Measurements show that large phase voltage shifts and distortions occur at the transformer terminals. This is not a normal situation because a Medium Voltage (MV) / Low Voltage (LV) transformer is traditionally performed as Dy_0 transformer (Figure 10). As a consequence phase voltages will be imposed at secondary LV windings.

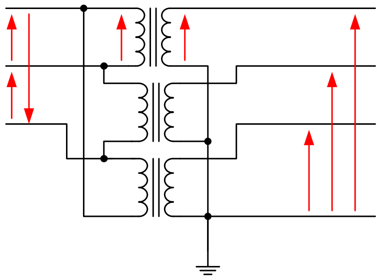

Figure 10: DY_0 Transformer

Analysis has shown that this installation is equipped with a Yy_0 transformer (Figure 11). This type of transformer does impose the line voltages but does not impose phase voltages. As a consequence both voltage variations and phase shifts may occur.

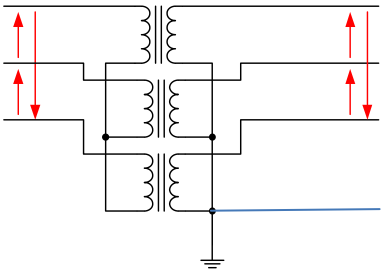

Figure 11: YY_0 Transformer

In order to reduce the number of calculations for a three phase system a symmetrical component transformation, can be used in order to analyze unbalanced situations.

In Eq.(4) the Fortesque transform is performed for impedances. Analogue expression will be found for current and voltage values.

$$\begin{bmatrix} Z_0 \\ Z_+ \\ Z_- \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix}\begin{bmatrix} Z_a \\ Z_b \\ Z_c \end{bmatrix} \tag{4}$$

With Z_a, Z_b and Z_c being the complex impedances of the different phases, and Z_0, Z_+ and Z_- the complex zero sequence, positive sequence and negative sequence impedance. And a is a complex phase shift equal to $e^{j\,2\pi/3}$.

For a common used Dy_0 transformer the zero sequence impedance is low (Table 2). In this case a Yy_0 the Fortesque transformation shows a high zero sequence impedance (Table 2).

Table 2: overview of the zero sequence field reactance as a factor of normal reactance

	Yy_0	Dy_0	Y_0Dy	Yz_0
3-leg	3…10	0,65…0,9	1…2,4	0,10…0,15
5-leg and 3 x single phase	10…100	1	1…2,4	0,10…0,15

The installation consist of single phase inverters nearly balanced over the three phases [5]. A small zero sequence current in combination with a high zero sequence impedance will lead to high values of zero sequence voltages.

From the symmetrical components, the actual phase components can be recalculated by the invers Fortesque transform Eq. (5).

$$\begin{bmatrix}\underline{V_a}\\ \underline{V_b}\\ \underline{V_c}\end{bmatrix}=\begin{bmatrix}1 & 1 & 1\\ 1 & a^2 & a\\ 1 & a & a^2\end{bmatrix}\begin{bmatrix}\underline{V_0}\\ \underline{V_+}\\ \underline{V_-}\end{bmatrix} \qquad (5)$$

Where V_a, V_b V_c being the actual phase voltages, and V_0, V_+ and V_- being the zero, direct and inverse sequence voltage. Eq. (5) shows that a high zero sequence voltage will lead to a shift in the phase voltage.

The phase voltages are unbalanced and distorted while the line voltages remain constant. The unbalance of the voltage is higher if more power is injected. The distortion of the voltage also explains the flickering of the fluorescent lights.

B. Oscillating behavior of phase voltage and current

It can be stated that with three single phase inverters an unbalance in the current induces an increase of the voltage unbalance. Previous studies have shown that, for cable cross sections less than 150 mm² [3], the voltage rises on the phase where most power is injected. For the same power and an increased voltage the current should drop, eventually leading to an equilibrium.

However, the installation also includes VSD's. Consequently the line with the highest voltage holds the highest current. The interaction between load and source creates a oscillating behavior, mainly in function of the Proportional and Integrator settings (PI) of the current controller in the inverter. This also explains why no stable measurements could be performed.

C. RMS Current and FFT measurement Error

Eq. (1) and Eq. (2) show the importance of the correct integration time for a correct indication of RMS values. The measurement device determines its integration time, or the fundamental frequency of the grid, by the zero crossings of the phase voltage of the first channel.

This reference is used in order to determine the other values such as RMS values or Fourier analyses of voltage and current. Since the frequency of voltage and current are different, possible measurement errors can occur.

If the measured timebase of the voltage Eq.(1) (T_{meas}) is higher than the real timebase of the current Eq.(2) (T_{real}), and the RMS value of the current is calculated by the timebase of the voltage, the calculated RMS current (I_{RMS_meas}) versus the real RMS current (I_{RMS_real}) can be calculated from Eq. (1).

Since measurement will be executed using the left part of expression (6) one can ask if the real gathered measurement (right part of expression (6)) is less or not.

$$\frac{1}{\mathrm{T}_{meas}}\int_0^{\mathrm{T}_{meas}} i^2(\mathrm{t})\mathrm{dt} \;>\; \frac{1}{\mathrm{T}_{Real}}\int_0^{\mathrm{T}_{Real}} i^2(\mathrm{t})\mathrm{dt} \qquad (6)$$

After calculation of time windows expression (7) is found.

$$\mathrm{k}\frac{\mathrm{T}_{real}}{2} > \quad \mathrm{T}_{meas} > \quad \mathrm{k}\frac{\mathrm{T}_{real}}{2}+\frac{\mathrm{T}_{real}}{4} \qquad (7)$$

From Eq. (7) is can be shown that for deviations of T_{maes} versus T_{real} smaller than $T_{real}/4$ the I_{RMS_meas} is higher than I_{RMS_real} .

For the determination of both the harmonic spectrum and RMS value of a signal a correct timebase is extremely important. The THD(U) and RMS values of the voltage are correct since the timebase of the voltage is used in calculating these values. Since the determination of both the THD(I) and RMS values of the current are based on the frequency of the voltage, these values are wrong calculated.

As a conclusion: "the current harmonics as shown in Figure 3 are not representing the real currents (Figure 5) and the RMS values of the currents are wrong."

A electronic circuit breaker uses the same principle to measure the current as the stated Power Quality analyzer, the device will calculate RMS currents higher than in reality, with a tripping of the circuit breaker as a result. With half of the PV panels connected the circuit breaker still measures a fault in the current but not high enough in order to trip on overload.

V. CONCLUSIONS

Small unbalance in the current injection causes distortion of the phase voltage due to the zero sequence grid impedance. For high zero sequence impedances such as in Yy_0 transformers high unbalance voltages can occur.

As zero crossings of voltage and current are not equal at the time of calculation of RMS voltage and current, neither RMS values nor FFT values are correct. Since electronic circuit breakers use the same measurement principle a higher current is measured what will cause an circuit breaker tot trip.

The solution in this case consisted in replacing the Yy_0 transformer with a Dy_0 transformer. As a result, the zero sequence impedance is negligible and phase voltage remains constant. The circuit breaker measures the correct current and does not trip. This has been practically implemented with success.

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