Single Phase Controlled Rectifier using TN3050H-12 Thyristor and VS-E5PX3012 Diode: Power Control and Energy Efficiency in Marine Applications

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Abstract: - This paper is the result of research on the application of a single-phase controlled rectifier using TN3050H-12LY type thyristor and VS-E5PX3012 type diode, focusing on its application in an electric propulsion system for ships. This rectifier allows precise control of the DC power supplied to the load, optimizing the performance of the propulsion motor while increasing energy efficiency. This paper provides detailed calculations for the output DC voltage, power control through phase angle modulation, system efficiency, and thermal management. The simulation results with an AC voltage of 400 V, 50 Hz with the rectifier system and components used are capable of producing voltages up to 360 Volts DC and can deliver electrical power of around 12 kW with a variation in the trigger angle and an efficiency of around 90% in its working area.

Key-Words: - Single-Phase Controlled Rectifier, Thyristor, Power Efficiency, Marine Propulsion, TN3050H-12LY

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1 Introduction

Energy efficiency in marine propulsion systems has been an issue and a growing demand for solutions over the past decade. With increasing awareness of environmental regulations and fuel economy, the marine industry is turning to technologies that optimize power usage while maintaining reliable performance. One of the key components in these systems is the rectifier, which converts alternating current (AC) to direct current (DC) to power motors or charge energy storage systems.

Specifically, controlled rectifiers using thyristors allow for precise modulation of the DC output voltage, providing adjustable power delivery to the load. This makes them ideal for propulsion systems that require variable speed and torque control. Traditional rectifiers can only deliver a fixed voltage, but by incorporating thyristors in the design, the rectifier can control the output voltage based on system demands, [1].

Electric motors for ship propulsion may be either DC or AC. DC motor drives are still used where very high torque and or precise speed control is acquired. Traction drives, such as electric trains and submarines, use DC motors. The torque is governed by magnetic field and electric current, and the speed is due to electric voltage comparable to electrical voltage and inversely proportional to magnetic field, [2]. The real ratings of the electrical equipment 230/400 volt, 50 Hz, [3]. One of the options of the electric propeller system is shown in Figure 1.

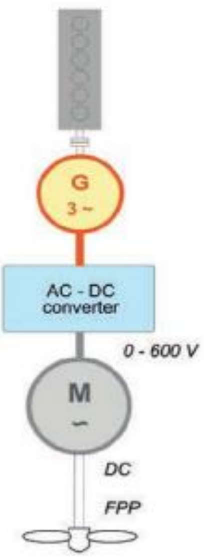

Fig. 1: DC electric propulsion option, [1]

This paper explores the design and efficiency of a single-phase full-wave controlled rectifier using two TN3050H-12LY thyristors and two VS-E5PX3012 diodes. The rectifier is designed to operate in marine propulsion systems, where it will regulate the power delivered to electric motors that drive ship propellers. The thyristors allow phase angle control of the rectified output, enabling dynamic speed and power control of the motors, [4], [5]. A simple overview of the system is shown in Figure 2. In this paper, we will discuss the technical specifications of the components used, circuit configuration, output power calculations, efficiency analysis, and component temperature management considerations. [6], [7].

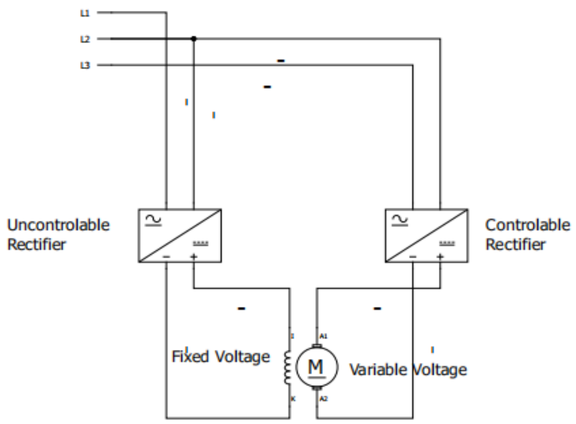

Fig. 2: Simple overview of DC motor driving

2 Single-Phase Controlled Rectifier Configuration

The rectifier's configuration allows it to convert the AC supply from the marine vessel's power generation system into a controlled DC output. The circuit operates in two modes: during the positive half-cycle of the AC input, one thyristor and one diode conduct, delivering power to the load. During the negative half-cycle, the other thyristor and diode pair take over, ensuring continuous power flow. Figure 3 illustrates the basic circuit diagram of the rectifier, including the placement of the thyristors, diodes, AC source, and load. The circuit layout is designed to maximize power delivery while maintaining control over the output voltage. GTC (*Gate Triggering Control*) is a circuit to control thyristor firing angle.

The motor uses resistors and inductors in series to model the motor R = 10 Ω, L = 100 mH. A basic circuit design is shown in Figure 3.

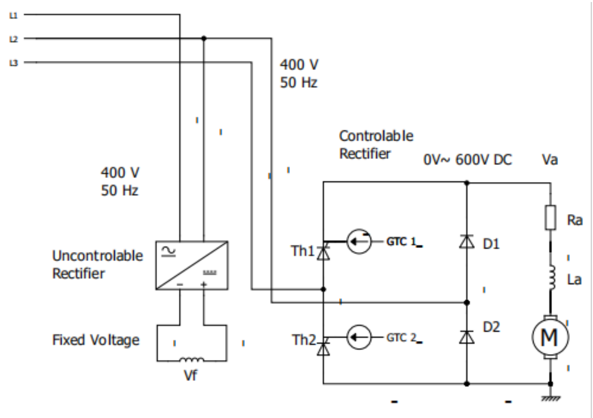

Fig. 3: Illustrated basic circuit proposed

3 Power Control Calculations

The power control in this rectifier is achieved by adjusting the firing angle of the thyristors. By delaying the point at which each thyristor is triggered within the AC cycle, the effective output voltage can be reduced or increased according to the system's requirements, [6].

3.1 Output Voltage Control

The output DC voltage of the rectifier can be calculated as a function of the firing angle α. The general expression for the output voltage of a single-phase full-wave controlled rectifier is:

$$V_{out(DC)} = \frac{2V_m}{\pi}.\cos(\alpha) \tag{1}$$

where V_m is the peak AC voltage and is the firing angle (in degrees). As the firing angle increases, the output voltage decreases, allowing for finer control over the motor's speed and power consumption.

As shown in Figure 3 when the effective voltage is 400 volts [3], then the approximate peak voltage is (*ideal sine wave assumption*):

$$V_m = \sqrt{2}.\ V_{eff} \tag{2}$$

$$V_m = 566\, Volt$$

3.2 Power Output

The power delivered to the load is a function of the output voltage and the resistance and inductance of the load. The general expression for the output voltage of a single-phase full-wave controlled rectifier is:

$$P_{out} = \frac{V^2_{out(DC)}}{R_{load}} \tag{3}$$

4 Energy Efficiency of the Rectifier

Energy efficiency is a crucial factor in marine propulsion systems, where fuel economy and environmental impact are of primary concern. The efficiency of the controlled rectifier depends on both the conduction and switching losses in the thyristors and diodes.

The efficiency η of the rectifier is defined as the ratio of the output power to the input power.

$$\eta = \frac{P_{out}}{P_{in}} \tag{4}$$

The input power for a single-phase system can be calculated as:

$$P_{in} = V_{in(effective)} . I_{in(effective)} . cos(\theta) \tag{5}$$

$$\theta = tg^{-1} \frac{2\pi . f . L}{R} \tag{6}$$

where is the $I_{in(effective)}$ input current and $cos(\theta)$ The power factor is load impedance angle.

5 Thermal Management

Thyristors and diodes generate heat during operation due to conduction and switching losses. Effective thermal management is critical to ensure that the components operate within their safe temperature limits, especially in high-power applications such as marine propulsion, [6], [7].

5.1 Conduction Losses

The conduction loss in each thyristor is calculated as the product of the forward voltage drop $V_{T(on)}$.and the current flowing through the device, the conduction loss is:

$$P_{loss\ (conduction)} = V_{T(on)} . I_{load} \tag{7}$$

5.2 Switching Losses

Switching losses occur when the thyristor transitions from the off-state to the on-state. These losses are dependent on the switching speed and the current.

$$P_{loss(switching)} = \frac{1}{2} . V_T . I_{load} . f . t_s \tag{8}$$

6 Simulation and Results

Using LTspice, we simulated the performance of the single-phase controlled rectifier with varying firing angles. The results confirm that the output voltage and power delivered to the load are directly proportional to the firing angle. At lower firing angles, the rectifier delivers higher DC voltage and more power to the load, while at higher firing angles, the output voltage decreases.

6.1 Power Output

The output DC voltage of the rectifier and the power delivered to the load is a function of the output voltage as a function of the firing angle α and load resistance 10 Ω, shown in Table 1.

Table 1. The output DC voltage of the rectifier

Firing Angle		Vout (Volt)	Pout (Watt)
(Degree)	(Radian		
0	0	360.18	12,973.09
15	0.08333333333	358.93	12,883.21
30	0.1666666667	355.19	12,616.05
45	0.25	348.98	12,179.03
60	0.3333333333	340.36	11,584.24
90	0.5	316.09	9,991.24
120	0.6666666667	283.06	8,012.43
150	0.8333333333	242.19	5,865.63
170	0.9444444444	211.14	4,457.84

Figure 4 shows the output current waveform for GTC1 and GTC2 to firing angle based on PWM simulation on LTSpice. The gate current trigger current is only about 80 mA.

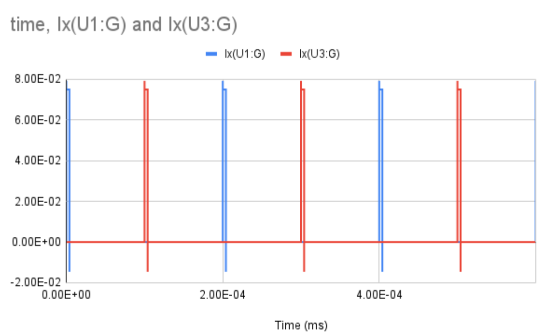

Fig. 4: Gate triggering control graph

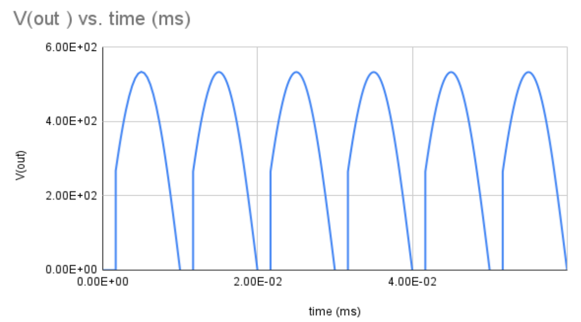

Fig. 5: Output voltage waveform for a firing angle of 30° degree

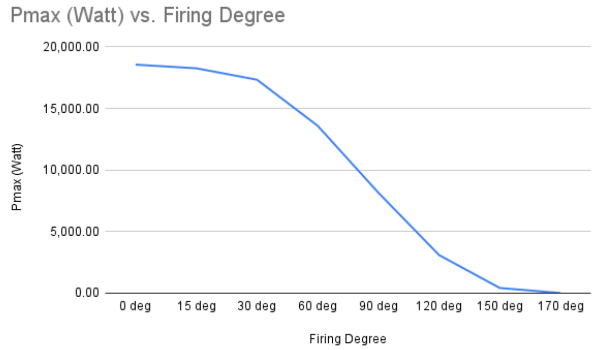

Fig. 6: Power delivered to the load as a function of the firing angle

Figure 5 shows the output voltage waveform for a firing angle of 30° degree, while Figure 6 depicts the power delivered to the load as a function of the firing angle. These results validate the theoretical calculations presented earlier and demonstrate the rectifier's ability to control the output power effectively.

6.2 Energy Efficiency of the Rectifier

In this case the motor uses resistors and inductors in series to model the motor R = 10 Ω, L = 100 mH, the effective voltage is 400 volts and frequency 50 Hz, the efficiency can be calculated. The load impedance angle is about 17,67 degrees, so the power factor is about 0,952846. The efficiency of firing angle respectively is shown in Table 2.

To regulate the power delivered to electric motors that drive ship propellers. The thyristors allow phase angle control of the rectified output, enabling dynamic speed and power control of the motors 15 to 90 degrees effectively in operation mode.

Table 2. Efficiency of the rectifier

Firing Angle	Out Power	Electric Current	Input Power	Efficiency
(Degree)	(Watt)	(Ampere)	(Watt)	
0	12,973.09	36.02	13,727.91	94.50%
15	12,883.21	35.89	13,680.27	94.17%
30	12,616.05	35.52	13,537.69	93.19%
45	12,179.03	34.90	13,301.14	91.56%
60	11,584.24	34.04	12,972.29	89.30%
90	9,991.24	31.61	12,047.38	82.93%
120	8,012.43	28.31	10,788.59	74.27%
150	5,865.63	24.22	9,230.82	63.54%
170	4,457.84	21.11	8,047.21	55.40%

6.3 Thermal Management

Based on Thyristor testing TN3050H-12LY datasheet, forward voltage drop $V_{T(on)}$ = 1,65 Volt , and for Diode forward voltage drop $V_F = 2{,}1\ V$ at 125^0 C. For the TN3050H-12LY, the switching time $t_s = 10\ \mu s$ and the switching loss can be calculated, shown in Table 3.

Table 3. Losses in each thyristor at 125^0 C and 50 Hz

Firing Angle	Electric Current	$P_{loss\ (conduction)}$	$P_{loss\,(switching)}$
(Degree)	(Ampere)	(Watt)	(Watt)
0	36.02	59.43	0.029715
15	35.89	59.22	0.029612
30	35.52	58.61	0.029303
45	34.90	57.58	0.028791
60	34.04	56.16	0.028079
90	31.61	52.15	0.026077
120	28.31	46.71	0.023353
150	24.22	39.96	0.019980
170	21.11	34.84	0.017419

For a frequency $f = 50$ Hz, the switching loss is relatively small compared to conduction losses but must still be considered in the overall thermal management strategy.

Based on Thyristor TN3050H-12LY datasheet, the junction temperature of the thyristors is $150^0\ C$maximum, junction to case is 0.8 °C/W, and Junction to ambient is 45 °C/W. So, when using a thyristor, it will increase heat as the power increases, which must be maintained so that it does not reach 150 degrees Celsius. To dissipate the heat generated by the thyristors, a properly sized heat sink is required. The heat generated from the conduction and switching of each thyristor can be calculated and displayed in Table 4.

Table 4. The heat generated by the conduction and switching of each thyristor

Firing Angle	Power	Heat Generated °C		
(Degree)	(Watt)	Junction to case	Junction to ambient	Total
0	59.46	47.57	2,675.69	2,723.25
15	59.25	47.40	2,666.40	2,713.80
30	58.64	46.91	2,638.61	2,685.52
45	57.61	46.09	2,592.51	2,638.60
60	56.19	44.95	2,528.41	2,573.36
90	52.18	41.74	2,348.14	2,389.88
120	46.73	37.38	2,102.79	2,140.17
150	39.98	31.99	1,799.16	1,831.15
170	34.85	27.88	1,568.47	1,596.35

The heat sink must be low enough to maintain the junction temperature of the thyristors below $150^0\ C$maximum rated temperature. The total power dissipation and the ambient temperature conditions will determine the heat sink design, which can be optimized using thermal simulation tools.

7 Conclusion

The single-phase controlled rectifier using TN3050H-12LY thyristors and VS-E5PX3012 diodes offers a reliable and efficient solution for power control in marine propulsion systems. By adjusting the firing angle of the thyristors, the rectifier can deliver variable DC output voltage, allowing for precise control of motor speed and power. The high efficiency and effective thermal management make this rectifier well-suited for use in demanding marine environments where energy conservation and performance are critical.

Future work will focus on implementing advanced control techniques, such as closed-loop feedback control, to further enhance the performance of the rectifier in real-world marine applications and design the heatsink to its components, [10].

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Declaration of Generative AI and AI-assisted Technologies in the Writing Process

During the preparation of this work the authors used ChatGPT - OpenAI in order to help determine an article title that is appropriate to the topic and to organize the systematic flow of the paper. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

References:

[1] Dennis T.Hall, *Practical Marine Electrical Knowledge 4th Edition*, Witherby Publishing, 2019. ISBN: 9781856098571.

[2] John Bird, *Electrical Principles and Technology for Engineering*, Elsevier, 2007. ISBN: 978-0-75-068556-6.

[3] Katarzyna Markowska, Dmytro Zhuk,Oleksandr Zhuk,Maksym Kozlov,Serhii Stepenko,Viktor Voskoboenko,Kinga Stecuła,Oleksandr Miroshnyk, Taras Shchur, *Analysis and Improvement of Power Quality in the Onboard Electrical Power Systems within a Self-Propelled Floating Crane*, International Journal of Electrical Power and Energy Systems. Vol. 161, 2024, 110179, https://doi.org/10.1016/j.ijepes.2024.110179.

[4] M.H. Rashid, *Power Electronics: Circuits, Devices and Applications*, Pearson, 2013. ISBN: 0133743888, 9780133743883.

[5] Elstan A. Fernandez, Divyam Verma, Swarup Hati, Yadukrishnan KM, *Basic Electronics for Seafarers*, A Free Compilation As per IMO Model Courses 7.02, 7.04, 7.08, 2021.

[6] B.W. Williams, *Power Electronics: Devices, Drivers, Applications, and Passive Components*, McGraw-Hill, 2014, https://doi.org/10.1007/978-1-349-18525-2_5.

[7] Amol R. Dhumal, Atul P. Kulkarni and Nitin H. Ambhore, *A comprehensive review on thermal management of electronic devices*, Journal of Engineering and Applied Science, Vol 70, 2023,140. https://doi.org/10.1186/s44147-023-00309-2.

[8] STMicroelectronics NV, *TN3050H-12WY Datasheet*, [Online]. https://www.st.com/resource/en/datasheet/tn3050h-12wy.pdf (Accessed Date: December 9, 2024).

[9] Vishay Semiconductors, *VS-E5PX3012L-N3 Datasheet*, [Online]. https://www.vishay.com/docs/96442/vs-e5px3012l-n3.pdf (Accessed Date: December 9, 2024).

[10] ROHMSmiconductor, *How to Use Thermal Models*, Application Note No. 62AN113J Rev.001, 2020.

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The author(s) contributed to the present research, at all stages from the formulation of the problem to the final findings and solution.

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Conflict of Interest

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