4-21-2023

Single-Phase Controlled Full-Wave Thyristor Bridge Rectifier with RL Load and Continuous Current

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***Abstract*—This report investigates the power electronics design of a Single-Phase Controlled Full-Wave Thyristor Bridge Rectifier with RL Load and Continuous Current through PSIM circuit simulations, the calculation for and the generation of circuit parameters, and analysis of underlying principles causing thyristor switching effects, load outputs, and generations of circuit's SIMVIEW waveforms.**

***Index Terms*—Full-Wave Rectifiers, Single-Phase Controlled Full-Wave Rectifier with RL Load and Continuous Current, thyristor switching, thyristor bridge, alpha control, PSIM, SIMVIEW Waveforms, Fourier Series analysis, harmonics, power electronics**

I. Introduction

THIS REPORT is a technical paper for the Final Term Project (Undergraduate) required by EE511: Power Electronics. The objective of the investigation is to design a circuit that meets the following specifications: [1] Generates an average current of 15A across the load resistor, [2] obtains a peak-to-peak variation in load current that is no more than 10% of the dc current, and [3] has a voltage source that is a single-phase 480-V rms at 60 Hz. The report must show the calculation or generation of the average, RMS, and peak currents in each circuit element. Since additional circuit elements are permitted to be added, an inductor is added in series with the resistive load to satisfy the requirement of an average current of 15A across the resistive load. The alpha and inductor values are determined through calculations. The circuit simulation in PSIM and respective waveform generations in SIMVIEW accompany the theoretical calculations and are used to verify that the circuit meets the specifications. *Note:* The derived expressions, numerical values, and circuit design are obtained using equations and standard circuit configurations from "Power Electronics, 1st Edition" by Daniel W. Hart.

II. Power Electronics Circuit Theory

A. Controlled Rectifier with RL Load and Continuous Current

A controlled rectifier with 4 thyristors and an RL Load is shown in a theoretical circuit below:

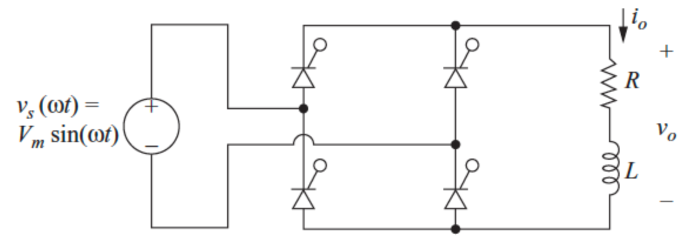

Figure 1. Controlled rectifier with RL Load

The associated theoretical output current and voltage waveforms for a continuous current is shown below:

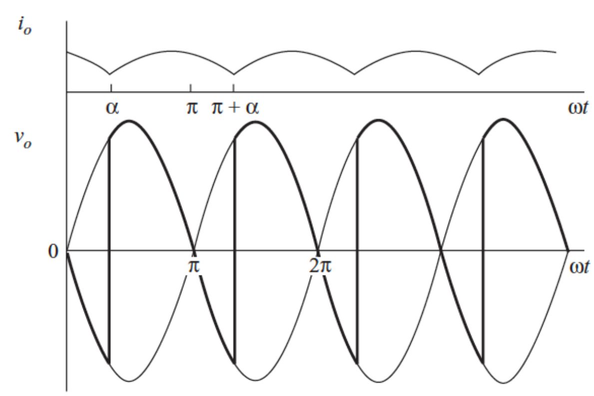

Figure 2. Continuous current load outputs for controlled rectifier with RL Load

The generated SIMVIEW waveforms should resemble these theoretical current and voltage output waveforms if the current is continuous. To find if the current is continuous, the alpha value, α, must be compared with the value of θ.

III. Theoretical Calculations in Application

A. Alpha and DC Values

$$\theta = tan^{-1}(\frac{\omega L}{R})$$

$\alpha \le tan^{-1}(\frac{\omega L}{R})$ for a continuous current.

With $\omega = 2\pi f \approx 377\ rad/s$, $R = 20\Omega$, and $L = 1\ H$,

$$\theta = tan^{-1}\left(\frac{\omega L}{R}\right) = tan^{-1}(18.85) \approx 86.96°$$

$\alpha \le tan^{-1}(\frac{\omega L}{R})$ means $\alpha \le 86.96°$ for a continuous current. The chosen α value is 45°.

The dc (average) value is:

$$V_O = \frac{1}{\pi}\int_{\alpha}^{\alpha+\pi} V_m \sin(\omega t)\, d(\omega t) = \frac{2V_m}{\pi} cos\alpha$$

$$V_O = \frac{2\sqrt{2}\,(480)}{\pi}\cos(45°) \approx 305.58\ V$$

$$V_O = I_O \times R$$
$$305.58\ V = I_O \times 20\ \Omega$$

$$I_O \approx \frac{305.58\ V}{20\ \Omega}$$

$$I_O \approx 15.28\ A$$

$$I_{dc} \approx 15.28\ A$$

B. Fourier Series Harmonics Analysis for Ripple Current and RMS Current Calculations

Using Fourier Series analysis, I_{rms} can be approximated from the dc term and only the second harmonic term (where $n = 2$), as the higher-frequency terms produce negligible values.

$$V_n = \sqrt{{a_n}^2 + {b_n}^2}$$

$$a_n = \frac{2V_m}{\pi}\left[\frac{\cos\,[(n+1)(\alpha)]}{n+1} - \frac{\cos\,[(n-1)(\alpha)]}{n-1}\right]$$

$$b_n = \frac{2V_m}{\pi}\left[\frac{\sin\,[(n+1)(\alpha)]}{n+1} - \frac{\sin\,[(n-1)(\alpha)]}{n-1}\right]$$

where $n = 2, 4, 6, \ldots$

After substitution of values, for $n = 2$,

$$a_2 = 432.1518318\left[\frac{\cos\,(135°)}{3} - \frac{\cos\,(45°)}{1}\right]$$
$$a_2 \approx -407.4366544$$

$$b_2 = 432.1518318\left[\frac{\sin\,(135°)}{3} - \frac{\sin\,(45°)}{1}\right]$$
$$b_2 = -203.7183272$$

$$V_2 = \sqrt{{a_2}^2 + {b_2}^2}$$
$$V_2 = \sqrt{(-407.4366544)^2 + (-203.7183272)^2}$$
$$V_2 = 455.5280279\ V$$

$$I_n = \frac{V_n}{Z_n} = \frac{V_n}{|R + jn\omega L|}$$

$$I_2 = \frac{V_2}{Z_2} = \frac{455.5280279}{|20 + j(2)(377)(1)|}$$

$$I_2 \approx 0.604148578\ A$$

$$I_{rms} \approx \sqrt{{I_o}^2 + \sum_{n\,=\,2,4,6,\ldots}^{\infty} (\frac{I_n}{\sqrt{2}})^2}$$

$$I_{rms} \approx \sqrt{(15.28)^2 + (\frac{0.604}{\sqrt{2}})^2}$$

$$I_{rms} \approx 15.286\ A$$

IV. Circuit Simulation and Waveforms

A. PSIM Circuit Simulation

The Single-Phase Controlled Full-Wave Thyristor Bridge Rectifier with RL Load and Continuous Current using a single-phase ac voltage source, an ideal transformer, a single-phase thyristor bridge control module, and an alpha control unit is designed in PSIM. A current probe is wired in series with the RL load to obtain the measurements of the average, RMS, and peak current values across the load resistor and inductor. A voltage probe is wired across the RL load to obtain the expected output voltage waveforms that correspond with a continuous current. The alpha control unit is used to set the calculated alpha value that causes the continuous current. Since the given voltage source is 480-V rms, the voltage value set at the voltage source as $V_{max} = \sqrt{2} \times 480 \approx 678.823\ V$ in PSIM.

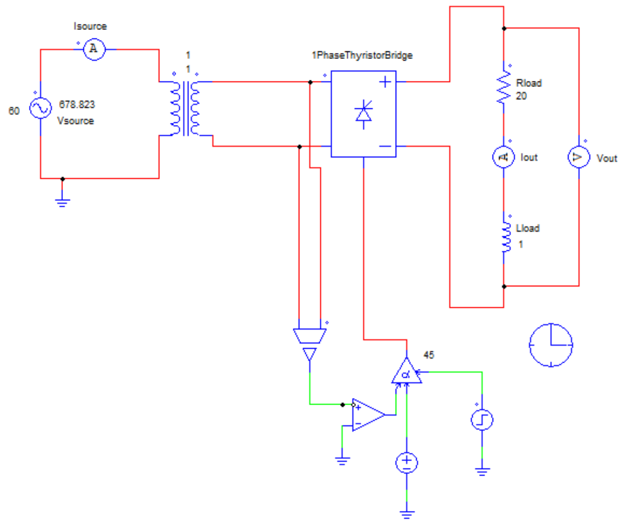

Figure 3. Single-Phase Controlled Full-Wave Thyristor Bridge Rectifier with RL Load and Continuous Current in PSIM

B. SIMVIEW Plot of Output Current Across RL Load

The specifications require that:

$$I_{p-p,load} < (0.10)(I_{dc})$$
$$I_{p-p,load} < (0.10)(15\text{ A})$$
$$I_{p-p,load} < 1.5\text{ A}$$

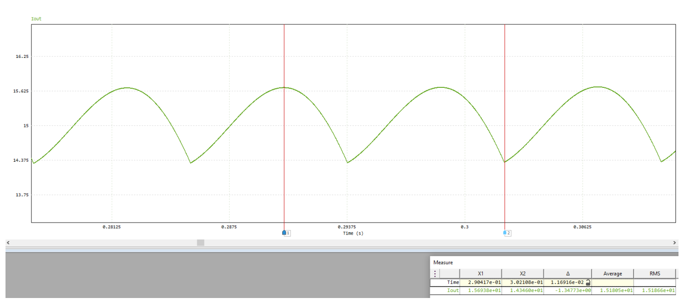

Figure 4. Output current waveform and measurements for peak load current, average load current, and rms load current

As shown in the output current waveforms above, $I_{p-p,load}$ ≈ 1.3478 A, which is below the maximum allowable peak differential between the maximum and minimum values of the output load current, as per the specifications.

From the measurement probes, $I_{peak} \approx 15.6938\ A$, $I_{avg} \approx 15.1805\ A$, and $I_{rms} \approx 15.1866\ A$.

C. SIMVIEW Plot of Output Voltage Across RL Load

The output voltage waveform shape verifies that the current is continuous.

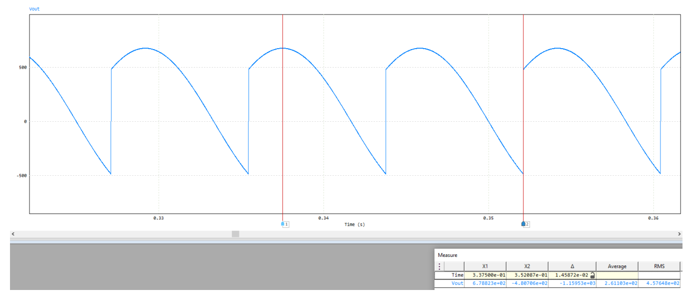

Figure 5. Output voltage waveform and measurements

The measurement probes show that the output rms voltage ≈ 457.648 V, which is significantly close to the calculated value of 455.5280279 V.

V. Conclusion

This report is for the power electronics project investigating the Single-Phase Controlled Full-Wave Thyristor Bridge Rectifier with RL Load and Continuous Current. The theoretical waveforms, hand calculations, PSIM waveforms, and PSIM values all verify each other and meet the specifications given in the project's requirements. The calculations are found for the two elements in the load, across the resistor and inductor, while the second harmonic current in the Fourier Series analysis is used in the ripple current calculation.

References and Footnotes

References

[1] Hart, Daniel W., "Power Electronics, 1st Edition," New York: McGraw Hill Higher Education, 2011. ISBN: 13-9780073380674
[2] Powersim, PSIM Release 2021a.

Haruka Kido received a Bachelor of Science (B.S.) in interdisciplinary studies (minor in architecture) from Cornell University, Ithaca, NY in 2017. She has recently worked as an Embedded Processing Intern for NASA and is currently studying towards earning a Bachelor of Science (B.S.) in electrical engineering (minor in mathematics) from the University of North Dakota.