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Modeling and experimental validation of residential cyclic loads

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ABSTRACT

The development of strategies that involves the participation of demand for increasing the flexibility of power systems requires defining accurate residential load models. The work proposes a new model for cyclic loads characterized by different operating cycles. Here, we propose a discrete-time version of the ZIP model. The proposed model is developed starting from the collection of measurements gathered in real operating conditions from a washing machine. The subsequent statistical and clustering analysis allows the model to be generalized for cyclic appliances. A comparison with the classic ZIP model is carried out to evaluate the performances in terms of energy consumptions and active power absorption. Results show that the proposed model simulates more reliably the real behavior of cyclic loads.

1. Introduction

Smart technologies allow demand response to be effective for residential and commercial customers. Furthermore, techniques, such as conservation voltage reduction (CVR) and voltage-led load management represent a possible solution for achieving energy savings [1–5] and increasing the flexibility of power systems. To this end, it is essential to develop accurate load models to analyze and accurately simulate electric power systems.

In the literature, residential and commercial loads are usually modeled considering two classical approaches: measurement-based and component-based. The component-based building-up the load model from information on constituent part [6–9]. The measurement-based approach involves using of metering tools to determinate the sensitivity of load among electrical parameters (i.e.: active power/reactive power vs. voltage/frequency) [8,10–12]. A significant alternative approach takes advantage of the analysis of user behaviors, thanks to the possibility to have effective tools for collecting user data and performing statistical analysis [13–20].

Here, we want to develop a steady-state load model by using a measurement-based approach. A widespread method is the ZIP model [8], also known as polynomial model, which is composed of constant impedance (Z), constant current (I), and constant power (P) components. ZIP model expresses the active and reactive power of the load as function of the applied voltage. In [5], the authors calculate the ZIP coefficients of multiple appliances by collecting experimental measurements. An interesting approach to model consumer electronics is shown in [12,21], where the authors evaluate the impact of consumer electronics on network stability by estimating the ZIP parameters of liquid-crystal display and light-emitting diode (LED) televisions. Other studies on ZIP load models are in [22–24]. In [22], a load component database for household appliances and office equipment is created by Bonneville Power Administration and Pacific Northwest Laboratory; in [23], ZIP coefficients are calculated by using a least-squares regression technique and in [24], Sartomme et al. estimate the ZIP parameters for four electrical vehicles.

It is clear that, generally, the literature tends to estimate a single time-invariant ZIP model for each appliance. Anyway, some loads cannot be described by a single triplet of parameters. For instance, thermostatic loads are characterized by different working phases and exhibit a periodic behavior. Wrong results can be achieved if models do not consider voltage variations produced by a change in both active power absorptions and length of the working phases.

To this end, we propose a discrete-time version of the ZIP model (DT-ZIP) that is able to simulate both loads with a flat power absorption profile and loads characterized by different operating phases, such as thermostatic loads. The analysis starts by collecting a set of measurements on a washing machine operating in real conditions. Electrical parameters such as voltage, current, active power, and energy are collected by using a portable measurement station.

We classify the working phases of the washing machine under test by means of a clustering technique. Thus, we calculate two triplets of *Z*, *I*, and *P* parameters for each working phases by solving two optimization problems. A generalized version of the DT-ZIP is formulated and a comparison with the classic ZIP model is performed. A comprehensive framework is proposed to extend the modeling procedure to other

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cyclic loads.

Summarizing, compared with previous studies, the main contributions of this paper are: (i) the definition of a generalized formulation, based on the ZIP model, for modeling residential cyclic loads (two or more working phases), which is able to incorporate also the classic ZIP approach; (ii) the ability of the DT-ZIP model of considering the thermostatic behavior of some loads that influences the different operating phases; (iii) the provision of a more accurate estimation of active power absorptions and energy consumptions.

The remainder of the paper is organized as follows. Section 2 presents the classic ZIP model and the problem formulation. Section 3 describes the load surveys, the statistical analysis and the clustering technique applied to load measurements. Section 4 presents the formulation of the DT-ZIP and a framework to apply the model to every cyclic load. In Section 5 the validation of the proposed model is presented. Finally, Section 6 contains conclusions.

2. The ZIP model formulation

Here, we deal with load modeling for steady-state analysis. A large number of steady-state models have been developed in the literature [2,4,8]. The main goal of these models is to make explicit the dependence of the voltage with the active and reactive power. A well-known formulation in the literature is the ZIP model (or polynomial model) in which the power of the load is expressed as a quadratic function of the voltage:

$$\begin{cases} P = P_0\left[Z_p\left(\frac{V}{V_0}\right)^2 + I_p\frac{V}{V_0} + P_p\right] \\ Q = Q_0\left[Z_q\left(\frac{V}{V_0}\right)^2 + I_q\frac{V}{V_0} + P_q\right] \end{cases} \tag{1}$$

where P and Q are the active and reactive powers; V is the operating voltage; V_0 is the reference voltage; P_0 and Q_0 are the active and reactive powers calculated at the reference voltage; Z_p, I_p, and P_p are the ZIP parameters for the active power; Z_q, I_q, and P_q are the ZIP parameters for the reactive power. Anyway, the triplets of ZIP parameters are not able to represent the behavior of loads characterized by more than one working phase (cyclic loads). The aim of the paper is to develop a compact formulation able to describe cyclic loads starting from (1). We consider a full load cycle with discrete time-steps of one minute for which dynamics models are overly detailed. Furthermore, we want to identify the ZIP parameters only for the active power, deferring to further works the evaluation of ZIP parameters for the reactive power. Moreover, at residential level is interesting to understand the active power profiles to measure the impact of techniques such as voltage-led load management [2]. In order to obtain an accurate load formulation, we perform: (i) a field survey on a residential cyclic load considering voltage variations in real operating conditions; (ii) a statistical analysis of the collected measurements; (iii) a clustering of the measurements; (iv) an evaluation of the ZIP parameters by solving a constrained optimization problem.

3. Measurements and statistical results

We set-up an appropriate portable station to perform measurements (Fig. 1). We pay attention to make the equipment easy to carry in a residential environment. The portable station is composed by: (1) a single-phase auto-transformer *HSG 0302 Metrel*; (2) a electronic power and energy meter *Schneider Power LogicTM PM5561*; and (3) a current transformer (CT) *TAQB50B150 IME* (Fig. 1a).

Security is ensured by two 16 A circuit breakers installed downstream and upstream of the auto-transformer. A bipolar switch, as depicted in Fig. 1b, allows disconnecting the load and performing no-load measurements of voltage on the secondary side of the auto-transformer. Measurements are recorded in the data-logger integrated into the meter and downloaded by means of an Ethernet port, as shown in Fig. 1b.

Tests have been conducted on a washing machine. Data are recorded during 30 full cycles, 10 for each voltage level considered in the experiment: −5%, +0%, and +5% of the reference voltage $V_0 = 230$ V. Because measurements are collected in a residential environment, voltage range has been limited. Anyway, the method can be extended to the entire allowable voltage range under laboratory conditions. The time-step is 1 min, while the laundry program chosen lasts about 2 h (it means that 120 data points are collected for each laundry program). We collect active power, energy, and voltage measures. The washing machine is an Ariston Hotpoint Aqualtis AQXXD 169 h (7.5 kg). To consider real working conditions of the appliance, measurements are performed in an apartment connected to a LV network. Measures are collected on different days of the week, different hours, and by running the washing machine with different laundry loads.

3.1. Statistical analysis of the results and clustering of data

The washing machine is characterized by different working phases depending on the laundry program. We use the same laundry program to collect ten active power profiles for three different voltage levels. Different operating settings are adopted to simulate real operating conditions. For instance, the washing machine is loaded with an amount of laundry that is each time comparable but not equal.

Nine full cycle measurements collected at the reference voltage level of 230 V are shown in Fig. 2. The identification of a specific pattern, able to model the active power absorption of the washing machine, is difficult to capture. The complexity is due to the uncertainty and the variability of working phases.

To this end, we have calculated the correlation between the different patterns using Pearson coefficients to quantify possible similarities among active power profiles. The Pearson coefficients are formulated as follows

$$\rho_{p_i p_j} = \frac{\sigma_{p_i p_j}}{\sigma_{p_i}\sigma_{p_j}} \tag{2}$$

where p_i and p_j indicate two of the ten active power profiles, $\sigma_{p_i p_j}$ is the covariance between p_i and p_j, and σ_{p_i}, $\sigma_{p_j}$are the standard deviations associated with them. In Fig. 3 are represented the correlation coefficients on a color map. Except for case 4, there is a high correlation between active power profiles. The existing correlation allows looking for a general representative model able to describe active power absorptions of the washing machine under test.

To do so, we have collected 30 full cycle measurements for different voltage levels (−5%, +0% and +5% of the reference voltage value $V_0 = 230$ V) with 1 min resolution. Each measure is depicted in Fig. 4. Active power data points in the top part of the graph are due to the water heating process. Instead, data points in the bottom of the graph are characterized by lower active power consumptions (rinsing and spinning phases), which do not exceed 500 W.

As the aim of the work is to provide a discrete steady-state load model able to simulate the real characteristics of a cyclic load in power systems, an approach that reduces the complexity of the problem is strongly required. Thus, a *k-means* clustering method has been applied to partition independently the measurements collected for different voltage levels (Fig. 4). Euclidean metric (L2 distance) has been used to calculate the distance between data points and centroids at each iteration step. A silhouette analysis has been applied to estimate the number of clusters to use for each voltage setting. Even though, in this case, clusters are very clearly identifiable by eye, we calculate the silhouette values for an increasing number of clusters (from two to six) to proof that the optimal number of clusters is two for the three voltage levels, as showed in Fig. 5.

The coordinates of the centroids of each cluster (V_c, P_c) are reported in Table 1.