

A Conservative Power Theory-Based Programmable Load for Time Domain Simulations

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Abstract—Time-domain simulation of variable power consumption is a challenging task. Most common strategies for modelling variable loads are inaccurate and fail to represent a real load profile. Additionally, the use of purely sinusoidal current sources can lead to non-linear behaviour if the source voltages are non-sinusoidal. Hence, this paper proposes a programmable load model that enables the simulation of variable power consumption in linear, non-linear, and unbalanced loads using data obtained from power quality meters. The proposed model uses the current decomposition defined by the Conservative Power Theory (CPT) to generate reference signals for controllable current sources. The application cases show the efficacy of the proposed programmable load in simulating typical load profiles from CIGRÉ benchmark microgrid. This model can serve as a useful tool for a variety of studies that require analysis of time-domain simulations.

Keywords—Load Modelling, Conservative Power Theory, Programmable Load, Time-domain Simulation.

I. INTRODUCTION

Time-domain variable load profiles are essential in planning and analysis in the energy sector. These profiles represent the energy use by distinct types of consumers, such as residential, commercial, and industrial, thus being a valuable dataset for billing models, infrastructure planning and power flow optimization [1], [2]. In addition, a detailed analysis of load profiles allows for accurate estimation of the grid expansion, improving grid design and mid-/long-term planning studies [3].

Even though load modelling strategies have been a relevant topic in the literature [4], it is essential to continue studying and updating existing models to incorporate power flow characteristics of modern power grids. This is particularly relevant in light of the emergence of technologies and concepts, such as distributed generators (DGs), electric vehicles (EVs), energy storage systems (EMSs), smart meters (SMs), demand-side management (DSM), and behind-the-meter applications, which are already in operation. In this scenario, the complexity of load modelling is influenced by the diversity of modern loads, behind-the-meter generators, and EMSs, as well as by uncertainties imposed by climate change, and the lack of load-side measurements.

The main goal of load modelling is to define simplified mathematical models that approximate load behaviour with low computational costs [4]. This process involves two main steps: firstly, the definition of the model architecture, and subsequently the identification of model parameters, which can be obtained from component specifications or experimental measurements.

The component-based approach for load modelling presented in [5], [6] uses detailed knowledgebase of physical phenomena related to load operation and their mathematical modelling. However, the implementation of this approach is not always feasible due to its inherent complexity and lack of load specifications.

On the other hand, the measurement-based approach reported in [7], [8] has been considered an efficient alternative. By using data measured in real loads, this approach results in a more precise representation of load operation. Research related to this approach has adopted Artificial Neural Networks (ANNs) to obtain the load model from measured data [9]. However, this approach requires large amounts of data, which may result in high computational cost. In addition, the resulting load model cannot be generalized to other loads with similar characteristics without re-training the ANNs.

Approaches based on power theories such as p - q theory have been applied to dynamic load modelling [10], [11]. Nevertheless, p - q theory does not describe adequately some physical phenomena related to loads operating under non-sinusoidal and/or unbalanced voltages [12]-[14]. Regarding simulation software, some sort of built-in models for load are available. However, these models are very restrictive when modelling loads change dynamically during the simulation process. Alternatively, current source-based built-in models, such as the Three-Phase Dynamic Load from MATLAB/Simulink [15] can emulate variable active/reactive power consumption along the simulation without load changes (load dynamics). However, this model only emulates balanced and sinusoidal currents, which may result in non-linear behaviour when the source voltages are unbalanced and/or have harmonic distortion.

Hence, this paper proposes a novel programmable load model based on Conservative Power Theory (CPT), enabling

accurate simulation of load dynamics with respect to power consumption. This model provides a precise representation of physical phenomena, such as load imbalance and harmonic distortion, even under non-sinusoidal source voltages. In addition, the proposed model enables load modelling through the utilisation of information derived from load specifications or measurements, such as nominal single-phase and three-phase power and harmonic content. The following sections briefly describes the CPT quantities for three-phase systems; the proposed programmable load model; and simulation case studies using three distinct load profiles from CIGRÉ low-voltage distribution network benchmarks [16].

II. CONSERVATIVE POWER THEORY

The Conservative Power Theory (CPT) consists of a mathematical formulation to characterize physical phenomena observed in polyphase electrical circuits with non-sinusoidal source voltages [17]. Since it defines orthogonal decompositions for electrical current and power, the CPT is suitable for modelling either linear or non-linear loads [18].

The main quantities defined by the CPT are the instantaneous active power $p(t)$ and the instantaneous reactive energy $w(t)$ presented in (1) and (2), respectively, for a three-phase system of phases $m = \{a, b, c\}$:

$$p(t) = \sum_{m=\{a,b,c\}} v_m i_m = v_a i_a + v_b i_b + v_c i_c \quad (1)$$

$$w(t) = \sum_{m=\{a,b,c\}} \hat{v}_m i_m = \hat{v}_a i_a + \hat{v}_b i_b + \hat{v}_c i_c \quad (2)$$

on which v_m and i_m are the instantaneous voltage and current of the m^{th} phase and $\hat{v}_m$ is the unbiased integral of v_m defined by (3) [17].

$$\hat{v}_m = \int_0^t v_m(\tau) d\tau - \frac{1}{T} \int_0^T \left[\int_0^t v_m(\tau) d\tau \right] dt \quad (3)$$

The average values of the three-phase active power (P) and the three-phase reactive energy (W) are presented in (4) and (5), respectively.

$$P = \frac{1}{T} \int_0^T p(t) dt \quad (4)$$

$$W = \frac{1}{T} \int_0^T w(t) dt \quad (5)$$

The current of each phase m of the three-phase system can be decomposed into five orthogonal components, defined as follows:

- i. Balanced active currents ($\underline{i}_a^b$) corresponds to the current amount that transfers three-phase active power to the load;
- ii. Balanced reactive currents ($\underline{i}_r^b$) corresponds to the current amount related to the three-phase reactive energy flow in each phase of the system;
- iii. Unbalance currents ($\underline{i}^u$), which can be decomposed into active ($\underline{i}_a^u$) and reactive ($\underline{i}_r^u$) components. These currents represent the differences between the current amounts that transfer active power and the related reactive energy flow in each phase and the

corresponding balanced current components responsible for transferring three-phase active power and three-phase reactive energy;

- iv. Void current ($\underline{i}_v$) is the current amount that neither transfers active power nor is related to reactive energy flow in each phase, thus corresponding to the non-linearity between voltage and current.

The sum of the instantaneous currents vectors results in $\underline{i}_m$, as shown in (6).

$$\underline{i}_m = \underline{i}_a^b + \underline{i}_r^b + \underline{i}_a^u + \underline{i}_r^u + \underline{i}_v = \underline{i}_a^b + \underline{i}_r^b + \underline{i}^u + \underline{i}_v \quad (6)$$

By defining the collective value operation as $\mathbf{X} = \sqrt{\sum_{m=\{a,b,c\}} X_m^2}$, in which X_m is the RMS value of phase voltages or currents, a three-phase power component can be associated to each current component by the product between the collective RMS value of the current component and the collective RMS value of the phase voltages ($\mathbf{V}$), as shows in (7) – (10).

$$P = \mathbf{V} \mathbf{I}_a^b \quad (7)$$

$$Q = \mathbf{V} \mathbf{I}_a^b \quad (8)$$

$$N = \mathbf{V} \mathbf{I}^u \quad (9)$$

$$D = \mathbf{V} \mathbf{I}_v \quad (10)$$

on which P is active power, Q is reactive power, N is unbalanced power and D distortion power. The relationship between the collective RMS values of the current components and the collective RMS value of the phase currents is presented in (11). When multiplying every term of (11) by $\mathbf{V}$, the relationship between the three-phase power components and the three-phase apparent power is obtained (12). Finally, the power factor (λ) is defined as the relationship between active power and apparent power as shown in (13).

$$\mathbf{I}^2 = \mathbf{I}_a^{b^2} + \mathbf{I}_r^{b^2} + \mathbf{I}^{u^2} + \mathbf{I}_v^2 \quad (11)$$

$$A^2 = P^2 + Q^2 + N^2 + D^2 \quad (12)$$

$$\lambda = P/A \quad (13)$$

Thus, by defining proper values for three-phase and active and reactive power components (P and Q), as well as for active and reactive powers (P_a, P_b, P_c, Q_a, Q_b and Q_c) and void current in each phase, a programmable load model for linear or non-linear loads can be obtained, as described in Section III.

For a more comprehensive discussion and detailed analysis of the current and power components within the CPT framework, refer to [17], [18], [21], [22].

III. THE PROPOSED PROGRAMMABLE LOAD MODEL

Fig. 1 presents the architecture of the proposed programmable load. The current source-based approach is adopted, on which the current components from the CPT are used as reference signals for the current sources. The inputs for the CPT current decomposition in this model are:

- i. The instantaneous voltages measured on a RC branch connected to each current source, for which small

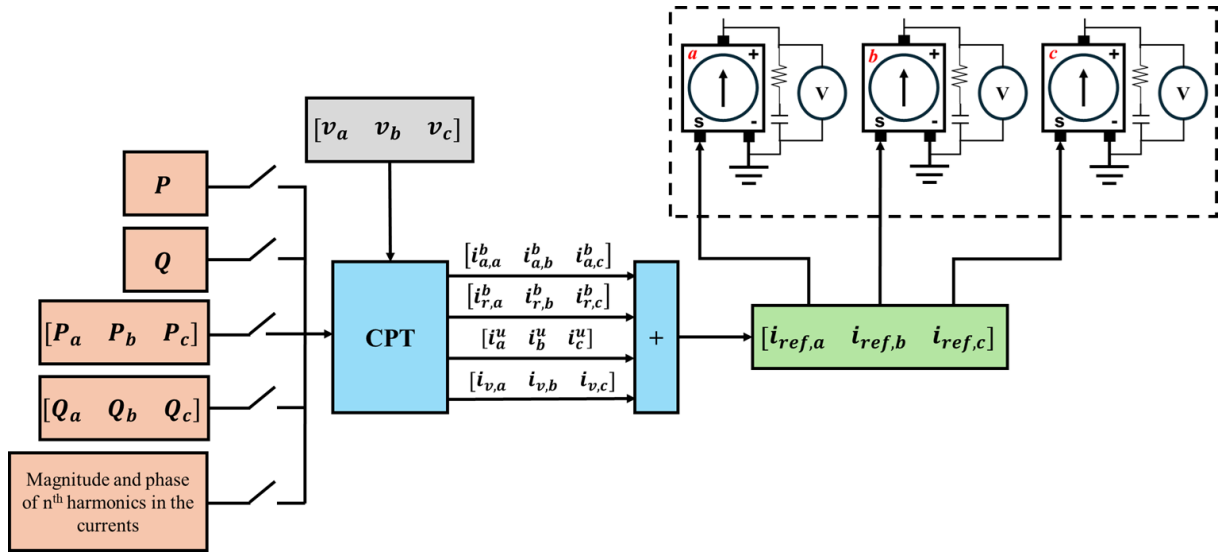


Fig. 1. Architecture of the proposed programmable load model.

- values of capacitance and resistance are adopted ($R = 100 \mu\Omega$ and $C = 5 \mu F$);
- ii. Three-phase active and reactive power values;
- iii. Active and reactive power values for each phase, if the modelled load is unbalanced;
- iv. Information about harmonic components, if the modelled load is non-linear (e.g., power electronics converters).

Power and harmonic input can be obtained from measured data from a real load or its specifications. If the power consumed by the modelled load changes during simulation, the power inputs can be modelled as time series vectors (i.e., one vector for the power data and one vector for the time instants when the power value changes). Fig. 2 presents a flowchart to calculate the reference signals during a simulation process.

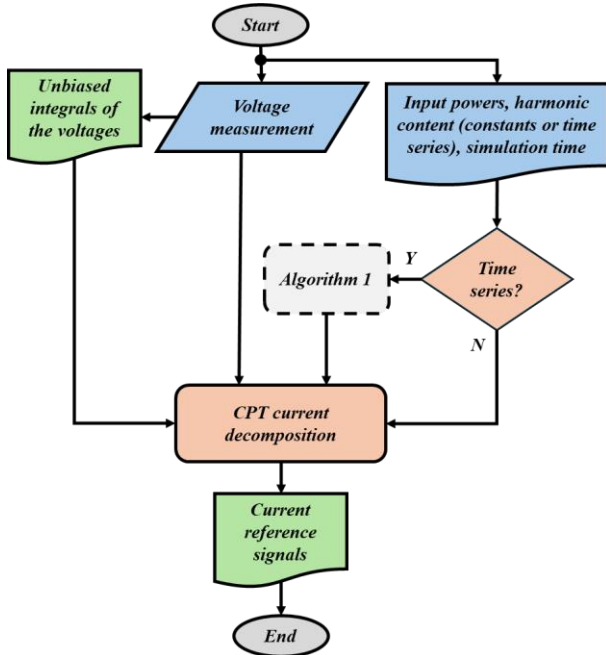


Fig. 2. Flowchart to calculate reference signals during simulation.

At every simulation time step, the measured voltages, their corresponding unbiased integrals, and the input information about the load (power components and harmonic content) are used to calculate the current components of the CPT. These are then summed up to calculate the reference signals for the current sources. If any of the input information is constant, it is directly applied in the current decomposition. Else, if any of the inputs is a time series vector, the Algorithm 1 presented in Fig. 3 is used to adjust the counter that is used as index for the time series vectors.

In Algorithm 1, the vector *flagcounter()* is set to 1 so that the variable *counter* is incremented just once at every time interval between two time instants defined by vector *time_instants()*. In addition, since the counter is used as an index for the vectors, it is limited to the size of vector *time_instants()*. Variable *t_{simu}* corresponds to the simulation time, which may be a built-in variable of the simulation software or be generated in the simulation code.

Algorithm 1: Counter for time series

```

Start
If  $t_{simu} \geq \text{time\_instants}(\text{counter})$  Then
  If  $\text{flagcounter}(\text{counter}) == 0$  Then
     $\text{flagcounter}(\text{counter}) = 1$ 
     $\text{counter} = \text{counter} + 1$ 
    If  $\text{counter} > \text{size}(\text{time\_instants})$  Then
       $\text{counter} = \text{size}(\text{time\_instants})$ 
    End
  End
End
End
Output: counter

```

Fig. 3. Pseudo-code of Algorithm 1.

IV. APPLICATION CASES

The proposed programmable load model was applied to simulate the daily load curves of European low-voltage distribution network benchmark defined by CIGRÉ [16]. Fig. 4 shows these curves reproduced through a MATLAB script by modelling the Power x time inflection points from the original figure [16].

The load curves were modelled as 241 element-time series vectors by applying linear interpolation to the points obtained from the original curves (16 points for the commercial load curve, 22 points for the industrial load curve, and 19 points for the residential load curve). Since the power values were expressed in the 0 – 100% range, it has been defined that they correspond to three-phase active power values in the range 0 – 100 kW. The voltage source parameters were 13.8 kV (line-line, RMS), 60 Hz. The CPT was also used to analyse the current synthesized by the programmable load. The simulations were set as Discrete with fixed step equal to 1/600k s. Total simulation time was 2.4 s, thus the *time_instant()* vector elements were normalized from 0 – 24 h to 0 – 2.4s. The simulation results for each load curve are presented in the following.

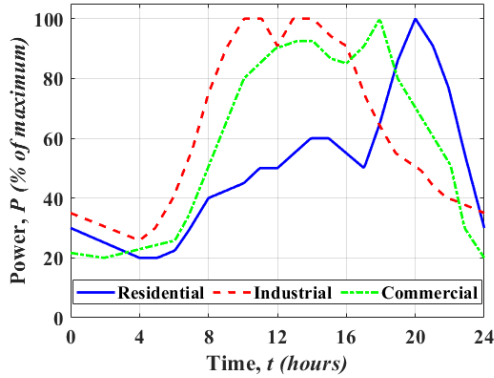


Fig. 4. Daily load curves reproduced from [16].

A. Residential load curve

Figs. 5, 6, and 7 present the source voltages, load currents and three-phase active power calculated during the simulation. Since the source voltages were purely sinusoidal and the line impedances were neglected, their profile did not change along with the simulation. Moreover, as the voltages had that same behaviour in all the analysed simulations, their results will be omitted in the next cases. On the other hand, the amplitude of the currents synthesized by the programmable load follows the three-phase active power profile modelled as time series input. A peak in power consumption can be observed from $t_{simu} \approx 1.8$ s (~ 18 h) to $t_{simu} = 2.4$ s (24 h), which is a typical characteristic of residential consumers (see Fig. 4).

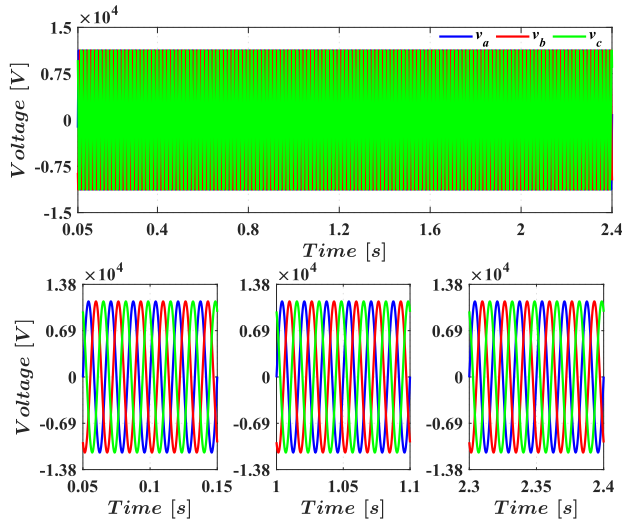


Fig. 5. Three-phase voltages during simulation of the residential load curve.

B. Commercial load curve

Figs. 8 and 9 present the current and active power calculated along with the simulation. It can be observed that the highest power consumption occurs between $t_{simu} = 0.8$ s (8 h) and $t_{simu} = 1.8$ s (18 h), which corresponds to the typical operational period of operation of commercial consumers (see Fig. 4). Additionally, [16] points out that the power consumption may increase in the afternoon due to an increasing use of air conditioning systems and lighting.

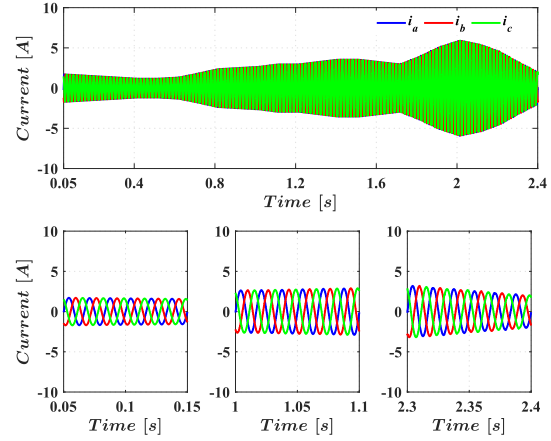


Fig. 6. Three-phase currents during simulation of the residential load curve.

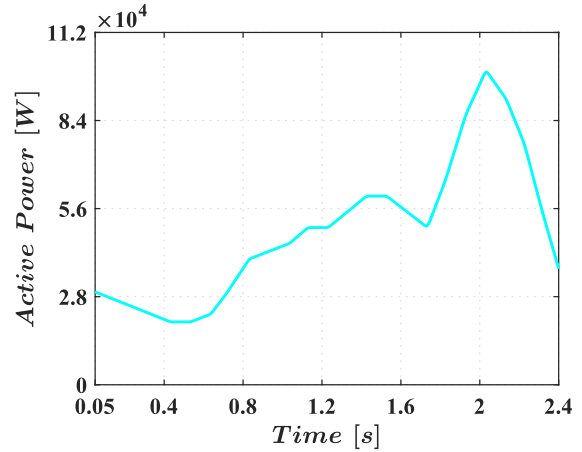


Fig. 7. Three-phase active power measured during simulation of the residential load curve.

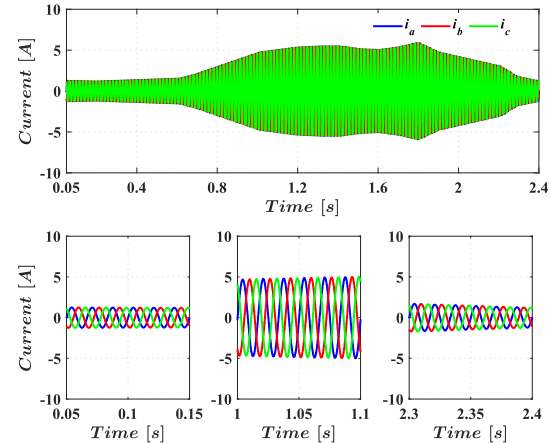


Fig. 8. Three-phase currents during simulation of the commercial load curve.

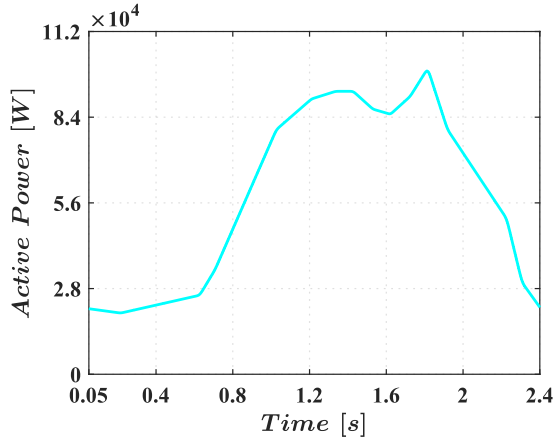


Fig. 9. Three-phase active power during simulation of the residential load curve.

C. Industrial load curve

Figs. 10 and 11 present the current and active power calculated along with the simulation. Similarly to the commercial load, the highest power consumption occurs between $t_{simu} = 0.8$ s (8 h) and $t_{simu} = 1.8$ s (18 h), with a slightly decrease around noon, $t_{simu} = 1.2$ s (see Fig. 4). However, the industrial power profile can vary considerably depending on industry's activities and daily working cycles. Consequently, the maximum power can be much higher than the 100 kW adopted in this application case.

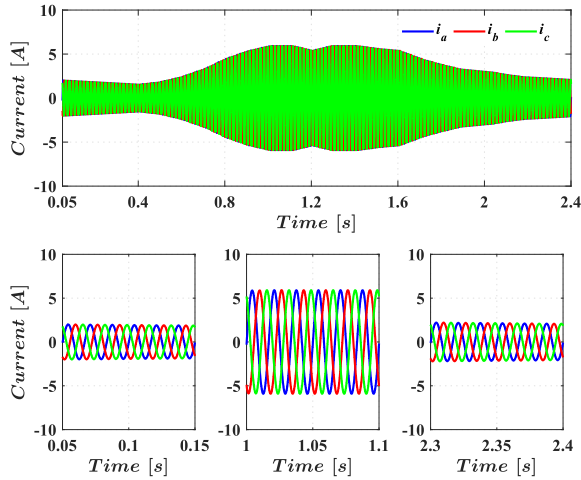


Fig. 10. Three-phase currents during simulation of the industrial load curve.

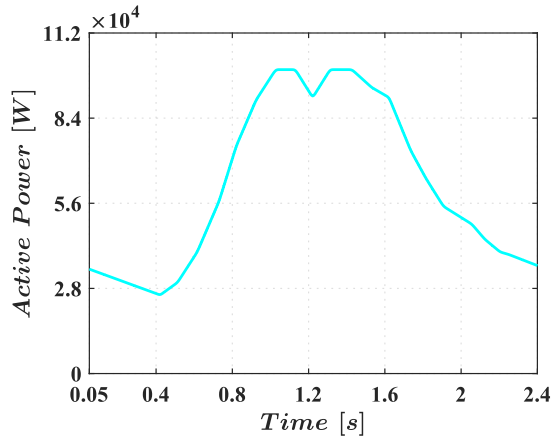


Fig. 11. Three-phase active power during simulation of the industrial load curve.

D. Discussion

In the results presented previously, the currents synthesized by the programmable load correspond to the balanced active currents (i_a^b), since the only power input was the three-phase active power. However, reactive power, load imbalance and harmonic distortion are relevant characteristics to be assessed in the residential, commercial and industrial consumers to define demand management and power quality improvement strategies. Thus, Fig. 12 shows the power components of CPT calculated during a simulation of the residential load profile with a three-phase reactive power time series input. The same vectors from the active power were used to generate the reactive power time series. The peak value of reactive power was calculated considering power factor λ equal to 0.85 (inductive) and $P = 100$ kW, which results in $A = 117$ kVA from (11). Then, considering $N = D = 0$, and isolating Q in (12), $Q = 62$ kvar is obtained.

In this case, the reference signals for the current sources were composed by $(i_a^b + i_r^b)$ components in each phase, which result in load currents with phase displacement in relation to the source voltages, as shown in Fig. 13 for voltage and current of phase a .

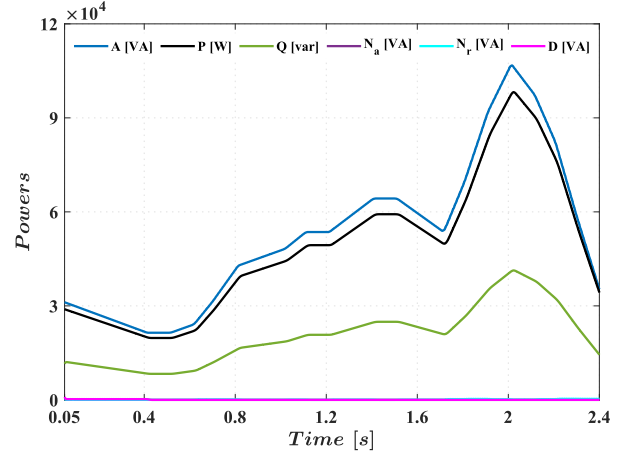


Fig. 12. Three-phase power components of CPT during simulation of residential load with active and reactive power profile.

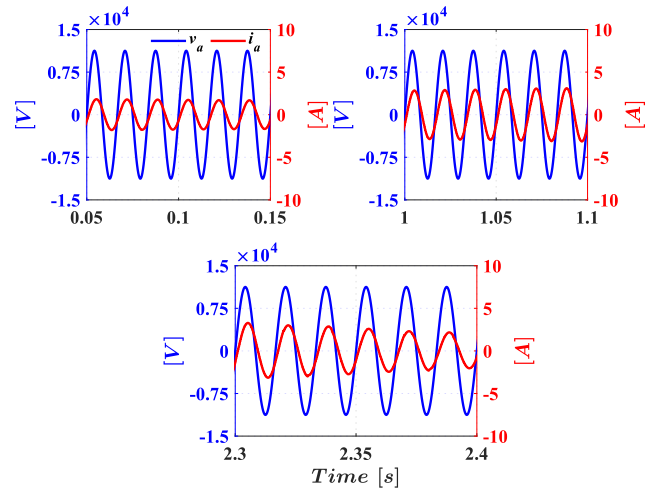


Fig. 13. Voltage and current of phase a during simulation of residential load with active and reactive power profile from Fig. 12.

To represent a group of residences with different single-phase and electronic loads, a new operating condition was established, in which the reference current is defined as the sum of all CPT current components ($i_a^b + i_a^p + i_a^u + i_a^h + i_a^v$), thus resulting in the power components as shown in Fig. 14. The loads were configured with peak active power per phase of $P_a = 50 \text{ kW}$, $P_b = 30 \text{ kW}$ and $P_c = 20 \text{ kW}$, while the peak reactive power per phase was set to $Q_a = 30 \text{ kvar}$, $Q_b = 20 \text{ kvar}$ and $Q_c = 12 \text{ kvar}$. Regarding harmonic distortion, a fifth-order harmonic current with an RMS value of 1 A was considered, which resulted in non-sinusoidal and unbalanced load currents, as shown in Fig. 15.

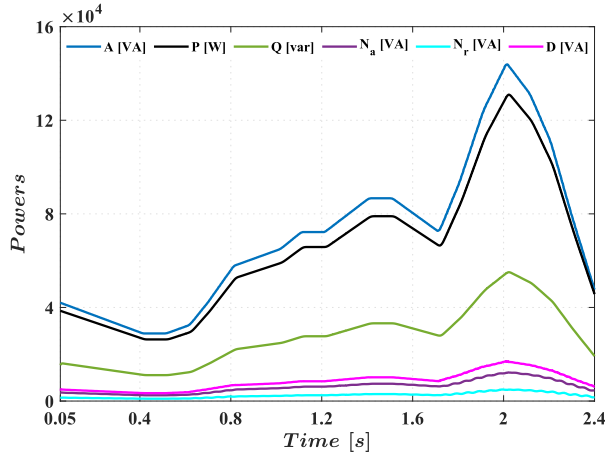


Fig. 14. Three-phase power components of CPT during simulation of residential load with active, reactive, unbalance and harmonics profile.

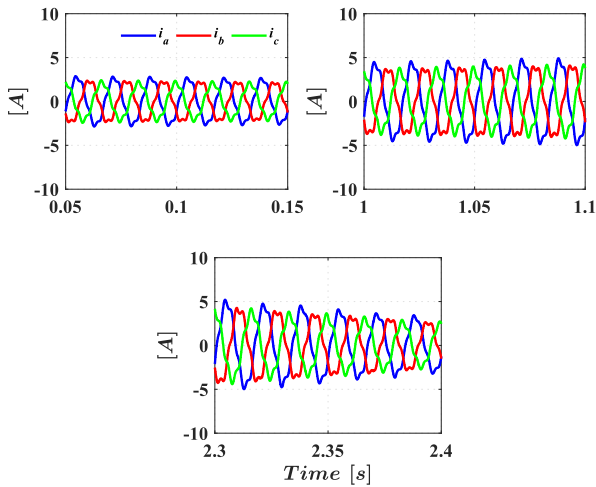


Fig. 15. Currents during simulation of residential load with active, reactive unbalanced and distortion powers profile from Fig. 14.

V. CONCLUSION

From the application cases presented in the previous section, it is possible to conclude that the programmable load model proposed allows simulating the load behaviour with dynamic variations. Moreover, the use of current components defined by the Conservative Power Theory CPT allows for modelling the most common steady-state characteristics of linear and non-linear loads, such as active and reactive power, load imbalance and harmonic distortion in the current. Additionally, the proposed model uses as inputs the information available in load specifications or measurements,

such as nominal single-phase and three-phase power values and harmonic content, thus being a flexible tool for load modelling in a variety of applications including power flow analysis, parametric simulations, and studies on microgrid operation and renewable energy integration [19], [20].

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