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Novel Average Value Model for Faulty Three-Phase Diode Rectifier Bridges

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Abstract

Rectifiers are widely used in industrial applications. Although detailed models of rectifiers are usually used to evaluate their performance, they are complex and time-consuming. Therefore, the Average Value Model (AVM) has been introduced to meet the demand for a simple and accurate model. This type of rectifier modeling can be used to simplify the simulations of large systems. The AVM of diode rectifiers has been an area of interest for many electrical engineers. However, healthy diode rectifiers are only considered for average value modeling. By contrast, faults occur frequently on diodes, which eventually cause the diodes to open-circuit. Therefore, it is essential to model bridge rectifiers under this faulty condition. Indeed, conventional AVMs are not appropriate or accurate for faulty rectifiers. In addition, they are significantly different in modeling. In this paper, a novel application of the parametric average value of a three-phase line-commutated rectifier is proposed in which one diode of the rectifier is considered open-circuited. In order to evaluate the proposed AVM, it is compared with experimental and simulation results for the application of a brushless synchronous generator field. The results clearly demonstrate the accuracy of the proposed model.

Key words: Average value modeling, Open circuit fault, Three-phase uncontrolled rectifier

I. INTRODUCTION

Diode rectifiers have been developed a great deal so that most of the pneumatic and hydraulic components have been substituted with electrical components in many applications [1]. There is a high demand for a reliable electric supply. Most power electronic systems in industrial and commercial applications use variable frequency sources supplied by a DC voltage that is usually provided by line-commutated rectifiers. Line-commutated rectifiers are widely used in the exciters of brushless synchronous generators, high voltage direct current (HVDC) systems, and electrical drives. In order to study a large power electronic system, an analytical model of the power electronic instruments is required. Precise and optimum modeling and analysis of rectifiers have become areas of interest for power engineers. Due to inherent repeated switching, detailed switching models are discontinuous. As a result, extracting the small-signal characteristic of a system is a challenging and time-consuming procedure [1]-[17]. The AVM can be used to alleviate the problems of time-consuming simulations, especially in large systems, and substituting switching intervals with non-switching intervals. In this method, by means of averaging, the average value of the input signal is calculated in each period, and it is used instead of instantaneous values. AVMs are computationally fast and since they are time-invariant, they can be linearized in terms of any desired operating point for small-signal analysis [2].

A method is proposed to derive AVMs of the six-pulse and multi-pulse rectifiers used in aircraft applications [1]. In [2], [11], AVMs based on nodal analyses of the six-pulse rectifier are proposed, which enhance the AVM accuracy. The AVM is extended for diode rectifiers to include significant harmonics of interest in [3]. The AVM is extended to use in thyristor-controlled rectifiers [4]. A modified dynamic average

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value model of the line-commutated rectifier for EMTP-type solutions and simulation packages are investigated [6]. The effects of changes in the topology of AC filters on the performance of the AVM is analyzed in [7]. The AVM is developed for the alternator-rectifier-battery systems for automotive applications in [8]. An overview of dynamic average value modeling is represented for front-end rectifiers with and without a smoothing ac choke inductor and for variations of a dc filter in two operating modes [9]. Definitions and acceptable properties of the AVM for conducting large-signal time-domain transient studies and small-signal frequency-domains are discussed in [10]. The state space averaging method of a three-phase four wire generator-rectifier system is investigated in [12]. The AVM of three-phase and six phase rectifiers are modified for utilization in PSCAD/EMTDC software [13]. By considering the diode forward drop voltage, an accurate parametric AVM of a car alternator-rectifier is presented in [14]. Analytical relations are developed which can be used to predict the average-value characteristics of a dual line-commutated converter six phase synchronous motor system [15]. The AVM of a twelve-pulse diode rectifier and a six-phase synchronous machine system are investigated in [16]. A model of a three-phase diode bridge rectifiers is presented in [18], where a single bridge and complex systems such as series and parallel bridges can be described. In [19], an input ac impedance model of a three-phase diode rectifier is derived using the time domain Fourier series analysis and the time-domain mapping method. An analytical model for a six-pulse rectifier bridge connected to an unbalance three-phase supply is proposed in [20]. A state-space AVM for the direct symmetric topology of an 18-pulse AC-DC rectifier is represented in [21]. In [22], AVMs for three-phase and nine-phase diode rectifiers are proposed while a first order Taylor series expansion of the dc load current during the averaging period is used to improve the model accuracy.

There are two general types of faults on rectifier diodes, open-circuit and short-circuit. The short-circuit fault eventually becomes an open-circuit, while a short-circuit occurs in diodes because of current increments. By reviewing articles, it can be seen that the application of the average value model on open-circuited rectifiers has yet to be evaluated. In addition, all of the available research focuses on the healthy condition of a diode rectifier. Furthermore, due to the development of power electronics devices, as wells as the complexity and time-consuming analysis of power electronic systems, it is essential to model a rectifier bridge under faulty conditions.

In this paper, a novel parametric AVM is proposed to be utilized in a diode rectifier bridge under the one diode open-circuit fault condition, and the analytical equations of the rectifier bridge are derived. In order to evaluate the proposed analytical model, it is compared with simulation and experimental results. In addition, the results are compared with those of the conventional AVM in [2] to indicate that the model is not appropriate for faulty conditions.

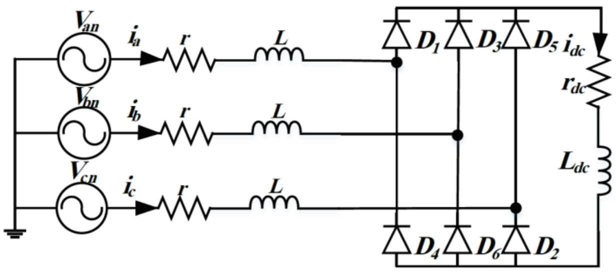


Fig. 1. Three-phase rectifier bridge along with its power supply and load.

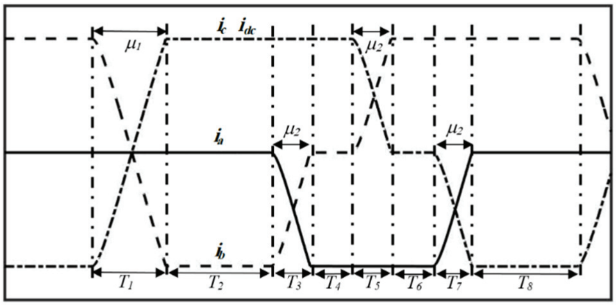


Fig. 2. Input 3-phase current (i_a, i_b, i_c) of a rectifier bridge when the diode D_1 is open-circuited. The conduction mode and two types of commutations with the times μ_1 and μ_2, and eight intervals (T_1-T_8).

II. ANALYSIS OF A RECTIFIER BRIDGE WITH AN OPEN-CIRCUITED DIODE

Fig. 1 illustrates the conventional 3-phase diode rectifier bridge used in synchronous generator field systems. In this figure, r and L are the internal resistance and inductance of the power source; and r_{dc} and L_{dc} are the load resistance and inductance, respectively. The diodes D_1-D_6 are power electronic switching components; V_{an}, V_{bn} and V_{cn} are the power supplies of the rectifier bridge, which are assumed to be balanced and symmetrical; i_a, i_b and i_c are the 3-phase currents of the rectifier bridge power supply; and i_{dc} is the rectifier bridge load current.

When a fault occurs on a rectifier bridge that leads to a diode open-circuit, the bridge becomes asymmetrical, resulting in a complex analysis. Since each diode conducts 60 degrees in a normal rectifier bridge, for the circuit analysis, there is no difference in which diode becomes open-circuit. To analyze a circuit under such the faulty condition, it is assumed that the diode D_1 is open-circuited. To analyze the rectifier, one cycle of an input 3-phase current wave is needed, which is obtained by simulations in MATLAB/Simulink. According to Fig. 2, due to the inductance of the power supply, commutation does not take place immediately. Note that in Fig. 2, the load current is assumed to be time-invariant. This assumption is considered for simplification in terms of modeling and simulation. It seems to result in some inaccuracies in the modeling. However, based on experimental and simulation results, the inaccuracy is insignificant. For the 3-phase current waveform of a faulty rectifier bridge, it is considered for two modes of operation: conduction mode and commutation mode. During conduction intervals, the diodes of two phases conduct and the other phase current is zero. In the commutation mode, unlike a normal rectifier bridge, the commutations take place in two types of states. In the first type, which is similar to the commutation of a normal rectifier bridge, the two phases currents commutate from the maximum negative or positive value of the current to zero and vice versa, and the other phase current remains at the maximum negative or positive value. In the second type of commutation, which would not take place in normal three-phase rectifier bridges, the current of the phase containing the diode D_1 is zero and the other two phases are commutating from the negative value to the positive value of the current and vice versa. In conventional average value modeling methods, only one-sixth of a cycle is considered.

According to Fig. 2, one whole cycle of a waveform is subdivided into eight switching intervals (T_1-T_8), where μ_1 and μ_2 refer to the interval times of the first and second types of commutation. Since some of the intervals are identical to each other, as can be seen in Fig. 2, only three intervals are considered for analysis. Therefore, the equivalent circuit models and analytical equations for the three switching intervals are derived and the times for each of the commutation intervals are calculated.

A. Interval T_1

In this interval, phases B and C are in the state of the second type of commutation. An equivalent circuit of the rectifier for this interval is illustrated in Fig. 3. Two phases of the power supply of the rectifier are short-circuited by the diodes D_3, D_5, D_2 and D_6. The load current can be obtained by (1) in this interval.

$$\mathrm{r_{dc}}\ \mathrm{i_{dc}} + \mathrm{L_{dc}}\ \frac{\mathrm{di_{dc}}}{\mathrm{dt}} = 0 \tag{1}$$

B. Interval T_2

In this interval, D_5 and D_6 are conducting and the current of phase A is zero. An equivalent circuit for this interval is shown in Fig. 4. In addition, the load current can be calculated by (2).

$$V_{cn} - V_{bn} = (r_{dc} + 2r)i_{dc} + (L_{dc} + 2L)\frac{d\ i_{dc}}{dt} \tag{2}$$

C. Interval T_3

As can be seen from Fig. 2, in this interval, the rectifier current is commutating from phase B to phase A (from D_4 to D_6) and the diode D_5 is conducting. Therefore, the first type of commutation is taking place.

Fig. 5 demonstrates an equivalent circuit for the interval in which there are two independent loops. Kirchhoff's voltage and current laws for each of the loops are as follows:

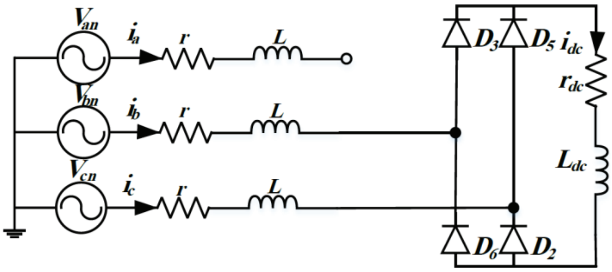


Fig. 3. Equivalent circuit of a rectifier bridge with the diode D_1 open-circuited during the interval T_1.

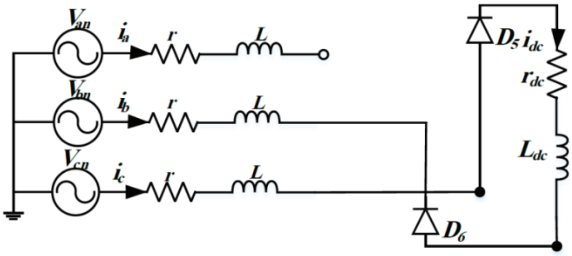


Fig. 4. Equivalent circuit of a rectifier bridge with the diode D_1 open-circuited during the interval T_2.

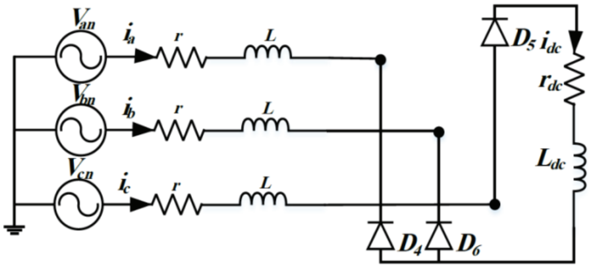


Fig. 5. Equivalent circuit of a rectifier bridge with the diode D_1 open-circuited during the interval T_3.

$$V_{bn} - V_{cn} + L\frac{d\ i_{dc}}{dt} + ri_{dc} + r_{dc}i_{dc} + L_{dc}\frac{d\ i_{dc}}{dt} \tag{3}$$

$$-ri_b - L\frac{d\ i_b}{dt} = 0$$

$$V_{an} {-} V_{bn} + L\left(\frac{d\ i_{dc}}{dt} + \frac{d\ i_b}{dt}\right) + r(i_{dc} + i_b) \tag{4}$$

$$+ri_b L\frac{d\ i_b}{dt} = 0$$

By simplification of equations (3) and (4), the load current can be obtained by:

$$V_{cn} - \frac{V_{bn}}{2} - \frac{V_{an}}{2} = \left(\frac{3}{2}L + L_{dc}\right)\frac{d\ i_{dc}}{dt} \tag{5}$$

$$+\left(\frac{3}{2}r + r_{dc}\right)i_{dc}$$

III. RECTIFIER BRIDGE AVM WITH AN OPEN-CIRCUITED DIODE

In order to model a 3-phase rectifier bridge when an open-circuit fault occurs on one of the diodes, equations (1), (2) and (5) along with the equations for the other intervals, which are derived in a manner similar to the expressed intervals, are rewritten in (6).

$$\frac{d\ i_{dc}}{dt}=$$

$$\begin{cases} \frac{-r_{dc}}{L_{dc}}\ i_{dc} & t\in T_1 \\ \frac{-(r_{dc}+2r)}{(L_{dc}+2L)}\ i_{dc}+\frac{V_{cn}-V_{bn}}{(L_{dc}+2L)} & t\in T_2 \\ \frac{\left(V_{cn}-\frac{1}{2}V_{an}-\frac{1}{2}V_{bn}\right)-\left(\frac{3}{2}r+r_{dc}\right)i_{dc}}{\left(\frac{3}{2}L+L_{dc}\right)} & t\in T_3 \\ \frac{-(r_{dc}+2r)}{(L_{dc}+2L)}\ i_{dc}+\frac{V_{cn}-V_{an}}{(L_{dc}+2L)} & t\in T_4 \\ \frac{\left(-V_{an}+\frac{1}{2}V_{bn}+\frac{1}{2}V_{cn}\right)-\left(\frac{3}{2}r+r_{dc}\right)i_{dc}}{\left(\frac{3}{2}L+L_{dc}\right)} & t\in T_5 \\ \frac{-(r_{dc}+2r)}{(L_{dc}+2L)}\ i_{dc}+\frac{V_{bn}-V_{an}}{(L_{dc}+2L)} & t\in T_6 \\ \frac{\left(V_{bn}-\frac{1}{2}V_{an}-\frac{1}{2}V_{cn}\right)-\left(\frac{3}{2}r+r_{dc}\right)i_{dc}}{\left(\frac{3}{2}L+L_{dc}\right)} & t\in T_7 \\ \frac{-(r_{dc}+2r)}{(L_{dc}+2L)}\ i_{dc}+\frac{V_{bn}-V_{cn}}{(L_{dc}+2L)} & t\in T_8 \end{cases} \tag{6}$$

According to the intervals and the load current equations for each of the intervals, three generalized equations for the intervals can be considered. Hence, equation (6) is generalized as (7), where V_x and V_y are the peak voltages of the phases, with positive and negative currents (in the conduction mode). In commutation mode, V_u is the peak voltage of a phase that is starting to conduct and V_v and V_w are the peak voltages of the others. Note that STC, CM and FTC stand for second type commutation, conduction mode and first type commutation, respectively.

$$\frac{d\ i_{dc}}{dt}=$$

$$\begin{cases} \frac{-r_{dc}}{L_{dc}}\ i_{dc} & S' \\ \frac{-(r_{dc}+2r)}{(L_{dc}+2L)}\ i_{dc}+\frac{V_y-V_x}{(L_{dc}+2L)} & C \\ \frac{\left(\pm V_u\ \mp\frac{1}{2}V_v\mp\frac{1}{2}V_w\right)-\left(\frac{3}{2}r+r_{dc}\right)i_{dc}}{\left(\frac{3}{2}L+L_{dc}\right)} & F \end{cases} \tag{7}$$

The method from [23] is used to calculate the average value. The average value of a variable in the period T is defined by (8).

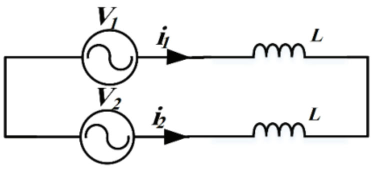


Fig. 6. Equivalent circuit for the commutation interval.

$$\bar{x}(t)=\frac{1}{T}\int_{t-T}^{t}x(\tau) \tag{8}$$

The derivative of the averaged variable is as below [23]:

$$\frac{d\bar{x}}{dt}=\overline{\frac{dx}{dt}} \tag{9}$$

By using relations (7-9) during the intervals T_1 to T_8, and considering the balance input voltage with a magnitude of V_m, the average value of (6) is calculated. Then the final equation is obtained as (10) by assuming $R_1\triangleq 2r+r_{dc}$, $R_2\triangleq 1.5r+r_{dc}$, $L_1\triangleq 2L+L_{dc}$ and $L_2\triangleq 1.5L+L_{dc}$.

In equation (10), the commutation intervals times, μ_1 and μ_2, are unknown and must be calculated. Consider an equivalent circuit of the phases that are commutating. Since the power supply resistance is negligible, the equivalent circuit becomes as Fig. 6. Applying KVL to the loop, equation (11) is derived [2-4].

$$V_1-V_2=2L\frac{d\ i_1}{dt} \tag{11}$$

Assuming $\theta=\omega t$ and choosing an appropriate origin for the 3-phase voltages, the general form of the commutation angle equation is obtained by integrating on the commutation interval.

$$\mu_x=ArcCos(1-\frac{2L\omega\Delta i_x}{\sqrt{3}V_m}) \tag{12}$$

where L, ω and V_m are the inductance, frequency and voltage peak of the power supply. In addition, Δi_x is the current change during the commutation interval. This equation is valid for both type of commutations due to some considerations. According to Fig. 2, in the first type of commutation, Δi_2 is equal to the load current; and in the second type of commutation, $\Delta i_1=2\Delta i_2$. Therefore, by substituting the values of the current change and other parameters, which are the same for both types, the commutation interval angle can be calculated.

IV. SIMULATION AND EXPERIMENTAL VALIDATION

In order to evaluate the proposed AVM for unbalancing three-phase rectifiers, the results obtained by the AVM are

$$\frac{d\overline{i_{dc}}}{dt}=\frac{-2\left(L_2\left(r_{dc}L_1\mu_1+L_{dc}R_1(2\pi-\mu_1-3\mu_2)\right)+3R_2L_{dc}L_1\mu_2\right)}{4\pi L_1L_2L_{dc}}\ \overline{i_{dc}}+\frac{V_mL_{dc}(5\sqrt{3}L_2+2\sqrt{3}L_2Cos(\mu_1)+3\sqrt{3}L_2Cos(\mu_2)+9Sin(\mu_2)(L_1-L_2))}{4\pi L_1L_2L_{dc}} \tag{10}$$

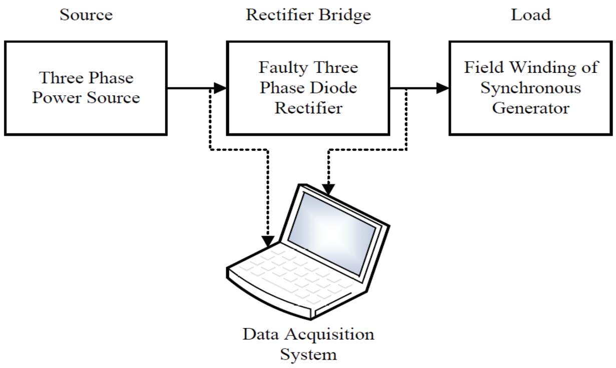
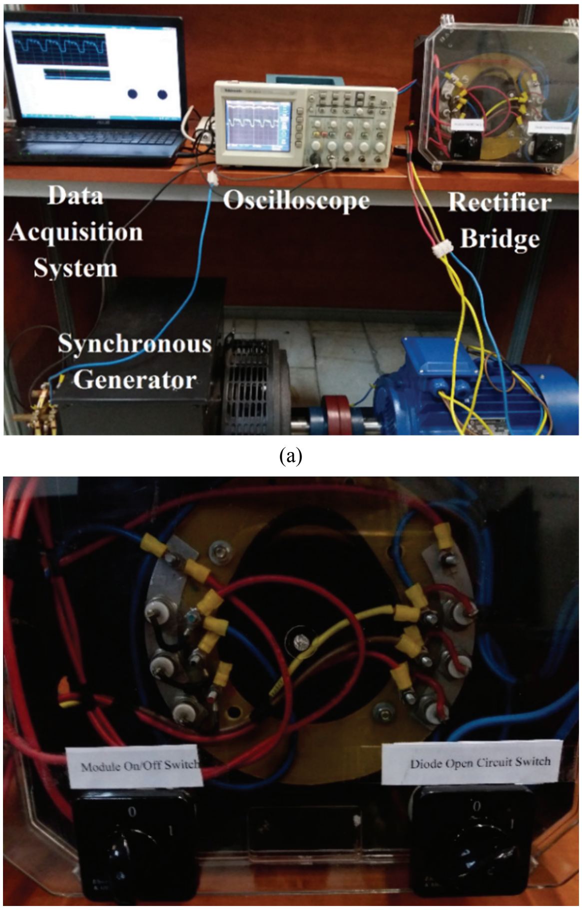


Fig. 7. Experimental set diagram.

TABLE I
PARAMETERS OF THE EXPERIMENTAL SETUP

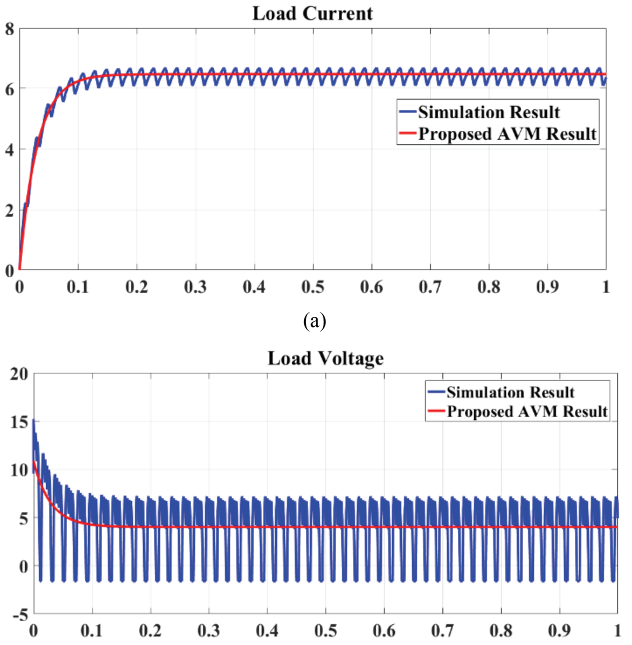
Symbol	Value	Description
$E(V)$	12	Phase Voltage of Power Supply
$r(\Omega)$	0.65	Internal Resistance of Power Supply
$r_{dc}(\Omega)$	0.62	Field Winding Resistance
$L(mH)$	0.85	Internal Inductance of Power Supply
$L_{dc}(mH)$	50	Field Winding Inductance



(a)

(b)

Fig. 8. Experimental setup: (a) Whole system; (b) Rectifier bridge with the key to open-circuit each diode.



(a)

(b)

Fig. 9. Simulation results and the proposed average value model of the: (a) Load voltage; (b) Load current.

compared with experimental and simulation results. A diagram of the experimental test set is illustrated in Fig. 7. The three-phase power source is connected to a diode rectifier bridge. The structure of the rectifier bridge is changed so that one diode can be open-circuited. The rectifier bridge is connected to the field winding of the synchronous generator at the output. The field winding is the load of the rectifier bridge. In order to study the system, a data acquisition system is used.

The diagram in Fig. 7 is implemented in the "special machines and drives" laboratory of the Iran University of Science and Technology. Fig. 8(a) shows the experimental setup containing a data acquisition system, rectifier bridge and synchronous generator, where the field winding is the load of the rectifier bridge. In Fig. 8(b), the diode rectifier bridge is shown where some changes are made so that one of the diodes can be open-circuited. The experimental set parameters are given in Table I.

A simulation of the rectifier bridge with a resistive and inductive load is carried out in MATLAB/Simulink with the parameters shown in Table I. The proposed AVM of a 3-phase rectifier bridge with an open-circuited diode is calculated with the equations given in the previous section. The load current and voltage of the rectifier bridge, which are obtained by simulation, are shown in Fig. 9 along with the average value of the current and voltage, which are calculated by the proposed AVM. The load current and voltage obtained from an experiment are shown in Fig. 10. In Fig. 11, a magnified view of the experimental, simulation and proposed AVM results of the current and voltage are presented for comparison. In this figure the simulation and experimental

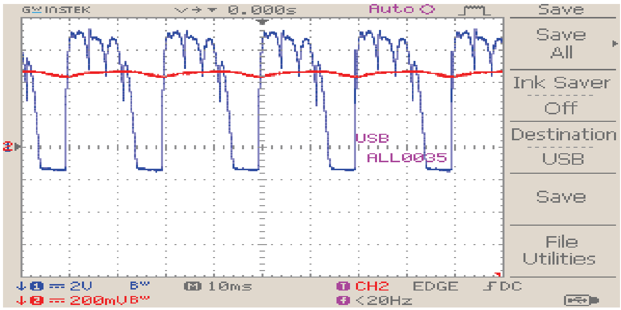
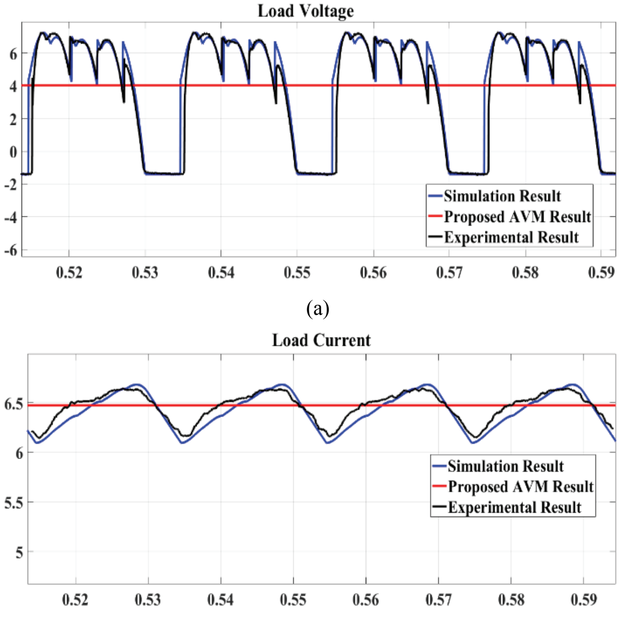


Fig. 10. Experimental results of the load current and voltage.



(a)

(b)

Fig. 11. Simulation result, experimental result and proposed average value model of the: (a) Load voltage; (b) Load current.

TABLE II
AVERAGE VALUES OF THE PROPOSED AVM, THE SIMULATION RESULTS, THE EXPERIMENTAL RESULTS AND THE CONVENTIONAL AVM

Method	Average value	
	Voltage(V)	Current(A)
Proposed AVM	4.026	6.491
Simulation result	4.056	6.542
Experimental result	3.8	6.461
Conventional AVM	5.484	8.845

results are time-varying while the proposed method results are not.

As can be seen in figures 9 and 10, the proposed AVM has good accuracy. For a quantitative comparison, the average value of the simulation and experimental results are calculated [9] and compared with the proposed AVM result in Table II. In addition, the average value calculated by the conventional AVM, which is appropriate for a normal rectifier bridge, is given in Table II. Therefore, it can be determined from Table II that the discrepancy between the conventional AVM and the results of the simulation and experiment is significant.

V. CONCLUSIONS

A rectifier bridge can become asymmetric due to the presence of one diode open-circuit. Therefore, the analysis of a faulty rectifier bridge differs from that of conventional normal rectifier bridges. To enjoy the simplicity of the AVM, this model is modified to consider one diode open-circuit fault in a rectifier. For this purpose, the performance of the faulty rectifier bridge has been subdivided into eight intervals according to the input three-phase current waveform, which generally includes three modes including the conduction mode and two types of commutation modes. For each state, mathematical equations are derived and simplified in three general equations. To verify the proposed model, a comparison between simulation results and experimental results obtained with the proposed AVM is made. These results show that the proposed model has a good accuracy and is a suitable alternative for analyzing uncontrolled three-phase rectifiers with an open circuit diode fault. Moreover, comparing experimental and simulation results obtained with the proposed AVM and the conventional AVM shows that the conventional AVM is not accurate. Therefore, it is not useful for analyzing faulty rectifiers.

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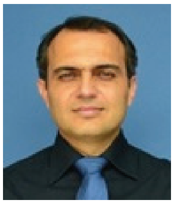

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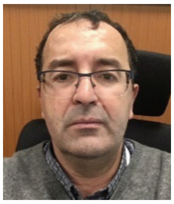

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