Energy Research and Development Division

FINAL PROJECT REPORT

Hyper-Efficient Pump Motor Unit with Fully Integrated Permanent Magnet Motor and Motor Controls with Combined Liquid Cooling

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PREFACE

The California Energy Commission's (CEC) Energy Research and Development Division supports energy research and development programs to spur innovation in energy efficiency, renewable energy and advanced clean generation, energy-related environmental protection, energy transmission and distribution and transportation.

In 2012, the Electric Program Investment Charge (EPIC) was established by the California Public Utilities Commission to fund public investments in research to create and advance new energy solutions, foster regional innovation and bring ideas from the lab to the marketplace. The CEC and the state's three largest investor-owned utilities—Pacific Gas and Electric Company, San Diego Gas & Electric Company and Southern California Edison Company—were selected to administer the EPIC funds and advance novel technologies, tools, and strategies that provide benefits to their electric ratepayers.

The CEC is committed to ensuring public participation in its research and development programs that promote greater reliability, lower costs, and increase safety for the California electric ratepayer and include:

- Providing societal benefits.
- Reducing greenhouse gas emission in the electricity sector at the lowest possible cost.
- Supporting California's loading order to meet energy needs first with energy efficiency and demand response, next with renewable energy (distributed generation and utility scale), and finally with clean, conventional electricity supply.
- Supporting low-emission vehicles and transportation.
- Providing economic development.
- Using ratepayer funds efficiently.

Hyper-Efficient Pump Motor Unit with Fully Integrated Permanent Magnet Motor and Motor Controls with Combined Liquid Cooling is the final report for the Hyper-Efficient Pump Motor Unit with Fully Integrated Permanent Magnet Motor and Motor Controls with Combined Liquid Cooling project (Contract Number EPC-16-044) conducted by Terzo Power Systems, LLC. The information from this project contributes to the Energy Research and Development Division's EPIC Program.

For more information about the Energy Research and Development Division, please visit the CEC's research website (www.energy.ca.gov/research/).

ABSTRACT

The purpose of this study is to summarize the current state of hydraulic systems and to introduce a new technology to address past challenges. Methods to increase system efficiencies have been developed for decades, as well as systemic steps to reduce occupational hazards, environmental impacts, and typical procurement barriers. Despite these efforts, overall gains have been limited.

Substantial efficiencies through a novel product, the Hyper-Efficient Pump Motor Unit, demonstrate a ground-up product development approach that either eliminates or integrates common hydraulic system components. As a result, cost is greatly reduced and efficiency significantly increased, resulting in a viable bridge between a mature industry and a modern technology.

The integration and addition of embedded intelligence together generate several key benefits. Electricity reductions of up to 80 percent can be realized in some industry applications by replacing a traditional hydraulic power unit with the Hyper-Efficient Pump Motor Unit. Variations in application duty cycles and the effective use of computational logic available to end users will also affect energy use. Worker benefits were noted due to a demonstrated 10-fold decrease in noise energy generated by the unit.

Energy savings were demonstrated and quantified with a Fluke 1736 Power and Energy Analyzer meter. Using a 300-ton press and a repeatable cyclic profile between a 30-kilowatt Hyper-Efficient Pump Motor Unit and an equivalently powered hydraulic power unit, power and energy consumption data were collected. In this controlled experiment, this difference in energy use translated into annual savings of at least $2,000.

These quantifiable results and the empirical data collected for this project support adoption of this novel technology. This constructive first step underscores potentially labeling the Hyper-Efficient Pump Motor Unit as a disruptive technology and represents an evolutionary leap for hydraulic system design and use. This study concludes with proof of this novel technology’s benefits and sets the framework for next steps on its path to commercial adoption.

Keywords: E-pump, servo motor pump, servo hydraulic, electro-hydraulic, integrated hydraulic pump, integrated drive control pump, efficient hydraulics

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Introduction

Statewide adoption of the novel technology known as the Hyper-Efficient Pump Motor Unit provides a valuable opportunity to achieve energy savings, create safer working environments, and reduce environmental impacts from hydraulic oil usage, transportation, and disposal. This new technology's intended targets are pump-motor units in general, industrial hydraulic power units, and specifically pump-motor units in agricultural irrigation and water distribution systems.

Project Purpose

Industrial hydraulic power unit applications are of particular importance because these power units are part of virtually all industrial manufacturing and agricultural processes statewide. Additionally, no significant improvements have been made to the current technology since its inception during the Industrial Revolution over two centuries ago. The primary goal of this project was to research and quantify the efficiency of a permanent magnet motor with integrated motor controls while supplying pumped fluids for industrial hydraulic systems, without using highly inefficient valves. Researchers then developed a demonstration pilot to spur rapid advancement and statewide market adoption that will reduce electricity use in industrial, agricultural, and water-pumping applications.

Project Approach

This research project developed economic and efficient configurations for the large-scale integration and adoption of highly efficient, liquid-cooled permanent magnet synchronous motors and fully integrated, liquid-cooled motor controls. The project applied these two technologies to a smart pump motor unit that can be both quickly commercialized and adopted statewide to deliver near-immediate benefits. The research team developed a system that integrates a permanent magnet motor and intelligent motor control system into a single unit.

Targeted objectives of the project were to:

1. Demonstrate the improved efficiency of an instant response, valve-less distributed pump network combining liquid-cooled permanent magnet motors and liquid-cooled motor controls that improve safety, reduce noise pollution and other environmental impacts, and significantly reduce hazardous hydraulic oil transportation and disposal.
2. Provide direction and market channels that allow accelerated adoption of this novel technology.
3. Identify potential barriers to the timely adoption of this technology and provide acceptable solutions to those barriers.
4. Develop industry standards and validation procedures that accelerate the new technology's widespread adoption in the state's industrial, agricultural, and water-pumping sectors.

Project Results

Energy Savings of greater than 80% were achieved compared to state-of-the-art technologies over a range of operational scenarios.

Technology/Knowledge Transfer/Market Adoption

On November 6, 2020 Terzo Power Systems announced the partnership with global manufacturing provider, QCC, to enable high volume production of their hydraulic smart pump line of products, the Hydrapulse®. Demonstration units are now available.

Benefits to California

The Terzo Power Systems team structured the project’s research and development to deliver a realistic and cost-effective technology capable of quick future adoption. This project could generate substantial electricity savings for California with demonstrated 80%+ electricity reduction as well as worker benefits due to a demonstrated 10 fold decrease in noise energy generated by the unit.

CHAPTER 1: Introduction

The foundational basis of fluid power is pressurized fluid. Fluid power is defined as the use of fluids under pressure to generate, control, and transmit power. In a typical hydraulic cylinder, contained pressurized fluid is forced through a series of cavities, pipes, hoses, collapsing pathways, ports, and orifices before ultimately reaching the enclosed area of a cylinder bore's gears, vanes, and other fluid-pumping geometry. The physical manifestation of this principle is readily demonstrable in everyday life. It exists in systems that slow down a vehicle, propel earth-moving equipment, or operate building elevators.

Because of the historic execution and practical use of fluid mechanic principles, fluid power remains a versatile contributor to work-producing processes across many industries. There is no alternate cost-effective method that offers its power-dense characteristics that are also easily applicable and deployable to diverse industry sectors from simple agriculture harvesting equipment, to military applications, to aerospace operations.

Such elementary science offers limited opportunities for improvement. Although major advancements have historically been introduced since the inception of fluid power, there has been little impetus to challenge the design and implementation of traditional hydraulic systems.

Chapter 1 provides a general discussion of traditional hydraulics and highlights some of the drawbacks in modern hydraulic systems. This leads the way to describing how the novel technology would overcome the deficiencies that hydraulic system designers, operators, and technicians have come to accept.

Motivation for New Technology

Over the years, hydraulic systems and their components have evolved into intelligent, efficient, increasingly power-dense systems than their predecessors. Fluid power is mechanical, so many of these advancements have stemmed from improvements in material compositions and mastery in manufacturing processes.

Perhaps the most modern industrial advancements originated from the marriage between electronics and hydraulic components. An electronic signal to a coil actuates a control valve, where it is magnetized and "pulls" on a spool, which in turn allows fluid to continue its directed path.

The introduction of electronics contributed its benefits by allowing the miniaturization of components and increasing the flexibility of hydraulic system design while paving the way for future innovation. While this did indeed offer overall enhancements, it also "complicated" hydraulic systems by requiring a basic knowledge of low-voltage electricity. As the evolution of hydraulic systems has developed over time, so has the need for greater specialized skills, which ultimately increases the overall cost of system implementation.

Aside from advancements to hydraulic components, the core characteristics of hydraulic systems have remained the same. And though the fluid power industry is both proven and ubiquitous, its drawbacks also persist.

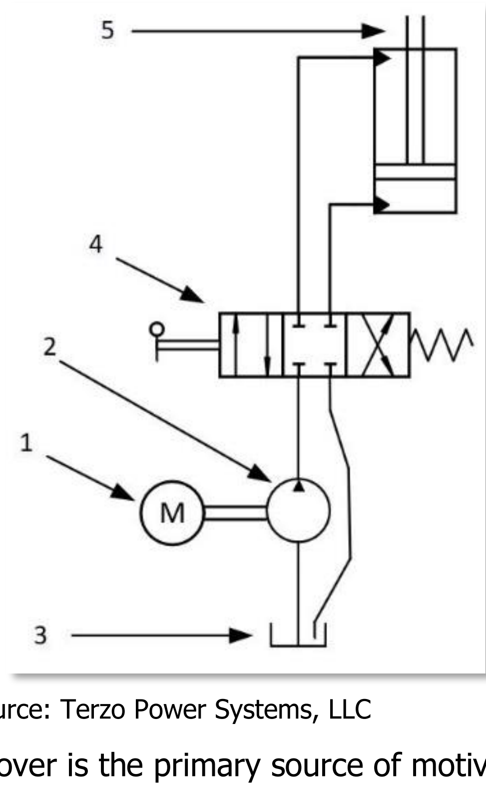
Existing Methods

Discussions about the current implementation of fluid-power equipment have appeared in earlier reports over the duration of this research project. What follows here is an overall review of basic hydraulic systems that sets the stage for the development and implementation of the novel technology that is the subject of this report.

Some of the weaknesses inherent in most if not all hydraulic systems concern the origination of heat at various points along a system. Many heat sources are intrinsic to hydraulics, while others are results of persistent system design and implementation practices established decades ago. To first establish a firm understanding of those practices, Figure 1 is a simple schematic of the general architecture of most hydraulic systems. It shows the primary components required to both create and utilize pressurized fluid to generate, control, and transmit power. Its five chief components are:

- A prime mover.
- A pump.
- A reservoir.
- A directional control valve.
- A linear or rotary actuator (linear actuator shown).

Figure 1: Basic Hydraulic Circuit



Source: Terzo Power Systems, LLC

A hydraulic system's prime mover is the primary source of motive power for any system. The prime mover exists in two variants. In the mobile industry, the prime mover acts as a combustion engine. In an industrial setting, such as a factory floor, the prime mover is an electric motor. The main purpose of these motive power appliances is to provide rotational force to the directly coupled hydraulic pump. In traditional designs, both the combustion engine and the electric motor continuously operate regardless of whether work is being performed. This continuous operation wastes both fuel and electricity. Adding to these are elevated noise exposure to personnel, heat generation, and higher costs from intermittent maintenance and down times.

The hydraulic pump is connected to the prime mover. It converts the prime mover's mechanical power to hydraulic energy, and its primary purpose is to generate fluid flow while overcoming pressures from both the load and the internal workings of the hydraulic system. It operates concurrently with the prime mover because of this physical coupling. It is also affected by unnecessary wear and tear, noise levels, and generated heat.

As fluid leaves the pump's outlet, it travels to a manifold that contains the component shown as number 4 in Figure 1. As shown, directional control valves direct fluid flows to travel downstream to the next component. Additionally, the directional control valves regulate how much fluid is allowed to pass. The flow amount, usually expressed in gallons per minute (GPM), directly correlates to how fast an actuator extends, retracts, or rotates. These also generate heat. Unlike the previous two components, these produce heat when fluid is allowed to pass. These are critical to the usefulness of any system. Depending upon the application's design philosophy, directional control valves can account for a significant portion of overall system costs. The finer the required valve control, the higher the cost.

From the control valves, the fluid makes its way to the hydraulic actuator. Whether linear or rotational, this is where hydraulic energy is converted back to mechanical energy to produce useful work. Like other components described, not all of the energy is converted to useful work and, to a certain degree, heat is generated as well.

As a final component, the hydraulic fluid is diverted back through the directional control valves and returned to the reservoir. The reservoir traditionally serves as a repository of "fresh" fluid. Maintaining non-aerated, cool, and laminar fluid is a performance requirement of the reservoir. Another is providing a large surface area for convection and conduction heat dissipation of the post-work fluid. A customary rule of thumb dictates that the reservoir be at least three times the flow rate of the pump, which can result in oversized reservoirs, increased capacity, increased weight, and increased cost.

At minimum, conventional hydraulics are made up of the components just described. As previously stated, they have their drawbacks, many in the areas of cost, heat generation, and maintenance. These drawbacks paved the way for the new approach to system design and implementation that is the subject of this research.

Benefits of the New Technology

Even the simplest of applications, broken down into their basic components, share similar deficiencies that have not to date been proactively addressed. Reactively, oil coolers are deployed for thermal management, system design is geared to efficient fluid transport, and telematics are installed to remotely monitor equipment so that operators are shielded from harmful noise levels.

Hydraulic components and their inherent byproduct deficiencies are among the most persistent arguments against modern hydraulic systems. Planning and review therefore provided the platform from which to focus research and development of the new technology. Key target metrics that guided its development are:

- Cost reduction (system, maintenance, and reliability).
- Reduced down times.

- Prompt root-cause results.
- Reduction of occupational hazards.
- Increased efficiencies.

To address these target metrics, a novel approach to product design was undertaken to essentially create the next iteration of a hyper-efficient hydraulic system. Even small enhancements will encourage adoption of the new technology. Remaining discussion topics are excerpts from the overall philosophy of the engineering design and manufacturing methods selected for the mechanical and electrical aspects of the new technology.

Approach to Development of the New Technology

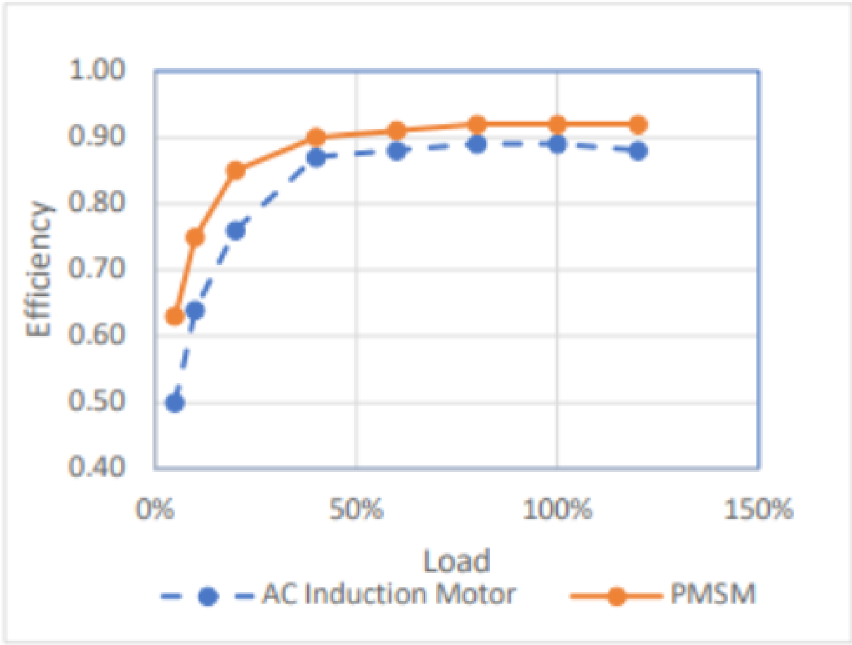
Clearly understanding the weaknesses inherent in conventional hydraulic systems led to the new generation of target metrics that drove design decisions throughout development of what will now be referred to as the Hyper-Efficient Pump Motor Unit (HEPM-U). With the advantage of developing this novel unit from its earliest conceptual stages, tangible solutions were developed for each of the problem areas described so far in this report. This report's remaining sections highlight some of the unit's prominent design features and the decisions made to best meet the project's initial goals.

Electrical and Power Electronics Development

At the heart of the system lies a permanent-magnet synchronous motor (PMSM), which functions as the system's prime mover. A PMSM is a 3-phase electric motor with a shaft that is magnetically synced with a controlled rotating magnetic field. The vast majority of traditional hydraulic systems use induction motors as their prime movers. A PMSM has many advantages over induction motors, all of which contributed to the ultimate creation of the HEPM-U.

This section describes both the advantages and disadvantages of using a PMSM over an induction motor. Induction motors are traditionally used in hydraulic systems because they are inexpensive and simple to use. But modern advancements in PMSMs have increased their power density and cost-effectiveness sufficiently to replace induction motors. Once these factors improved, choosing a PMSM became an easy choice since PMSMs are more efficient due to the physics of different motor types. Reliability of a system is another top priority, especially when a machine controls heavy duty equipment. Since PMSMs are more efficient, they do not produce as much heat, which makes them more robust and longer lasting. Power density is another important factor. Since PMSMs are far more power dense, they are much smaller than equivalent systems. The final primary difference is the complexity of controlling individual motors. A PMSM requires a specific drive to control it while an induction motor does not. This was ultimately a nonissue since a custom integrated drive was planned from the beginning to increase robustness and control for the project. Figure 2 graphically illustrates typical efficiency curves for induction motors and permanent-magnet synchronous motors.

Figure 2: Induction vs. PMSM Efficiency



Source: White paper on induction vs. PMSM efficiency

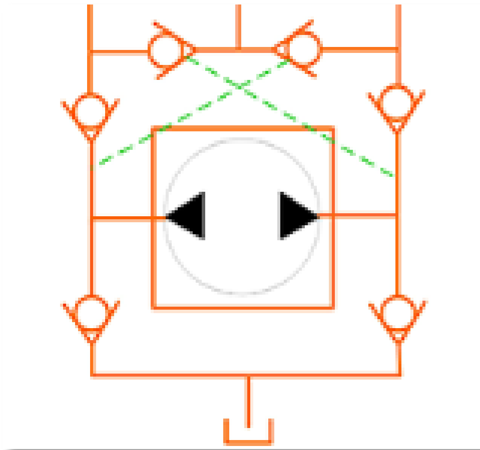
The inverter board houses the high-power semiconductor devices that deliver power to the 3-phase motor. Reliable and robust electronics were primary goals in designing the inverter board. This design philosophy will ultimately reduce costs for end users through lower maintenance costs and lower failure rates. Additional efficiencies include quality semiconductor devices and redundant safety measures throughout the board. An insulated gate bipolar transistor (IGBT) was the ideal choice for this application since IGBTs can handle both the high voltage and currents required for high-power applications and the low-conduction losses that keep IGBTs cooler and increase their efficiency. Mitsubishi's G1 Series Intelligent Power Modules (IPMs) were chosen because of their many performance and safety benefits. They are efficient and their many safety features are built into the devices themselves. Using the described inverter board to control the PMSM allows a solid and efficient core to meet the goals targeted in designing the HEPM-U.

Mechanical Design

The design of the HEPM-U focused on many issues common to hydraulic equipment. One of the more notable is its significantly lower energy consumption. The overall size and cost were reduced by integrating various components of a typical hydraulic system to create a compact, efficient, and affordable unit.

Much of the mechanical design of the HEPM-U involved the packaging of all necessary hardware in a single low-volume envelope. This small form effectively reduces surface area for adequate heat management. To solve this problem, the return fluid from an actuator was ported after the hydraulic work. This ensures that the working fluid will return from the work function relatively cool, and that the return path of the fluid passes over the motor and a heat sink for the drive electronics to provide cooling. This is done with the hydraulic schematic shown in Figure 3.

Figure 3: Hydraulic Circuit



Source: Terzo Power Systems, LLC

This hydraulic circuit allows the fluid flow to be controlled by the direction of the pump rotation, which in turn is controlled by the motor and the motor inverter. The return fluid passes through one of two pilot-operated check valves, depending on the direction of the flow, which then passes over the motor and the heat sinking elements of the drive electronics that maintain them below their maximum operating temperature. Integrating the cooling system with components already present in both the motor and electronics housings significantly reduces the size and cost of the overall system. Coupled with cost considerations, serviceability and reliability were also major design considerations.

Regarding serviceability, traditional power units can have very complex hydraulic circuits that are unique to their applications. It is common for equipment end users to be so far removed from a system's design that knowledge of its intricacies has been lost. This creates a situation where determining the root cause of a problem becomes a lengthy process.

To simplify this process, the HEPM-U's design consolidates all of the traditionally complex componentry that make up the hydraulic system into two major, independent subsystems. These subsystems are referred to as the pump side and drive side, as shown in Figure 4.

Figure 4: Pump and Drive Sides

Source: Terzo Power Systems, LLC

The pump side of the system contains everything related to the system's hydraulics, including the hydraulic pump itself and any valves or hoses required to connect the pump to the work. The drive side of the system contains the electric motor and all essential drive electronics that allow the device to function. Ultimately, if a problem arises, its origin would be limited to three possibilities: the pump side, the drive side, or the actuator. Both sides were designed with the ability to be decoupled mechanically and independently for easy replacement.

CHAPTER 2: Current Technology

Chapter 1 provided a brief and generalized description of traditional hydraulic systems, inherent drawbacks, and potential areas to improve upon. Acknowledging key areas of improvement, provides direction to formulate a feature set leading to a performance level that would provide a competitive advantage in the marketplace and eliminate cost barriers making adoption of the new technology degrees more accommodating.

Chapter 2 will be a prominent description of a sample hydraulic system implementation along with showcasing the classic complexities represented as a hydraulic schematic. This will be a natural lead in into Chapter 3 providing greater detail to the mechanics and features of the Hyper Efficient Pump Motor Unit that characterize it as the next stage in hydraulic system innovation.

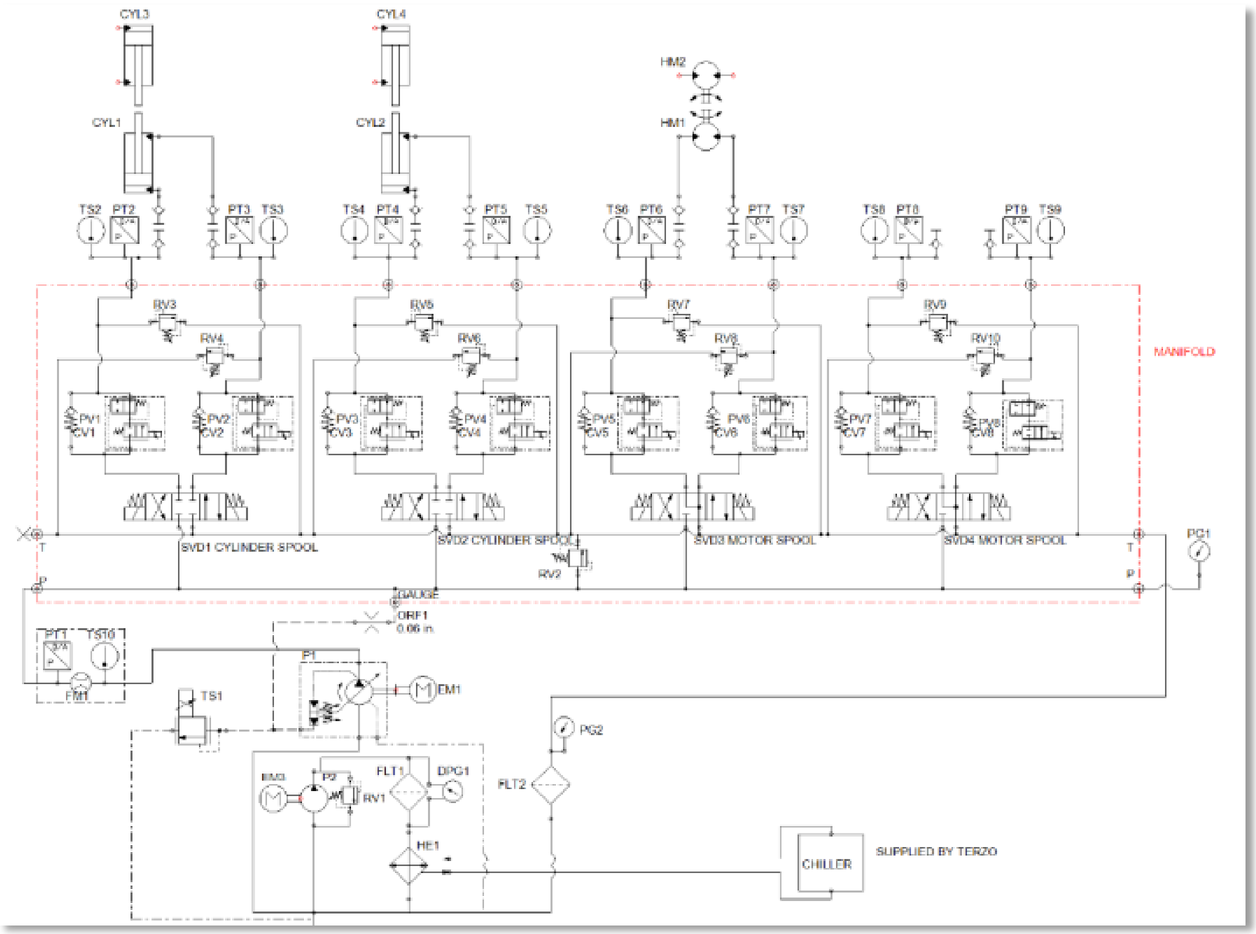
Modern Hydraulic Systems

Variations are vast among hydraulic systems. They can be simple actuator systems, such as the one shown in Figure 1, or as complex as the sample schematic in Figure 5. That particular schematic represents a 40-horsepower (hp) conventional hydraulic power unit (HPU). This power unit played a major role in producing both content and data for this research report.

The purpose of Figure 5 is to provide a visual depiction of the intricacies of a "standard" HPU. Even a seasoned industry professional expends considerable time deciphering an HPU's purpose and the roles of its various components in relation to its functions. Adding to the complexity of the system, the component selection process itself requires a time-consuming march through catalogs for each component. It is the aim of the next exercise to increase awareness of modern practices and enhance the benefits of the Hyper-Efficient Pump Motor Unit.

The elaborate process of hydraulic system design begins with an understanding of an HPU's purpose. Once understood, a hydraulic system designer reviews catalogs for each of the components required to deliver the HPU's specifications. In Figure 5, there are no fewer than 20 individual components to reference and select. A critical point is that each component is offered in dozens of configurations. Because of these many variations, each selected component is considered a "built-to-order" product. In most instances lead times are weeks away because of this practice.

Figure 5: Sample HPU Hydraulic Schematic



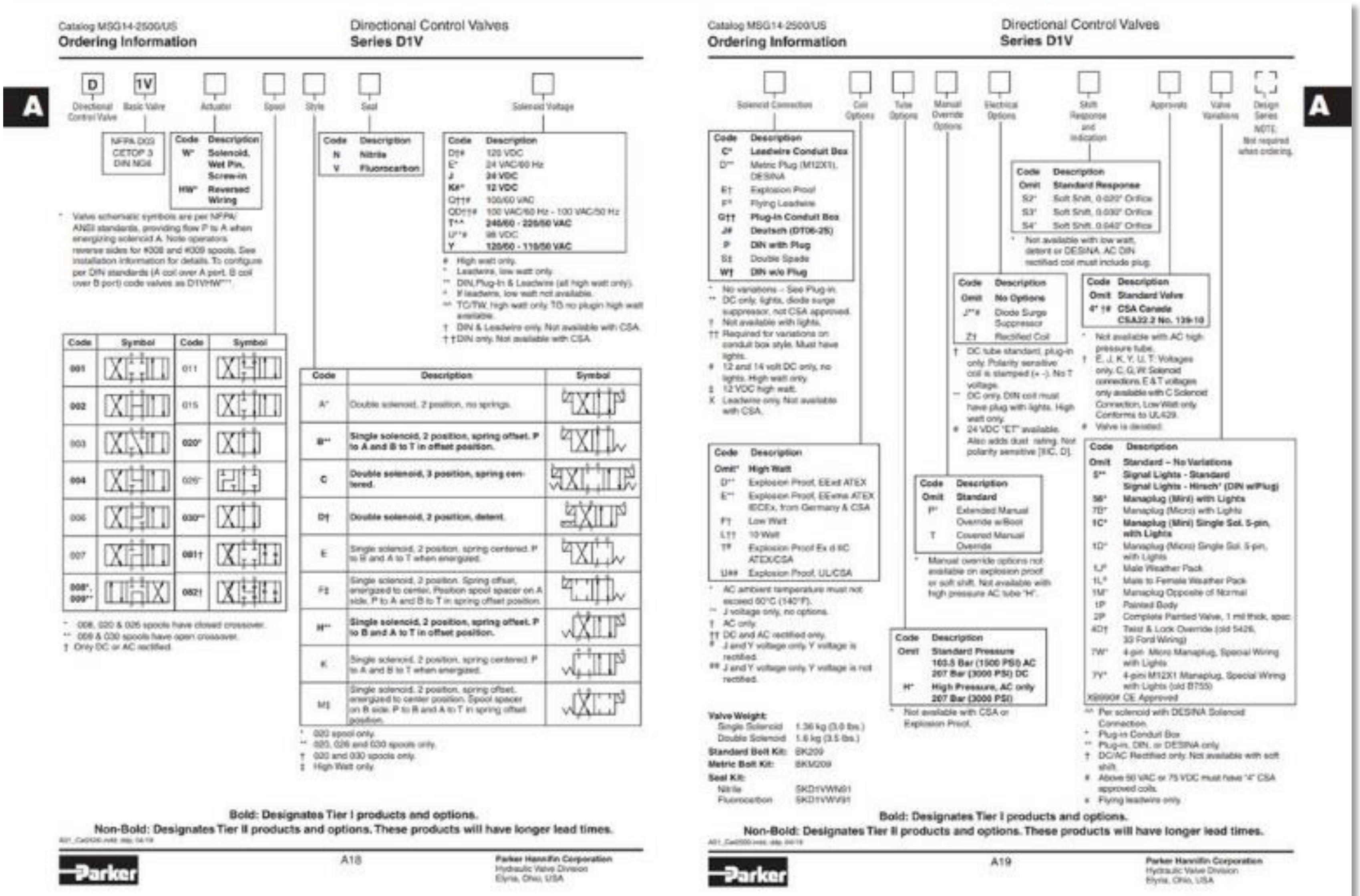
Source: Terzo Power Systems, LLC

To illustrate the many combinations available when ordering a directional control valve, a two-page spread of a particular line of valves is presented in Figure 6. To order a specific valve, the part number (consisting of 15 designator blocks) must first be deciphered. Of the 15 designators, 13 have variations ranging between 2 and 14 options, in one case. Some of the available options include the:

- Actuator type.
- Spool type.
- Style type.
- Seal type.
- Solenoid voltage.
- Solenoid connection.
- Coil options.

This activity is then applied to the remaining 19 components that make up the various circuits in the HPU represented in Figure 5. This illustration of component variability exemplifies the cumbersome and tedious practice of hydraulic system design.

Figure 6: Valve Order Code Selection



Source: Parker Hannifin

As illustrated, the example of the 40-hp HPU is a prime case of the level of complexity a hydraulic system can assume. There are systems where schematics span sheets of fluid line paths, directional control valves, relief valves, actuators, and multiple pumps. Ancillary components that can be added to a system include hydraulic oil filters, oil coolers, and additional hydraulic circuits such as "kidney" filtering loops, used in some systems. The main point of showing this circuit is to graphically illustrate the complexity of a system that even many fluid-power industry professionals consider complicated.

This complexity holds true for nearly all systems. Each hydraulic system starts off as a statement of work to perform a certain function or activity. Much like the many configurations available for a directional control valve, there are also multiple ways to design a system to perform a desired activity. This complexity in turn adds to already lengthy lead times for hydraulic components.

From a business strategy perspective, companies typically retain stock of limited items. With hundreds of thousands of combinations of components available from hundreds of vendors with their own numbering systems, there would not be enough room in a company's warehouse to house all requested components. This prompts companies to stock only strategic, marketable items so anything outside of those items is considered to be a custom order, generally causing long lead times. With the integrated approach of the HEPM-U, shorter lead times are a valuable additional benefit.

Another drawback to long lead times is potential hazards to both operators and the environment. Referring to the schematic in Figure 5, each intersecting line ending on another line, or leading into a block, is a hydraulic connection point. Each connecting point effectively doubles as a potential leak point. Machines and equipment generate both noise and vibration. With excess vibration, each connecting point can potentially dislodge or loosen and leak hydraulic oil. Most municipal authorities regulate the disposal of used oil, including hydraulic oil, to prevent contamination of both soil and water. Because of this, any contingency that reduces the frequency and amount of possible contamination is warranted.

Observing hydraulic systems as a whole, there is a common thread among all of them: their primary power source. The system operates all of the time whether work is being performed or not. While hydraulic systems themselves have introduced technologies and clever hydraulic system designs for increased efficiencies, not much has been done with regard to the prime movers themselves, which boils down to two technologies: a diesel engine or an electric motor.

To recap some of the drawbacks of modern hydraulic systems just discussed, they include environmental contamination risks, health and safety hazards to operating personnel, complex system designs, costly hydraulic components, and long lead times. These objections are only a few of a complete list of driving factors for adoption of the HEPM-U novel technology.

New Approach to Fluid Power

With a list of target deficiencies to address, the stage was set to focus on the HEPM-U's product specifications. The HEPM-U is a variant on the well-established norms of hydraulic systems. In a generalized statement, the novel technology takes the five most prominent components of a hydraulic system and either eliminates them or integrates them into a single system. This technique has several proven benefits, described next.

Cost Reduction

The single-component design approach has the advantage of either eliminating or integrating up to 80 percent of traditional hydraulic system components. This greatly reduces the size of a typical power unit and eliminates much of its cost as well. In the HEPM-U example, one of the most expensive components of any HPU, the proportional directional control valve, is eliminated. Couple that with other eliminated or integrated components and costs are reduced even further.

Increased Efficiency

The proportional directional control valve maintains its cost stature because of the nature of its design. It adds proportional flow control out to a system's actuators. Inherently, a major byproduct of proportional flow control is heat. Another benefit, one that will be discussed later, is the on-board electronics that maintain a power-on-demand architecture. Unlike the behavior of previously discussed prime movers, the need for continuously running engines and motors can be eliminated, further increasing overall system efficiencies.

Positive Environmental Impact

Positive environmental impacts come in different forms. To name a few, hydraulic system connections to and from the HEPM-U are reduced to only two. These are the work ports going out to the actuators. This helps to greatly reduce the number and locations of potential leak points down to four: two at the HEPM-U and two at the actuators. Because of the reduction in size, the hydraulic reservoir can then deviate from the 3-times pump gallons per minute (GPM) sizing rule-of-thumb and be designed for less oil. That means less oil to dispose of after it is used. Fewer system components also lead to less disposal of oil-contaminated components.

Perhaps one of the most critical benefits for the future of hydraulics with the new technology is improved health and safety for operators.

Occupational Health and Safety

Noise reduction is a massive and immediate observation of the HEPM-U. This is immediately pointed out at nearly all demonstrations to date. Noise reduction comes in two forms. The first one comes from the power-on-demand nature of the product. If no work is required to be performed, there is no actuation of the permanent-magnet synchronous motor (PMSM) and thus no spinning of the hydraulic pump, which in turn results in pumping of fluid. The second is in the form of noise itself. Unlike the sound of a combustion engine operating at 3,000 revolutions per minute (RPM) or the sound of a 40-hp motor, the HEPM-U emanates mid-seventies decibel (dB) of noise. For perspective, the sound of an average vacuum cleaner or radio is 75 dB.

Table 1 summarizes the decibel data collected while both technologies operated. As listed, decibel readings were taken at six feet. Because of the cyclical nature of the testing session, sound intensity varied based on the press operation at any given moment. Keeping in mind the logarithmic nature of the decibel scale, a 3dB change is a doubling or halving of sound intensity. For reference, the Occupational Health and Safety Administration (OSHA) classifies the risk of hearing damage as low as 85dB if continued and sustained exposure is not mitigated. Because of that, OSHA requires a ceiling of eight hours maximum exposure in work settings.

Table 1: Decibel Levels

	Conventional HPU	New Technology
Decibel level range	85-87 dB	73-78 dB
Distance	6 feet	6 feet
Improvement over HPU	—	10 factor reduction

Source: Terzo Power Systems, LLC

Embedded Intelligence

The idea of component integration extends to the realm of embedded electronics. Having the capacity to develop custom electronic circuitry from design through assembly helps amplify many of the benefits described. For instance, it is because of the microprocessor and proprietary algorithms that there is now power on demand. Via controller area network (CAN) communication, once an HEPM-U receives a signal to commence work, it immediately starts to pump fluid. Another benefit is constant monitoring of critical system safety parameters. Constant pressure monitoring is critical in over-pressure conditions. This adds to safety benefits in the form of HEPM-U controlled safety shutdowns. In summary, many components that have been eliminated or integrated are often overlooked and not considered for possible elimination. This is partly due to the ingrained nature of how a hydraulic system has "always been designed." Most components have never been considered for elimination. A secondary objective of this report is therefore to educate a mature industry on the advantages of this new approach to hydraulics.

CHAPTER 3: In-Depth Novel Technology

With the groundwork to existing technology discussed so far in Chapters 1 and 2, a more in-depth exploration of this novel technology follows. The HEPM-U's primary advantages present the largest and most immediate impacts. This chapter highlights the novel technology's new and advanced features.

The first feature has a quantifiable benefit by which most consumers will assess its adoption. That feature is its ability to provide power on demand. Examples of this feature are presented in Chapter 4. For this chapter, only the mechanics of this feature will be discussed.

The second beneficial feature is the HEPM-U's mobile-hardened inverter. Rather than the procurement of a third-party inverter to integrate with a system, a custom inverter was developed to strict efficiency and reliability standards. This allowed for a smaller inverter package that can be scaled to both power and size for greater flexibility.

Lastly, the selection process for the electric machine at the core of the HEPM-U is a PMSM, generally described in the first chapter of this report. Its benefits and advantages conclude this chapter.

Advanced Capabilities

Power on Demand

One of the most commercially viable features of the HEPM-U is its ability to provide power on demand. This feature delivers the most prominent and impactful benefits of this new technology. After analyzing data from the pilot demonstration, the 40hp HPU used for the 1,000-cycle testing session consumed 6kW of power in standby mode. In that mode, the induction motor prime mover consumes power to run at its static 1,750 RPM. Because the hydraulic pump is directly coupled to the induction motor, it too spins at that RPM. This is common behavior for most hydraulic systems.

In the case of the 40hp HPU and its prime mover, the reason for the "constant on" position is the lack of motor feedback to any type of controller. The nature of an induction motor limits its operation. Figure 7 shows the nameplate for the induction motor described.

Figure 7: Induction Motor Nameplate

Source: Terzo Power Systems, LLC

Depending on its wiring configuration, an almost 100 Amp current draw is possible to achieve its operating speed. This calculates to a power demand of up to 23kW. Not only is 23kW approximately three-quarters of the motor's output power capability but operating the HPU in an on-off state would cause constant and undue stress to the motor, incoming line power, and electrical integrity.

The power-on-demand feature of the HEPM-U addresses those disadvantages by not requiring standby operation. This means the elimination of 6kW of standby power consumption. In addition, the startup nature of the HEPM-U can be performed in a controlled and ramped-up method. This translates to less stress on both the upstream and downstream electrical components of the unit and also eliminates the massive 23kW power draw.

Because of the custom-designed inverter and oversight from the embedded microcontroller, constant monitoring of critical components and load demands can be continuously observed. Inputs are taken in the form of CAN commands, sensor feedback (speed, temperature, pressure), and shaft position. When demand for fluid flow is requested, the onboard CAN controller sends that request to the field programmable gate array (FPGA). From here, the FPGA determines the state of the system and commands the performance of specific functions. Depending on the configuration, those functions can reach a certain torque load, stop until a specified pressure is reached, or increase rotor RPM to a fixed value. Increases or decreases of RPM can be either immediate or proportionate.

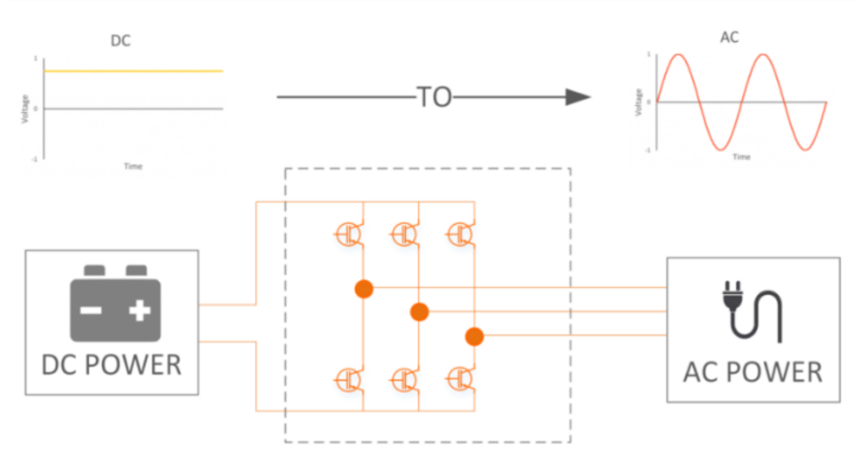
Mobile-Hardened Inverter

The off-highway mobile market is extremely demanding. Its principle design goal is to produce work; all other metrics receive secondary- or tertiary-level attention. Off-highway hydraulic machinery operates in some of the worst everyday conditions. It is exposed to high ambient temperatures, dusty conditions, and extreme vibrations.

This market's electronics need special consideration given these demanding performance factors. A quick review of the inverter's role follows.

From the basic standpoint of an inverter's purpose, it simply takes incoming DC voltage from a power source and "inverts" the voltage to AC voltage. Figure 8 is a block diagram that illustrates this process.

Figure 8: Inverter Block Diagram

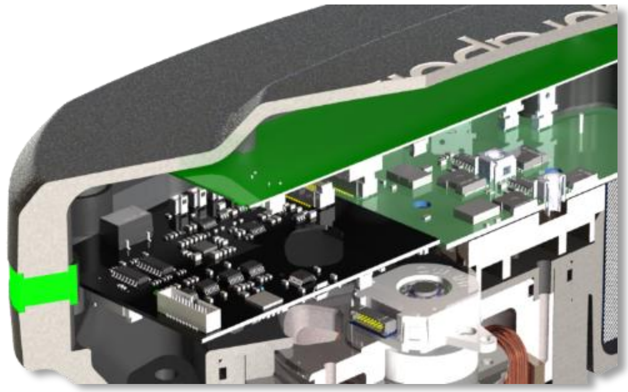


Source: Terzo Power Systems, LLC

The importance of the inverter stems from the role it plays in the HEPM-U. At its core, it is the component that controls the speed and torque of the PMSM. As part of the inverter architecture, it incorporates input from a microprocessor control unit to control switching timing and frequency. The control scheme is specifically designed to control a 3-phase PMSM. When the DC-to-AC waveform conversion takes place, it allows control of both frequency and amplitude. This provides the capacity to adjust AC power to the PMSM motor to directly control its speed and torque. Unlike in an induction motor, there is no waveform control. Because of this, it is either on or off at full-line frequency and amplitude.

These embedded controls are of little value if the HEPM-U is incapable of operating under the conditions of an off-highway hydraulic machine. From the onset, the degree of durability and robustness was sought in the form of specifying automotive-grade electronic components. Because of the high-level performance requirements commanded by the automotive industry, there is an abundance of high-quality grade components from which to choose. The advantages of using components of such high caliber include proven and validated survivability in a wide range of environments and under electronically stressed conditions. Taking this approach ensures a longer design life for the product, fewer and shorter reliability-issue events, and, ultimately, wider adoption of this novel technology.

Figure 9: Automotive-Grade Electronics



Source: Terzo Power Systems, LLC

Permanent Magnet Synchronous Motor

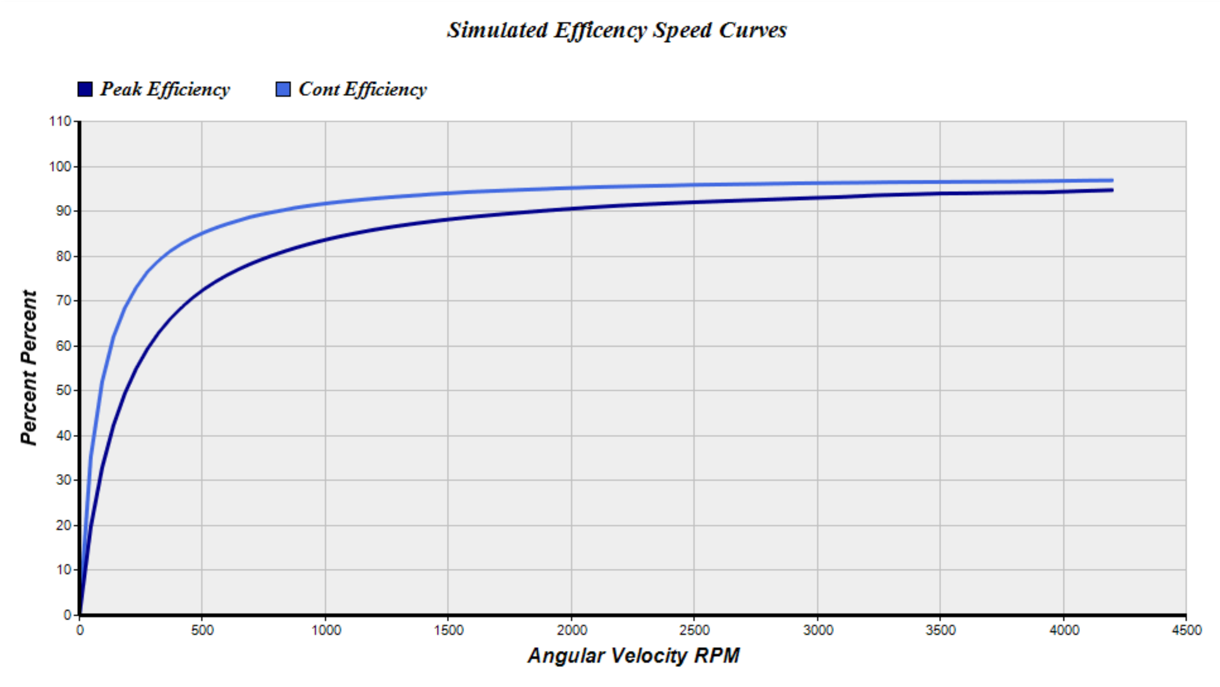
Permanent magnet synchronous motors have entered markets across various industries. Their acceptance is attributed to their small form factors and increased efficiencies. These attributes contribute to deployment of the novel technology. Their design aspects include prime placement of magnets and magnet types. These benefits are described in this report from the viewpoint of the HEPM-U's expanded adoption.

When compared with an asynchronous induction motor (ACIM), PMSMs have higher efficiencies than induction motors. Their basic modes of operation, however, are constrained by the same premise: generation of a magnetic field. What sets the PMSM apart is its suitability for operation using controllers that emphasize motor-control algorithms.

These algorithms include strict and precise instructions for smooth rotation over the complete RPM scale of a motor. These instructions are responsible for controlling the current of the multiple phases in use. The ability to control current at such granular levels results in complete control of a motor's shaft rotation. With this control, torque output can be managed in real time, motor acceleration and deceleration can be regulated, and the motor's integrity can be monitored.

Transitioning to the HEPM-U and demonstrating how it takes advantage of a PMSM's characteristics will keep efficiency in the forefront when seeking successful approval of the new technology. Illustrating that efficiency, Figure 10 shows an efficiency curve for the PMSM used in the HEPM-U.

Figure 10: Efficiency vs. RPM Curve



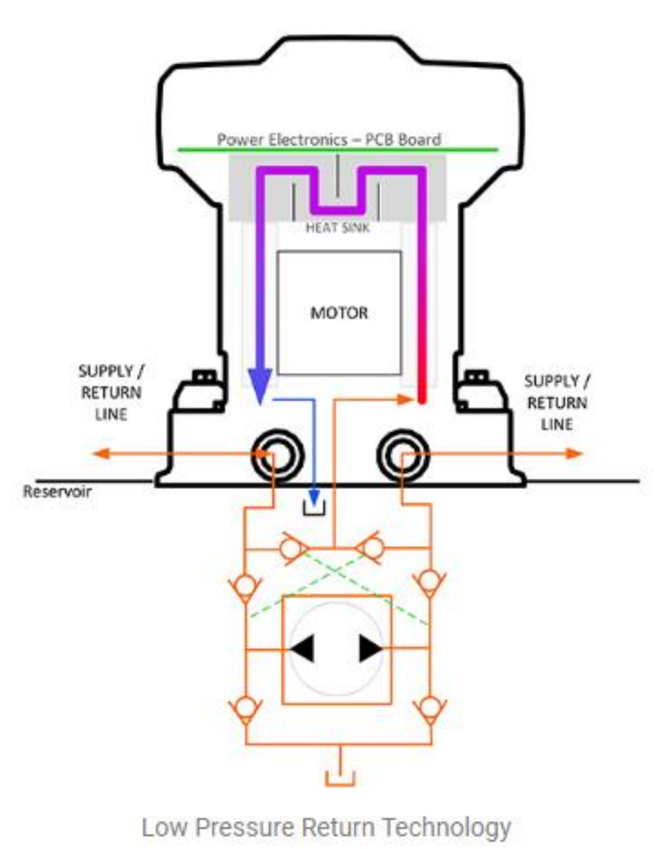
Source: Terzo Power Systems, LLC

Not accounting for rotor, stator, and switching losses, this efficiency curve illustrates an approachable range in the high 90s. Details adding to these efficiency numbers are proven insulated gate bipolar transistor (IGBT) switching timing, power on demand, and high-efficiency automotive-grade components.

Integrated Cooling

What is called "low-pressure return cooling technology" is a set of physical features and thermal management practices that combine to create a proven and effective method of cooling embedded electronics. Figure 11 illustrates these features.

Figure 11: Integrated Cooling



Source: Terzo Power Systems, LLC

The concept of this proprietary cooling process begins at the return port after the actuator has performed its function. As part of the fluid path back to the HEPM-U's reservoir, the fluid travels along outer liquid cooling pathways for the motor. These pathways lead to a heat-conductive element located below the highest heat-emitting electronics. As the fluid travels past the conductive element, the higher heat energy is carried away from the electronics through the return oil. The heated energy-carrying oil is directed through another set of outer cooling pathways and, finally, drains into the reservoir to be used again.

This integrated cooling is an important feature because it affects so many elements in a positive manner. With the integrated approach of this heat-exchanging mechanism, it provides a cooling method for the electronics and adds to the number of components that can be eliminated from a system.

All these described benefits add to the HEPM-U's level of performance and forge the compelling opportunity to challenge existing norms on weight, cost, efficiency, flexibility, and traditional methods of hydraulic system design.

CHAPTER 4: Product Validation

Chapter 4 focuses on communicating previously introduced metrics, but with a core discussion of efficiency based on energy consumption data collected during various duty-cycle testing sessions. It proves the HEPM-U's superiority, in many ways, over conventional technology. The overall goal is the affirmation of these efficiency advantages over traditional fluid-power methods and the ease of adoption of this new technology.

Cyclic and Duty-Cycle Testing Explanation

A precursor to this final report was a performance and durability test for both the HEPM-U and a conventional HPU. The primary purpose of that test was to ensure that all pertinent systems were functional. The proposed test called for 1,000 cycles of retraction and extension activities for both technologies. This ensured that all of the systems required for the performance of these tests were fully functional and that they could endure rigorous run times of seven to nine hours.

In addition to the collected data, successful completion of the 1,000-cycle testing sessions provided a benchmark of empirical observations on the "normal" operation of both systems. With this baseline knowledge of both systems' performance, it was then possible to plan continual test sessions. Table 2 is a matrix describing four duty-cycle testing sessions that compared the energy consumption of the two technologies.

Table 2: Testing Sessions Performed

	Session 1	Session 2	Session 3	Session 4
Extension Dwell Time	5 sec	60 sec	300 sec	600 sec
Retraction Dwell Time	5 sec	5 sec	5 sec	5 sec
Cycles	1000	10	10	10

Source: Terzo Power Systems, LLC

Four sessions were performed, all with different "dwell times." Using the hydraulic press that was part of the Pilot Demonstration Report, the dwell time represented the time required for a completed process where pressure was maintained for a period of time (extension), and the approximate time to change out a finished work piece with new material (retraction). The logic controller was programmed with the flexibility to adjust these dwell-time parameters to adapt to testing of the various industry processes and scenarios.

Cyclic Testing Results

The premise for performing these tests was to quantify the efficiency advantages of the HEPM-U under different duty cycles when compared with traditional hydraulics. Summarized in Table 3 are the energy consumption results from the testing sessions described in Table 2.

Table 3: Power-Consumption Results

Test Session	Test Session Time (hr)	Avg. Power (kW)	Total Energy Consumed (kWh)	% Diff
1000 cycles – 30 kW HEPM-U	8.05	2.20	17.70	–82.36
1000 cycles – 30 kW HPU	7.45	13.47	100.36	
1-minute, 10 cycles – 30 kW HEPM-U	0.24	1.78	0.43	–84.38
1-minute, 10 cycles – HPU	0.30	9.16	2.75	
5-minutes, 10 cycles – 30 kW HEPM-U	0.61	0.61	0.37	–93.91
5-minutes, 10 cycles – HPU	0.98	6.20	6.05	
10-minutes, 10 cycles – 30 kW HEPM-U	1.11	0.35	0.39	–96.06
10-minutes, 10 cycles – HPU	1.78	5.57	9.91	

Source: Terzo Power Systems, LLC

A series of four energy-analysis sessions was performed for each version of the technology. The first, as part of the pilot demonstration's deliverable, was to operate both technologies for the time it takes to perform 1,000 cycles of the hydraulic cylinder. Each cycle is defined as either a full-cylinder extension or a retraction. Between the two technologies, the sessions lasted an average of approximately eight hours. This data and power consumption values are listed in the first two rows of Table 2, below the column titles.

The first two rows of data show the 1,000-cycle sessions. The entries ending with HEPM-U show sessions where the novel technology was the device under test (DUT) and are labeled "30kW HEPM-U." Labels ending with "HPU" refer to the conventional power unit. The pairs of rows beginning with prefixes 1, 5, and 10 correspond to test sessions 2 through 4 with profiles listed in Table 1. Lastly, the column at the far right lists the percentage difference of power consumption between both technologies when performing equal profiles. The negatives represent reductions in power consumption when compared with conventional HPUs.

Taking Test Session 2 as an opportunity to elaborate on the data collected, the profile for that session begins with the hydraulic cylinder in the retracted position. At this point, the test parameters and profile values would have been entered in the logic controller. Pressing the "cycle-start" icon on the human machine interface (HMI) begins the process of extending the hydraulic cylinder at full system speed. This will continue until the cylinder enters the range of a proximity sensor that signals a speed reduction. Up to this point, the pressure developed is only what is needed to extend the cylinder and overcome any flow restrictions in the system. Once the cylinder's travel is obstructed by the top platen of the press, pressure begins to build until the predefined pressure set point is reached. At this moment, the dwell time figures take effect. Pressure is then maintained for 60 seconds. Expiration of the dwell time shows that a cycle has taken place, after which the cylinder retreats to its retracted state and ends with the expiration of a 5-second dwell time and an increase in cycle count. This continues until 10 cycles are accumulated.

From the standpoint of energy consumption, Figure 12 and Figure 13 show the results of collected data from the same session. Figure 12 is the power-consumption graph for the HEPM-U and Figure 13 shows the conventional HPU.

Understanding the collected data is key to recognizing the validity of posted efficiency gains. Graphically, there are key details that highlight broad decreases in power consumption. There are two primary details in the previous graphs that reflect the two main principles upon which the HEPM-U's design philosophy was predicated.

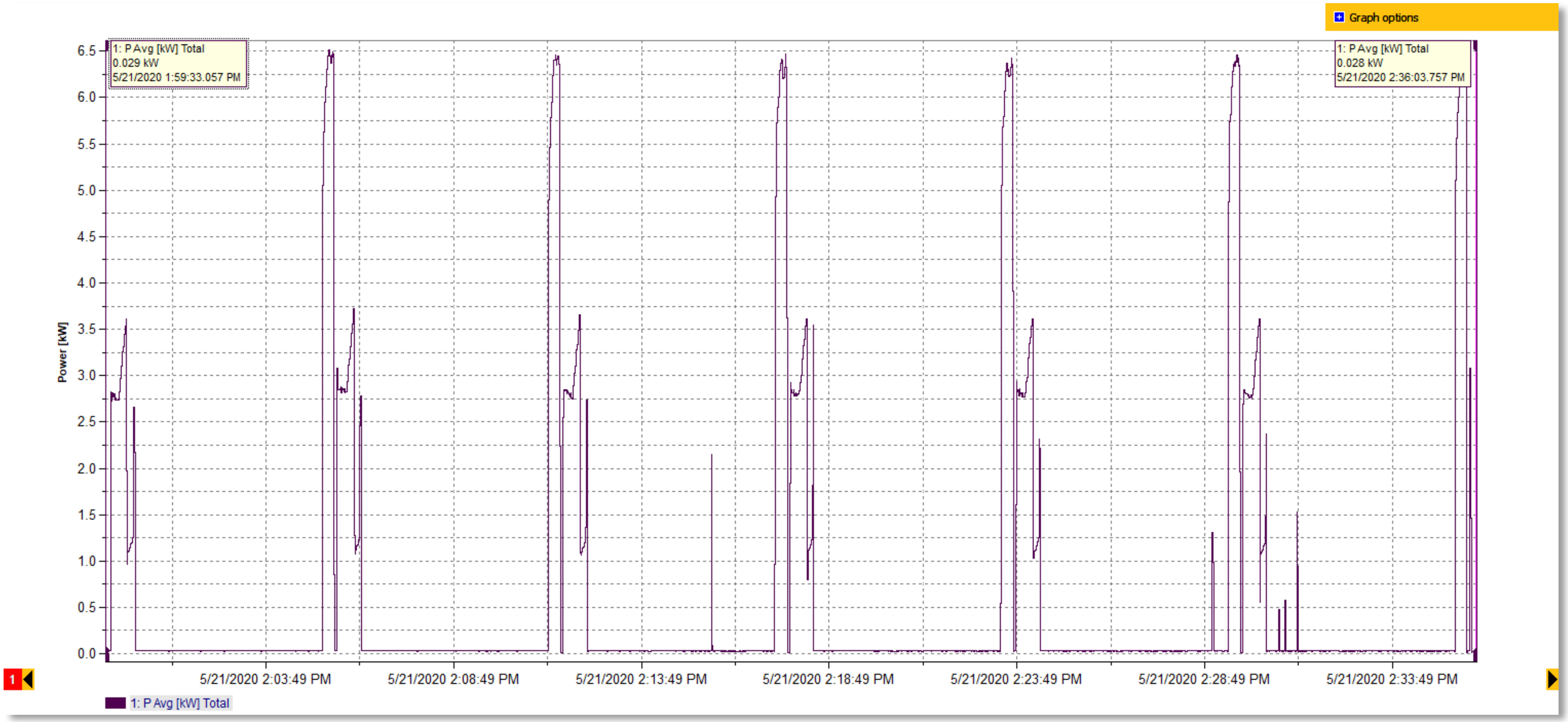
The first, and perhaps the most prominent, is the power-on-demand mode of operation. The importance of the novel technology's power-on-demand innovation is apparent even in the lowest power-consumption numbers in both graphs. The long, horizontal, and plateaued line represents the 60-second dwell time. It shows that it takes approximately 5kW of power for the conventional HPU to simply operate in a pressure-holding state. The pressure-holding state is the state at which the press achieves a target force (via pressure feedback) and maintains that force for a period of time. This action is prevalent in many applications. Some examples are coining, composite forming, hydro forming, and molding. It should also be noted that the pressure-holding dwell time can last up to 10 minutes. When implementing the new technology's power-on-demand capability, the longer the dwell time, the lower the power consumption, which increases operational savings. Figure 12 shows near-zero power consumption for the HEPM-U's dwell time.

The second prominent detail in Figure 12 and Figure 13 shows maximum values reached for power consumption. Maximum power consumption for the HPU is above 19kW at times, while that of the HEPM-U seldom approaches a 6.5kW threshold. This accounts for the novel technology's 65-percent decrease in power demand, which greatly enhances the benefit of integrating many components for the generation and transmission of fluid power.

As an example of this componentry integration, there is a distance associated with the paths required for fluid to travel between the reservoir and actuator to perform work. There are approximately 50 linear feet for the hydraulic fluid to travel from the reservoir to the actuator and back to the reservoir. In that 50 feet, there are both continuous changes in pathway diameters and abrupt changes in direction. In each instance, the pump must overcome and compensate for pressure drops in order to maintain a consistent flow. This compensation requires additional power to move the fluid. With this new approach to hydraulic system design and integration, an estimated 20 feet of travel resulted with much less variation in both pathway diameters and abrupt direction changes. This dynamic further adds to the HEPM-U's overall efficiency.

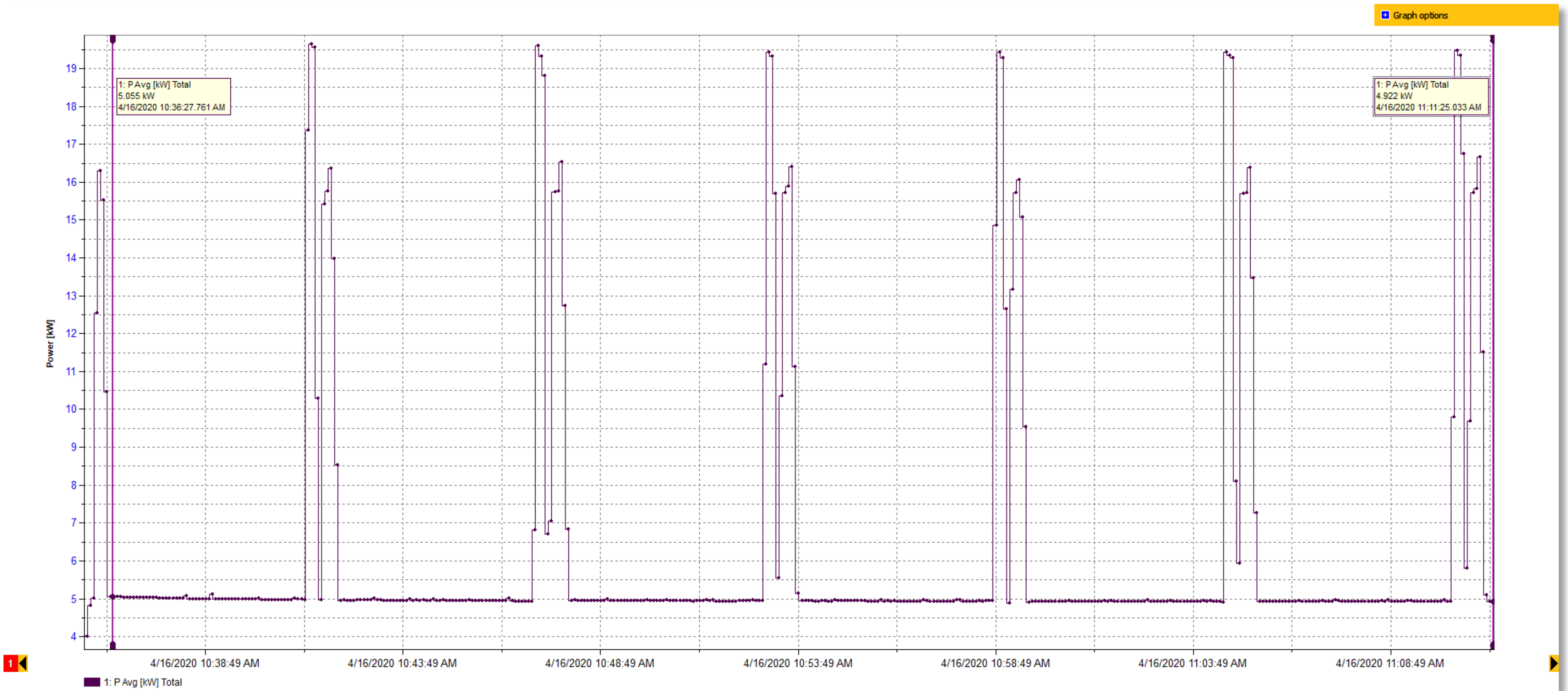
Energy-study graphs appear in this report's appendix.

Figure 12: Power Consumption, 1-Minute Dwell: 30kW HEPM-U



Source: Terzo Power Systems, LLC

Figure 13: Power Consumption, 1-Minute Dwell: HPU



Source: Terzo Power Systems, LLC

Benefits to Deployment of the Novel Technology

To quantify the two energy-saving attributes just described, a scenario was created where the HPU and the HEPM-U operated in an industrial setting. Data from test session 4 was used in this scenario. This profile consisted of a 600-second (10 minutes) dwell time for the cylinder's extension portion. The HPU's cycle parameters are listed in Table 4. Similar parameters were used for the novel technology, where applicable.

Table 4: HPU Cycle Parameters

Description	Value	Unit
Number of cycles	10	n/a
Pressure limit	1500	psi
Extension limit dwell time	600	second
Retraction limit dwell time	5	second
System pressure	1600	psi
Flow command	varies (0-100)	%
End of stroke flow limit	65	%

Psi=pounds per square inch

Source: Terzo Power Systems, LLC

For the duration of the 10-minute dwell time, the HPU maintained a steady 5kW power demand to keep everything running. The following calculations are based on commercial energy-rate data as published by the U.S. Energy Information Administration. (Source: U.S. EIA Data on commercial energy rates). Last updated on May 26, 2020, California's average commercial rate was 15.57 cents/kWh.

The 5kW average power needed during the 10-minute dwell time yielded a .833kWh energy expenditure for those 10 minutes. Using dimensional analysis to amortize energy use over the span of one year yielded the following:

$$\#\ of\ 10\ minute\ dwell\ sessions\ in\ 1\ hour = \frac{10\ sessions}{1.783hrs(actual\ length\ of\ test\ session)} = 5.6\ sessions/hr$$

$$Dwell\ time\ energy\ used\ in\ 1\ hour = .833kWh * 5.6sessions = 4.666kWh$$

$$10\ hour\ workday\ dwell\ time\ energy\ used = 4.666kWh * 10 = 46.666kWh$$

$$1\ month\ energy\ used\ (business\ days) = 46.666kWh * (31 - 8)days = 1073.333kWh$$

$$1\ year\ amortized\ energy\ used = 1073.333kWh * 12\ months = 12880kWh$$

$$1\ year\ cost\ to\ operate\ dwell\ time = 15.57\frac{cents}{kWh} * \frac{1dollar}{100cents} * 12880kWh = \$2005.42$$

Similarly, for a complete expression of possible efficiency gains, costs associated with the HPU's power use, above the maximum of the HEPM-U's power use, were calculated and summarized. The HEPM-U's overall cost to perform that work was additionally calculated and summarized.

Taking the average time, the HPU consumed power above 6.5kW and amortizing it over the same 1-year span yielded:

$$Variables:$$
$$14.544kWh - average\ power\ above\ 6.5kW, per\ cycle$$
$$45\ seconds - average\ time\ above\ 6.5kW, per\ cycle$$

$$45\ second\ power\ usage = 45sec * \left(\frac{1min}{60\text{sec}}\right) * \left(\frac{1hr}{60min}\right) * 14.544\ \text{kWh} = \ 0.182\text{kWh}$$

$$(Performing\ same\ steps\ as\ above)\ 1\ year\ power\ consumption\ cost = \$437.50$$

$$Cumulative\ yearly\ cost\ for\ 10 - minute\ dwell\ time\ processes = \$2442.92$$

Table 5 is a compilation of the values used for previous calculations.

Table 5: Energy Used and Cost - HPU

	Energy Used (kWh)	**Dwell Time Cost**	**Cost Above 6.5kW**
Single 10-minute session	0.833	$0.13	$0.03
1 hour of operation at 10-minute sessions	4.667	$0.73	$0.16
10-hour workday	46.667	$7.27	$1.59
1-month, cumulative	1,073.334	$167.12	$36.46
One calendar year, cumulative	12,880.003	$2,005.42	$437.50
		Total Cost:	$2,442.92

Source: Terzo Power Systems, LLC

CHAPTER 5: Conclusions

Of the many benefits realized by implementing the Hyper-Efficient Pump Motor Unit, perhaps the most persuasive is its potential to reduce a business's expenses. Using the results explained in Chapter 4 as an example, if the press and the hydraulic power unit were combined in an actual production setting, the cost of the non-working 10-minute dwell time frame would be $2,442.92. Test sessions illustrated in Table 2 show additional monetary savings.

Verifiable and consistent test results present a strong and convincing case for broad acceptance and implementation of the Hyper-Efficient Pump Motor Unit. Because a majority of business decisions are based upon the principle of return on investment, it would be a simple matter to present energy consumption studies to any industrial or mobile process to accurately evaluate their monetary impacts. Collectively, those returns could be expressed in many forms, encompassing costs of procurement, savings on operational costs, and occupational health benefits to end users.

Recap

The fluid power industry is vast, and the subjects discussed in this research report are keys to understanding this novel technology and its path to development and widespread future adoption. Chapter 1 provides a brief discussion of the motivation to address the typical impairments of modern hydraulics including noise, complexity, high cost, and other factors. This leads into Chapter 2, which explains the Hyper-Efficient Pump Motor Unit's primary value metrics. Ultimate resolution of most design issues studied throughout the development process stemmed from the requirements detailed in Chapter 2. This process and the technical requirements for meeting performance goals are further explained in Chapter 3. A few of the technologies could create competitive marketplace advantage and pave the way to patent-pending status. Encompassing both highlighted features and the hardware, Chapter 4 explains the quantifiable advantages of the Hyper-Efficient Pump Motor Unit over a traditional hydraulic power unit and re-emphasizes the claims and goals that directed this project as a whole.

Technology/Knowledge Transfer

As with any new technology, initial hurdles must be overcome to ensure mainstream acceptance and investment. A research report and proof of performance alone are not enough to turn a skeptic into a supporter. Both hands-on demonstrations and onsite application reviews are critical. Since education is so key to broad market acceptance of the Hyper-Efficient Pump Motor Unit, internal programs have been developed to educate potential buyers about its capabilities. This education campaign includes an online product overview, "lunch and learn" teaching sessions, and online video demonstrations on various aspects of operation.

Onsite application reviews are arguably the most valuable educational marketing tool since they specifically illustrate the novel technology's application in a potential customer's actual business setting. Planning for data collection exercises is also under development. The results of the energy consumption studies also provide a compelling case for future customers. Immersion pilot programs could ultimately result from these activities.

The levels and acceptance of these various educational activities would be pivotal for demonstrating and promoting the Hyper-Efficient Pump Motor Unit's capabilities and broad marketing potential.

Future Developments

As interest grows in the Hyper-Efficient Pump Motor Unit, customer feedback will be gathered and used to further refine and improve upon this already-robust novel technology. Commercialization of the Hyper-Efficient Pump Motor Unit will simultaneously ramp up so that a healthy inventory will allow the quick delivery of units to qualifying pilot projects. As interest grows, units with different power levels will be developed.

In the interim, more testing and data procurement of the novel technology will be performed to further identify areas for improvement. For both wider acceptance and increased validation, third-party certification for various industry standards will also be sought. Some of those are J1455 certifications, which outline stress testing against various environmental subjections, UL certifications for safety risk compliancy, and CE certification for compliance with health, safety, and environmental standards.

With the outcomes presented in this report, the Hyper-Efficient Pump Motor Unit already represents an evolutionary leap forward for hydraulic system design and use. Its efficiency gains are substantial and its comparative cost with competing technologies is compelling. What lies ahead is an education campaign to pique customer engagement and showcase this promising novel technology. Challenging well-established norms and overcoming common barriers to new technology adoption always yields better and smarter ways to use energy. It is in the best interests of California and its taxpayers to consider adopting Hyper-Efficient Pump Motor Units wherever traditional hydraulics operate.

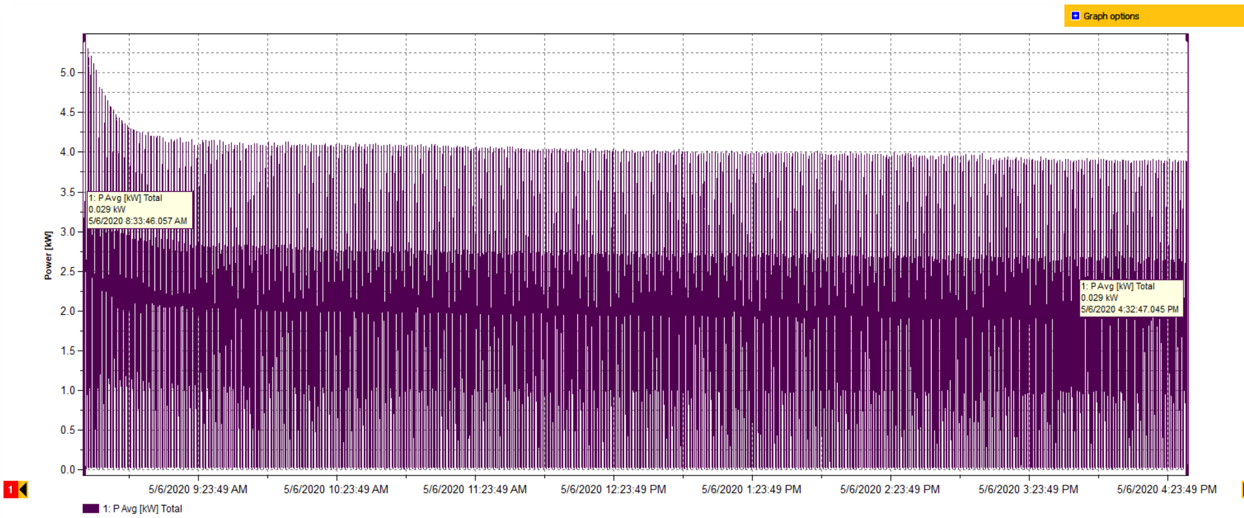
GLOSSARY AND LIST OF ACRONYMS

Term	Definition
AC	Alternative Current: Flow of electricity that constantly changes direction between positive and negative sides. Almost all power produced by electric utilities in the United States moves in current that shifts direction at a rate of 60 times per second.
ACIM	Asynchronous Induction Motor: AC electric machine which produces torque by electromagnetic induction derived from the magnetic field of the stator winding
CEC	California Energy Commission
CNC	Computer Numerical Control: Automated control of machining tools.
CAN	Controller Area Network: Message-based communication protocol for intercommunication of a multi-microcontroller system.
DC	Direct Current: A charge of electricity that flows in one direction and is the type of power that comes from a battery.
dB	Decibels: Unit of measurement, or degree of loudness, for the intensity of sound.
DUT	Device Under Test: Component, device, or system undergoing testing.
FPGA	Field Programmable Gate Array: An integrated circuit that can be programmed with binary logic and complex digital circuits.
GPM	Gallons per minute
HMI	Human Machine Interface: User interface in which a user (human) interacts with a machine. Typically, a graphical display.
Hp	Horsepower
HPU	Hydraulic Power Unit: Self-contained system comprising of main driving components for fluid power generation.
HEPM-U	Hyper-Efficient pump motor unit: The novel technology funded by the CEC for the research and development of an ultra-efficient power unit alternative to conventional hydraulic systems.
IGBT	Insulated Gate Bipolar Transistor: Three-terminal power semiconductor. Operates as a high frequency switching device.
IPM	Intelligent Power Modules: G1 series modules from Mitsubishi's high power and high switching frequency line of power modules.
kW	Kilowatt
OSHA	Occupational Health and Safety Administration: United States agency under the Department of Labor responsible for ensuring safety at work and a healthy work environment.
PCB	Printed circuit board: A non-conductive mechanical support for electronic components. Also includes paths to electrically connect electronic components.

Term	Definition
PMSM	Permanent Magnet Synchronous Motor: An electric motor using permanent magnets to maintain a constant magnetic field. The rotating elements rotate at a synchronized rate equal to the frequency of the supply current.
ROI	Return on investment: Performance metric used to evaluate the return on an investment, relative to the investment's cost.
RPM	Revolutions per minute

APPENDIX A:
Test Session Graphs and Logging Details

Figure A-1: Power Consumption Graph, 1000 Cycles: 30kW



Source: Terzo Power Systems, LLC

Figure A-2: Power and Logging Session Details, 1000 Cycles: 30kW

30KW BASELINE

Active Power [kW]	A	B	C	Total
Max	1.860 kW 5/6/2020 8:34:52 AM	1.822 kW 5/6/2020 8:34:52 AM	1.847 kW 5/6/2020 8:34:51 AM	5.459 kW 5/6/2020 8:34:51 AM
Avg	0.728 kW	0.710 kW	0.761 kW	2.199 kW
Min	0.0036 kW 5/6/2020 1:23:24 PM	-0.0007 kW 5/6/2020 3:54:58 PM	0.0023 kW 5/6/2020 3:28:47 PM	0.0065 kW 5/6/2020 3:28:47 PM
Apparent Power [kVA]	**A**	**B**	**C**	**Total**
Max	2.727 kVA 5/6/2020 8:34:52 AM	2.633 kVA 5/6/2020 8:34:55 AM	2.714 kVA 5/6/2020 8:34:51 AM	7.969 kVA 5/6/2020 8:34:51 AM
Avg	1.336 kVA	1.275 kVA	1.377 kVA	3.988 kVA
Min	0.0067 kVA 5/6/2020 2:49:26 PM	0.0048 kVA 5/6/2020 12:10:13 PM	0.0029 kVA 5/6/2020 3:28:47 PM	0.018 kVA 5/6/2020 3:28:47 PM
Non-Active Power [kvar]	**A**	**B**	**C**	**Total**
Max	2.005 kvar 5/6/2020 1:40:54 PM	1.989 kvar 5/6/2020 1:40:54 PM	2.102 kvar 5/6/2020 1:40:54 PM	6.105 kvar 5/6/2020 1:40:54 PM
Avg	1.120 kvar	1.059 kvar	1.147 kvar	3.327 kvar
Min	0.0055 kvar 5/6/2020 12:00:37 PM	0.0048 kvar 5/6/2020 12:10:13 PM	0.0017 kvar 5/6/2020 3:28:47 PM	0.016 kvar 5/6/2020 12:29:29 PM
Power Factor [1]	**A**	**B**	**C**	**Total**
Max	0.68* ind 5/6/2020 8:34:51 AM	0.69* ind 5/6/2020 8:34:51 AM	0.68* ind 5/6/2020 8:34:51 AM	0.69* ind 5/6/2020 8:34:51 AM
Avg	0.55	0.56	0.55	0.55
Min	0.11* 5/6/2020 2:58:55 PM	0.099* 5/6/2020 2:58:55 PM	0.11* 5/6/2020 2:58:55 PM	0.10* 5/6/2020 3:09:44 PM

Logging Information

Study type:
Energy study

Topology:
3-ph Wye

Start date:
5/6/2020 8:33:46 AM

End date:
5/6/2020 4:37:12 PM

Duration:
8h 3m 26s

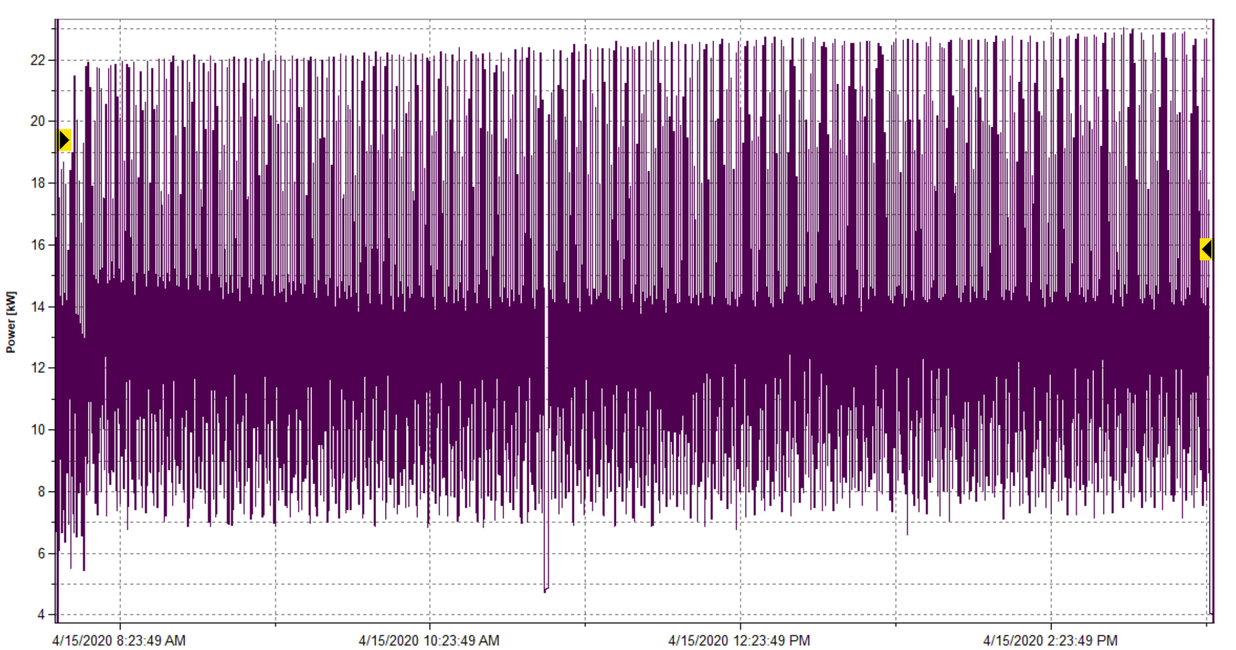
Averaging interval:
1sec

Number of averaging intervals:
29007 (29007)

* ... series contained invalid values that have been discarded for the shown result.

Source: Terzo Power Systems, LLC

Figure A-3: Power Consumption Graph, 1000 Cycles: HPU



Source: Terzo Power Systems, LLC

Figure A-4: Power and Logging Session Details, 1000 Cycles: HPU

HPU BASELINE

Active Power [kW]	A	B	C	Total
Max	9.679 kW 4/15/2020 11:09:40 AM	9.279 kW 4/15/2020 11:09:40 AM	9.924 kW 4/15/2020 11:09:40 AM	28.882 kW 4/15/2020 11:09:40 AM
Avg	4.504 kW	4.359 kW	4.608 kW	13.471 kW
Min	0.960 kW 4/15/2020 8:09:50 AM	0.899 kW 4/15/2020 8:08:10 AM	0.982 kW 4/15/2020 8:09:50 AM	2.841 kW 4/15/2020 8:09:50 AM
Apparent Power [kVA]	**A**	**B**	**C**	**Total**
Max	11.768 kVA 4/15/2020 11:09:40 AM	11.265 kVA 4/15/2020 11:09:40 AM	11.572 kVA 4/15/2020 11:09:40 AM	34.604 kVA 4/15/2020 11:09:40 AM
Avg	6.118 kVA	5.905 kVA	6.028 kVA	18.052 kVA
Min	1.873 kVA 4/15/2020 8:09:50 AM	1.814 kVA 4/15/2020 8:02:00 AM	1.812 kVA 4/15/2020 8:05:30 AM	5.520 kVA 4/15/2020 8:09:50 AM
Non-Active Power [kvar]	**A**	**B**	**C**	**Total**
Max	8.283 kvar 4/15/2020 8:14:50 AM	7.906 kvar 4/15/2020 8:14:50 AM	7.940 kvar 4/15/2020 8:14:50 AM	24.131 kvar 4/15/2020 8:14:50 AM
Avg	4.140 kvar	3.983 kvar	3.888 kvar	12.017 kvar
Min	1.593 kvar 4/15/2020 8:10:10 AM	1.565 kvar 4/15/2020 8:03:50 AM	1.492 kvar 4/15/2020 8:05:50 AM	4.672 kvar 4/15/2020 8:09:20 AM
Power Factor [1]	**A**	**B**	**C**	**Total**
Max	0.86 ind 4/15/2020 8:00:00 AM	0.86 ind 4/15/2020 8:00:00 AM	0.90 ind 4/15/2020 8:00:00 AM	0.87 ind 4/15/2020 8:00:00 AM
Avg	0.74	0.74	0.76	0.75
Min	0.49 ind 4/15/2020 3:25:50 PM	0.52 ind 4/15/2020 3:25:50 PM	0.52 ind 4/15/2020 3:25:50 PM	0.51 ind 4/15/2020 3:25:50 PM

Logging Information

Study type: **Energy study**

Topology: **3-ph Wye**

Start date: **4/15/2020 7:58:51 AM**

End date: **4/15/2020 3:26:32 PM**

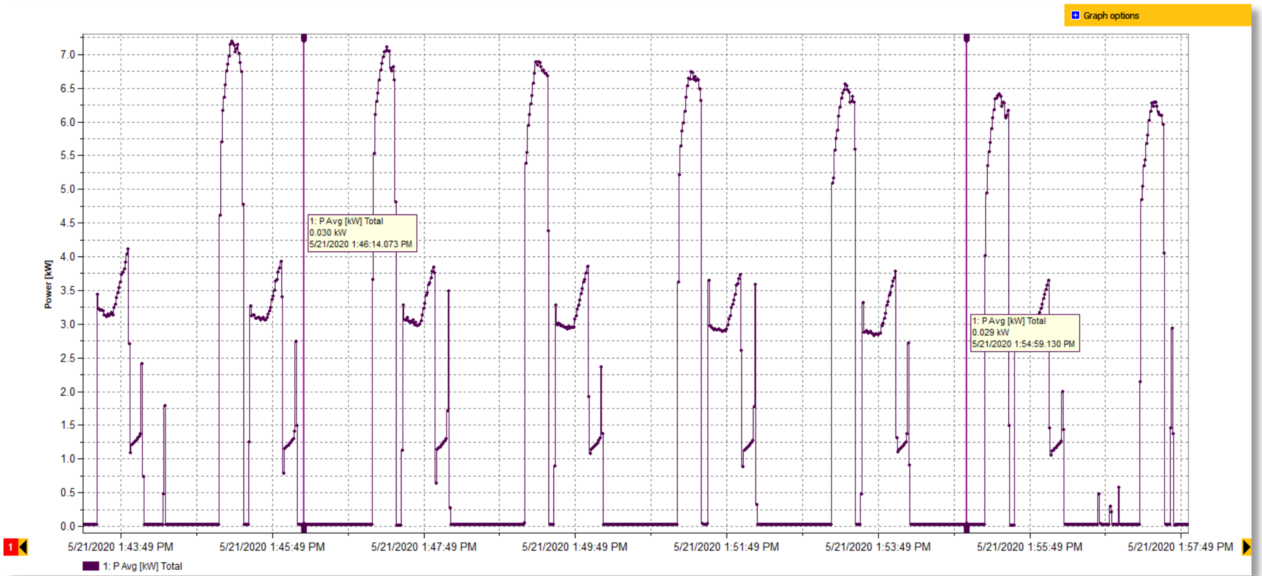
Duration: **7h 27m 41s**

Averaging interval: **10sec**

Number of averaging intervals: **2687 (2687)**

Source: Terzo Power Systems, LLC

Figure A-5: Power Consumption Graph, 1-min Dwell: 30kW



Source: Terzo Power Systems, LLC

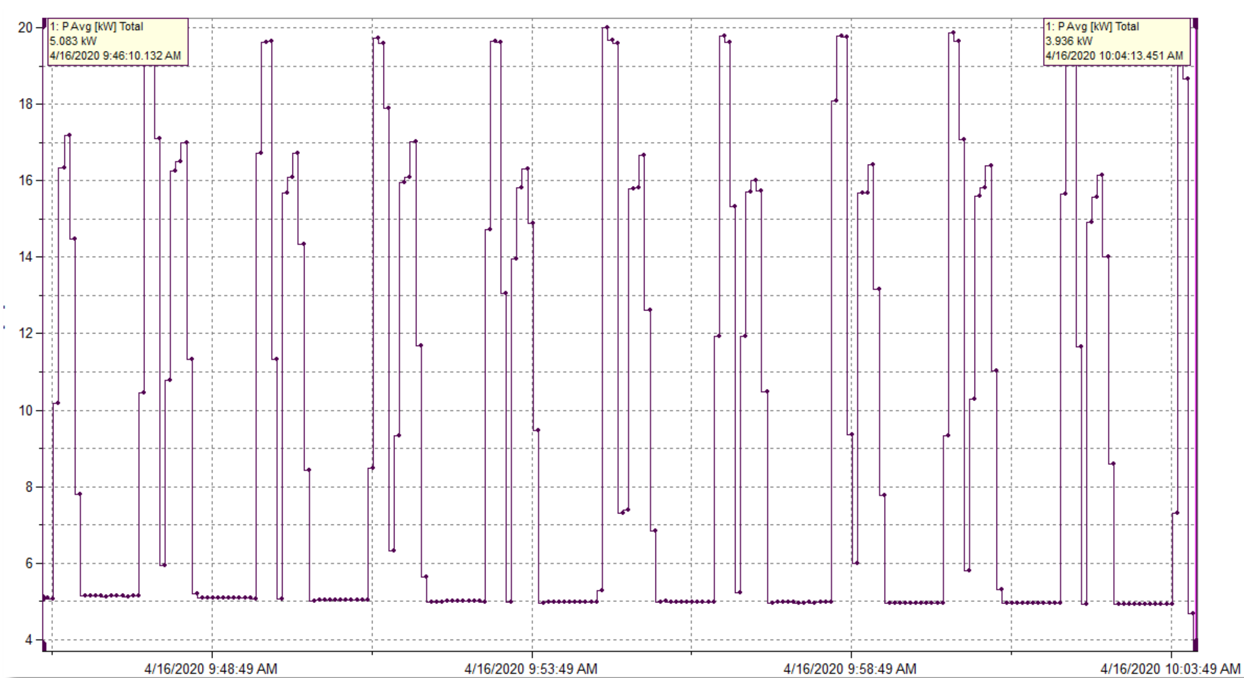
Figure A-6: Power and Logging Session Details, 1-min Dwell: 30kW

HP 1 MINUTE				
Active Power [kW]	**A**	**B**	**C**	**Total**
Max	2.501 kW 5/21/2020 1:45:18 PM	2.350 kW 5/21/2020 1:45:17 PM	2.487 kW 5/21/2020 1:45:16 PM	7.280 kW 5/21/2020 1:45:18 PM
Avg	0.601 kW	0.562 kW	0.613 kW	1.776 kW
Min	0.0043 kW 5/21/2020 1:47:30 PM	-0.0010 kW 5/21/2020 1:55:34 PM	0.0050 kW 5/21/2020 1:53:32 PM	0.0094 kW 5/21/2020 1:47:30 PM
Apparent Power [kVA]	**A**	**B**	**C**	**Total**
Max	3.531 kVA 5/21/2020 1:45:18 PM	3.309 kVA 5/21/2020 1:45:17 PM	3.502 kVA 5/21/2020 1:45:16 PM	10.261 kVA 5/21/2020 1:45:18 PM
Avg	1.472 kVA	1.370 kVA	1.479 kVA	4.321 kVA
Min	0.0071 kVA 5/21/2020 1:47:31 PM	0.0057 kVA 5/21/2020 1:47:31 PM	0.0063 kVA 5/21/2020 1:55:35 PM	0.021 kVA 5/21/2020 1:47:29 PM
Non-Active Power [kvar]	**A**	**B**	**C**	**Total**
Max	2.532 kvar 5/21/2020 1:53:23 PM	2.364 kvar 5/21/2020 1:53:24 PM	2.530 kvar 5/21/2020 1:53:22 PM	7.344 kvar 5/21/2020 1:53:22 PM
Avg	1.344 kvar	1.250 kvar	1.346 kvar	3.940 kvar
Min	0.0053 kvar 5/21/2020 1:57:37 PM	0.0057 kvar 5/21/2020 1:55:35 PM	0.0035 kvar 5/21/2020 1:47:28 PM	0.018 kvar 5/21/2020 1:47:29 PM
Power Factor [1]	**A**	**B**	**C**	**Total**
Max	0.71* ind 5/21/2020 1:45:18 PM	0.71* ind 5/21/2020 1:45:16 PM	0.71* ind 5/21/2020 1:45:17 PM	0.71* ind 5/21/2020 1:45:17 PM
Avg	0.41	0.41	0.41	0.41
Min	0.18* ind 5/21/2020 1:48:10 PM	0.17* ind 5/21/2020 1:48:10 PM	0.19* ind 5/21/2020 1:48:10 PM	0.18* ind 5/21/2020 1:48:10 PM

Logging Information
Study type: **Energy study**
Topology: **3-ph Wye**
Start date: **5/21/2020 1:43:19 PM**
End date: **5/21/2020 1:57:55 PM**
Duration: **14m 36s**
Averaging interval: **1sec**
Number of averaging intervals: **876 (876)**
* ... series contained invalid values that have been discarded for the shown result.

Source: Terzo Power Systems, LLC

Figure A-7: Power Consumption Graph, 1-min Dwell: HPU



Source: Terzo Power Systems, LLC

Figure A-8: Power and Logging Session Details, 1-min Dwell: HPU

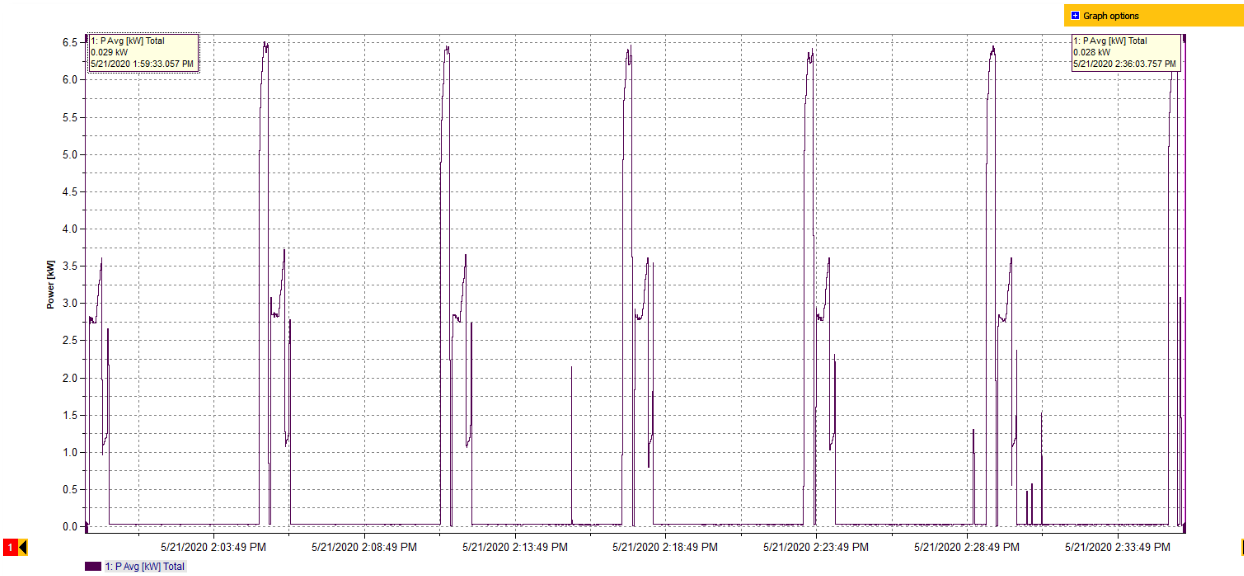
1 MINUTE CYCLES

Active Power [kW]	A	B	C	Total
Max	8.814 kW 4/16/2020 9:55:00 AM	8.454 kW 4/16/2020 9:55:00 AM	9.004 kW 4/16/2020 9:55:00 AM	26.272 kW 4/16/2020 9:55:00 AM
Avg	3.047 kW	2.973 kW	3.143 kW	9.164 kW
Min	1.207 kW 4/16/2020 10:04:05 AM	1.212 kW 4/16/2020 10:04:05 AM	1.350 kW 4/16/2020 10:04:13 AM	3.782 kW 4/16/2020 10:04:05 AM
Apparent Power [kVA]	**A**	**B**	**C**	**Total**
Max	10.455 kVA 4/16/2020 9:47:45 AM	10.058 kVA 4/16/2020 9:47:45 AM	10.320 kVA 4/16/2020 9:47:45 AM	30.833 kVA 4/16/2020 9:47:45 AM
Avg	4.713 kVA	4.583 kVA	4.668 kVA	13.965 kVA
Min	2.636 kVA 4/16/2020 10:04:13 AM	2.642 kVA 4/16/2020 10:04:13 AM	2.672 kVA 4/16/2020 10:04:13 AM	7.975 kVA 4/16/2020 10:04:13 AM
Non-Active Power [kvar]	**A**	**B**	**C**	**Total**
Max	8.317 kvar 4/16/2020 9:50:15 AM	7.900 kvar 4/16/2020 9:50:15 AM	8.005 kvar 4/16/2020 9:50:15 AM	24.227 kvar 4/16/2020 9:50:15 AM
Avg	3.596 kvar	3.488 kvar	3.451 kvar	10.538 kvar
Min	2.310 kvar 4/16/2020 10:04:13 AM	2.309 kvar 4/16/2020 10:04:13 AM	2.302 kvar 4/16/2020 10:04:13 AM	6.946 kvar 4/16/2020 10:04:13 AM
Power Factor [1]	**A**	**B**	**C**	**Total**
Max	0.84 ind 4/16/2020 10:02:20 AM	0.84 ind 4/16/2020 9:53:15 AM	0.87 ind 4/16/2020 9:58:45 AM	0.85 ind 4/16/2020 10:02:20 AM
Avg	0.65	0.65	0.67	0.66
Min	0.48 ind 4/16/2020 10:04:13 AM	0.49 ind 4/16/2020 10:04:13 AM	0.51 ind 4/16/2020 10:04:13 AM	0.49 ind 4/16/2020 10:04:13 AM

Logging Information	
Study type:	Energy study
Topology:	3-ph Wye
Start date:	4/16/2020 9:46:10 AM
End date:	4/16/2020 10:04:13 AM
Duration:	18m 3s
Averaging interval:	5sec
Number of averaging intervals:	217 (217)

Source: Terzo Power Systems, LLC

Figure A-9: Power Consumption Graph, 5-min Dwell: 30kW



Source: Terzo Power Systems, LLC

Figure A-10: Power and Logging Session Details, 5-min Dwell: 30kW

HP 5 MINUTE

Active Power [kW]	A	B	C	Total
Max	2.248 kW 5/21/2020 2:29:42 PM	2.145 kW 5/21/2020 2:11:36 PM	2.316 kW 5/21/2020 2:05:30 PM	6.572 kW 5/21/2020 2:05:36 PM
Avg	0.201 kW	0.190 kW	0.214 kW	0.605 kW
Min	0.0044 kW 5/21/2020 2:11:41 PM	-0.0017 kW 5/21/2020 2:24:15 PM	0.0040 kW 5/21/2020 2:35:49 PM	0.0083 kW 5/21/2020 2:35:49 PM
Apparent Power [kVA]	**A**	**B**	**C**	**Total**
Max	3.235 kVA 5/21/2020 2:11:29 PM	3.089 kVA 5/21/2020 2:11:31 PM	3.311 kVA 5/21/2020 2:35:42 PM	9.584 kVA 5/21/2020 2:11:30 PM
Avg	0.823 kVA	0.779 kVA	0.848 kVA	2.451 kVA
Min	0.0067 kVA 5/21/2020 2:11:41 PM	0.0055 kVA 5/21/2020 2:17:43 PM	0.0051 kVA 5/21/2020 2:35:49 PM	0.020 kVA 5/21/2020 2:35:49 PM
Non-Active Power [kvar]	**A**	**B**	**C**	**Total**
Max	2.409 kvar 5/21/2020 2:11:29 PM	2.272 kvar 5/21/2020 2:11:27 PM	2.438 kvar 5/21/2020 2:11:29 PM	7.097 kvar 5/21/2020 2:11:29 PM
Avg	0.799 kvar	0.756 kvar	0.821 kvar	2.375 kvar
Min	0.0051 kvar 5/21/2020 2:11:41 PM	0.0054 kvar 5/21/2020 2:17:43 PM	0.0031 kvar 5/21/2020 2:35:49 PM	0.017 kvar 5/21/2020 2:17:44 PM
Power Factor [1]	**A**	**B**	**C**	**Total**
Max	0.70* ind 5/21/2020 2:29:40 PM	0.71* ind 5/21/2020 2:05:30 PM	0.70* ind 5/21/2020 2:05:32 PM	0.70* ind 5/21/2020 2:29:40 PM
Avg	0.24	0.24	0.25	0.25
Min	0.15* 5/21/2020 2:15:43 PM	0.13* 5/21/2020 2:15:43 PM	0.16* 5/21/2020 2:15:43 PM	0.15* ind 5/21/2020 2:15:43 PM

Logging Information

Study type:
Energy study

Topology:
3-ph Wye

Start date:
5/21/2020 1:59:33 PM

End date:
5/21/2020 2:36:04 PM

Duration:
36m 31s

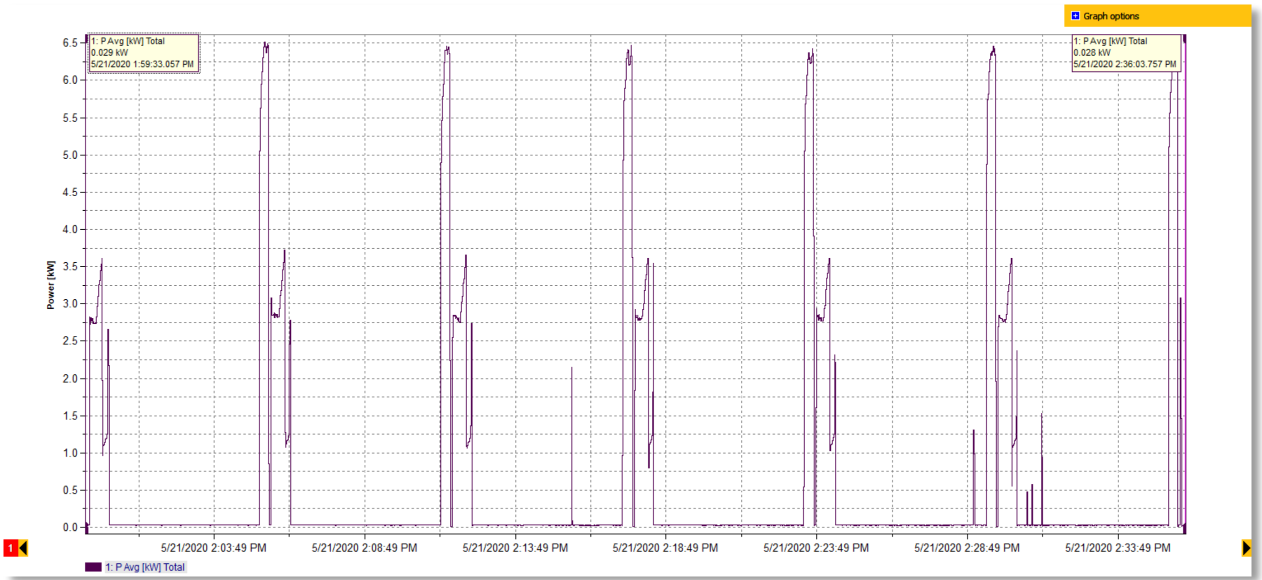
Averaging interval:
1sec

Number of averaging intervals:
2191 (2191)

* ... series contained invalid values that have been discarded for the shown result.

Source: Terzo Power Systems, LLC

Figure A-11: Power Consumption Graph, 5-min Dwell: HPU



Source: Terzo Power Systems, LLC

Figure A-12: Power and Logging Session Details, 5-min Dwell: HPU

5 MINUTE CYCLES

Active Power [kW]	A	B	C	Total
Max	8.822 kW 4/16/2020 10:41:25 AM	8.414 kW 4/16/2020 10:41:25 AM	8.999 kW 4/16/2020 10:41:25 AM	26.236 kW 4/16/2020 10:41:25 AM
Avg	2.052 kW	2.018 kW	2.131 kW	6.201 kW
Min	1.259 kW 4/16/2020 11:34:05 AM	1.267 kW 4/16/2020 11:34:10 AM	1.333 kW 4/16/2020 11:34:05 AM	3.883 kW 4/16/2020 11:34:05 AM
Apparent Power [kVA]	**A**	**B**	**C**	**Total**
Max	10.425 kVA 4/16/2020 10:41:25 AM	9.929 kVA 4/16/2020 10:41:25 AM	10.226 kVA 4/16/2020 10:41:25 AM	30.578 kVA 4/16/2020 10:41:25 AM
Avg	3.529 kVA	3.458 kVA	3.502 kVA	10.492 kVA
Min	2.627 kVA 4/16/2020 11:34:10 AM	2.627 kVA 4/16/2020 11:34:00 AM	2.642 kVA 4/16/2020 11:34:00 AM	7.919 kVA 4/16/2020 11:34:10 AM
Non-Active Power [kvar]	**A**	**B**	**C**	**Total**
Max	8.156 kvar 4/16/2020 10:36:15 AM	7.707 kvar 4/16/2020 10:36:15 AM	7.824 kvar 4/16/2020 10:36:15 AM	23.690 kvar 4/16/2020 10:36:15 AM
Avg	2.872 kvar	2.808 kvar	2.779 kvar	8.463 kvar
Min	2.300 kvar 4/16/2020 11:33:55 AM	2.295 kvar 4/16/2020 11:34:00 AM	2.275 kvar 4/16/2020 11:34:00 AM	6.895 kvar 4/16/2020 11:33:55 AM
Power Factor [1]	**A**	**B**	**C**	**Total**
Max	0.84 ind 4/16/2020 10:58:55 AM	0.84 ind 4/16/2020 11:04:45 AM	0.87 ind 4/16/2020 11:33:45 AM	0.85 ind 4/16/2020 11:33:45 AM
Avg	0.58	0.58	0.61	0.59
Min	0.48 ind 4/16/2020 11:34:05 AM	0.48 ind 4/16/2020 11:34:05 AM	0.51 ind 4/16/2020 11:34:05 AM	0.49 ind 4/16/2020 11:34:05 AM

Logging Information	
Study type:	Energy study
Topology:	3-ph Wye
Start date:	4/16/2020 10:35:45 AM
End date:	4/16/2020 11:34:16 AM
Duration:	58m 31s
Averaging interval:	5sec
Number of averaging intervals:	703 (703)

Source: Terzo Power Systems, LLC

Figure A-13: Power Consumption Graph, 10-min Dwell: 30kW

Source: Terzo Power Systems, LLC

Figure A-14: Power and Logging Session Details, 10-min Dwell: 30kW

HP 10 MINUTE

Active Power [kW]	A	B	C	Total
Max	2.266 kW 5/21/2020 3:21:16 PM	2.197 kW 5/21/2020 3:32:20 PM	2.389 kW 5/21/2020 2:48:12 PM	6.742 kW 5/21/2020 3:21:16 PM
Avg	0.115 kW	0.109 kW	0.126 kW	0.350 kW
Min	0.0044 kW 5/21/2020 3:43:37 PM	-0.0010 kW 5/21/2020 3:43:38 PM	0.0046 kW 5/21/2020 2:48:14 PM	0.0085 kW 5/21/2020 3:43:38 PM
Apparent Power [kVA]	**A**	**B**	**C**	**Total**
Max	3.253 kVA 5/21/2020 2:48:03 PM	3.089 kVA 5/21/2020 3:32:20 PM	3.382 kVA 5/21/2020 2:48:12 PM	9.601 kVA 5/21/2020 3:21:16 PM
Avg	0.615 kVA	0.584 kVA	0.637 kVA	1.837 kVA
Min	0.0070 kVA 5/21/2020 3:21:24 PM	0.0052 kVA 5/21/2020 3:43:37 PM	0.0063 kVA 5/21/2020 3:43:36 PM	0.020 kVA 5/21/2020 3:43:37 PM
Non-Active Power [kvar]	**A**	**B**	**C**	**Total**
Max	2.344 kvar 5/21/2020 3:43:19 PM	2.174 kvar 5/21/2020 3:21:16 PM	2.394 kvar 5/21/2020 2:48:12 PM	6.835 kvar 5/21/2020 3:21:16 PM
Avg	0.604 kvar	0.574 kvar	0.625 kvar	1.803 kvar
Min	0.0052 kvar 5/21/2020 3:43:41 PM	0.0052 kvar 5/21/2020 3:43:37 PM	0.0031 kvar 5/21/2020 3:21:23 PM	0.017 kvar 5/21/2020 3:43:37 PM
Power Factor [1]	**A**	**B**	**C**	**Total**
Max	0.70* ind 5/21/2020 3:32:15 PM	0.71* ind 5/21/2020 3:32:21 PM	0.71* ind 5/21/2020 3:10:17 PM	0.71* ind 5/21/2020 3:32:15 PM
Avg	0.19	0.19	0.20	0.19
Min	0.16* ind 5/21/2020 3:23:46 PM	0.15* ind 5/21/2020 3:23:46 PM	0.17* ind 5/21/2020 3:23:46 PM	0.16* ind 5/21/2020 3:23:46 PM

Logging Information

Study type:
Energy study

Topology:
3-ph Wye

Start date:
5/21/2020 2:37:09 PM

End date:
5/21/2020 3:43:42 PM

Duration:
1h 6m 33s

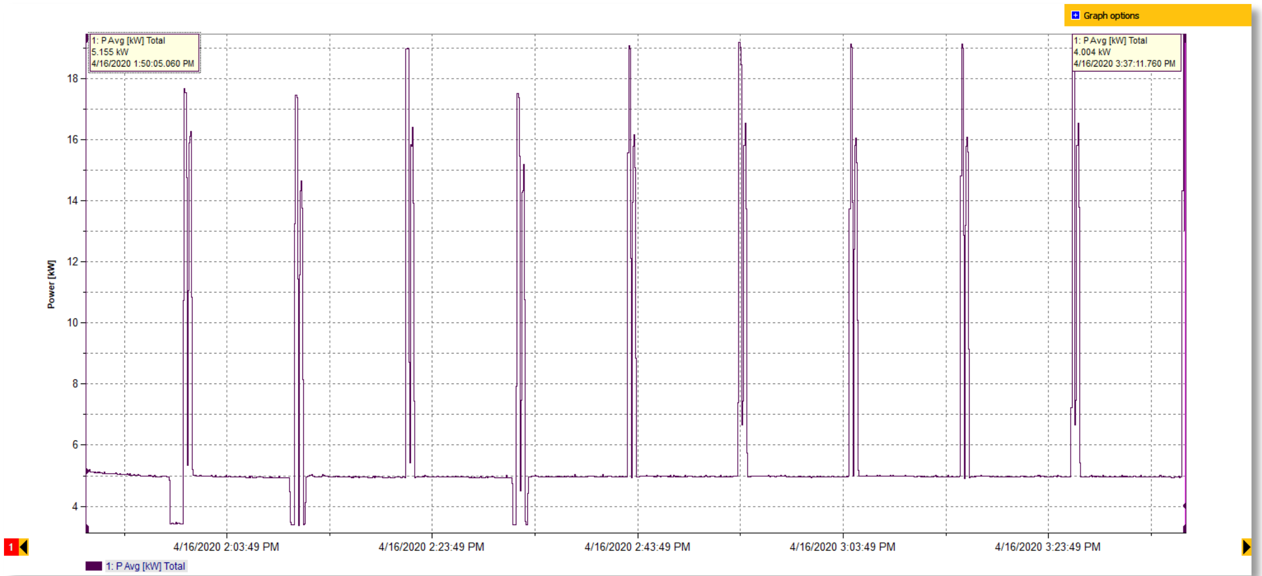
Averaging interval:
1sec

Number of averaging intervals:
3993 (3993)

* ... series contained invalid values that have been discarded for the shown result.

Source: Terzo Power Systems, LLC

Figure A-15: Power Consumption Graph, 10-min Dwell: HPU



Source: Terzo Power Systems, LLC

Figure A-16: Power and Logging Session Details, 10-min Dwell: HPU

10 MINUTE CYCLES

Active Power [kW]	A	B	C	Total
Max	8.577 kW 4/16/2020 2:53:40 PM	8.237 kW 4/16/2020 2:53:40 PM	8.831 kW 4/16/2020 2:53:40 PM	25.645 kW 4/16/2020 2:53:40 PM
Avg	1.824 kW	1.818 kW	1.927 kW	5.569 kW
Min	1.012 kW 4/16/2020 2:32:05 PM	0.961 kW 4/16/2020 2:32:05 PM	1.092 kW 4/16/2020 2:32:05 PM	3.065 kW 4/16/2020 2:32:05 PM
Apparent Power [kVA]	**A**	**B**	**C**	**Total**
Max	10.136 kVA 4/16/2020 2:53:40 PM	9.686 kVA 4/16/2020 2:53:40 PM	10.031 kVA 4/16/2020 2:53:40 PM	29.853 kVA 4/16/2020 2:53:40 PM
Avg	3.169 kVA	3.115 kVA	3.176 kVA	9.463 kVA
Min	2.075 kVA 4/16/2020 2:32:05 PM	1.995 kVA 4/16/2020 2:32:05 PM	2.032 kVA 4/16/2020 2:10:30 PM	6.102 kVA 4/16/2020 2:32:05 PM
Non-Active Power [kvar]	**A**	**B**	**C**	**Total**
Max	7.173 kvar 4/16/2020 2:32:50 PM	6.821 kvar 4/16/2020 3:05:10 PM	7.013 kvar 4/16/2020 3:05:10 PM	20.948 kvar 4/16/2020 3:05:10 PM
Avg	2.592 kvar	2.530 kvar	2.524 kvar	7.650 kvar
Min	1.792 kvar 4/16/2020 2:32:30 PM	1.734 kvar 4/16/2020 2:32:30 PM	1.685 kvar 4/16/2020 1:58:30 PM	5.227 kvar 4/16/2020 2:32:30 PM
Power Factor [1]	**A**	**B**	**C**	**Total**
Max	0.85 ind 4/16/2020 2:32:10 PM	0.85 ind 4/16/2020 1:59:50 PM	0.89 ind 4/16/2020 2:10:40 PM	0.86 ind 4/16/2020 2:10:40 PM
Avg	0.58	0.58	0.61	0.59
Min	0.49 ind 4/16/2020 3:37:12 PM	0.50 ind 4/16/2020 3:37:12 PM	0.53 ind 4/16/2020 3:37:12 PM	0.51 ind 4/16/2020 3:37:12 PM

Logging Information

Study type: **Energy study**
Topology: **3-ph Wye**
Start date: **4/16/2020 1:50:05 PM**
End date: **4/16/2020 3:37:12 PM**
Duration: **1h 47m 7s**
Averaging interval: **5sec**
Number of averaging intervals: **1286 (1286)**

Source: Terzo Power Systems, LLC