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Derivation and evaluation of generic measurement-based dynamic load models

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ABSTRACT

Online recorded responses can be used for aggregate dynamic load modelling, taking advantage of the advent of smart grids and the growing installation of phasor measurement units. Although several measurement-based dynamic load models have been proposed in the literature, still most network utilities and system operators take advantage of well-known formulations such as the polynomial and the exponential recovery models. However, these types of load models are only valid for a specific range of operating conditions, thus minimizing their applicability and efficiency. This is mainly due to the fact that the model parameter estimation procedure relies on iterative processes. To this extent, the specific scope of this paper is to present a comprehensive identification procedure for evaluating load models under different loading conditions and further to propose two generic modelling approaches that can be used to derive robust load models that are suitable for dynamic simulations over a wide range. Towards achieving the scope of this paper, Monte Carlo simulations are used to train and validate the data of the loading conditions. Finally, several simulations are performed within the DIgSILENT PowerFactory software to assess the accuracy of the proposed models.

1. Introduction

Aggregate load models represent the overall coordinated behaviour of individual electric and electronic components, such as motors, lighting, electrical appliances, etc. supplied by a common power system busbar [1]. The impact of the accurate representation of the steady-state and dynamic characteristics of power system loads has been long recognized and investigated both at the transmission and distribution network levels, especially considering studies pertaining to voltage and angular stability [2–6]. Nevertheless, in the last decades the increased penetration of motors and the introduction of new power electronic interfaced loads combined with the need for more operational flexibility as well as the application of advanced voltage and frequency control strategies in the distribution network have renewed the scientific interest on load modelling [7]. Although, detailed load models provide very accurate load representation, this method requires significant computational power and large simulation times for extended networks. However, detailed information of the real load characteristics is rarely available to transmission and distribution utilities. Thus, load busbars are represented by equivalent models representing the aggregation of different individual components, such as static, inductive and capacitive loads, motor driven consumers, etc. [1,6].

In aggregate load modelling there are two main approaches: the component-based and the measurement-based [8]. The former involves the derivation of an aggregate load model based on information from its constituent parts, including [8]: (a) the load class mix (industrial, agricultural, residential), (b) the composition of each of those classes (heating, cooling, air conditioning, etc.) and (c) characteristics of each load component related to the corresponding physical characteristics. The advantages of this approach are that it does not require field-measurements and that it can be easily applied to different bus substations [1]. However, the component-based approach is not considered accurate enough to represent the distinct load characteristics under various system disturbances. On the other hand, in the measurement-based approach the model parameters are typically defined a priori and their values are estimated using system identification techniques to fit the input–output data obtained from measurements. Significant

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advantages of the latter approach are: (a) load dynamics are directly captured in the derived models, thus presenting high fidelity and yielding more accurate and realistic system studies and (b) model parameters can be updated almost in real-time [9]. It should be noted at this point that this technique requires in situ measurements as well as the placement of measurement system at the load buses [1]. However, the advent of smart grids and the installation of phasor measurement units (PMUs) at transmission and distribution networks have enabled the measurement-based approach as more appealing than it was in the past [10,11].

Moreover, load models are mainly classified in static and dynamic models. Static load models are not dependent on time, thus they describe the relationship of the load real/reactive power at any time instant with the voltage and/or frequency [1,12,13]. On the other hand, dynamic load models express the load real/reactive power at any time instant as a function of the voltage and/or frequency of the present and past time instants. Static models are typically used to represent resistive, lighting, residential loads, etc., in steady-state calculations [1]. However, a recent study revealed that about 70% of the system utilities and operators worldwide also use static load models in dynamic power system studies [7].

Most of the existing static and dynamic modelling studies concentrate on the parameter estimation procedure of models, e.g. the polynomial [13], the exponential recovery (ER) [14,15], the composite [16] and the transfer function models [17]. However, most of these models consider only a simple form of load recovery after the disturbance, thus they cannot accurately represent more complex oscillatory cases of load dynamics. Another significant issue is that in most cases the derived load models are valid only for a given operating condition. Therefore, the model parameter estimation procedure must be repeated several times to account for different operating conditions.

Considering the above issues, the scope of the paper and its main contribution are to present a comprehensive identification procedure to derive generic measurement-based load models for simulating dynamic responses under a wide range of operating conditions.

Initially, in the proposed procedure the accuracy of the widely used polynomial and the ER load models of the first and second order are systematically investigated and proper criteria are proposed to determine their usability according to the load mix composition of the total load. To fulfil this objective, the training and validation data are generated using Monte Carlo simulations, assuming a combination of different types of dynamic loads and dynamic–static load mixture. Additionally, the application of the MultiStart routine is proposed to calculate the optimal solution for the estimation of the load model parameters [18].

Subsequently, for extending the applicability of the dynamic load models to different operating conditions and for developing generic load models, two methodologies are evaluated. The first methodology is based on the calculation of the mean characteristics [15], while the second is introduced for the first time in the archived literature and is based on artificial neural networks (ANN). Finally, the robustness of the developed generic models is evaluated under realistic operating conditions, following a systematic procedure that considers different noise levels.

2. Load models overview

2.1. Polynomial – ZIP model

One of the most wide spread static load model is the polynomial, which is also known as ZIP, since it consists of constant impedance (Z), current (I) and power (P) terms. Although the ZIP model is suitable for steady-state power system studies, still 19% of network

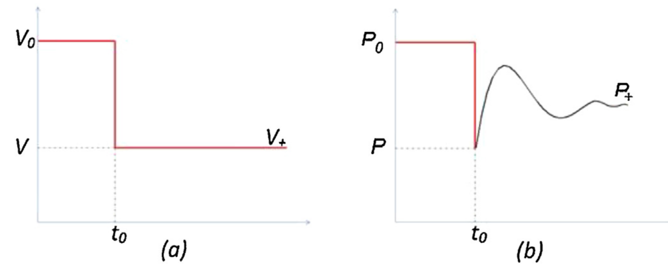

Fig. 1. General load response, (a) voltage disturbance, (b) real power response.

operators and utilities worldwide are utilizing it in dynamic simulations [12]. It should be noted that the ZIP model is among the three most popular load models used for power systems analysis [7]. The formulation that relates the real (P) and reactive (Q) power to the bus voltage (V) is given in (1) and (2), respectively.

$$P_{ZIP} = P_0\left[a_2\left(\frac{V}{V_0}\right)^2 + a_1\left(\frac{V}{V_0}\right) + a_0\right] \tag{1}$$

$$Q_{ZIP} = Q_0\left[b_2\left(\frac{V}{V_0}\right)^2 + b_1\left(\frac{V}{V_0}\right) + b_0\right] \tag{2}$$

where V_0, P_0, and Q_0 are the steady-state pre-disturbance voltage, real and reactive power, respectively. With reference to (1) and (2) the parameters a_k and b_k correspond to the constant impedance load, current and power participation in the total load (for index k equal to 0, 1 and 2, respectively). Therefore, the sum of the corresponding parameters must be equal to unity.

2.2. Exponential recovery

In Fig. 1 the general form of the real power dynamic response $P_d(V)$ to a step change in the bus voltage V is presented. The response $P_d(V)$ can be analyzed into two terms as shown in (3) [14]. The first term pertains to the power response $P_t(V)$ that immediately follows the abrupt step of V. The second term embraces the gradual recovery element of the power response to a new steady-state value $P_s(V)$. The recovery $P_r(V)$ can be assumed of exponential form, while the size and the recovered steady-state are nonlinearly related to the bus voltage [1].

$$P_d(V) = P_t(V) + P_r(V). \tag{3}$$

Specifically, in their work Karlsson and Hill have used the general block diagram representation shown in Fig. 2 to express $P_d(V)$ [14]. The recovery term is described by the function N_{P_1} and the transfer function $G(s)$:

$$N_{P_1}(V) = P_s(V) - P_t(V) \tag{4}$$

$$G(s) = \frac{b_m s^m + b_{m-1}s^{m-1} + \cdots + b_0}{s^n + a_{n-1}s^{n-1} + \cdots + a_0} \tag{5}$$

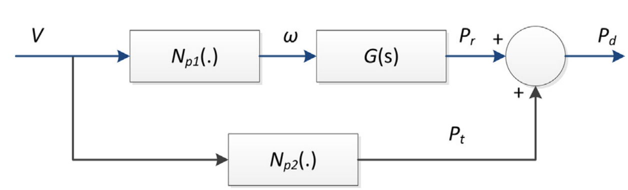

Fig. 2. Block diagram representation of the ER model.