Indian Journal of Science and Technology, *Vol 8(S7), 85–93, April 2015*

ISSN (Print) : 0974-6846
ISSN (Online) : 0974-5645

Decomposition of Power Electronic and Conventional Loads of Modern Power Systems by Discrete Wavelet Transform

Hamidreza Toodeji[1*], S. Hamid Fathi[1] and Mahmoud Reza Haghifam[2]

[1]Electrical Engineering Department, Amirkabir University of Technology (Tehran Polytechnic), Tehran, Iran; toodeji@aut.ac.ir

[2]Electrical and Computer Engineering Department, Tarbiat Modares University, Tehran, Iran

Abstract

Load composition data is used in different static and dynamic studies of present power systems. Increasing the number and capacity of power electronic loads in the modern power systems, especially micrgrids, makes it necessary to perform various harmonic studies, beside considering this new load type in the conventional studies. For this purpose, new methods are required to decompose power electronic loads from conventional loads of power systems. This paper introduces a novel non-intrusive decomposition method, based on digital wavelet transform. The contribution of the proposed method is its ability to decompose most common power electronic loads, including uncontrolled/semi-controlled rectifiers with both constant power and resistive DC loads, in steady state and especially in transient and asymmetric conditions. Moreover, this method is significantly easier and more accurate than available machine learning-based decomposition methods. Another advantage of this paper is employing excellent denoising ability of digital wavelet transform, compared to conventional digital filters, for noise elimination of actual measured waveforms. The validity of proposed decomposition method is evaluated by simulation of dominating rectifiers in combination with induction motor and inductive load, as conventional load, in MATLAB/Simulink. Laboratory-implementation of the test system is also employed for further validation of the proposed method.

Keywords: Denoising, Discrete Wavelet Transform, Line-Commutated Rectifiers, Load Decomposition, Microgrids, Transient Conditions

1. Introduction

Decomposition of power system loads for finding the load components is an important issue in many studies, from planning to the operational stages[1]. Load forecasting and load research activities are counted with the former, while, power flow and dynamic studies belong to the latter stages. Prediction of load requirements across time, in load forecasting studies, requires present demands of each load classes. The results can be utilized for capacity expansion and long-term capital investment return problems[2]. In another power system study, real-time decomposition of power demand can be used for demand managing and reducing unnecessary consumptions[3]. This demand decomposition is also the basis of energy saving works[4]. Each type of load has its unique impact on dynamic studies, like transient and voltage stability analysis. So, load decomposition can decreases the complexity of such studies by separating the effect of each load[5,6]. In load modeling issue, identification of all parameters of different load models through the whole system response is a complicated problem[7]. Load decomposition separates the response of each load types, so unknown parameters of each model can be independently identified, and consequently model identification is reduced to a less complicated problem with more accurate results. The importance of using accurate load models in power system studies is depicted in [8,9].

**Author for correspondence*

Different load decomposition methods fall into two main categories: intrusive and non-intrusive methods[10]. In the former methods, very detailed and reliable information can be obtained by monitoring each appliance. This costly approach could not attract utilities, because of its drawbacks such as connecting multiple measuring devices to a central metering point and reliability problems due to existence of large number of meters. Non-intrusive methods, instead, trace the electrical waveforms only at service entry points. Nowadays, they have attracted significant interests due to the improved computational ability of embedded devices, beside the development of measuring instruments. In these methods, the signatures of various appliances are extracted from the measured waveforms, then, different algorithms are applied to classify the appliances. Signature is a unique behavior that distinguishes the behavior of specific appliance from others[11]. Steady state and transient characteristics of the appliance can be utilized as its signature. For classification, matching between extracted and index features is evaluated through two machine-learning techniques: supervised and unsupervised learning. The former, which needs offline training before usage, includes Artificial Neural Networks (ANN), Support Vector Machines (SVM) and k-Nearest Neighbor (kNN). Clustering is the main method of unsupervised learning that gives the opportunity of implementation of on-line decomposition method[10].

Now a day, innumerable power electronic loads are operating in the modern power systems, especially in microgrids. These increasing newly emerged loads can be found from household appliances, with low-current rectifiers, to metal industries, with very high-current rectifiers[12]. Because of large number of these rectifiers and their high cumulative capacities, they should be taken into account in different studies of present power systems[6]. In this condition, decomposition of power electronic from conventional loads can be helpful, or even necessary, from different viewpoints. Harmonic allocation to customers[13], harmonic load flow analysis[14], harmonic filter design and similar issues need to measure power electronic loads demand in steady state conditions, since these loads are the main harmonic sources in the present power systems. Moreover, the obtained composition data can be used in common static and dynamic studies of power systems. For example, simultaneous identification of power electronic load model beside conventional ones, like well-known composite load model[15], can be performed easier by load composition data.

Different methods have been introduced to decompose conventional static and dynamic loads. To cover power electronic loads, new decomposition methods should be developed. Using this new method for power electronic loads beside available decomposition methods for decomposed conventional loads can decompose most important loads of modern power systems. This paper proposes a novel non-intrusive method for decomposition of power electronic and conventional loads more accurately, compared with the available scant methods. Easy implementation of the proposed method is one of its features, since non-intrusive decomposition approaches require electrical data, only at service entry points. The ability of proposed method to current decomposition in transient as well as asymmetric, beside steady state conditions, is another advantage of introduced method.

Periodic zero current intervals in the rectifier current is a feature that makes it different from continuous current of conventional loads, which are usually consisted of various induction motors in combination with static loads. This feature can be used as signature for current decomposition, but zero current intervals are not constant and vary with line inductance. So, it is firstly required to specify these intervals in the main current, before decomposition. However, some studies, e.g. [16] have simply assumed these intervals with constant width and fixed position. But, the proposed method utilizes discrete wavelet transform to find accurate width and position of zero current intervals. This transformation, among the available signal processing approaches, has attracted great attentions in some studies of power system, because of its suitability for analysis of certain types of unusual waveforms[17,18]. It should be noted that the fast calculation of wavelet transform provides the opportunity of performing real-time decomposition for proposed wavelet-based method.

This paper is organized as follows: first, the most usual configurations of uncontrolled (diode) and semi-controlled (thyristor) line-commutated rectifiers with both constant power and resistive DC loads are introduced in brief. These configurations cover almost all existing power electronic loads in the present power systems. In the next part, discrete wavelet transform is shortly introduced and then, the noise cancellation from the measured waveform and decomposition of power electronic load by means of this transformation is explained. To verify the ability of proposed load decomposition method, the mentioned rectifier's configurations, beside conventional loads are simulated in MATLAB/Simulink. Finally, laboratory implementation of uncontrolled rectifier with resistive load, operating beside induction motor and inductive load is tested to confirm validity of the proposed method, experimentally.

2. Line-Commutated Rectifiers

From control viewpoint, rectifiers are classified as uncontrolled, which utilize power diodes in their structure, semi-controlled, which employ thyristors, and fully-controlled rectifiers that use IGBT, MOSFET or other fully-controllable solid-state switches[19]. The first two classes are also called line-commutated rectifiers, while the latter are known as force-commutated rectifiers. The ability of the fully-controlled rectifiers in correcting power factor and limiting harmonic emission level is significant[20], but the line-commutated rectifiers are often utilized more, because of lower price, higher reliability, simpler control and some other advantages. Therefore, uncontrolled and semi-controlled classes are considered in the present study.

A common three-phase line-commutated rectifier, together with a filter capacitor, feeding a resistive or constant power DC load is shown in Figure 1. In case of single-phase rectifiers, which are the common structure in household appliances, their cumulative effect on the three phases can be considered with acceptable approximation.

Two different DC loads, i.e. resistive and constant power loads, are considered. Physical resistance or those DC loads that are modeled by resistance, like melting materials in metal industries, are the more common loads

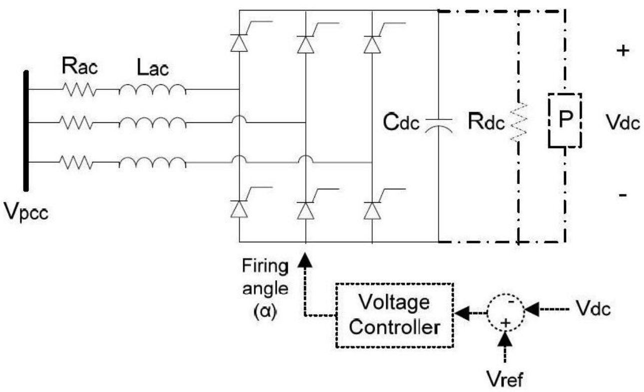

Figure 1. The configuration of uncontrolled (diode)/ semi-controlled (thyristor) rectifier with constant power/resistive load.

of the rectifiers. Examples of constant power loads include chopper fed DC motors with constant torque, and those AC drives that use DC-DC converter in their DC side[19]. Some other types of constant power loads have been discussed in [21].

3. Decomposition of Rectifier Current

The proposed non-intrusive decomposition method utilizes zero current intervals in the rectifier's input current as its unique feature (signature). The principles of power electronic loads decomposition by means of this signature is considered, firstly. In the next section, a brief description about discrete wavelet transform, which is employed for determination of these zero intervals, is presented. Finally, the denoising ability of this transformation for noise cancelation of the measured current is studied and compared to that of digital low-pass filters.

3.1 Principle of Proposed Decomposition Method

A typical waveform of the input current of a three-phase rectifier is shown in Figure 2(a). The zero current intervals, observed twice in each period of the waveform, are the salient feature of the rectifier current, which can be used to distinguish it fromcontinuous current of conventional loads. Assuming a pure sinusoidal supply voltage, the conventional load absorbs sinusoidal current (I_C), while the rectifier's current (I_R) is distorted. Therefore, in a composite load, consisting conventional and rectifier loads, the total current (I_T) can be expressed as:

$$I_T = I_C + I_R = \left[I_C \cos(\omega t + \alpha) \right] + \left[\sum_{n=1} I_{R,n} \cos(n\omega t + \varphi_n) \right] \quad (1)$$

In zero intervals of I_R, the total current is equal to the conventional load current. There are two intervals in each period, where I_R is zero, so two pieces of I_C can be extracted. By extrapolation of these current pieces, I_C is derived with acceptable approximation. Then, by subtracting this current from the total current, I_R can be found.

Implementation of proposed idea may seem straightforward, but finding the length of the zero current intervals is a real problem. Reference [6], which has studied single-phase rectifier, assumes a fixed zero current interval with

90^o width, centered at zero crossing point of the fundamental component of voltage. In practice, however, the width of these periodically happening intervals are shortened by the inductance of input filter and transformer, and it is not necessarily centered at voltage zero crossing of voltage. Typical variation of zero current interval of a three-phase rectifier with the line inductance, obtained by simulation, is presented in Figure 2(b).

More attention to the total current, as combination of continuous and discontinuous currents, clears periodic discontinuities that can be distinguished at the start and end of zero current intervals. Wavelet analysis can determine the zero current intervals through detection of these discontinuities.

3.2 Discrete Wavelet Transform

Analysis of electrical waveforms by means of signal processing tools sometimes gives valuable data about power system situation. Among available signal processing techniques, wavelet analysis is suitable for studying certain types of unusual waveforms. As an example, its application in harmonic analysis can be found in [22].

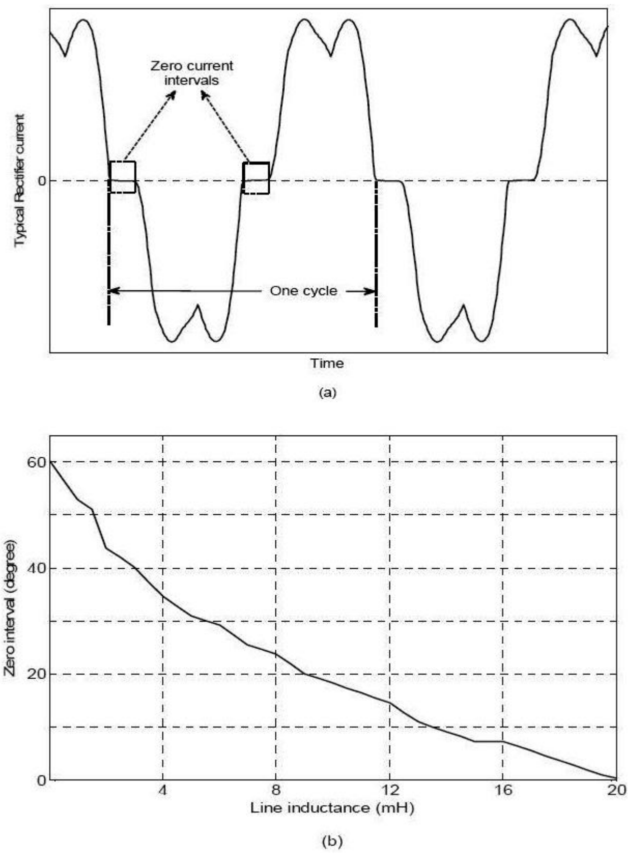

Figure 2. (a) Typical input current of line-commutated rectifiers (b) variation of zero current interval with the line inductance.

Compared to the Fourier transform, which indicates the frequency-based view of the signal and looses its time-based information, wavelet transform retains both the time and frequency-based views. Short Time Fourier Transform (STFT) also gives time and frequency-based views of the waveform, but using time window with particular size for all frequencies limits its usage for transient waveforms[23].

There are two types of wavelet analysis: Continuous Wavelet Transform (CWT) and Discrete Wavelet Transform (DWT)[23]. The former uses shifted and scaled versions of an original (mother) wavelet and calculate wavelet coefficients at every possible scale. This produces a lot of data, in comparison with DWT that chooses only a subset of scales, so faster and more efficient wavelet transform is obtained by the latter. In DWT, original signal passes through two complementary filters and consequently, approximation and detail components of signal are obtained. Approximations are the high-scale, low-frequency components, while the details are the low-scale, high-frequency components of the original signal. This filtering process, in turn, can be iterated to obtain lower resolution components. With appropriate mother wavelet and adequate levels of decomposition, the point of discontinuity on the main current waveform can be detected accurately.

3.3 Denoising Measured Current

In practice, the measured electrical waveforms of power system include high frequency noises. In many applications, these noises have trivial effect on the calculations, but sometimes the measured signal is required to pass through low-pass filters, before being processed. In the proposed decomposition method, also, the measured current should be denoised before applying DWT, since finding the points of discontinuity in the noisy current may lead to wrong results. On the other hand, employing common digital filters, which change amplitude and phase of the original signal, may also lead to miscalculation. Wavelet transform has the ability of signal denoising with less signal manipulation, compared to the digital filters[24].

To show denoising ability of digital wavelet transform, a Gaussian distributed noise is added to typical total current of a line-commutated rectifier in combination with a conventional load, as shown in Figure 3(a). The denoised current waveforms by means of both digital wavelet transform and digital low-pass filter, beside the noise-free waveform, are presented in Figure 3(b).

As it is seen, due to high similarity, the noise-free waveform, as index, and denoised current by wavelet transform cannot be distinguished, while, digital filter has changed amplitude and phase of the index current. Moreover, digital wavelet transform denoises signals without compromising the high-frequency information, like discontinuities that should be specified.

4. Evaluation of Proposed Decomposition Method

At first, the proposed decomposition method is numerically evaluated by simulation of test systems in steady state and transient conditions. Uncontrolled and semi-controlled rectifiers, both with resistive and constant power loads are considered, to show the validity of the proposed method for different types of available rectifiers and their DC loads. In the next section, laboratory-implementation of a test system, including an uncontrolled rectifier with constant power load, will be considered to validate the proposed method, experimentally.

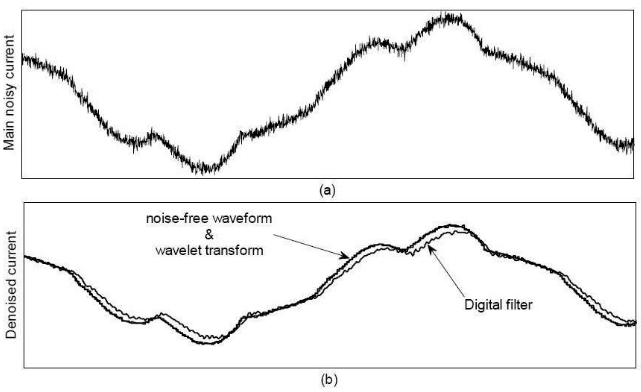

Figure 3. (a) Noisy current (b) noise elimination by digital wavelet transform and digital low-pass filter.

4.1 Numerical Results

The presented test system in Figure 4, which is simulated in MATLAB/Simulink, consists of a three-phase induction motor and static $R - L$ load beside a three-phase rectifier, as conventional and power electronic loads, respectively. The rectifier is connected to PCC through a series $R - L$, representing the input transformer and/or filter. In this test system, uncontrolled rectifier with constant power/resistive load and semi-controlled rectifier with both DC load types will be simulated, separately.

Parameters of the simulated test system and their values, which are shown in Figure 4, are presented in Table 1. For output voltage regulation in the case of semi-controlled rectifier, a PI controller, which is commonly utilized in practical rectifiers, is employed and its coefficients can be found in Table 2.

To show the ability of proposed method in decomposing current in transient as well as steady state conditions, these two conditions are considered separately.

4.1.1 Steady State Conditions

In this section, uncontrolled rectifier with constant power load beside conventional load is considered as test system. Typical absorbed current of this system, which is

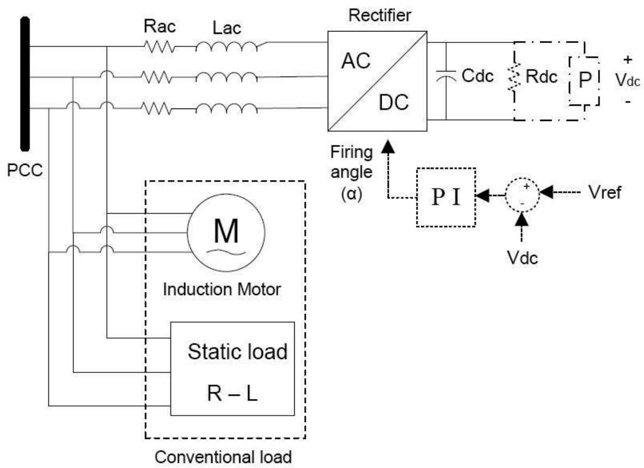

Figure 4. Schematics of simulated test system.

Table 1. Parameters of simulated and laboratory-implemented test systems

Supply voltage	Three-phase rectifier					Three-phase induction motor								Static load	
	R_{ac}	L_{ac}	C_{dc}	R_{dc}	P_{dc}	S	R_s	L_{ls}	R'_r	L'_{lr}	L_m	J	F	R	L
380V 50Hz	10 Ω	10 mH	2200 μF	250 Ω	500 Watt	1 kVA	1.45 Ω	5.23 mH	1.43 Ω	5.23 mH	0.183 H	0.011 kg.m^2	0.0026 N.m.s	200 Ω	380 mH

Table 2. *PI* controller coefficients in semi-controlled rectifier

DC Load type	Proportional gain	Integral gain
Resistive	10	350
Constant power	10	200

measured at PCC, beside its rectifier current in steady state condition are presented in Figure 5(a). Zero current intervals are indicated by double-arrow lines and to extract rectifier current, these intervals should be specified. Simulated total current is loaded into the Wavelet toolbox of MATLAB and Biorthogonal wavelet family[23] is chosen as the wavelet filter. By trial and error, it was seen that this wavelet family gives more clear results to distinguish zero current intervals. Detail component of total current, due to performing 1-level decomposition, is shown in Figure 5(b). It should be mentioned that carrying out two or more levels of decomposition increases required time for wavelet analysis without obtaining more valuable data.

Repetitive unique pattern, indicated by dash-dotted rectangular, can be seen in the detail component of main current. This pattern coincides with zero current intervals, so it can be utilized for specification of these intervals. Sudden changes in detail component at the start of zero current intervals, followed by unique signal damping manner, are features of this pattern. Cross-correlation of this pattern, which is padded with enough zero samples, with main current can effectively specify zero current intervals. It can be seen that detail component clearly shows discontinuities of the main current, and indicates start and ends of the zero current intervals in steady state condition.

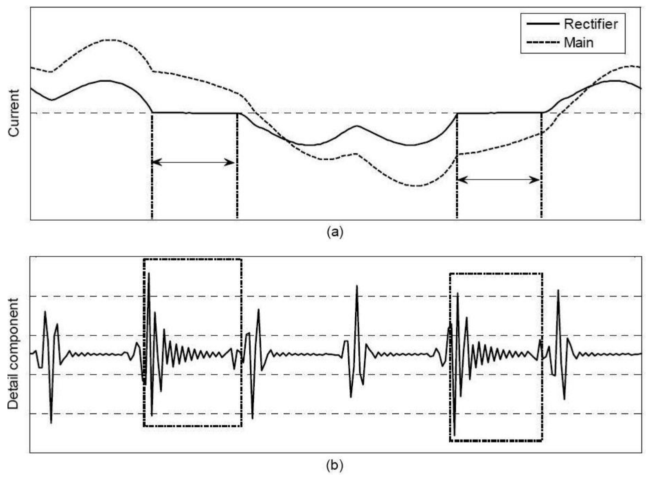

Figure 5. (a) Typical currents of rectifier and supplying bus in steady state condition (b) detail component of main current.

4.1.2 Transient Conditions

Sometimes, load composition data in transient condition is required. For instance, to identify the unknown parameters of measurement-based load models, the load response to a disturbance, such as sudden voltage drop, should be known. As mentioned earlier, simultaneous identification of conventional and power electronic loads is a high-order identification problem with a bunch of unknown parameters. Load decomposition by the proposed method separates the response of power electronic and conventional loads, so their parameters can be identified independently and simplifies such complicated identification problem.

To generate transient condition, PCC voltage drop with 0.3 p.u. depth is arranged at t = 0.05 s. Like previous section, three-phase uncontrolled rectifier with constant power load is considered beside conventional load.

Figure 6 shows that by onset of voltage drop, rectifier current is ruptured and consequently, detail component of the main current becomes zero. This is because AC side voltage of rectifier is dropped below its capacitor voltage and consequently, the rectifier is blocked. In this condition, DC load is supplied only by stored energy in the filter capacitor that leads to decrease capacitor voltage. In a short time, DC voltage is reduced to the level of dropped AC voltage and then, rectifier starts to operate in this new voltage condition. Further attention clears that similar

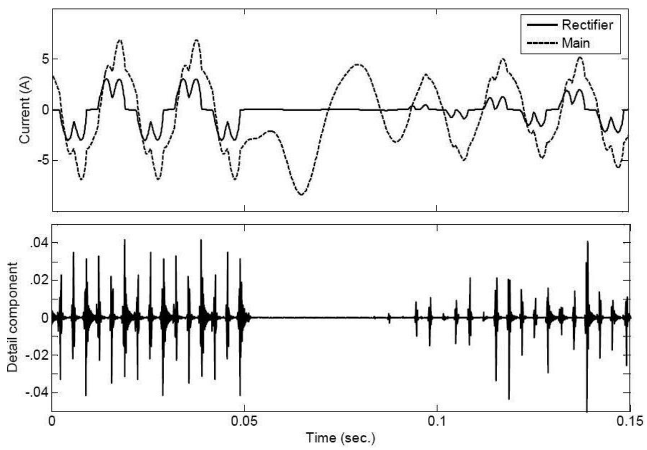

Figure 6. Detail component of main current in dropped voltage condition.

pattern, like previous section, can be seen before and after blocking rectifier. Figures 5 and 6 show that wavelet analysis can specify blocking duration of rectifiers after deep voltage drops, beside their zero current intervals.

During zero current intervals, which are clearly specified by wavelet analysis, total current is constituted merely by the conventional load's current, which include three-phase induction motor and static load. Therefore, complete waveform of the conventional load current, can be constructed from these discontinuous pieces by fitting toolbox of MATLAB. Subtraction of this built current from the total current results in the absorbed current of line-commutated rectifier.

Figure 7 presents individual currents of conventional load and rectifier, for uncontrolled and semi-controlled rectifiers with the two types of DC loads, which are obtained by both simulation and decomposition method. Strong coherence of the results indicates effectiveness of the proposed decomposition method. It is worth to mention that proposed method decomposes the current of each phase, independently. So, this method can be also applied in asymmetric conditions, in which each phase has different current.

Different rectifier blocking durations, after onset of voltage drop, can be seen in Figure 7. This duration depends mainly on the consumption level of DC load and depth of AC voltage drop that is specified by PCC voltage drop and the amount of series $R - L$.

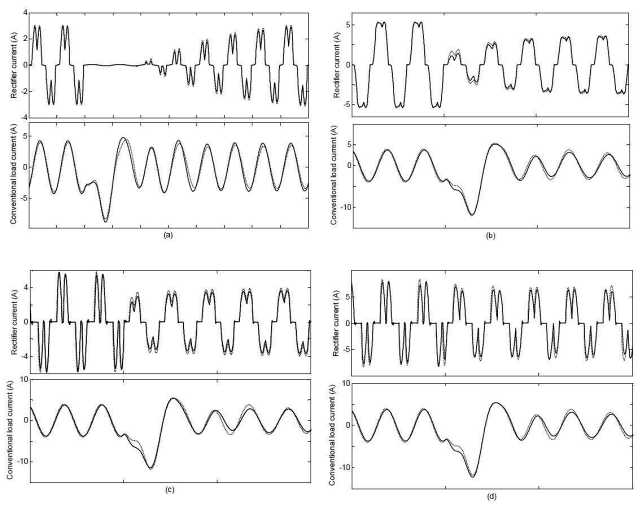

Figure 7. Decomposed (dashed lines) and simulated (dotted lines) current waveforms of conventional load and uncontrolled rectifier with (a) constant power (b) resistive load, semi-controlled rectifier with (c) constant power (d) resistive load.

5. Experimental Results

In this section, the proposed method is evaluated experimentally by a laboratory-implemented test circuit, as schematically shown in Figure 8. The fundamental structure and parameter values of this circuit are similar to those of simulated test system, with uncontrolled rectifier and constant power load.

A forward DC-DC converter[19], with well-known PWM controller, is placed at the DC side of rectifier. This sub-circuit provides constant voltage for its resistive load (R_{dc}), so that a constant power load is realized. A DC generator, feeding a variable resistance and mechanically coupled with three-phase induction motor, serves as the induction motor's load. Parameters of the DC generator are presented in Table 3. A low-voltage high-power converter, model SV-iS7[25], is used as controllable voltage source to produce voltage drop with specified depth.

Laboratory implementation of the test system is presented in Figure 9. The same voltage drop as in the previous section, with 0.3 p.u. depth, is produced by the controllable voltage source.

The measured source current is saved and loaded into the wavelet toolbox of MATLAB for analysis. A digital storage oscilloscope, Tektronix® TDS1002B, is employed to record the current waveform. Measured current waveform at the onset of voltage drop is shown in Figure 10.

The noisy measured current is first denoised by wavelet analysis, and then its detail component is extracted to specify zero current intervals and probable blocking

Table 3. Parameters' value of DC generator

P_n	Exciter	Armature	R_L
2.89 kW	150 V, 1.7 A	150 V, 24 A	30 Ω

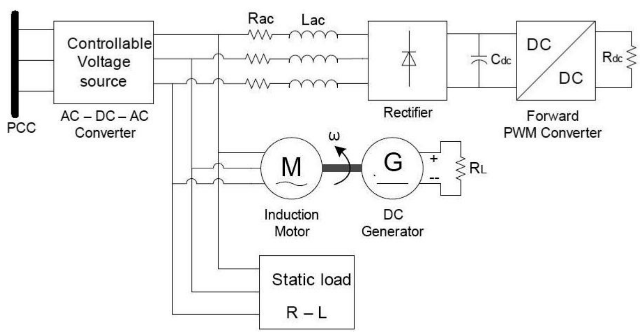

Figure 8. Schematic diagram of laboratory-implemented test system.

Figure 9. Laboratory implementation of test system.

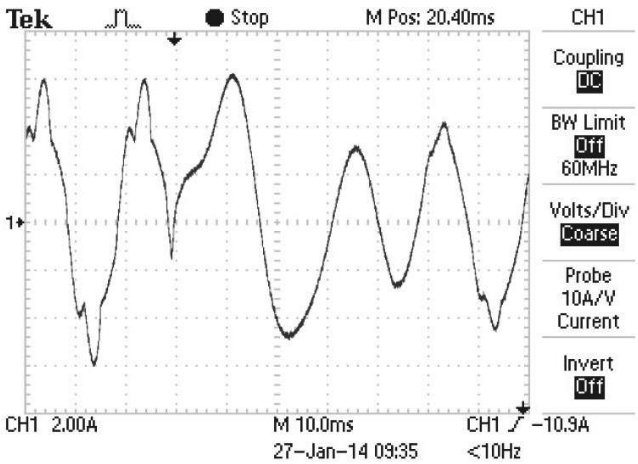

Figure 10. Measured main current at onset of voltage drop.

duration. Figure 11 presents decomposed currents of rectifier and conventional load, beside their actual noisy waveforms, measured by oscilloscope. A close conformity, which is observed between the decomposed and experimental currents, verifies validity of the proposed method, experimentally.

6. Conclusion

A novel load decomposition method is proposed in the present study to extract power electronic loads' current from the total feeder current. The obtained composition data is the basis of some harmonic studies and is valuable for various static as well as dynamic studies of modern

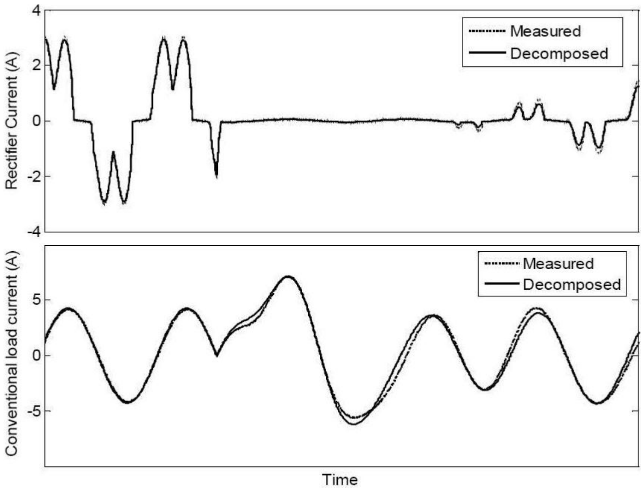

Figure 11. Decomposed and measured currents of rectifier and conventional load.

power systems, especially microgrids. In the proposed method, electrical waveforms are only required to be measured at service entry point. So, it is classified in the non-intrusive decomposition methods, which exhibits significant advantages over intrusive methods.

Zero current intervals in the absorbed current of almost all power electronic loads, as their unique feature, is utilized for decomposition of these loads from conventional loads, which exhibit continuous current nature. It is shown that digital wavelet transform with appropriate mother wavelet can successfully specify these zero intervals, beside probable blocking duration. Moreover, its verified ability for decomposition in transient, asymmetric and steady state conditions makes the proposed method applicable to wide range of power system's studies.

Denoising ability of wavelet analysis is another feature that is used in the proposed method to noise elimination from the measured current before decomposition. Comparison with common digital filters reveals the superiority of proposed method for noise elimination purposes. The validity of the proposed decomposition method for practical rectifiers in the modern power systems is confirmed by the results of simulated test system in MATLAB/Simulink as well as its laboratory implementation.

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