Investigation of Harmonic Distortion in Multi-Pulse Rectifiers for Large Capacitive Charging Applications

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***Abstract*— The United States Navy's future fleet of vessels will deploy an increasing number of high power electrical loads that will operate in a transient nature. As the electrical requirements increase, the efficiency of power conversion will become more important than ever before. Converting AC power to DC power can be very inefficient due to the generation of harmonics that are injected into the power system during conversion. Previous work has shown that the magnitude of the harmonics generated can be reduced significantly when multi-pulse rectifiers are implemented. These types of rectifiers work through splitting the three-phase input into additional phases so that the output ripple and distortion can be reduced. Higher numbers of phases result in improvement in power quality but come with added costs and complexity. Previous work in the literature has evaluated these types of converters into purely resistive or slightly inductive loads but not into highly capacitive loads, similar to those the Navy has plans to utilize. The work presented here investigates the harmonic content of multi-pulse rectifiers when used to charge large capacitive loads. Six, twelve, eighteen, and twenty-four pulse rectifiers have been simulated using Simulink® to predict how higher pulse numbers reduce the injection of harmonic distortion. Model validation will be carried out using a hardware implementation of each rectifier at the 1 kW level using a three-phase motor-generator source. Preliminary results from the simulations will be presented here.**

Keywords*— *multi-pulse rectifier, total harmonic distortion, capacitive load, pulsed power

I. Introduction

As the Navy integrates more electrical generation and loads into the fleet, their need for more efficient power electronic converters will increase considerably [1]. The primary source of energy aboard naval vessels is, and likely will continue to be, large diesel and gas turbine generators. These generators typically generate three-phase voltages, ranging somewhere between 4 kV and 13 kV at 60 Hz. The AC power generated can be used to source the ship's AC loads, either alone or in conjunction with other distributed generation sources, however; conversion from AC to DC is needed to power the future high voltage DC loads the Navy is developing. The pulsed power loads under development include but are not limited to electromagnetic railguns (EMRGs) [2-5], solid-state lasers (SSLs) [6-8], and high power microwave (HPM) generators [9-12]. Rectification is required to convert the generator's fixed AC output to an adjustable DC magnitude. The simplest form of three-phase rectifier would utilize six diodes, two on each phase, as a full bridge. The output voltage of this type of rectifier is not controllable and will have a great deal of ripple on the output. By replacing the diodes with silicon controlled rectifiers (SCRs) [13], the firing angle of the rectification can be varied allowing the output DC voltage to adjusted as needed. The simplest form of three-phase multi-pulse rectifier is called a six-pulse rectifier and one is shown schematically in Fig. 1. In the six-pulse form, this type of converter introduces high magnitudes of harmonic distortion, leading to a low power factor in the generator [14]. The more the power factor diverges from unity, the more the power generation must be oversized to meet the demand of the load. Another issue with this rectifier is the difficulty in filtering the DC output, as the ripple frequency is very low and therefore requires very highly valued filtering components, increasing the size and cost of the filters. Introducing more input phases to increase the pulse number of the rectifier can address both issues. In theory, this cancels out certain harmonics and thus decreases the total harmonic distortion. In addition, adding more pulses to the output increases the ripple frequency of the DC output which decreases the difficulty, size, and cost of the filters. While many researchers have presented methods of increasing the number of pulses present in the rectifier, in most, if not all, of these cases, the rectifiers have been shown to be loaded by either resistive or inductive elements [15-17]. It is proposed that the most common converters: the six-pulse, twelve-pulse, eighteen-pulse, and twenty-four-pulse rectifiers be considered as AC/DC converters to charge the large capacitive loads. The effectiveness of each pulse rectifier will be evaluated by examining the total harmonic distortion of the source current. In addition, it will be determined if each rectifier meets military specification MIL-STD-1399 [18] without any additional filtering.

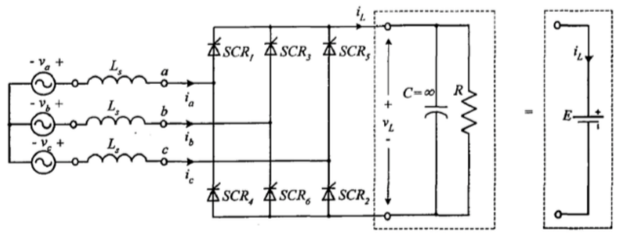

Fig. 1: Six-pulse, three-phase rectifier with ideal load [1].

II. BACKGROUND

A full bridge rectifier for three phase systems consists of six power electronics rectifiers, such as diodes or SCRs, arranged two per phase as seen in Fig. 1. This topology converts a 3-phase source into a single DC bus. With a non-ideal load, there exists a ripple voltage at the output. The ripple consists of various harmonics based on the fundamental frequency of the source. In the case of a six-pulse rectifier, the ripple consists of the 5^{th}, 7^{th}, 11^{th}, 13^{th}, 17^{th}, 19^{th}, etc. harmonics [19]. In addition to affecting the output, the rectification process creates harmonic distortion and decreased power factor in the source.

Multi-pulse rectifiers use additional rectifier bridges and additional phases that are created from the source to increase the pulse number. The increase in pulses theoretically cancels many of the harmonics, affecting the output ripple and source efficiency. For example, when a twenty-four-pulse topology is used, which is seen schematically in Fig. 2, the harmonics injected don't theoretically begin until the 23^{rd} [1].

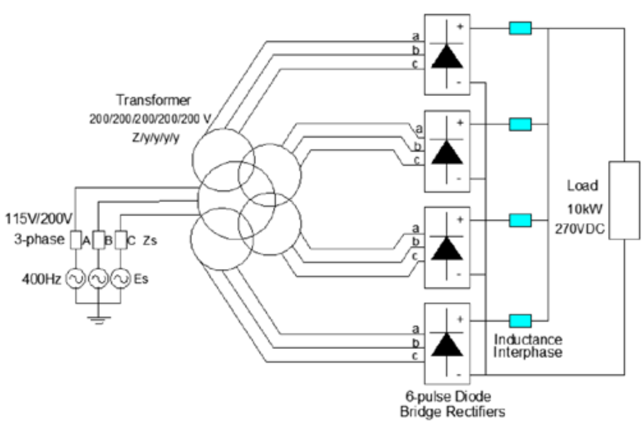

Fig. 2: Twenty-four-pulse, twelve-phase rectifier with ideal load [24].

A literature search of capacitive chargers for pulsed power applications reveals that in most cases, the charge process is achieved using a source capable of implementing either a constant voltage or a constant current charge mode, respectively [20]. Series resonance inverters have been used to charge capacitors with a constant current from a DC source [20]. Additionally, capacitors have been charged in the constant voltage mode using a DC source supplied by a boost power converter [21].

III. MODEL

The work being performed here is aimed at characterizing how six, twelve, eighteen, and twenty-four pulse controlled rectifiers perform when they are used to charge highly capacitive loads. The work is being performed in three stages. First, an electrical model is being developed using Simulink® so that preliminary expectations of harmonic content can be determined. In the second, 1.5 kW hardware variants of each type of rectifier will be experimentally evaluated and electrical data collected. Finally, the model will be validated using the experimental data collected. The experimental work will be performed using a 2 HP, 1 kW "physical scale model alternator" and "dc motor prime mover" that produces three phase, 120 V, 60 Hz power [22]. The controlled rectifiers were designed and procured from Applied Power Systems, Inc. [23]. In this report, only the electrical simulation model will be discussed as the experimental work has not yet begun.

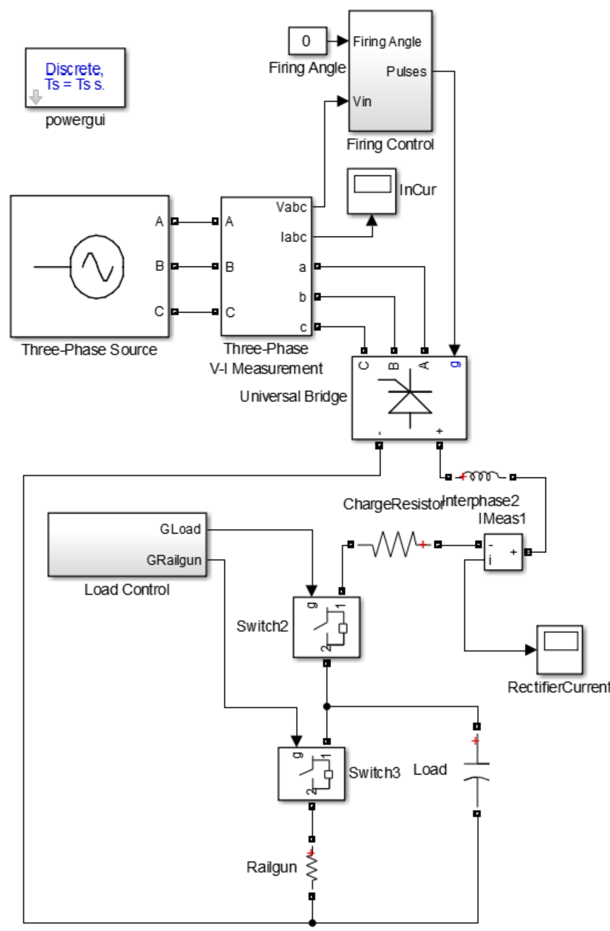

Fig. 3: Six-pulse rectifier model schematic.

A top-level schematic of the six-pulse rectifier simulation model developed here is presented in Fig. 3 while that of the twenty-four-pulse rectifier is shown in Fig. 4. The model was created in Simulink® using the "simpowersystems_ST" library. Within the model, a 3-phase source is utilized with non-ideal parameters in order to mimic the series resistance and inductance found in a motor-generator pair [22]. Built-in rectifier bridges were used to rectify the incoming signal. These allowed for the use of a built-in pulse generator and PLL to properly fire the SCRs in the right sequence with the correct timing. An ideal switch with a necessary leakage resistance is used to engage the load after the PLL has locked. The load consists of a charge resistor in series with the load capacitor.

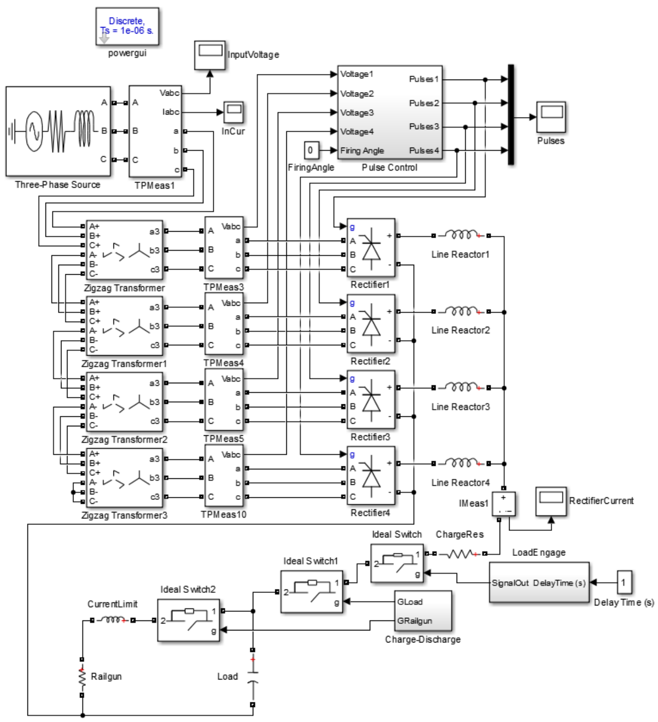

Fig. 4: Twenty-four-pulse rectifier model.

The twelve, eighteen, and twenty-four pulse rectifiers, respectively, remain largely identical to the six pulse. However, on the input side, phase shifting transformers were added to create additional phases for rectification. On the output side, since rectifier bridges are in parallel, interphase transformers were added to balance the differing pulse voltages between rectifier bridges.

IV. Simulation Results

Simulation results from six pulse and twenty-four pulse rectifiers are presented below. Both use the same load setup with the following parameters: a 347.222Ω charge resistor, a 4.8mF load capacitor, a zero degree firing angle, a 7 second total simulation time, and a 1 second delay before engaging load. Fig. 5 shows an example of a typical charge curve of the load capacitor.

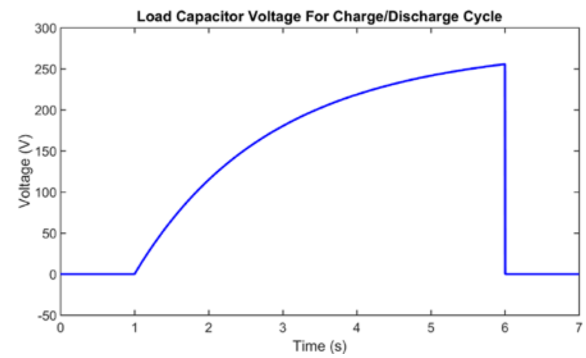

Fig. 5: Charge section begins at 1 second and transitions to discharge at 6 seconds.

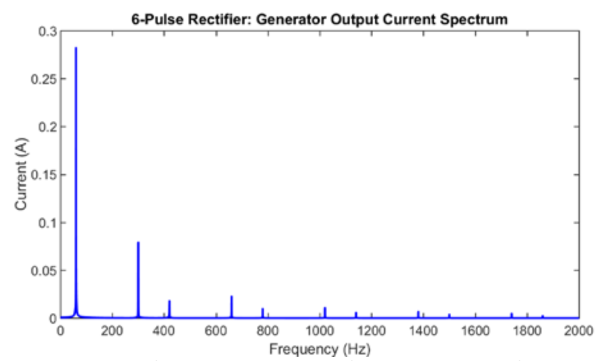

Fig. 6: Spectrum of the generator current for the 6-pulse rectifier topology over the charge cycle.

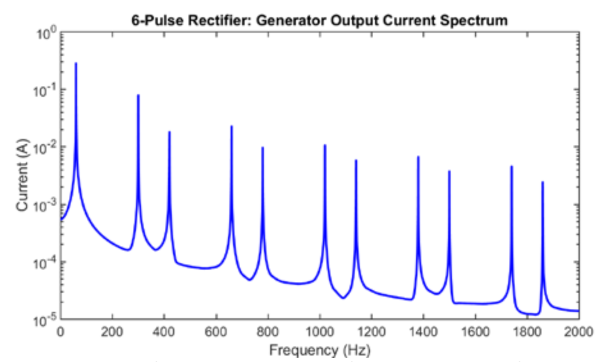

Fig. 7: Spectrum of the generator current for the 6-pulse rectifier topology over the charge cycle in a logarithmic scale.

Taking the spectrum over the entire charge cycle, the current harmonic cancellations occur according to theory. Despite the capacitive load, the current harmonics tend to decrease as the harmonic order increases as seen in Fig. 6 and 7. The resulting %THD is calculated to be 86.973%, which is too high to be within limits imposed by MIL-STD-1399.

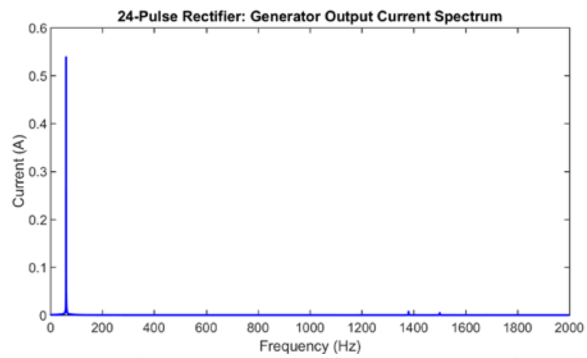

Fig. 8: Spectrum of the generator current for the 24-pulse rectifier topology over the charge cycle.

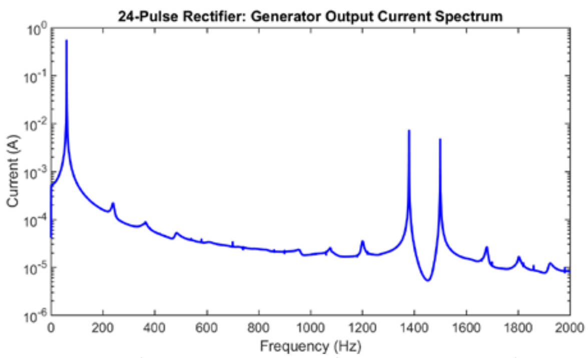

Fig. 9: Spectrum of the generator current for the 24-pulse rectifier topology over the charge cycle in a logarithmic scale.

The highest pulse rectifier studied at twenty-four pulses appears to deliver better harmonic performance, as seen in Fig. 8 and 9, where only the 17^{th} and 19^{th} harmonics, respectively, are visible at small percentages. This results in a greater than expected %THD of 36.482%. A summary for the calculated %THD values of the 6, 12, 18, 24-pulse rectifiers, respectively, are presented below in Table 1.

Rectifier Topology	Generator current %THD at 95% charge
6-pulse	86.973%
12-pulse	63.002%
18-pulse	31.521%
24-pulse	36.482%

Table 1: %THD values for multi-pulse rectifier topologies

V. Conclusions

In simulation, capacitive loads exhibit a constantly changing and undesirable harmonic content for the source current. Raising the pulse number of the rectifiers decreases the %THD dramatically; however, even with a twenty-four-pulse rectifier, the %THD is still significant, and certainly not within the 5% total required by MIL-STD-1399. Additional input filtering will likely be needed to bring the rectifier %THD within MIL-STD-1399 for capacitor charging applications.

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