A Fault Diagnostic Method of 24-Pulse Uncontrolled Diode Rectifier Based on the Voltage Waveform Analysis

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Abstract. A fault diagnostic method of 24-pulse uncontrolled diode rectifiers based on the voltage waveform analysis was proposed. The voltage waveform analytic expressions of individual diode running under normal and fault conditions were derived in detail. The analytic results are consistent with the simulation model and reveal the characteristics of the voltage waveform of the rectifier diodes. By utilizing voltage dividers and isolated amplifiers, the voltage waveform of individual diode can be measured by the microcontroller. According to the characteristic values calculated by the fault characteristic function, the fault diode can be located on line. The experimental results are in agreement with theoretical analysis and demonstrate the effectiveness of the method, which is of great value to improve the reliability of equipments.

Introduction

The 24-pulse uncontrolled diode rectifiers are usually the first interface to the electric utility and widely used at the front end of power electronic equipment in many fields such as the rail transit power systems and vessel electric propulsion systems, which demand for high quality DC voltage[1]-[2]. When the rectifiers are in fault state, the DC output voltage performance will degrade, which may cause system malfunction and electromagnetic interference. So, it is necessary for on-line monitoring and evaluation of the health condition of the rectifiers.

The 24-pulse uncontrolled diode rectifiers are mainly made of power diodes, capacitors and resistors. Faults of rectifiers are usually caused by the power diodes. Diodes damaged and in O-C state would be the most probable fault case for the rectifiers. Diagnostic methods were proposed for classifying fault types by analyzing the DC output voltage waveform of the rectifier [3]-[6]. A detection method was proposed for open-circuit faults in a 3-phase uncontrolled rectifier that forms the input stage of a single-phase current controlled power converter based on fault signatures embedded within the output voltage ripple of the rectifier [7]. A model-based approach for open-switch fault diagnosis of the single-phase pulse width modulation rectifier was proposed, based on the mixed logical dynamic model and residual generation [8]. However, all the diagnostic methods above can only infer the rectifier is under fault state and classify the fault type in general. The exact position where the damaged diodes localized cannot be known.

This paper presents a new online diagnostic method for localization of the fault diodes based on the voltage waveform analysis of the diodes in 24-pulse uncontrolled diode rectifiers under normal and fault conditions. And experiments are carried out to demonstrate the validity of the fault diagnostic method.

System Model

The conventional structure of the 24-pulse uncontrolled diode rectifier contains 4 parts: three-phase AC input, phase displacement traction rectifier transformers, rectifier bridges and load. In order to analysis the circuit structure, the diodes are named as D_1~D_{24}, which are shown in Fig.1.

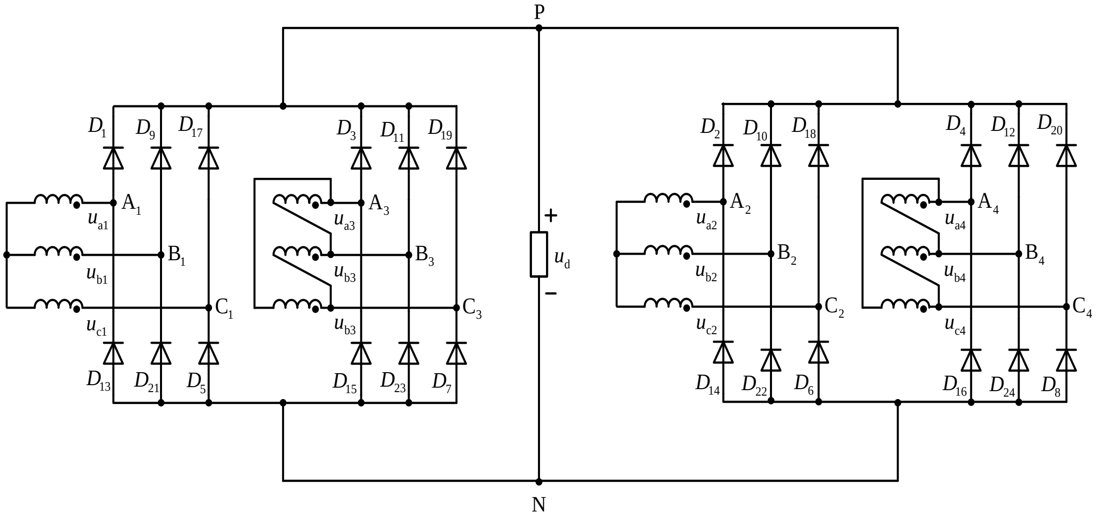

Fig. 1 Structure of 24-pulse uncontrolled diode rectifier circuit.

The input line voltages of the four three-phase rectifier bridges can be expressed as:

$$\begin{cases} u_{\mathrm{a}i\mathrm{b}i} = \sqrt{6}U_{\mathrm{s}} \sin\left(\omega t + 5\pi/24 - (i-1)\pi/12\right) \\ u_{\mathrm{b}i\mathrm{c}i} = \sqrt{6}U_{\mathrm{s}} \sin\left(\omega t + 5\pi/24 - (i-1)\pi/12 - 2\pi/3\right) \qquad i = 1,2,3,4 \\ u_{\mathrm{c}i\mathrm{a}i} = \sqrt{6}U_{\mathrm{s}} \sin\left(\omega t + 5\pi/24 - (i-1)\pi/12 + 2\pi/3\right) \end{cases} \tag{1}$$

Assume that the diodes are equivalent to 0 ohms resistors when they are conducted and very high ohms resistors when they are cut off. The overlap of the current commutation is not in consideration. The power source is ideal. Every diode can only be conducted with the other diodes in the same three-phase bridge. The two diodes with the greatest input line voltage value at a time. According to (1), the input line voltage is the greatest, and D_{18}-D_{22} is conducted. The conducted sequence of the power diodes is: D_{18}-D_{22}, D_{19}-D_{23}, D_{20}-D_{24}, D_{21}-D_1, D_{22}-D_2, D_{23}-D_3, D_{24}-D_4, D_1-D_5, D_2-D_6, D_3-D_7, D_4-D_8, D_5-D_9, D_6-D_{10}, D_7-D_{11}, D_8-D_{12}, D_9-D_{13}, D_{10}-D_{14}, D_{11}-D_{15}, D_{12}-D_{16}, D13-D17, D_{14}-D_{18}, D_{15}-D_{19}, D_{16}-D_{20}, D_{17}-D_{21}, D_{18}-D_{22}.

Voltage Waveform Analysis OF The Diode

In this section, we focus on the analytical analysis of the diode's voltage waveform. The 24-pulse uncontrolled diode rectifiers have 24 diodes in total. The combination of all 24 diodes would be numerous. In most cases, the number of the damaged diodes is not more than 2. So, one diode damaged and in an O-C state would be the most probable fault case for the rectifier and we take that as an example. For all of the 24 diodes are similar, the analysis is done by D_1 for generality.

Voltage Waveform Analysis under Normal Condition

The DC output voltage of 24-pulse uncontrolled diode rectifier under normal condition can be expressed as [9]:

$$u_{\mathrm{d}} = \frac{24\sqrt{6}U_{\mathrm{s}}}{\pi}\sin\left(\frac{\pi}{24}\right)\left(\begin{array}{l} 1+\dfrac{2}{23\times 25}\cos 24\left(\omega t-\dfrac{\pi}{24}\right)-\dfrac{2}{47\times 49}\cos 48\left(\omega t-\dfrac{\pi}{24}\right) \\ +\dfrac{2}{71\times 73}\cos 72\left(\omega t-\dfrac{\pi}{24}\right)-\dfrac{2}{95\times 97}\cos 96\left(\omega t-\dfrac{\pi}{24}\right) \end{array}\right) \tag{2}$$

The three-phase bridge where D1 is located is conducted

In that case, we assume the other 3 three-phase bridges are in the cut-off state. When analyzing D_1 at the $3\pi/12$ moment, D_{21}-D_1 is conducted (denoted by $\mathrm{a}_1^+\mathrm{b}_1^-$) and the voltage value of D_1 is zero. At the $11\pi/12$ moment, D_5-D_9 is conducted (denoted by $\mathrm{b}_1^+\mathrm{c}_1^-$) and the voltage value of D_1 is donated by $-u_{\mathrm{a1b1}}$.The voltage value of D_1 for the other moment when the three-phase bridge where D_1 is located is conducted can be derived in this way. So, u_{D1} can be expressed as

$$u_{\mathrm{D1}}=\begin{cases}0 & when\ \ 3\pi/12\le\omega t<4\pi/12 \quad (\mathrm{a}_1^+\mathrm{b}_1^-)\\ 0 & when\ \ 7\pi/12\le\omega t<8\pi/12 \quad (\mathrm{a}_1^+\mathrm{c}_1^-)\\ -u_{\mathrm{a1b1}} & when\ \ 11\pi/12\le\omega t<12\pi/12 \quad (\mathrm{b}_1^+\mathrm{c}_1^-)\\ -u_{\mathrm{a1b1}} & when\ \ 15\pi/12\le\omega t<16\pi/12 \quad (\mathrm{b}_1^+\mathrm{a}_1^-)\\ u_{\mathrm{c1a1}} & when\ \ 19\pi/12\le\omega t<20\pi/12 \quad (\mathrm{c}_1^+\mathrm{a}_1^-)\\ u_{\mathrm{c1a1}} & when\ \ 23\pi/12\le\omega t<24\pi/12 \quad (\mathrm{c}_1^+\mathrm{b}_1^-)\end{cases} \tag{3}$$

The three-phase bridge where D1 is located is cut off

In that case, the DC output voltage is provided by other 3 three-phase bridges. By equalizing all the diodes to the resistances, the voltage of the diodes is constituted by AC input voltage and DC output voltage according to the circuit superposition principle. The equivalent circuit diagrams are shown in fig.2 and fig.3.

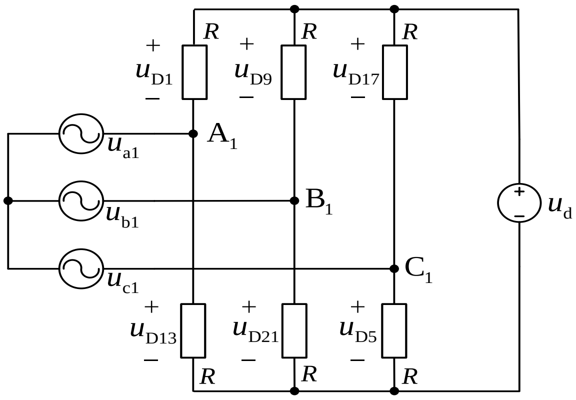

Fig. 2 Equivalent circuit of the three-phase bridge under cut-off state.

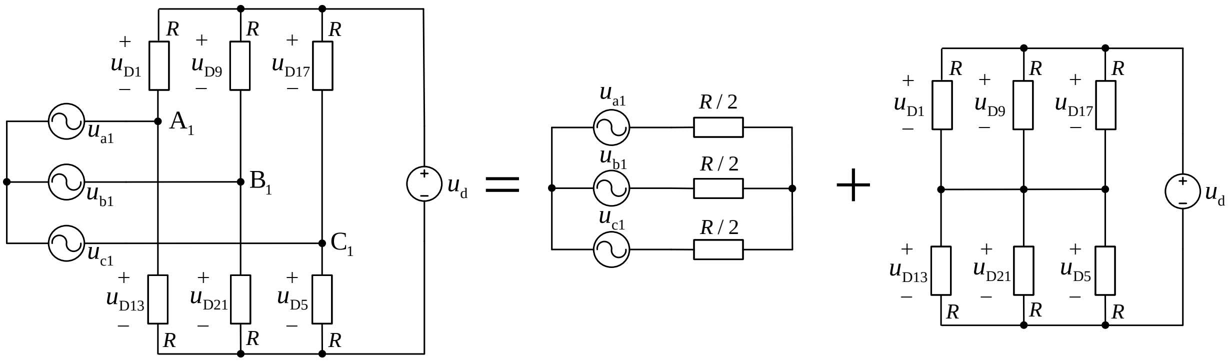

Fig. 3 Equivalent circuit of the fig.2 according to the superposition principle.

In fig.2, according to the KVL theorem, we can get the voltage of D_1

$$\begin{cases} u_{\mathrm{D1}} = u_{\mathrm{d}} - u_{\mathrm{D13}} \\ u_{\mathrm{D1}} = u_{\mathrm{D9}} - u_{\mathrm{a1b1}} \\ u_{\mathrm{D1}} = u_{\mathrm{d}} - u_{\mathrm{D21}} - u_{\mathrm{a1b1}} \\ u_{\mathrm{D1}} = u_{\mathrm{D17}} + u_{\mathrm{c1a1}} \\ u_{\mathrm{D1}} = u_{\mathrm{d}} - u_{\mathrm{D5}} + u_{\mathrm{c1a1}} \end{cases} \tag{4}$$

In fig.3, the expression of each diode in the three-phase bridge under cut-off state is

$$\begin{cases} u_{\mathrm{D1}} = \frac{1}{2}u_{\mathrm{d}} - \frac{1}{3}\left(u_{\mathrm{a1b1}} - u_{\mathrm{c1a1}}\right) \\ u_{\mathrm{D13}} = \frac{1}{2}u_{\mathrm{d}} + \frac{1}{3}\left(u_{\mathrm{a1b1}} - u_{\mathrm{c1a1}}\right) \\ u_{\mathrm{D9}} = \frac{1}{2}u_{\mathrm{d}} - \frac{1}{3}\left(u_{\mathrm{b1c1}} - u_{\mathrm{a1b1}}\right) \\ u_{\mathrm{D21}} = \frac{1}{2}u_{\mathrm{d}} + \frac{1}{3}\left(u_{\mathrm{b1c1}} - u_{\mathrm{a1b1}}\right) \\ u_{\mathrm{D17}} = \frac{1}{2}u_{\mathrm{d}} - \frac{1}{3}\left(u_{\mathrm{c1a1}} - u_{\mathrm{b1c1}}\right) \\ u_{\mathrm{D5}} = \frac{1}{2}u_{\mathrm{d}} + \frac{1}{3}\left(u_{\mathrm{c1a1}} - u_{\mathrm{b1c1}}\right) \end{cases} \tag{5}$$

When formula (5) is calculated, the voltage value of the diode may be less than zero. That means the diode bears negative voltage in the circuit and is in the cut-off state. The voltage value of the diode should be set to zero in that case. For example, during the time period $0 \le \omega t < 3\pi/12$, we get $u_{\mathrm{D21}} < 0$ according to the formula (5). In this situation, we should let $u_{\mathrm{D21}} = 0$ and could get $u_{\mathrm{D1}} = u_{\mathrm{d}} - u_{\mathrm{a1b1}}$ by formula (4). The voltage value of the diode should be set to zero in that case. So when the three-phase bridge where D_1 is located is cut off, u_{D1} can be expressed as

$$u_{\mathrm{D1}} = \begin{cases} u_{\mathrm{d}} - u_{\mathrm{a1b1}} & when\ 0 \le \omega t < 3\pi/12 \quad (\mathrm{c}_2^+\mathrm{b}_2^-,\ \mathrm{c}_3^+\mathrm{b}_3^-,\ \mathrm{c}_4^+\mathrm{b}_4^-) \\ 0 & when\ 4\pi/12 \le \omega t < 7\pi/12 \quad (\mathrm{a}_2^+\mathrm{b}_2^-,\ \mathrm{a}_3^+\mathrm{b}_3^-,\ \mathrm{a}_4^+\mathrm{b}_4^-) \\ u_{\mathrm{d}} + u_{\mathrm{c1a1}} & when\ 8\pi/12 \le \omega t < 11\pi/12 \quad (\mathrm{a}_2^+\mathrm{c}_2^-,\ \mathrm{a}_3^+\mathrm{c}_3^-,\ \mathrm{a}_4^+\mathrm{c}_4^-) \\ -u_{\mathrm{a1b1}} & when\ 12\pi/12 \le \omega t < 15\pi/12 \quad (\mathrm{b}_2^+\mathrm{c}_2^-,\ \mathrm{b}_3^+\mathrm{c}_3^-,\ \mathrm{b}_4^+\mathrm{c}_4^-) \\ u_{\mathrm{d}} & when\ 16\pi/12 \le \omega t < 19\pi/12 \quad (\mathrm{b}_2^+\mathrm{a}_2^-,\ \mathrm{b}_3^+\mathrm{a}_3^-,\ \mathrm{b}_4^+\mathrm{a}_4^-) \\ u_{\mathrm{c1a1}} & when\ 20\pi/12 \le \omega t < 23\pi/12 \quad (\mathrm{c}_2^+\mathrm{a}_2^-,\ \mathrm{c}_3^+\mathrm{a}_3^-,\ \mathrm{c}_4^+\mathrm{a}_4^-) \end{cases} \tag{6}$$

Combining the formula (3) and (6), the analytical voltage expression of D_1 under normal state can be obtained

$$u_{\mathrm{D1}} = \begin{cases} u_{\mathrm{d}} - u_{\mathrm{a1b1}} & when\ 0 \le \omega t < 3\pi/12 \\ 0 & when\ 3\pi/12 \le \omega t < 8\pi/12 \\ u_{\mathrm{d}} + u_{\mathrm{c1a1}} & when\ 8\pi/12 \le \omega t < 11\pi/12 \\ -u_{\mathrm{a1b1}} & when\ 11\pi/12 \le \omega t < 16\pi/12 \\ u_{\mathrm{d}} & when\ 16\pi/12 \le \omega t < 19\pi/12 \\ u_{\mathrm{c1a1}} & when\ 19\pi/12 \le \omega t < 24\pi/12 \end{cases} \tag{7}$$

The u_{D1} in the formula (7) can be extended by Fourier series and can be expressed as

$$u_{\mathrm{D1}}(t) = A_0 + \sum_{n=1}^{\infty}\left[a_n \cos(n\omega t) + b_n \sin(n\omega t)\right] \tag{8}$$

The u_{D1} under normal condition can be calculated by matlab as:

$$
\begin{aligned}
u_{\mathrm{D1}}(t) = & 1.2213U_{\mathrm{s}} + 1.414U_{\mathrm{s}}\cos(\omega t + 13\pi/24) + 0.1995U_{\mathrm{s}}\cos(3\omega t + 15\pi/24) \\
& + 0.008262U_{\mathrm{s}}\cos(9\omega t + 21\pi/24) + 0.0029U_{\mathrm{s}}\cos(15\omega t - 21\pi/24) \\
& + 0.003624U_{\mathrm{s}}\cos(21\omega t - 15\pi/24) + 0.004248U_{\mathrm{s}}\cos(24\omega t + \pi)
\end{aligned} \tag{9}
$$

The analytical calculation and model simulation results under normal condition are shown in Fig.4. ($U_{\mathrm{s}} = 380V$)

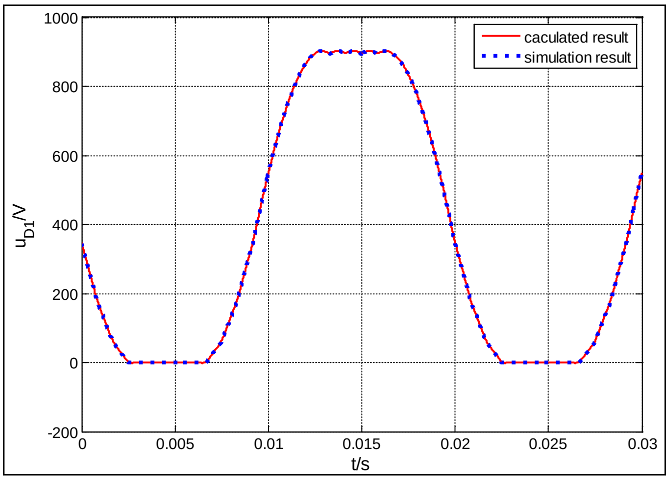

Fig. 4 The analytical and simulation results of the diode's voltage under normal condition.

Voltage Waveform Analysis under Fault Conditions

The voltage expression of the rectifying element under fault condition can be obtained in a similar way to that under normal condition. The analytical voltage expression of D_1 under fault state can be obtained by Fourier series and $u_{\mathrm{D1}}^{\mathrm{f}}$ can be expressed as

$$
\begin{aligned}
u_{\mathrm{D1}}^{\mathrm{f}}(t) = & 1.2211U_{\mathrm{s}} + 1.4938U_{\mathrm{s}}\cos(\omega t + 13\pi/24) + 0.07686U_{\mathrm{s}}\cos(2\omega t + 2\pi/24) \\
& + 0.2125U_{\mathrm{s}}\cos(3\omega t + 15\pi/24) + 0.05356U_{\mathrm{s}}\cos(4\omega t - 20\pi/24) \\
& + 0.03930U_{\mathrm{s}}\cos(5\omega t + 17\pi/24) + 0.02549U_{\mathrm{s}}\cos(6\omega t - 18\pi/24) \\
& + 0.01915U_{\mathrm{s}}\cos(7\omega t - 5\pi/24) + 0.01062U_{\mathrm{s}}\cos(8\omega t - 16\pi/24) \\
& + 0.009417U_{\mathrm{s}}\cos(9\omega t - 3\pi/24) + 0.005680U_{\mathrm{s}}\cos(10\omega t + 10\pi/24) \\
& + 0.004640U_{\mathrm{s}}\cos(24\omega t - \pi)
\end{aligned} \tag{10}
$$

The analytical computation and model simulation results under fault condition are shown in Fig.5. ($U_{\mathrm{s}} = 380V$)

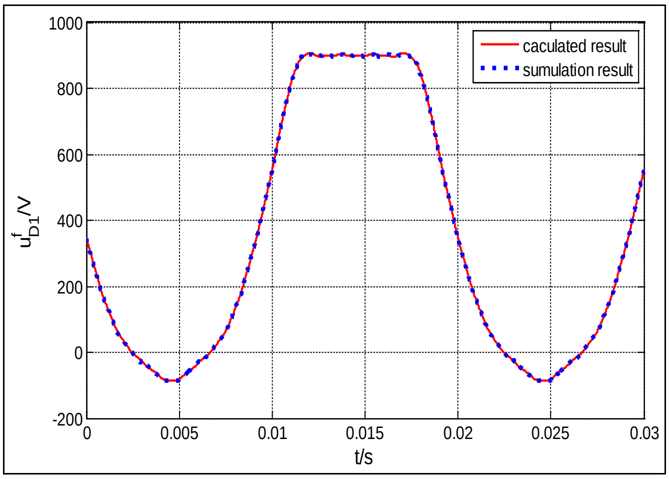

Fig. 5 The analytical and simulation result of the diode's voltage under fault condition.

Fault Diagnosis and Experiment Results

From the analysis above, the voltage value of D_1 is above zero under normal condition and the voltage value of D_1 is obviously below zero in a certain interval under fault condition. The diodes under normal condition have a good unilateral conductivity and the forward voltage value is approximately zero. However, the forward voltage value of diode under fault condition is much greater. We can define the fault characteristic function by the diode's forward voltage value. The fault function is defined as

$$f_{\mathrm{D}i}(t)=\begin{cases}u_{\mathrm{D}i}(t) & \text{when } u_{\mathrm{D}i}\le 0\\ 0 & \text{when } u_{\mathrm{D}i}>0\end{cases}\qquad i=1\sim 24 \tag{11}$$

The characteristic value of the fault function is calculus of the diode's voltage sampling data on several sampling period. The characteristic value λ is defined as

$$\lambda=\int_0^T\left|f_{\mathrm{D}i}(t)\right|\mathrm{d}t\qquad i=1\sim 24 \tag{12}$$

The characteristic value is determined by the diode's forward voltage value, the ration of the voltage divider and the number of sample points in the calculus. Experiment was performed to demonstrate the validation of the fault diagnostic method based on the voltage waveform analysis. A three-phase synchronous generator was used as three-phase power source. Three-phase supply was given into phase-shifting transformers connected to four three-phase bridges converting three-phase AC to DC. Fig. 6 shows the diode's voltage waveforms under normal and fault conditions.

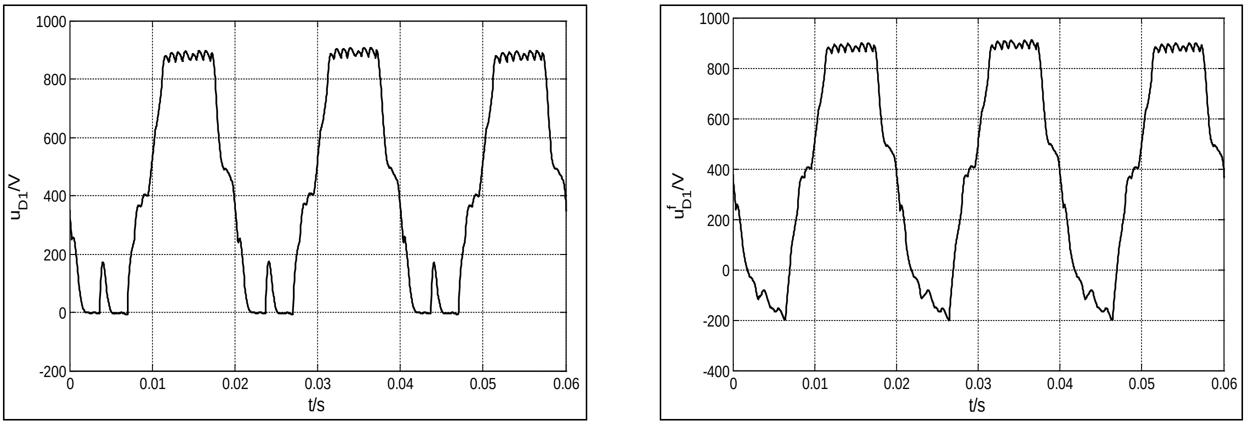

Fig. 6 The experimental voltage waveform of the diode under normal and fault condition.

The experimental results are consistent with theoretical analysis of the diode's voltage waveform. The absolute value of the diode's forward voltage is approximately zero under normal condition and is much greater than zero under fault condition. In the experiment, we chose λ=120 as the characteristic value of the fault function. With the sampling data and fault characteristic function, the fault characteristic value can be calculated out as being 14 under normal condition and 195 under fault condition. The experiment result shown that the fault detection method was valid.

Conclusion

We have proposed a fault diagnostic method of 24-pulse rectifier based on the voltage waveform analysis. Considering one diode of the rectifier damaged and in an O-C state, the analytic expression of the diode's voltage waveform was derived in detail under normal and fault condition. The analytic results are consistent simulation ones and we can judge the state of the diodes by a diagnosis characteristic function which is defined by the diode's forward voltage value. The fault diagnostic method is verified by the experiments and the method can be extended and applied to complex fault of the rectifiers.

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