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Modeling harmonic amplification effects of modern household devices

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ABSTRACT

Nonlinear devices are usually put under the spotlight of harmonic analysis as the main sources of harmonic distortion within residential low voltage grids. Nevertheless, household equipment that is commonly expected to draw almost sinusoidal currents, i.e. devices with single-phase motors, photo-voltaic inverters, etc., can produce significant levels of current harmonics under distorted supply voltage. In order to address the effects of harmonic amplification featured by linear equipment this paper proposes time-domain harmonic models of photo-voltaic inverter, single-phase induction motor and lighting fixture with magnetic ballast. These structured models are then converted into simplified generic ones thus enabling their use in resource-intensive network simulations. By the way of illustration, simulations for low voltage residential grids of single-family houses and office building are produced and analyzed.

1. Introduction

Traditional approach to harmonic analysis of low voltage (LV) residential grids focuses on energy-saving lighting, electronic equipment with switch-mode power supplies, adjustable speed drives, etc. as the main sources of current harmonics. Their current spectra are assumed to remain unchanged irrespective to supply voltage distortion. Other household devices, e.g. uncontrolled single-phase motors, are represented as linear and passive circuits.

However, there have been multiple reports considering unexpected increase of harmonic emission amplified by linear equipment under distorted supply voltage, inter alia by air conditioning units and fridges with single-phase induction motors (SPIM) [1,2], fluorescent lamps with magnetic ballasts (FL with MB) [3] or photo-voltaic (PV) inverters [4]. These references point out oversensitivity of certain household devices to voltage harmonics that generally originates from the resonant conditions inherent to the equipment's operating principle. In fact, the presence of a series resonant *LC* circuit introduces a dip in the impedance of the device at the particular harmonic frequency. As a result, if the voltage harmonic matches the resonant frequency, corresponding harmonic currents are amplified. Selective harmonic impedance of these devices is similar to that of passive harmonic filters tuned to provide low impedance path for particular frequency [1].

Mass utilization of similar devices in residential grids creates a strong group effect that alters the shape of the grid impedance characteristic by shifting existing network resonances, as a consequence of introducing additional capacitance and inductance to the grid [5,6]. For example, the match of grid impedance parallel resonance with low order harmonic currents from nonlinear loads can cause significant amplification of supply voltage distortion [7].

This paper studies harmonic behavior of linear household devices containing resonant circuits under grid voltage distortion by addressing harmonic impedance of PV inverter, SPIM and FL with MB. Time-domain harmonic simulations of these devices allow to produce equivalent linear models suitable for use in network harmonic simulations and, thus, study their impact on harmonic current flow within the grid. The body of the paper consists of two parts corresponding to individual harmonic modeling of devices with resonant properties and simulations of the network impedance affected by these devices. The first part sequentially describes Simulink-based time-domain harmonic models of a single-phase PV inverter, fridge and air-conditioner with SPIM and FL with MB. To give a clearer insight in the modeling process the sections considering modeling methodology and validation are provided. In the second part of the paper, the use of proposed models in simulations of the grid impedance is demonstrated for the cases of LV residential grids feeding multiple single-family houses and a separate office building. The simulation results are analyzed to define the impact of devices with resonant properties on network harmonic impedance.

2. Time-domain harmonic modeling of residential equipment

2.1. Modeling methodology

Several assumptions are made within the modeling process:

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1 Steady-state operation and respective harmonic emission of devices is considered. The distortion level is evaluated via total harmonic distortion factor:

$$THD_I = \sqrt{\sum_{h=2}^{N} (I_h/I_1)^2}, \tag{1}$$

here I_1—fundamental current, I_h—harmonic currents.

2 Parasitic parameters of circuit elements and related losses are neglected.
3 Average modeling techniques are utilized for simulating harmonic emission of the PV inverter, i.e. all high frequency switching phenomena are neglected.
4 Simulated harmonic impedance of the devices are derived applying Exact Linearization tool available in Simulink Control Toolbox [8] to the developed time-domain models. Real impedance characteristics are measured using the frequency sweep technique in the range of up to 2.5 kHz with 50 Hz steps [9].

2.2. Harmonic model of a single-phase PV inverter

The Simulink-based time-domain model of a single-phase PV inverter used for analyzing its harmonic impedance is presented in Fig. 1*a*. The model consists of inverter block Universal Bridge interconnecting the PV DC current source CCS with the grid AC voltage source CVS through the *LCL*-filter. The phase and the shape of inverter current are regulated by control system depicted as Control block that produces a reference signal for the Universal bridge.

The detailed schematic of the control system is presented in Fig. 1*b* [10]. The main blocks affecting harmonic distortion of the inverter output current are the current control loop and the switching function block. The former defines the current waveshape, the latter simulates the effects of zero-crossing distortion under light load operating conditions [11].

Described model was tested to reproduce the harmonic behavior of commercially available single-phase 3 kW PV inverter with the power output of 0.8 kW. Thus, a typical harmonic distortion produced by the PV inverter under light load conditions could be addressed. To this end, parameter values of the model (Table 1) were adjusted to best match the measurement results (Fig. 2*a*, *b*).

Fig. 2*a* presents the current waveform of considered PV inverter for the cases of sinusoidal and non-sinusoidal supply voltages revealing significant increase of the current harmonic emission even under moderately distorted voltage. Observed oversensitivity to voltage harmonics can be explained by analyzing harmonic impedance of the device. In the considered frequency range impedance characteristic (Fig. 2*b*) features inductive nature with increasing magnitude and phase angle tending to 90°. Near 2.5 kHz there is a resonant peak, that originates from the parallel resonance conditions introduced by *LCL*-filter. Low magnitude values of impedance in the frequency range near the fundamental result in high current harmonic emission of the PV inverter if the supply voltage contains harmonics with corresponding frequencies. (Fig. 2*b*). Altogether, comparison of the simulated (Fig. 2, red line) and measured (Fig. 2, green line) data confirms sufficient capability of the model of a PV inverter to reproduce harmonic behavior of the real device.

2.3. Harmonic model of a single-phase induction motor

In order to model harmonic behavior of household devices with asynchronous motors a standard model of capacitor-run SPIM available in Simulink [12] is utilized with minor modifications (Fig. 3). In particular, saturation effects of magnetizing [12] and rotor inductances as well as the iron-core losses [2] were added to the model. Corresponding mathematical equations written for the *q* axis of the SPIM are as follows:

$$\psi_{mq}^{sat} = \psi_{mq} - \Delta\psi_{mq};\;\; \Delta\psi_m = f(\psi_m^{sat}) \tag{2}$$

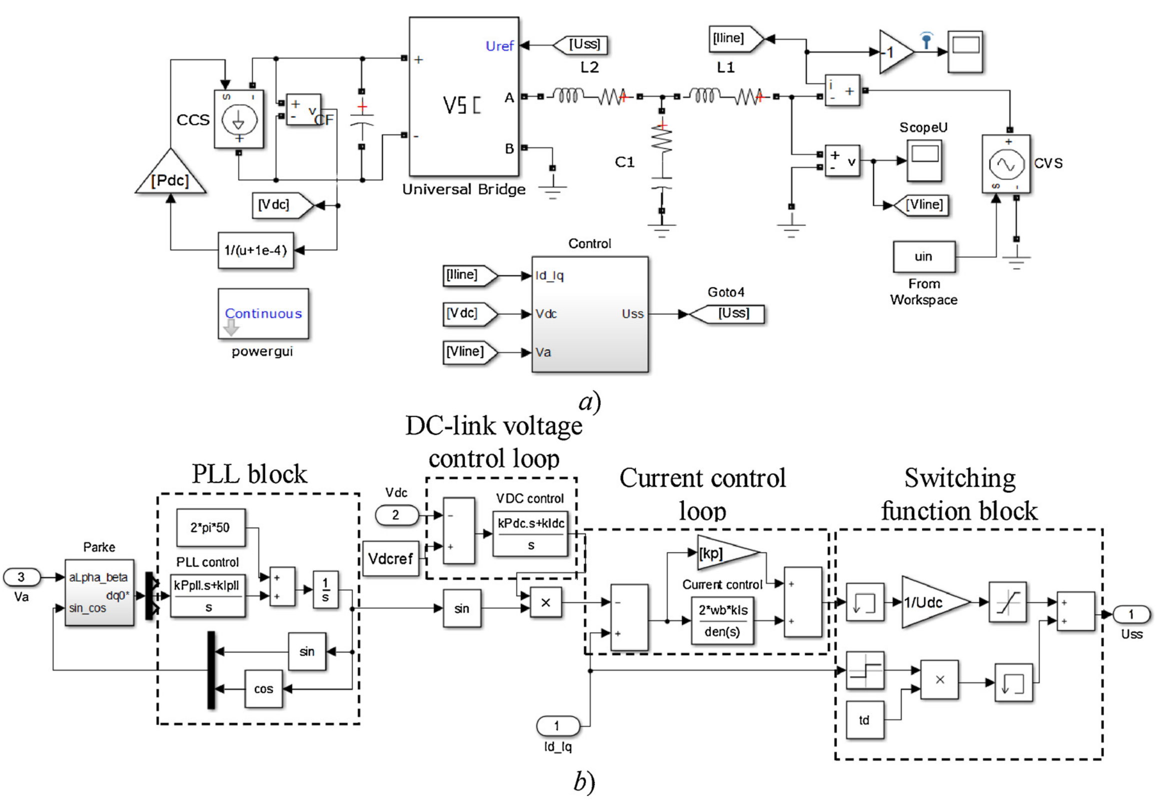

Fig. 1. Simulink-based model of a single-phase PV inverter (*a*) and schematic of respective control system (*b*).