Study on Ripple Characteristics of Uncontrolled Rectifier Circuit

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Abstract. The ripple in DC charging is a basic indicator of the voltage quality, which is related to the filter capacitor and external load. In this paper, the single-phase bridge rectifier circuit is used as the research object. It analyzes the generation process of ripple voltage and derives the expression of ripple voltage. And the effects of filter capacitor C, voltage U and external load R on the ripple coefficient are simulated and analyzed, as well as the spectrum distribution characteristics of the ripple.

Introduction

With the development of electric vehicles, the application of DC charging device is more and more popular\textsuperscript{[1,2]}. Usually when AC power is treated with processes such as rectification, filtering and voltage stabilizing, we can get DC power. Due to the limes of filter capacitance or inductance, it is inevitable that the DC output voltage consists of AC component, which is also called ripple\textsuperscript{[3]}. Ripple is the key performance index of the charging device, which reflects the ability of the device outputting steady DC voltage. There are different requirements in different application areas (such as electrolysis, battery charging, etc.). What’s more, the ripple is also related to the working state of charging.

At present, there are mainly two methods to measure the ripple voltage, oscilloscopes and AC voltmeter, the former can be directly used for waveform measurement and can measure many waveforms, while the accuracy is general; the latter can be with high sensitivity and can measure quite small AC voltage\textsuperscript{[4]}, while cannot give direct information of DC voltage. There are also many simulation studies about ripple, which mostly focus on specific ripple calculation. But the studies lack of systematic derivation and simulation verification. Therefore, the paper intends to deduce the expression of ripple voltage, and investigates the characteristics of R, C parameters and ripple voltage with ripple coefficient in the time domain while with spectral line in the frequency domain.

In this paper, the single-phase rectifier circuit is studied. Use Multisim to simulate DC charging and output DC voltage with ripple; then analyze ripple voltage with Matlab, calculate ripple coefficient and analyze ripple voltage spectrum. Last, analyze the relationship of AC voltage amplitude and ripple coefficient.

Single-phase Bridge Uncontrolled Rectifier Circuit

The single-phase bridge uncontrolled rectifier circuit is shown in Figure 1. Because the circuit transient process is relatively short, the stable working state of the circuit is analyzed emphatically.
The capacitor C in the figure is the filter capacitor of the DC charging device, and the load is considered as a resistance. Fig. 1 (b) is the voltage waveform in the steady state of the circuit. It is periodic and the frequency is 2 times of the power frequency, so the waveform in one cycle is considered in the analysis.

![Figure 1. Single phase bridge uncontrolled rectifier circuit and its working waveform.](image)

There are two stages, capacitor charging and discharging process, are shown in figure (2). In the charging process, rectifier diode VD₁ and VD₄ are conductive, the output voltage is the voltage of power supply; and in the discharging stage, the diode are in off, the output voltage is determined by the filter capacitor discharge voltage. Thus, the expression of the DC voltage output in the charging circuit can be expressed as a piecewise functional:

\[
U_d(t) = \begin{cases} 
\sqrt{2}U'_1 \sin(\omega t + \delta) & 0 < t < \theta/\omega \\
\sqrt{2}U'_1 \sin(\theta + \delta)e^{-\omega t/RC} & \theta/\omega < t < \pi/\omega
\end{cases}
\]  

(1)

The δ is the phase between turn-on time of the diode and the zero crossing point, and the θ is the conduction angle. In the discharging process of the filter capacitor, the output voltage is given by the RC discharge circuit and attenuates exponentially. The time constant is 1/RC. The process of determining the conduction angle is that when \(\omega t = \theta\), the voltage in the side of the filter capacitor is higher than the supply voltage, and then the VD₁ and VD₄ turn off, finally, the charging process is over. When the diode is switched, the filter capacitor and the load resistance current are satisfied:

\[
i_d = \sqrt{2} \omega C U_1 \cos(\omega t + \delta) + \sqrt{2} U_1 \sin(\omega t + \delta) / R
\]  

\[= 0
\]  

(2)

Thus obtained

\[
tan(\theta + \delta) = -\omega RC
\]  

(3)

With the discharge of the filter capacitor, the output voltage drops. When the amplitude of the supply voltage in the second half is higher than the capacitor voltage, the diode VD₁ and VD₂ are turned on, and the filter capacitor starts the next charging cycle. At the diode opening time,

\[
\sqrt{2}U'_1 \sin(\theta + \delta)e^{-\omega t/RC} = \sqrt{2}U'_1 \sin \delta
\]  

(4)
As we know, the $\delta + \theta$ is the angle of the second quadrant, which can be obtained by formula (3) and formula (4):

$$\pi - \theta = \delta + \arctan(\omega RC)$$  \hspace{1cm} (5)$$

$$\frac{\omega RC}{\sqrt{(\omega RC)^2 + 1}} e^{-\arctan(\omega RC)/\omega RC} e^{-\delta/\omega RC} = \sin \delta$$  \hspace{1cm} (6)$$

When the $\omega RC$ is known, the $\delta$ can be obtained by formula (6) and then the $\theta$ can be obtained by formula (5). $\delta$ and $\theta$ depend on the $\omega RC$ and are determined by the circuit parameters.

Based on the definition of the effective value.

$$U_i = \sqrt{\frac{1}{T} \int_0^T u_i^2 dt}$$

$$= \frac{1}{T} \left( \int_0^{\pi/\omega} \left( \sqrt{2} U_1 \sin(\omega t + \delta) \right)^2 dt + \int_{\pi/\omega}^{2\pi/\omega} \left( \sqrt{2} U_1 \sin(\theta + \delta) e^{-\omega t + \delta)} e^{-\omega RC} \right)^2 dt \right)$$

$$= \frac{U_i^2}{\pi} - \frac{U_i^2}{2\pi} (\sin 2(\theta + \delta) - 2\sin 2\delta - \frac{\omega RC U_i^2}{\pi} \sin^2(\theta + \delta)(e^{\frac{2\pi}{\omega RC}} - 1)$$  \hspace{1cm} (7)$$

According to the definition of ripple factor, the ripple factor is the ratio of the effective value of ripple voltage and DC component of the ripple voltage $[5]$.

$$\gamma = \frac{U_i}{U_d}$$  \hspace{1cm} (8)$$

Where $U_i$ is Ripple voltage, $U_d$ is DC component of the ripple voltage

At $RC \geq (3-5)T/2$, $U_d \approx 1.2U_i$, you can see that the ripple factor only depends on $\omega RC$.

**Simulation**

This section mainly simulates rectifier circuit by Multisim and then analyze the influence of $R$, $C$ on ripple harmonic parameters. The simulation result is the same with that of the theory, then single-phase rectifier circuit simulation process is given. Take $U_i=15V$, $f=50Hz$, $\omega = 2\pi f$ in Figure 1 (a).

**Influence of AC Voltage U on Ripple**

Set the AC voltage amplitude $U_i = 30V, 45V, C=1000\text{uf}$, $R=20$. Carry on simulation, and analyze by MATLAB. When $U_i=15V$, the ripple factor is 1.0095.

<table>
<thead>
<tr>
<th>U1</th>
<th>Ripple factor</th>
<th>Relative error</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>1.0059</td>
<td>0</td>
</tr>
<tr>
<td>45</td>
<td>1.0059</td>
<td>0</td>
</tr>
</tbody>
</table>
It can be seen that the amplitude of the AC voltage has no influence on the ripple factor, and the ripple factor only depends on $\omega RC$.

**Influence of R and C on Ripple Harmonic Parameters**

Analyze ripple voltage in frequency domain to investigate distribution of spectrum. The spectrum analysis adopts Hanning window interpolation FFT algorithm \[6\], and the window length is 10 cycles. In order to reflect the changes of harmonic amplitude with frequency more accurate, logarithmic coordinate is used. The ordinate amplitude is defined as:

$$A_h = 20 \log \left( \frac{V_h}{V_j} \right)$$

where, $V_h$ is the amplitude of the $h$ harmonic, and $V_j$ is the primary voltage effective value.

Select $C=1000\mu F$, $R=20\Omega$, $30\Omega$, $40\Omega$, get the ripple voltage signal through the Multisim simulation, the results of harmonic analysis is as shown in Figure 2, when the capacitor $C$ is constant, harmonic voltage amplitude decreased with the increasing of external load. The number of harmonics is even, and the harmonic content decreases with the increasing of harmonic number. The ripple factor decreases as the resistance increases.

Then, select $R=20\Omega$, $C=800\mu F$, $900\mu F$ and $1000\mu F$, and get the ripple voltage by Multisim simulation, and analyze the spectrum distribution, the result is as shown in figure 3. When the external load $R$ is constant, the amplitude of the harmonic voltage in the ripple signal decreases with the increasing of the capacitance. The number of harmonics is even, and the harmonic content decreases with the increasing of harmonic number. The ripple factor decreases as the capacitance increases.

**Influence of R and C on Current Harmonics**

Analyze ripple current in frequency domain to investigate the spectrum distribution based on the method used in 3.2.

$$A_h = 20 \log \left( \frac{I_h}{I_j} \right)$$

where, $I_h$ is the amplitude of the $h$ harmonic, and $I_j$ is the primary side current effective value.
Select C=1000uF, R=20Ω, 30Ω, 40Ω, get the ripple voltage signal through the Multisim simulation, the results of harmonic analysis is as shown in Figure4, when the capacitor is constant, harmonic amplitude of the harmonic signal increases with the increasing of external load. The harmonic number is odd, and the harmonic content decreases with the increasing of harmonic number. The harmonic distortion rate increases with the increasing of resistance.

![Figure 4. Influence of resistance.](image1)

![Figure 5. Influence of capacitance.](image2)

Then, select R=20Ω, C=800uF, 900uF and 1000uF, and get the ripple voltage by Multisim simulation, and analyze the spectrum distribution, the result is as shown in figure 5. When the external load is constant, the harmonic amplitude in the harmonic signal increases with the increasing of capacitance. The harmonic number is odd, and the harmonic content decreases with the increasing of harmonic number. The harmonic distortion rate increases with the increasing of capacitance.

Concluding

The paper deduces expressions of DC output voltage of single-phase and uncontrolled rectifier circuits; then calculates parameters of voltage expression with Matlab and analyzes ripple by Hanning window interpolation FFT; Finally, simulates charging circuit by Multisim. The results show that the magnitude of AC voltage does not affect the ripple factor, and the ripple factor is only related to the parameters of the DC side. The number of harmonics is even, and the harmonic content decreases with the increasing of harmonic number. The ripple factor decreases as the capacitance increases, and decreases as the resistance increases.

References