World Academy of Science, Engineering and Technology
International Journal of Electronics and Communication Engineering
Vol:1, No:9, 2007

Simple and Advanced Models for Calculating Single-Phase Diode Rectifier Line-Side Harmonics

Hussein A. Kazem, MIEEE, MIEE, Abdulhakeem Abdullah Albaloshi, Ali Said Ali Al-Jabri, and Khamis Humaid AlSaidi

***Abstract*—**This paper proposes different methods for estimation of the harmonic currents of the single-phase diode bridge rectifier. Both simple and advanced methods are compared and the models are put into a context of practical use for calculating the harmonic distortion in a typical application. Finally, the different models are compared to measurements of a real application and convincing results are achieved.

***Keywords*—**Single-phase rectifier, line side Harmonics.

I. Introduction

THE nonlinear characteristics of loads such as fluorescent lamps, televisions, computers, faxes, light dimmers and variable speed motor drives used in air-conditioning equipment have made harmonic distortion a common occurrence in electrical distribution systems. Harmonic currents injected by such loads are usually too small to cause a significant distortion in distribution networks. However, when operating in large numbers, the cumulative effect of these loads has the capability of causing serious harmonic distortion levels. Experience has shown that these currents do not upset the end-user electronic equipment as much as they overload neutral conductors and transformers, and in general, cause additional losses and reduced power factor [1]-[5].

Traditionally, single-phase ac–dc converters (see Fig. 1), which are also known as rectifiers, are developed using diodes and thyristors to provide controlled and uncontrolled unidirectional and bidirectional dc power.

They have the problems of poor power quality in terms of injected current harmonics, resultant voltage distortion and poor power factor at input ac mains and slowly varying rippled dc output at load end, low efficiency, and large size of ac and dc filters, [6]-[7].

Because of the strict requirement of power quality at the input ac mains, various harmonic standards such as IEC 1000-3-2, IEEE 519 (USA) and ER G5/4 (UK) are employed to limit the distortion at the point of common coupling, [1], [8]-[9].

Hussein A. Kazem, Abdulhakeem Abdullah Albaloshi and Ali Said Ali Al-Jabri are with the Department of Electrical and Computer, Faculty of Engineering, Sohar University, PO Box 44, Sohar, PC 311, Oman (e-mail: h.kazem@soharuni.edu.om).

Khamis Humaid AlSaidi is with Majan Electricity Company, Distribution Directorates, Oman.

In this paper four levels of modeling the single-phase diode rectifier are discussed. Fig. 2 illustrate the four level of modeling.

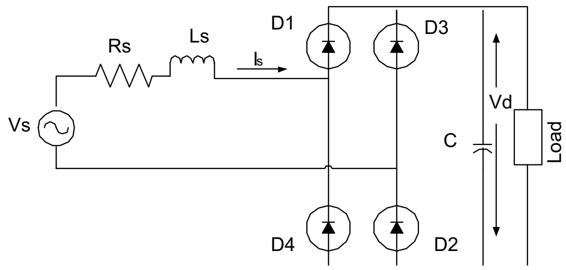

Fig. 1 Diode bridge rectifier circuit

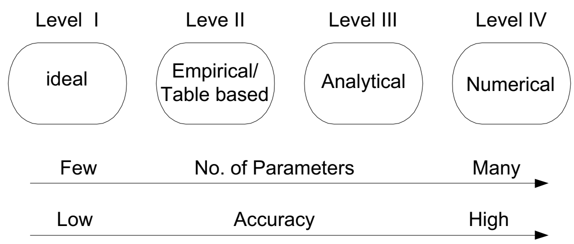

Fig. 2 Levels for modeling single-phase rectifier

The first level of modeling is the ideal one. In this model the diode is assumed to be ideal switch and the source resistance and inductance are neglected. The model has a very limited accuracy, but on the other hand nearly no parameters are needed.

The second level is a table-based model of diode rectifier. The inaccuracy obtained using this simple approach may be justified by the fact that only a limited number of parameters need to be known. Recognizing that in a practical application all system parameters are difficult to obtain one can claim that this approach is well suited for calculation of the harmonic distortion in practical applications.

The third level of the diode rectifier model presented is based on analytical model. The analytical model and especially in the discontinuous conduction mode is quite well described in the literature [11]-[13].

The fourth level of the diode rectifier model is the use of numerical based simulators are that non-linear components, such as diodes, are easily incorporated. Furthermore, predistortion can be simulated very simple compared to other methods. The disadvantage can be longer calculation times, and since it is a circuit-based simulator, all parameters must be known.

The paper compares the simplified and advanced models for estimation of harmonic line current of single-phase rectifier.

II. Ideal Diode Rectifier Model

Fig. 3, illustrate ideal model for single-phase rectifier. The current of the rectifier is assumed to be smooth on the dc side ($L_{dc}\sim \infty$) and commutation effect are neglected (L_s=0), the current is changing instantaneously from zero (R_s=0). This results in that the current appears as symmetrical square wave as shown in Fig. 4.

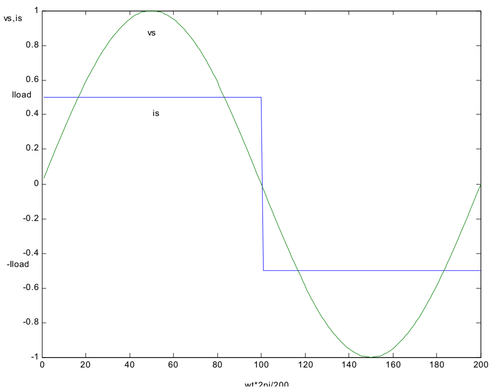

Fig. 3 The voltage & current of an idealized diode rectifier

For determining the characteristics of ideal diode rectifier a Fourier analysis done. The line current I_s can be expressed as:

$$i_s(t)=\begin{cases}-I_o & -\pi<\omega t<0\\ +I_o & 0<\omega t<\pi\end{cases} \qquad (1)$$

Calculating the Fourier coefficients gives:

$$a_h=0 \;\; \& \;\; b_h=\frac{4I_o}{h.\pi} \qquad (2)$$

Thus, the current of an idealized single-phase rectifier can be expressed as:

$$i_s(t)=\frac{4I_o}{\pi}(\sin\omega t+\frac{1}{3}\sin 3\omega t+\frac{1}{5}\sin 5\omega t+..) \qquad (3)$$

Equations (2) & (3) can for the characteristic harmonics be written to:

$$I_h=I_1/h \qquad (4)$$

III. Table based Harmonic Model of the Diode Rectifier

Recognizing the limits of the ideal model of the diode rectifier, the next level is to measure or simulate line current of the diode rectifier in a number of different cases and use a look-up table based approach to calculate harmonics.

Varying parameters such as the line impedance, additional ac reactance, dc-link inductance and load it is possible to achieve any necessary information regarding current behavior in these cases. The results are stored in a look-up table and the actual values for a given application are found by interpolation.

The disadvantage of using measurements of the line current for generating a look-up table is that it becomes very time consuming in measuring the large amount of data.

Usage of numerical circuit simulators like Saber, Pspice, EMTP is a common practice and they are powerful tools to simulate real applications. In this section the Pspice simulator has been used to generate the look-up tables.

Not all simulation databases will be shown but instead current THD and 3rd harmonic current for different short circuit ratios and different loads will be presented in this section. Obviously the tables can be extended even more, detailing individual harmonic currents up to the 31st.

Some assumptions should be made previous to the simulations. The assumptions made for the simulations are:

1. Input voltage is pure sinusoidal.
2. The supply is purely inductive.
3. All passive components are linear. i.e. the resistance and inductance are constant at all frequencies.

Furthermore, it is assumed that the diode rectifier is of the voltage-stiff type. This means that the dc-link capacitor is sufficient large to maintain a constant dc-link voltage. This is a fair assumption since most of the diode rectifiers used in today's power electronic converters are of this type.

Fig. 4 depicting the single-phase rectifier will be considered to be the base of simulations. Multiple simulations have been run independently changing one of these parameters:

1. Input source ac-reactance L_s, between 2mH to 10mH.
2. Dc-link inductance L_{dc}, between 2mH to 10mH.
3. Load resistance R_{load} 20Ω, input voltage V_s 120v, smoothing capacitor C_{dc} 1000μF, source resistance R_s 1m Ω.

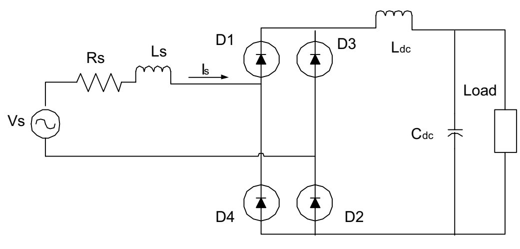

Fig. 4 Simulated single-phase rectifier used for table based model

Referring to the parameter values it can be seen that an initial value for L_s and L_{dc} at 2mH will get the largest value of THD with the effect of rapidly increasing the harmonic content. Fig. 5 illustrates only the 3rd harmonic current.

As an example of a table based model, a look-up table of the current Total Harmonic Distortion (THD_i), shown in Table I, will be described next for different values of ac-reactance and dc-link inductance.

Table I shows a very high harmonic content when both ac inductance and dc-link inductance have small values and also shows a continuously decreasing harmonic content as these inductances will have bigger values. Importantly it can be easily seen what is the harmonic content for specific values of different parameters.

TABLE I
SIMULATED THD WITH DIFFERENT L_S AND L_{DC}

L_s / L_d	2mH	4mH	6mH	8mH	10mH
2mH	55.466	49.001	44.072	41.270	46.999
4mH	49.005	42.956	38.461	36.109	35.630
6mH	43.866	38.900	35.915	32.562	33.061
8mH	39.738	35.780	32.553	31.478	30.593
10mH	36.301	33.016	30.494	28.769	26.927

In this point it is clear how the harmonic estimation algorithm will work:

- First step is to get all input information i.e. transformer impedance, dc-link inductance, load, nominal voltage, nominal power.
- Find the corresponding values of harmonic current and THD_i by the means of interpolation.

Once the tables are defined, this approach has the advantage of simple and fast estimation of the harmonic current for single-phase diode bridge rectifier.

IV. Analytical Model

If more detailed system parameters are known, such as the capacitance of dc-link capacitor, dc-link inductance, load, etc., analytical model may be used.

Single-phase diode bridge rectifier work into two model; continuous and discontinuous modes. . In both continuous and discontinuous current conductions, the AC current harmonic evaluation consists of two steps:

1. The expression of time evaluation of the AC current is obtained.
2. The Fourier analysis of current time evaluation is affected.

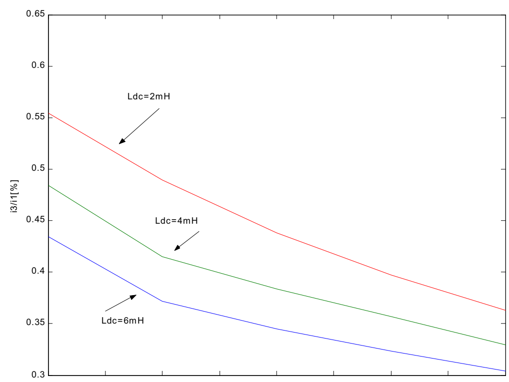

Fig. 5 Simulated relative 3rd harmonic current dependence on ac and dc-link inductance

It should be noted that the continuous current condition could be considered as a particular case of the discontinuous current condition. In order to obtain the time evaluation of input current during the charging model, the following differential equation system has to be solved (see Fig. 1):

$$i_S(\omega t) = \omega.C\frac{dV_d(\omega t)}{d\omega t} + \frac{V_d(\omega t)}{R_d} \quad \text{(KCL)} \tag{5}$$

$$V_{th}(\omega t) = R_s.i_S(\omega t) + \omega L_s\frac{di_S(\omega t)}{d\omega t} + V_d(\omega t) \quad \text{(KVL)} \tag{6}$$

There are many methods for solving equations (5) and (6). Reference [10] use state space and trapezoidal method to solve them. References [11] –[13] solve the two equations by applying Laplace transform. However depending upon the value of the circuit parameters, there are two characteristic roots: real and complex. So that there are two solutions.

The solution for equations (5) and (6) are implemented in a MATLAB program. Fig. 6 shows an example of a MATLAB simulation of a single-phase diode bridge rectifier.

V. Numerical Model

Numerical method gains much appreciation lately because of a constant increase in computing power and also because of performance improvement in software products.

Advantages of using reliable simulation software make this method very powerful when it is about flexibility and redesign. Also due to more advanced numerical algorithms and due to more precise implementation of real devices, (i.e. non-linearity with frequency, temperature, parametric sweep, parameter distribution, parasitic elements) numerical software increased very much in reliability.

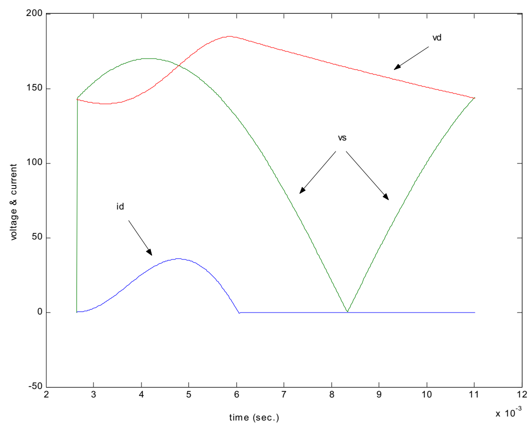

Fig. 6 MATLAB simulation of the single-phase diode bridge rectifier using analytical model

If an analytic approach is used to solve a real application it should be taken into account that any changes in design structure will have impact in rethinking the entire algorithm and redefining all equations. Whereas numerical simulation software allows very easy redesign of the schematic and thus faster "re-running". This way significant less time and effort will be spent compared to find new mathematical equations. It is clear that any other method will not be so fast in obtaining results when changes will appear on schematic. Adding a temperature sweep or a non-linearity could continue the experiments further.

Table based method it is very efficient when it is about computation speed, because of already defined look-up tables. But considering, that for achieving table-data some limitations must be imposed, the results could not be so accurate. Especially when a new parameter will appear to count into equation. The table based solution for this case is to achieve more data with the newest parameter.

Data from the table-based method were achieved by the numerical simulation method since it is providing faster speed and feasibility. As declared in the initial assumptions, the acquisition considers the source voltage to be sinusoidal. This limitation is more likely to be considered in the case of a non-ideal application.

VI. Verification of the Models

Recognizing that the requirements regarding accuracy of a harmonic current estimation in a practical application may vary, and also knowing that not all system parameters may be available to the part who actually will make the calculations it is crucial to know what kind of accuracy of the four models can be expected in actual application.

To verify the four models against laboratory measurements one example will be shown here. Verifying the models in a laboratory gives the advantage of a controllable environment; such as the quality of the supply voltage and parallel-connected loads etc. The measurements are made with single-phase diode bridge rectifier with the following parameters:

- Supply: sinusoidal voltage, V_m=12 v, L_s=10mH, R_s=0.001Ω.
- DC-link: L_{dc}=10mH.
- Smoothing-Capacitor: C_{dc}=220µF.
- Load-Resistor: R_d=33 Ω.

Figs. 7 and 8 compares measured and simulated currents. As the current of the ideal and table-based model are not available in the time domain, only currents of the circuit based model and analytical model are shown together with the measured current.

Table II summarizes some harmonic values of the measurements and all four models.

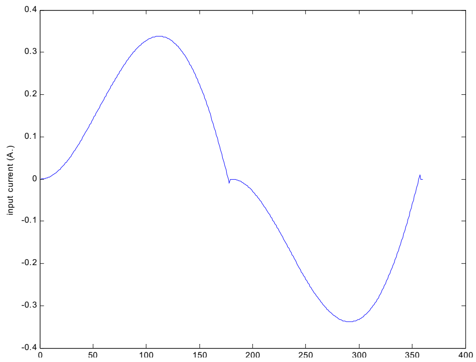

Fig. 7 Simulated input supply current

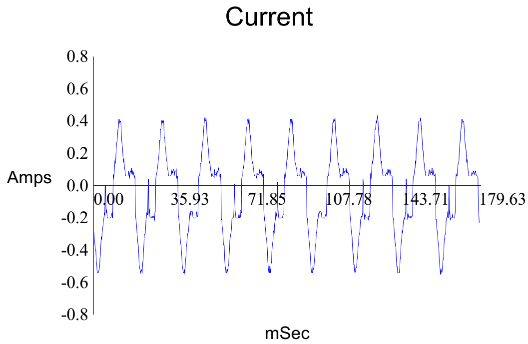

Fig. 8 Measured input supply current waveform

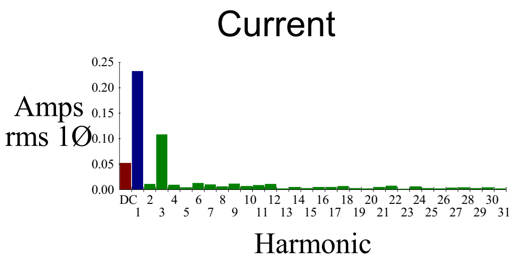

Fig. 9 Measured input supply current spectrum

TABLE II
Comparison between the Measured and Simulated Harmonic Current as well as the THD_i

h	measured	numerical	analytical	Table Based	ideal
1	0.410	0.40110	0.40112	0.40107	0.3910
3	0.111	0.16880	0.16881	0.16882	0.1303
5	0.012	0.02544	0.02555	0.02544	0.0782
7	0.011	0.01735	0.01700	0.01701	0.0558
9	0.010	0.01118	0.01100	0.01101	0.0434
11	0.010	0.00606	0.00611	0.00610	0.0355
13	0.001	0.00447	0.00449	0.00447	0.0300
THD_i	43.560	43.646	43.647	43.643	42.793

As shown in Figs. 7 and 8 and Table II the result of the numerical, analytical and table-based model show very good agreement with the actual measured values. Obviously the ideal model cannot estimate the 11th and 13th harmonic well.

Also, it is important to mention here to the high distortion in the measured waveform. Also, there are even harmonics which affect THD_i.

VII. Conclusion

In this paper four levels of the single-phase diode bridge rectifier models have been presented and the behavior of the diode rectifier at some different basic parameters such as the line-impedance and line voltage has been documented.

The ideal model of the diode rectifier has been given some attention since only a single parameter (fundamental input current) is needed and also because the ideal model is useful for some basic/illustrative calculations.

A table based diode rectifier model is presented and it is shown that good results can be achieved if the pre-simulated variables are carefully selected.

Furthermore, an improved analytical model for the rectifier was also presented and very good accuracy is achieved, which is validated by example.

References

[1] Hussein A. Kazem, Khamis Humaid AlSaidi, Saeed Hamad AlShibli & Ali Mohammed Suliman AlBlushi, “Harmonic Limitation and Standard in Sultanate of Oman Network – Sohar Industrial Area case study”, ICCCP’05 Conference, Sultan Qaboos University, Muscat, Sultanate of Oman. 14th –16th February 2005, pp. 145-149.

[2] E.F. El-Saadany, R. Elshatshat and M.M.A. Salama, “Reactance one-port compensator and modular active filter for voltage and current harmonic reduction in nonlinear distribution systems: A comparative study”, Electrical Power Systems Research, 1999, Vol. 52, pp. 197-209.

[3] A. Mansoor, W. M. Grady, A. H. Chowdhury and M. J. Samotyj, “An Investigation of Harmonics Attenuation and Diversity Among Distributed Single-Phase Power Electronic Loads”, IEEE Transactions on Power Delivery, Vol.10, No.1, January 1995, pp. 467-473.

[4] A. Mansoor, W. M. Grady, R. S. Thallam, M. T. Doyle, S. D. Krein and M. J. Samotyj, “Effect of Supply Voltage Harmonics on the Input Current of Single-Phase Diode bridge Rectifier Loads”, IEEE Transactions on Power Delivery, Vol. 10, No. 3, July 1995, pp. 1416-1422.

[5] G. Carpinelli, F. Iacovone, P. Varilone and P. Verde, “Single-Phase Voltage Source Converters: Analytical Modeling For Harmonic Analysis in Continuous and Discontinuous Current Conditions” International Journal of Power and Energy Systems, Vol. 23, No. 1, 2003, pp. 37-48.

[6] R.E. Owen, M.F. McGranaghan & J.R. Vivirito, "Distribution System Harmonics: Controls for Large Power Converters", IEEE Transactions on Power Apparatus a Systems, VOL. PAS-101, No.3, March 1982, pp. 644-652.

[7] B. Singh, B.N. Singh, A. Chandra, K. Al-Haddad, A. Pandey and D.P. Kothari, “A Review of Three-Phase Improved Power Quality AC-DC Converters”, 2004, IEEE Transactions on Industrial Electronics, Vol.51, No.3, pp. 641-660.

[8] Hussein A. Kazem, Khamis Humaid AlSaidi, Saeed Hamad AlShibli & Ali Mohammed Suliman AlBlushi, “Harmonic Reduction of Three-Phase Six-Pulse Rectifier Using Passive Filters – Case Study ", 20th International Technical Conference on Circuits/Systems, Computers and Communications, Seoul, Korea 4th – 7th July 2005.

[9] IEEE 519: 1992, IEEE Recommended Practices and Requirements for Harmonic Control in Electric Power Systems (ANSI), 1st May 1992, pp.1-112.

[10] Ned Mohan, Tore M. Undeland & William P. Robbins, “Power Electronics, Converters, Application & Design”, 2nd Edition, John Wiley & Sons, Inc., 1995.

[11] A. Mansoor, W. M. Grady, A. H. Chowdhury and M. J. Samotyj, “An Investigation of Harmonics Attenuation and Diversity Among Distributed Single-Phase Power Electronic Loads”, IEEE Transactions on Power Delivery, Vol.10, No.1, January 1995, pp. 467-473.

[12] A. Mansoor, W. M. Grady, R. S. Thallam, M. T. Doyle, S. D. Krein and M. J. Samotyj, “Effect of Supply Voltage Harmonics on the Input Current of Single-Phase Diode bridge Rectifier Loads”, IEEE Transactions on Power Delivery, Vol. 10, No. 3, July 1995, pp. 1416-1422.

[13] G. Carpinelli, F. Iacovone, P. Varilone and P. Verde, “Single-Phase Voltage Source Converters: Analytical Modeling for Harmonic Analysis in Continuous and Discontinuous Current Conditions” International Journal of Power and Energy Systems, Vol. 23, No. 1, 2003, pp. 37-48.