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Experimental study of the nonlinear distortion caused by domestic power plants

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ABSTRACT

An experimental study is presented in this work, where the distortion effect of a 4 kW photovoltaic domestic power plant, located in Hungary, has been examined. The power plant is connected to a low voltage grid by using a standard grid synchronized inverter. Based on the measured voltage and current signals we examined the frequency domain behavior of the power plant, and the effect of the power plant on the power quality, mainly the total harmonic distortion. The measurement database shows that the synchronous power injection of the photovoltaic domestic power plant has serious effect on the voltage distortion of the low voltage grid, and this effect highly depends on the actual generated power.

Based on the experimental results, suggestions on how to operate the photovoltaic domestic power plant are formulated that enable its energy-efficient operation with minimal distortion effect.

1. Introduction

There is an ongoing discussion in the scientific and public society on the exhaustion of fossil fuel reserves and on how 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. The predicted CO_2 concentration increases significantly, that results in rising average temperature values. Without intervention, significant anthropogenic impacts should be expected in the 21st century. We need to reduce the emissions by reducing the use of resources, which produce greenhouse gases. Surveys suggest that the economic sectors which are responsible for CO_2 emission in the European Union are as follows (in descending order): energy and heat production (32%), road transport (22%), household consumption (11%), manufacturing and construction facilities (15%) and other sectors (20%) [1]. A remedy of this situation could be the increased use of wind and solar energy production [2].

As a consequence of the Fukushima nuclear accident, the European Union has radically changed its 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 (photovoltaic (PV)) and wind turbines (wind generator (WG)). In addition to building large centralized power plants, the European Union largely intends to rely on a large number 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 production is greater than 10% of the total production [3]. One may choose the location of the photovoltaic grid connected power plants by using so called photovoltaic maps (see e.g. Ref. [4]), but it does not help avoiding a day-to-day fluctuation. A possible solution for this situation is a European smart grid (SG) [5].

The main technical obstacle to integrate solar or wind power plants into the electrical grid is the difficulty of storing efficiently the generated power in excess. For stand-alone industrial applications hybrid photovoltaic/thermal (PV/T) systems have shown a great potential, that consists of PV modules and heat extraction units mounted together [6]. A distributed power generation system with an electric energy storage unit is described in Ref. [7] to meet the dynamic electricity demand in a household. An interesting approach to construct a 100% independent energy system based on smart energy storage for integration of renewables and CO_2 emissions reduction is reported in Ref. [8]. Another challenge of integrating power production of wind and solar renewable energy sources to the grid is the unpredictable availability. In case of large scale injection the balance of production and consumption is very difficult to keep.

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In addition to the unpredictable availability, the changing whether conditions have a great influence on the generated power of a solar power plant caused by its highly temperature-dependent operation efficiency. The effect of whether conditions, e.g. solar radiation, ambient temperature, wind etc., is thoroughly investigated in the literature, for example in Ref. [9]. In order to analyze this effect and to improve the design of solar power plants, advanced thermal models have been proposed recently for photovoltaic panels under varying atmospheric conditions [10].

In order to increase the efficiency of power production with solar power panels, hybrid photovoltaic/thermal systems are most often in use, where the optimal design of a concentrated system is of great importance. The effect of solar radiation parameters, including yearly and daily variations as well as changes caused by weather conditions on the optimum concentration factor are investigated in Ref. [11]. With integration of a heat pump in the photovoltaic system one can achieve an increased performance and the widening of operating conditions, but the control of the heat pump can also serve as a tool for mitigating voltage rise caused by photovoltaic power generation systems [12].

Because of the importance of integrating power plants utilizing renewable energy sources into the existing energy generating and distributing infra structure, an increasing number of studies are published every year related to this topic. One approach to overcome the stochastic nature of the availability of solar and wind power is to integrate them with other renewable energy sources, such as biomass, for example [13]. A promising alternative is to use an existing thermal grid as a balancing support [14]. A comprehensive model of electrical power grid with outage planning and forced outage simulation for prospective studies of transmission system operators is presented in Ref. [15].

The above mentioned studies on the effect of changing solar radiation conditions on the power generation of solar power plants and their integration into the existing energy production/consumption systems are mainly concerned with analyzing the power production and the efficiency of the operation, but almost *no investigation is reported on the analysis of the generated power quality*. In the case of generated electrical power, its quality is most often characterized by the distortion from the normal sinusoidal shape of the voltage or current. If a significant distortion is present in the generated power, it causes also serious thermal effects and thereby energy losses on both of the transmission lines (in some countries even the medium-voltage networks are significantly affected besides of the low voltage ones), and the electrical transformers [16]. This way the energy efficiency of a solar power plant is effected by the quality of the power it generates, that is the subject of the present paper. State of the art methods for compensating this undesired effect uses active filters [24] and harmonic current injection [16].

Cold cathode compact fluorescent lamps (CCFL) and light emitting diode (LED) light sources and the increasing application of other switching-mode power supplies form a significant class of primary causes of a highly non-linear distortion on the low-voltage grid. In our laboratory we examined different types of energy efficient lighting products and measured serious current distortion values (up to 192.7%) [17]. This distortion causes distorted current waveforms in the well engineered linear products, too. *Because of the way of injecting electric power, solar power plants can in principle also cause non-linear distortion*. This undesirable distortion effect increases significantly year by year, and the electricity network operators are also paying an increased attention to this.

Despite of its importance, almost no experimental studies have been carried out to investigate the distortion effect of energy efficient consumers and power plants utilizing solar energy. The aim of this work is to investigate experimentally the distortion caused by small domestic power plants, and develop means to lower or eliminate this effect.

2. Power quality and nonlinear distortion

The switching mode operation of energy producers or consumers in an electrical network cause the presence of upper harmonic components in the current and voltage, that results in a significant distortion of their normal sinusoidal shape. The upper harmonic components cause power loss in the phase conductor, and more radically in the neutral conductor of the transportation line and may trigger the power safety system of the transformers, too.

One of the most important quantity that characterizes the power quality in a low voltage electrical grid is the *distortion* of the voltage shape. Based on the measurement data of the voltage V and current I values as functions of time, the distortion of the voltage shape can be described by the overall *reactive power formula*:

$$Q_B = \sum_{k=1}^{n} Q_k = \sum_{k=1}^{n} \frac{\left|\widehat{V}_s(k)\right|\left|\widehat{I}_l(k)\right|\varphi(k)}{2} \quad (1)$$

where the positive integer n is the (highest) number of harmonics of interest, Q_k, $\widehat{V}_s(k)$, $\widehat{I}_l(k)$ and $\phi(k)$ are 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. [18] as

$$PF = \frac{P}{S} = \frac{\langle V_s, I_s \rangle}{\|V_s\| \cdot \|I_s\|} \quad (2)$$

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 [19]

$$THD_U = \sqrt{\frac{\sum_{k=2}^{\infty}\left(|V(k)|^2\right)}{|V(1)|^2}} \quad (3)$$

$$THD_I = \sqrt{\frac{\sum_{k=2}^{\infty}\left(|I(k)|^2\right)}{|I(1)|^2}} \quad (4)$$

where $V(1)$ equals the voltage amplitude of the fundamental frequency, and $V(k)$ is the voltage amplitude of the k-th harmonic. Similarly, $I(1)$ equals the current amplitude of the fundamental frequency, and $I(k)$ is the current amplitude of the k-th harmonic component. The Fourier series expansion allows to calculate the different harmonic component values of voltage ($V(k)$) and current ($I(k)$) too based on the measured signals.

Table 1
Domestic power plant actual data provided by the web interface.

Feeding power	3345 W	Yield	14 kWh
Generator Power	3479 W	Yield	6.55 EUR
Inverter efficiency	96.2%	Specific Yield	3.18 kWh/kWp
Status	Generating	Maximum Value	3866 W
Total voided CO_2-emission	3990.8 kg	Set value (cumulative)	14.69 kWh