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Research Article

On the equivalent ZIP parameter extraction of desktop computer cases and LCD monitors connected in parallel

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ABSTRACT

Constant-impedance, constant-current and constant-power ZIP models of electrical loads are commonly used in smart grid and residential load applications. Some of residential loads are of nonlinear nature such as LCD monitors and computers. In this study, first, equivalent ZIP model formulas of parallel-connected electrical loads are derived. Then, the ZIP models of an LCD monitor, a computer case and the computer case and the monitor connected in parallel have been obtained using experimental data and least-squares curve fitting method. Finally, the equivalent ZIP model formulas are tested with the experimental data. It has been found that for the rectifier nonlinear loads with different ZIP parameters, the formulas do not give acceptable errors. Therefore, for rectifier nonlinear loads, the measurement-based approach for load modeling must be performed.

1. Introduction

In smart grids power system loads and their modelling is essential from many perspectives; such as, to provide grid reliability by controlling over loads and failures, and to control uncontrollable, untraceable energy consumption and losses, to prevent power cuts [1]–[4]. Power system loads may have different characteristics. The simplest load models could be obtained using mainly three approaches: constant impedance, constant current, or constant power. However, power system or residential loads cannot be always accurately modeled by applying each approach individually. Therefore, ZIP models that combine all these approaches are used to reach most accurate electrical load models. Modeling of active and reactive powers of a device as a function of load RMS voltage is done using ZIP parameters and this modeling is important not only for utility but also smart grid applications [1], [5]–[12].

Residential load modeling is becoming more important due to smart grid connection, harmonics and power requirements, dissipated power reduction etc. [1], [3], [16], [17], [8]–[15]. ZIP parameter models are commonly used to estimate static loads power consumption or loads operating in steady-state applications [1], [5]–[9]. There are parabolic and exponential load models [11], [12]. Parabolic models are commonly used. The ZIP parameters data can be extracted from data obtained by simulations or experiments [18] and least-squares method curve-fitting process is used for that purpose [1]–[10]. Experiments needed for determining ZIP parameters are quite simple: load voltage, active power, and reactive power is measured by varying the load voltage using a programmable AC voltage source or a variac [12]. Experimental data give better results than simulations. In a house, all loads are connected in parallel. To the best of our knowledge, there are no formulas given to calculate equivalent ZIP parameters of parallel connected loads using the loads individual ZIP parameters. In this paper, the ZIP parameter formulas for parallel connected loads are derived first.

CVR method is used to lower power consumption by lowering operating voltage in smart grid applications [1]. To estimate the power consumption, ZIP models of all loads are needed [1], [5], [7], [12]. Some loads have internal rectifiers and they withdraw non-sinusoidal currents. LCD monitors have lower power consumptions than CRT monitors and they are becoming more common nowadays. Due to production laws and/or regulations to

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eliminate harmonic mitigation to utility, Computer cases, LCD monitors or LCD televisions commonly have internal power factor correction circuits. Unfortunately, not all of them in use or in sales have these power factor correction circuits [19]. In developed world, since computers and LCD monitors are very common, it is also imperative to obtain their ZIP load models, too. The studies in [5], [12] have not considered rectifier loads. The study in [20] has examined nonlinear loads such as LCD TV, LED TV and game consoles. However, it has not considered their parallel connection. In [10], the nonlinear loads are also considered in residential loads, the loads contribution to total power is also examined but the equivalent zip parameters for the parallel connected loads are not derived. Since a computer and its LCD monitor are connected in parallel, they might be interacting with each other electrically. In this paper, using experimental data and the least-squares method, their individual and parallel-connected ZIP models are obtained. Then, the formula we derived is tested for their parallel combination.

The paper is arranged as follows. In the second section, the necessary formulas ZIP parameter estimation is given and the equivalent ZIP formula is derived. In the third section, information about the measurement system, experimental results and obtained ZIP parameters are presented. The paper is concluded with the conclusion section.

2. Determination of ZIP Parameters

2.1 A Brief Explanation of ZIP Model

The active and reactive power of a load fed by a sinusoidal voltage are given as

$$P = VI\cos(\varphi_V - \varphi_I) \tag{1}$$

$$Q = VI\sin(\varphi_V - \varphi_I) \tag{2}$$

Where V and I are the rms values of the device voltage and current, respectively. φ_V is the phase of load voltage and φ_I is the phase of load current.

$\varphi_V=0$ is taken for simplicity. In steady-state, RMS current and phase of any load depend on the device rms voltage with either a known or an unknown function:

$$I = f(V) \tag{3}$$

$$\varphi_I = g(V) \tag{4}$$

That's why not only active but also reactive power can be expressed as voltage dependent function. Usually polynomial or exponential functions are used for that purpose. If we assume a second-order polynomial dependency as done in [14], [20]:

$$P = P_0\left(Z_p\left(\frac{V}{V_0}\right)^2 + I_p\left(\frac{V}{V_0}\right) + P_p\right) \tag{5}$$

$$Q = Q_0\left(Z_q\left(\frac{V}{V_0}\right)^2 + I_q\left(\frac{V}{V_0}\right) + P_q\right) \tag{6}$$

Here, P and Q are active and reactive power corresponding to rms value of the operating voltage (V); P_0 and and Q_0 are active and reactive power corresponding to rms value of the nominal voltage (V_0), respectively. Z_p, I_p and P_p are ZIP coefficients of active power component; Z_q, I_q and P_q are ZIP coefficients of reactive power component, respectively.

In this paper, Least Squares Method (LSM) is employed used to obtain ZIP coefficients based on simulated or measured voltage-power values due to its simplicity as done in [6]. Here, V_i, P_i and Q_i are measured values of voltage, active and reactive powers, respectively. The ZIP coefficients are solved using the solution matrices are given as [6], [11], [12]:

$$\begin{bmatrix} Z_p \\ I_p \\ P_p \end{bmatrix} = \begin{bmatrix} \sum_{i=1}^{N} V_i^4 & \sum_{i=1}^{N} V_i^3 & \sum_{i=1}^{N} V_i^2 \\ \sum_{i=1}^{N} V_i^3 & \sum_{i=1}^{N} V_i^2 & \sum_{i=1}^{N} V_i \\ \sum_{i=1}^{N} V_i^2 & \sum_{i=1}^{N} V_i & N \end{bmatrix}^{-1} \begin{bmatrix} \sum_{i=1}^{N} P_i V_i^2 \\ \sum_{i=1}^{N} P_i V_i \\ \sum_{i=1}^{N} P_i \end{bmatrix} \tag{7}$$

$$\begin{bmatrix} Z_q \\ I_q \\ P_q \end{bmatrix} = \begin{bmatrix} \sum_{i=1}^{N} V_i^4 & \sum_{i=1}^{N} V_i^3 & \sum_{i=1}^{N} V_i^2 \\ \sum_{i=1}^{N} V_i^3 & \sum_{i=1}^{N} V_i^2 & \sum_{i=1}^{N} V_i \\ \sum_{i=1}^{N} V_i^2 & \sum_{i=1}^{N} V_i & N \end{bmatrix}^{-1} \begin{bmatrix} \sum_{i=1}^{N} Q_i V_i^2 \\ \sum_{i=1}^{N} Q_i V_i \\ \sum_{i=1}^{N} Q_i \end{bmatrix} \tag{8}$$

The following constraints,

$$\begin{aligned} Z_p + I_p + P_p &= 1 \\ Z_q + I_q + P_q &= 1 \end{aligned} \tag{9}$$

must also be provided.

2.2 Equivalent ZIP Model of n Parallel-Connected Loads

If n electrical load is connected in parallel, for the active and reactive powers of the ***k^th^*** load:

$$P_k = P_{0k}\left(Z_{pk}\left(\frac{V}{V_0}\right)^2 + I_{pk}\left(\frac{V}{V_0}\right) + P_{pk}\right) \tag{10}$$

$$Q_k = Q_{0k}\left(Z_{qk}\left(\frac{V}{V_0}\right)^2 + I_{qk}\left(\frac{V}{V_0}\right) + P_{qk}\right) \tag{11}$$

The total active and reactive powers are

$$P = \sum_{k=1}^{n} P_k = \sum_{k=1}^{n} P_{0k}\left(Z_{pk}\left(\frac{V}{V_0}\right)^2 + I_{pk}\left(\frac{V}{V_0}\right) + P_{pk}\right) \tag{12}$$

$$Q = \sum_{k=1}^{n} Q_k = \sum_{k=1}^{n} Q_{0k}\left(Z_{qk}\left(\frac{V}{V_0}\right)^2 + I_{qk}\left(\frac{V}{V_0}\right) + P_{qk}\right) \tag{13}$$

By doing some math, the following equations are obtained:

$$P = \sum_{k=1}^{n} P_k$$
$$= \sum_{k=1}^{n}\left(P_{0k} Z_{pk} \left(\frac{V}{V_0}\right)^2 + P_{0k} I_{pk} \left(\frac{V}{V_0}\right) + P_{0k} P_{pk} \right) \quad (14)$$
$$= \frac{\sum_{k=1}^{n} P_{0k} Z_{pk}}{\sum_{k=1}^{n} P_{0k}} \left(\frac{V}{V_0}\right)^2 + \frac{\sum_{k=1}^{n} P_{0k} I_{pk}}{\sum_{k=1}^{n} P_{0k}} \left(\frac{V}{V_0}\right) + \frac{\sum_{k=1}^{n} P_{0k} P_{pk}}{\sum_{k=1}^{n} P_{0k}}$$

$$Q = \sum_{k=1}^{n} Q_k$$
$$= \sum_{k=1}^{n}\left(Q_{0k} Z_{qk} \left(\frac{V}{V_0}\right)^2 + Q_{0k} I_{qk} \left(\frac{V}{V_0}\right) + Q_{0k} P_{qk} \right) \quad (15)$$
$$= \frac{\sum_{k=1}^{n} Q_{0k} Z_{qk}}{\sum_{k=1}^{n} Q_{0k}} \left(\frac{V}{V_0}\right)^2 + \frac{\sum_{k=1}^{n} Q_{0k} I_{qk}}{\sum_{k=1}^{n} Q_{0k}} \left(\frac{V}{V_0}\right) + \frac{\sum_{k=1}^{n} Q_{0k} P_{qk}}{\sum_{k=1}^{n} Q_{0k}}$$

The equivalent ZIP parameters of n parallel-connected electrical loads are obtained as:

$$Z_{peq} = \frac{\sum_{k=1}^{n} P_{0k} Z_{pk}}{\sum_{k=1}^{n} P_{0k}}, I_{peq} = \frac{\sum_{k=1}^{n} P_{0k} I_{pk}}{\sum_{k=1}^{n} P_{0k}}, P_{peq} = \frac{\sum_{k=1}^{n} P_{0k} P_{pk}}{\sum_{k=1}^{n} P_{0k}} \quad (16)$$

$$Z_{qeq} = \frac{\sum_{k=1}^{n} Q_{0k} Z_{qk}}{\sum_{k=1}^{n} Q_{0k}}, I_{qeq} = \frac{\sum_{k=1}^{n} Q_{0k} I_{qk}}{\sum_{k=1}^{n} Q_{0k}}, P_{qeq} = \frac{\sum_{k=1}^{n} Q_{0k} P_{qk}}{\sum_{k=1}^{n} Q_{0k}} \quad (17)$$

Therefore,

$$P = \sum_{k=1}^{n} P_k = P_{0eq}\left(Z_{peq} \left(\frac{V}{V_0}\right)^2 + I_{peq} \left(\frac{V}{V_0}\right) + P_{peq} \right) \quad (18)$$

$$Q = Q_{0eq}\left(Z_{qeq} \left(\frac{V}{V_0}\right)^2 + I_{qeq} \left(\frac{V}{V_0}\right) + P_{qeq} \right) \quad (19)$$

Where P_{0eq} and Q_{0eq} are the active and reactive power at the nominal voltage V_0, respectively and given as:

$$P_{0eq} = \sum_{k=1}^{n} P_{0k}$$
$$Q_{0eq} = \sum_{k=1}^{n} Q_{0k} \quad (20)$$

If two loads are connected in parallel (for n=2) the following parameters are obtained:

$$Z_{peq} = \frac{P_{01} Z_{p1} + P_{02} Z_{p2}}{P_{01} + P_{02}}$$
$$I_{peq} = \frac{P_{01} I_{p1} + P_{02} I_{p2}}{P_{01} + P_{02}}$$
$$P_{peq} = \frac{P_{01} P_{p1} + P_{02} P_{p2}}{P_{01} + P_{02}} \quad (21)$$
$$P_{0eq} = P_{01} + P_{02}$$

$$Z_{qeq} = \frac{Q_{01} Z_{q1} + Q_{02} Z_{q2}}{Q_{01} + Q_{02}}$$
$$I_{qeq} = \frac{Q_{01} I_{q1} + Q_{02} I_{q2}}{Q_{01} + Q_{02}}$$
$$P_{qeq} = \frac{Q_{01} P_{q1} + Q_{02} P_{q2}}{Q_{01} + Q_{02}} \quad (22)$$
$$Q_{0eq} = Q_{01} + Q_{02}$$

3. Experimental Results

A desktop computer with an ATX case and an LCD monitor is shown in Figure 1. An LCD monitor has a remarkable features compared to CRT monitors considering their resolution and low energy consumption. Since increasing number of LCD monitors would increase the harmonics injected to utility, regulations are made for them to have power factor correction circuits internally unfortunately not all of them have it. Uncontrolled rectifiers draw considerable harmonic content and they are the main reason for the utility harmonics.

The experiments are performed for a VESTEL desktop computer case with 300W power supply and Samsung brand 923NW model LCD display. The measurement system is shown in Figure 2. A power analyzer is used to measure and record voltage, current and powers of the load. The power analyzer has recorded the experimental data. The variable load voltage is provided using a variable transformer (a variac) connected to the utility. The variac is controlled manually to vary load voltage during the data acquisition with the power analyzer. In experiments, the active and reactive powers of the tested devices are inspected with several volt voltage increments. The starting value of the applied voltage at unloaded conditions was around 210 V and the ending value of the applied voltage is around 225 V.

Figure 1. Desktop Personal Computer and LCD screen

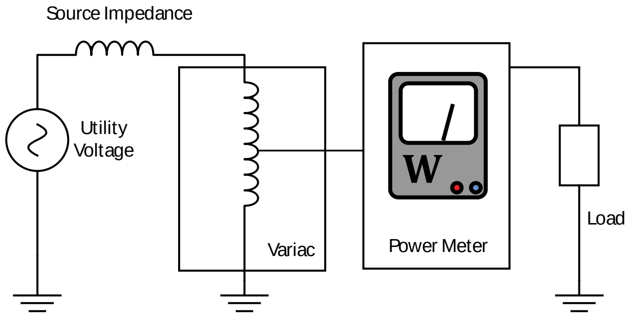


Figure 2. Measurement System

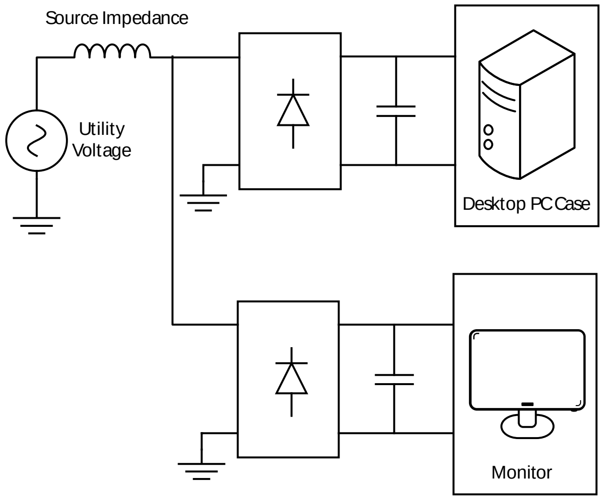


Figure 3. Equivalent circuit of the LCD monitor and Desktop computer system connected to the utility or the variac

Collected data for each specific load and the parallel combination of two loads as shown in Figure 3 is stored in an excel file and then is processed with MATLAB to calculate the ZIP coefficients.

For several voltage RMS values, the experiments are performed for loads connected separately and their parallel connection. For the space consideration, device voltage and current with respect to time for the parallel connection case is depicted in Figure 4. Active and reactive powers as a function of RMS utility voltage for LCD monitor, computer case and parallel combination of them are shown in Figure 5, Figure 6 and Figure 7 respectively. The current and voltage waveforms have harmonics at nominal voltage as shown in Figure 4. Also, it is obvious from the waveforms that the devices have no power correction circuits, just uncontrolled full-wave rectifiers with constant power loads. As shown in Figure 5, the LCD monitor has a narrow operation voltage range and it has almost constant active and reactive power. As can be seen from Figure 6, the computer case active and reactive power depends on the operation voltage and both varies about 10%.

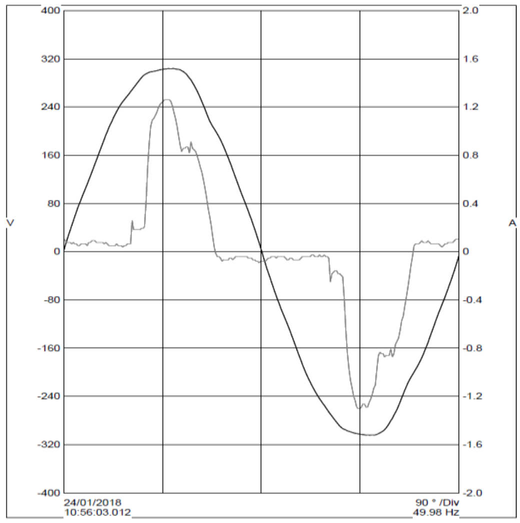
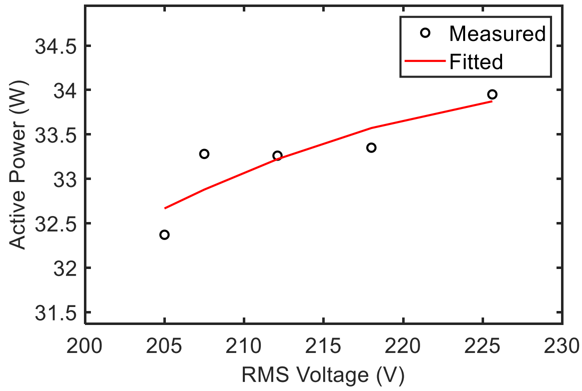
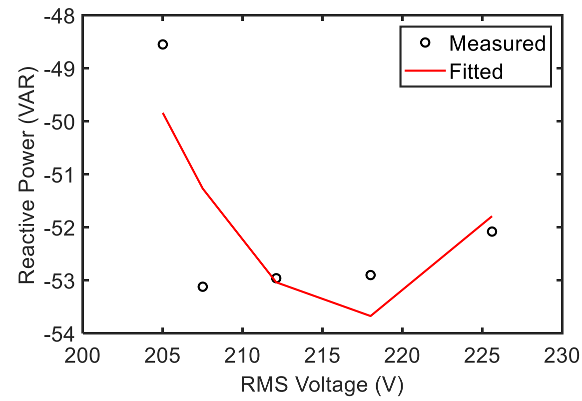


Figure 4. Paralel connection of computer case and monitor input voltage and current when the voltage effective value is 220 Volt



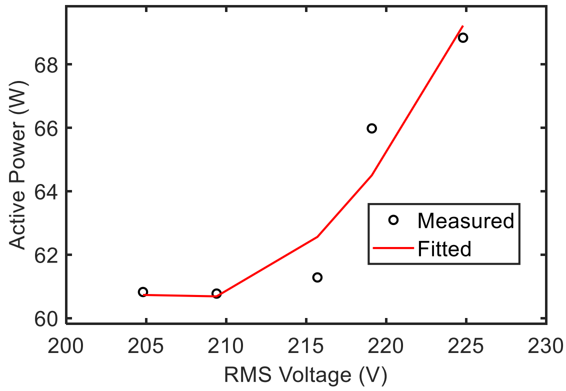
(a)



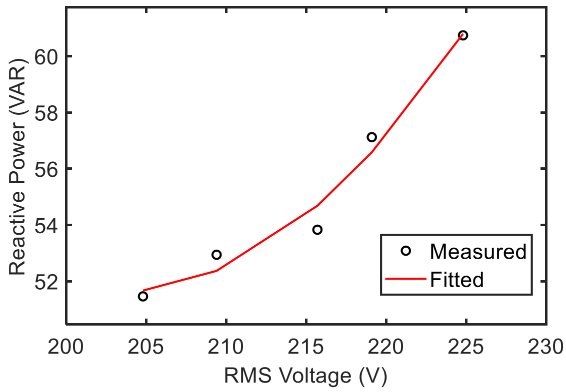
(b)

Figure 5. Active and reactive power of LCD monitor

MATLAB is used to calculate the ZIP parameters by post-processing the measured data using the LSM method. Calculated ZIP coefficients of each load and their combination are given Table 1. The equivalent ZIP parameters of the parallel loads are calculated using the formulas developed in Section 2 and listed in Table 1. The equivalent ZIP parameters calculated with the formulas is unable to predict the experimental ZIP parameters calculated from the experimental data.

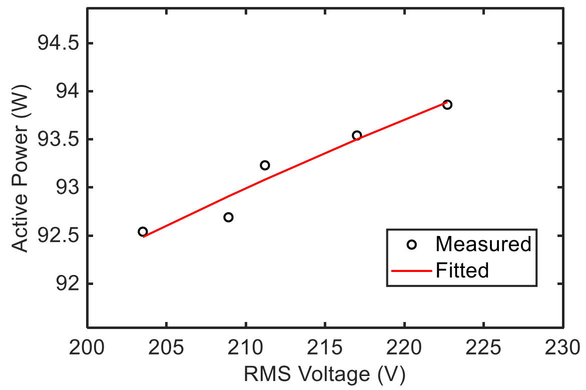


(a)

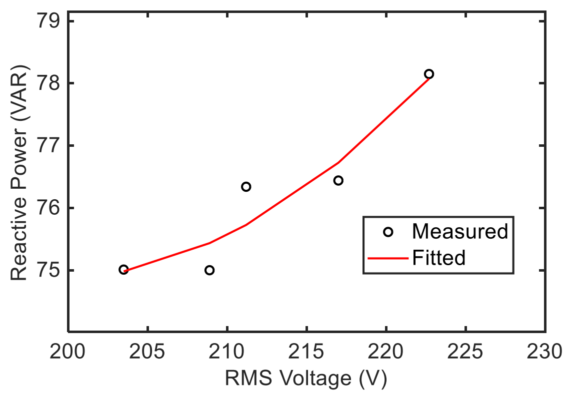


(b)

Figure 6. Active and reactive power of computer case



(a)



(b)

Figure 7. Active and reactive power of paralel connection of computer case and monitor

Table 1. Extracted ZIP parameters of the measured devices

Load	**P_0**	**Z_p**	**I_p**	**P_p**	**Q_0**	**Z_q**	**I_q**	**P_q**
LCD display only (experimental)	33.59	-2.10	4.49	-1.39	-52.68	-24.19	47.75	-22.54
PC case only (experimental)	66.43	20.55	-38.73	19.15	57.69	16.56	-30.61	15.03
Both device in parallel (experimental)	93.70	-0.20	0.56	0.63	77.34	3.49	-6.31	3.81
Both device in parallel (extracted)	99.93	12.95	-24.23	12.26	5.01	445.46	-855.1	410.41

4. Conclusion

In this study, for the first time in literature, a formula is derived to calculate the equivalent ZIP parameters of parallel connected loads by using their individual ZIP parameters. The formulas are tested for two loads having rectifiers. As shown in the table, the experimental and calculated equivalent ZIP parameters do not match well except for P_0. The reason can be explained as follows. As it can be seen from Figure 5 (a), the nonlinear loads both LCD monitor and PC case behave almost as constant (active) power loads. The controllers within the loads shape load currents to keep active power almost constant with just somewhat voltage dependency. Each load has a DC bus capacitor which also contributes the nonlinear dynamics.

The PC case draws inductive reactive power while as the LCD monitor draws capacitive reactive power. The nonlinear rectifier currents produce a non-sinusoidal voltage waveform at the rectifier output due to the source impedance (the variac impedance), the constant power controllers and DC bus capacitors. Since the rectifiers and their loads are not equal, each rectifier is affected differently from the non-sinusoidal input voltage exerted by the non-sinusoidal rectifier currents. Therefore, their ZIP parameters, i.e. their active and reactive power dependencies on the input rms voltage vary due to the harmonics in the rectifier voltage. Also, since the load impedance is not zero, the rectifier currents indirectly affect each other.

We have been able to estimate active power well since the constant power controllers force the loads to have constant powers and force the total active power to be sum of the load powers. There is somewhat nonlinear interaction and nonlinear reactive power compensation between the loads. That's why we are unable to predict their equivalent circuit parameters using the formula and the reactive power withdrawn from the utility by rectifiers could not be predicted with the equivalent ZIP model parameters. That's why it is important to determine ZIP parameter models of nonlinear loads or loads having a rectifier experimentally. Such a method can be applied to load extraction of the PC laboratories or big companies with computer clusters.

These formulas should also be tested for other loads. We believe it would give a better result for the nonlinear loads with low THD or for the linear loads.

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