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Effect of Domestic Power Plants to the Low Voltage Transformer Areas from the Nonlinear Distortion Point of View

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A case study is presented in this work, where a 4 kW photovoltaic domestic power plant, located in Hungary, has been examined. Based on the measured voltage and current signals we examined the frequency domain behaviour of the power plant and the effect to the power quality, mainly the total harmonic distortion, of the low voltage transformer area.
Evaluation of the measurement database suggests that this type of synchronous power injection has serious effect on the voltage distortion of the low voltage grid, and this effect highly depends on the ratio of the injected power magnitude related to the nominal power of the inverter part.
The available hardware structure enables us not only to eliminate this phenomenon but also to improve the existing quality of the low voltage grid.
It needs only a modified control structure that can be implemented in the inverter control device. It causes power loss reduction in the low voltage grid. This reduction helps lowering the power loss in the phase conductor, and more radically in the neutral conductor of the transportation line. In the case of electric power production from fossil sources, it lowers the greenhouse gas emission, to lower the environmental and social- welfare effects of the climate change.

1. Motivation and aim

There is an ongoing discussion in the scientific and public society on the exhaustion of fossil fuel reserves and on how the climate change is affecting our planet. Current opinion says that the primarily emitted greenhouse gases (GHG) from natural and artificial sources are responsible for the effects of climate change. These effect the solar radiation, and thus act as key factors affecting the global weather. Nobody denies the constrained nature of fossil energy resources, but they use optimistic estimations of the quantity and availability of these energy resources, that may become available with the help of new scientific and technological developments. There is a huge literature about the prediction of fossil energy resources, and their effect on the CO_2 concentration in the atmosphere, and as a result on further climate change impacts over the next 200 y period of time. The effects of fossil fuels depletion (Chiari and Zecca , 2011), economic growth (Nel and Cooper, 2009), the wind and solar energy production (Leggett and Ball, 2012) and the exploitation of methane hydrate deposits (Glasby, 2003) on global warming is predicted.
The predicted CO_2 concentration increases significantly, that result in rising average temperature values. The situation is getting worse by the global economic growth, and the extended use of newly available fossil energy sources (primarily deepwater oil and gas deposits) (Nel and Cooper, 2009). Without intervention, significant anthropogenic impacts should be expected in the 21st century.
We must influence this process by all means in order to avoid the above described anthropogenic effects. We need to reduce the emissions by reducing the use of resources, which produce greenhouse gases. Surveys suggest that the economic sectors responsible for CO_2 emission in the European Union are as follows (in descending order): energy and heat production (32 %), road transport (22 %), household

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consumption (11 %), manufacturing and construction facilities (15 %) and other sectors (20 %) (Pasaoglu et al., 2012).
These problems of using fossil energy resources become more serious as a consequence of the Fukushima nuclear accident. The European Union has radically changed his energy policy. They suspended the operation of nuclear power plants, and a lot of them will stop the operation in the coming years. Authorities want to cover the lost production capacity mostly with renewable energy sources (RES), primarily with wind and solar power (Photo voltaic (PV)) and wind turbines (Wind Generator (WG)). For achieving this goal, it is not sufficient to build high-capacity centralized power plants. In addition, the European Union largely intends to rely on a large numbers of small household plants (1 – 5 kW) in the future. Unfortunately, the uncertain nature of the availability of large-scale renewable energy sources makes it difficult to integrate these power plants into the distribution system, if the renewable energy produced is greater than 10 % of the total production (Battaglini et al., 2009). A possible solution for this situation is a European smart grid (SG) (Purvins et al., 2011).
In many countries the authorities are trying to remove the less energy efficient consumer products from the market enforced by the law. The European Union legislation directs consumers to purchase energy efficient lighting solutions, such as cold cathode compact fluorescent lamps (CCFL) and light emitting diode (LED) light sources. These products and the increasing application of switching-mode power supplies cause a highly non-linear distortion on the low-voltage grid (in some countries even the medium-voltage networks are significantly affected).

2. Description of distortion

The interpretation and evaluation of measurement data needs characterizing the extent of the distortion. The distortion of the voltage shape is commonly can be described by the overall reactive power formula:

$$Q_B = \sum_{k=1}^{n} Q_k = \sum_{k=1}^{n} \frac{|\hat{V}_s(k)||\hat{I}_l(k)|\sin\phi(k)}{2} \tag{1}$$

where the positive integer n is the (highest) number of harmonics of interest, Q_k, $\hat{V}_s(k)$, $\hat{I}_l(k)$ and $\phi(k)$ are the the reactive power, the source (s) peak voltage, the load (l) peak current and the phase-angle difference of the k-th harmonic, respectively. The *power factor* (PF) of the source is defined by Garcia et al., (2007) as

$$PF = \frac{\langle V_s, I_s \rangle}{||V_s|| \cdot ||I_s||} \tag{2}$$

where $P = \langle V_s, I_s \rangle$ is the active (real) power and the product $S = ||V_s|| \cdot ||I_s||$ is the apparent power calculated from effective values. From the Cauchy-Schwartz inequality, it follows that $P \le S$. Hence $PF \in [-1,1]$ is a dimensionless measure of the energy-transmission efficiency. The *total harmonic distortion of the voltage and current* (THD_U and THD_I) are defined as (Cerdeira et al., 2004):

$$THD_U = \sqrt{\frac{\sum_{k=2}^{\infty}(|V_k|^2)}{|V_1|^2}} \tag{3}$$

$$THD_I = \sqrt{\frac{\sum_{k=2}^{\infty}(|I_k|^2)}{|I_1|^2}} \tag{4}$$

where V_1 equals the voltage amplitude of the fundamental frequency and V_n is the voltage amplitude of the n -th harmonic and where I_1 equals the current amplitude of the fundamental frequency and I_n is the current amplitude of the n -th harmonic component. In our examined small domestic power plant voltage and curren distortion both, $THD_U > 0$ and $THD_I > 0$ holds.

This undesirable distortion effect increases significantly year by year, and the electricity network operators have also paying and increased attention to this. In hour laboratory we examined different type of energy efficient lighting products and we measured serious current distortion values (up to THD_I =192.7 %)) Two typical measurement evaluations can be seen in the next figure:

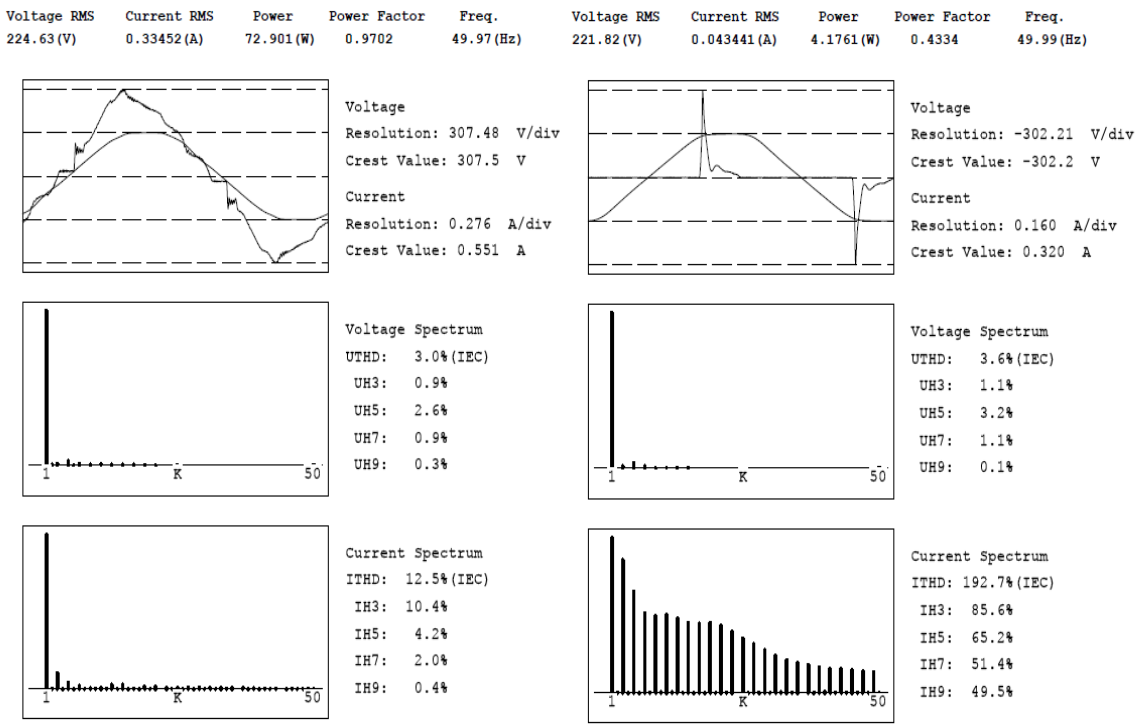

Figure 1: Measurement examples of nonlinear lighting devices ("LED 60x60 HuLux" on left and "LED retrofit 4W Osram" on right side)

3. Measurement

Our department have built up a small domestic power plant for demonstrational purpose in cooperation with EH-SZER limited (member of EON group). It consist of 18 pieces of 235 Wp polycrystalline photovoltaic (PV) panel (JAS235Wp) mounted south-facing 50-degree angled metal scaffold on the flat roof of their building. This PV panels connect to a web box for surge and lightning protection. The web box is connected to a singe phase SIEL-SOLEIL 4000 Wp solar inverter. A SolarLog1000 data logger with web interface has also been installed to it. The operation of the system started in 2011.12.15. The system can be supervised through its web interface. Here we can see the power production in daily, monthly and yearly range. The logger can give us not only the produced electric energy, but other data related to the actual state of the small domestic power plants as:

Table 1: Domestic power plant actual data

CURRENT		**Day**	
Feeding Power	3,345 W	Yield	14 kWh
Generator Power	3,479 W		6.55 €
Inverter efficiency	96.2 %	Specific Yield	3.18 kWh/kWp
Status	Generating	Maximum Value	3,866 W
Error	---------	Set value (cummulative)	14.69 kWh
voided CO_2-emission total: 3,990.8 kg		Actual	95.3 %

We needed additional data for describing the THD values of the low voltage transformer area, and to examine the additional effect of the power injection into the grid. We connected a NORMA D6000 wide band power analyzer to measure exact voltage time function in L1 and L2 and L3 phase conductor and current time function in the L1 line where to the inverter inject the generated power from the renewable source. The NORMA D6000 analyzer calculates the spectral components from this data from zero order (DC) up to 11th upper harmonic component. This spectral component has been sent to the PC for storing during the entire measurement period. For the evaluation we calculated the distortion values from this current and voltage spectral components on the basis of Eq (3) and Eq (4).

Table 2: Spectral components of measurement in % and V and calculated THD values in %

	Phase1			**Phase2**			**Phase3**		
	Voltage:	217.8 V		Voltage:	219.7 V		Voltage:	218.9 V	
	THD (%):	1.274		THD (%):	2.174		THD (%):	2.272	
Order	RMS %	RMS V	Phi	RMS %	RMS V	Phi	RMS %	RMS V	Phi
0.	0	0	-	0	0	-	0	0	-
1.	99.952	217.70	0	99.947	219.58	0	100	218.90	0
2.	0.019	0.04	-	0.005	0.01	-	0.01	0.02	-
3.	0.363	0.79	66.07	0.211	0.46	-168.38	0.374	0.82	68.97
4.	0.012	0.03	-	0.003	0.01	-	0.011	0.02	-
5.	0.998	2.17	167.25	2.015	4.43	163.86	2.063	4.52	165.98
6.	0.009	0.02	-	0.003	0.01	-	0.011	0.02	-
7.	0.686	1.49	178.19	0.762	1.67	172.17	0.851	1.86	175.39
8.	0.003	0.01	-	0.002	0.00	-	0.003	0.01	-
9.	0.144	0.31	127.32	0.18	0.40	131.05	0.193	0.42	138.75
10.	0.003	0.01	-	0.002	0.00	-	0.001	0.00	-
11.	0.028	0.06	-	0.071	0.16	-	0.046	0.10	-
12.	0.002	0.00	-	0.002	0.00	-	0.001	0.00	-

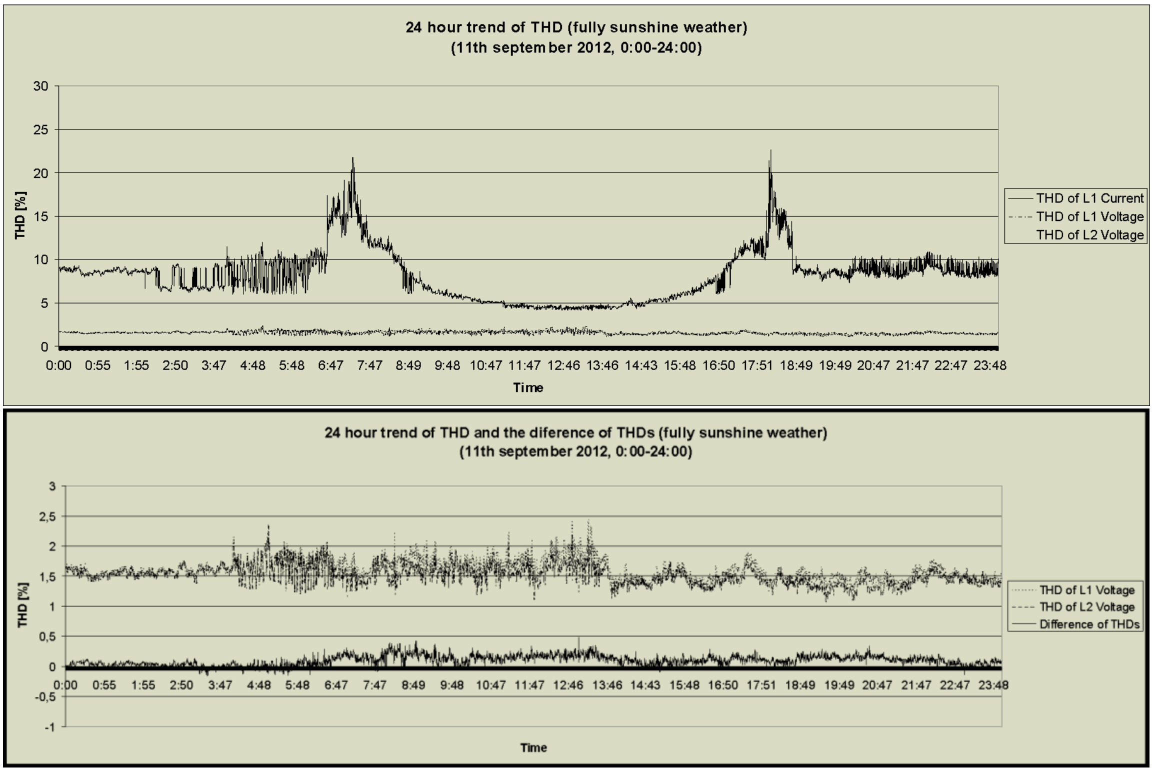

Figure 2: Graphical evaluation of measurement data: Current THD on L1 and Voltage THD on L1 and L2 line, 24 h trend and Voltage THD on L1 and L2 line and the difference between them, 24 h trend

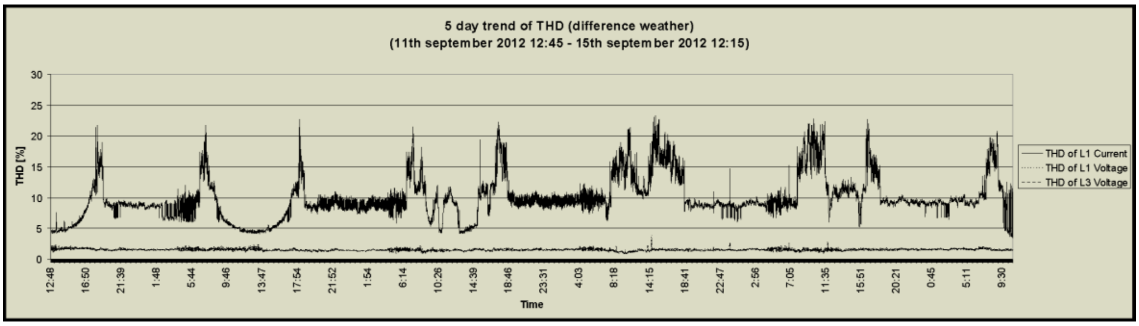

Figure 3: Graphical evaluation of measurement data: Current THD on L1 and Voltage THD on L1 and L2 line, 5 days

Based on the measurement data, can be seen in Figures 1, 2 and 3, that we have found effect of grid synchronized power injection into the low voltage electric network. Using single phase inverter we haven't got any effect or additional distortion on the other lines not used for power injection. Spreading these types of single phase small domestic power plants the injected current should be distributed carefully, the magnitude of the power taking into account, symmetrical between the phase lines. In our case the transportation lines where very rigid, because the connection point were close to the low voltage transformer with oversized cable diameter but we measured voltage amplitude increasing in the inverter connected line. It is important to reserve the symmetrical load of the transformer to avoid accidental protection shutdown.

On the other hand we have realised, the inverter gives additional high odd order current components to the phase conductors, and the 3^{rd} and 9^{th} components are remarkable, because these components are arriving at the star point at the same phase and adding to each other. It can give serious zero line current in perfect symmetrical load and injected power case too, and it can disturb the protection circuits of the electric distribution system, and can add serious power loss of the zero conductor to damage. On the other hand we have to pay the price of this power loss increasing in money and additional GHG emission.

It can be seen that the amplitude of this current distortion is highly depends on the amplitude of the injected power. The value is acceptable in full power range, but if the generated renewable energy is lowering, the current THD value rises radically. The ratio of the produced renewable energy are changing commonly because the relatively small geometric extent of the low voltage transformer area, the renewable energy sources (solar intensity, wind speed) are changing near simultaneously, this effect can't be compensated itself automatically, the current distortion can jump onto a dangerous level in terms of grid operation safety.

Only one positive effect has been realised, that the distributed generation lower the voltage drop on the line concerned in injection, thus the voltage effective value was closer to its standard nominal value. Planning these types of networks, the voltage margin could be smaller. Because of the distributed generation the power loss can be reduced on the phase transportation lines.

4. Conclusions

Based on the collected measured voltage and current-time function we calculated the voltage and current THD values characterizing the distortion of the whole low voltage transformer area and additional effect of the examined single phase solar inverter system. We found that the supposed nonlinear distortion has already been detectable in the examined low voltage transformer area without the inverter system too.

The inverter added serious current distortion in the evening (consumer), this effect is significantly higher (10 %) than the average distortion of the network, but the power consumption is minimal in this case. This undesirable effect significantly depends on the magnitude of the injected efficient electric power; the injected current THD is varying between 5 % and 20 %. Decreasing the injected power the performance decreases significantly.

We found barely measurable distortion increase in the measured phase voltage, and found minimal interaction effect between the voltage and current THD rising of the phase conductor, showing that the cabling sufficiently "rigid" in this small scale distributed generation. But the measurable existence of this interaction shows, that it should be considered to examine in significantly increase case of distributed generation.Based on the available literature other analyses coroborates our mesurement results (Martínez-Patino et al., 2012).

The calculated voltage THD values shows that it should be applying the radical reconfiguration of the regulatory structure of the grid synchronized inverter system to compensate the nonlinear distortion of the low voltage area with inject odd higher harmonic current components into the phase conductor in the near future. This type of controllers uses spectral analysis and compensates the distortion in the frequency in simple grid tie inverter application (Görbe et al., 2011), in a measurement based battery model(Göllei et al., 2011) and in a komplex renewable energy sytem with electrical vehicle application; (Göllei et al., 2012). With the help of this method, the lowering the power loss in the phase conductor, and more radically in the neutral conductor of the transportation line becomes feasible. In the case of electric power production from fossil sources, it could help to lowers the greenhouse gas emission, to lower the environmental and social-welfare effects of the climate change.

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