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SMALL-SCALE POWER EXTRACTION SYSTEM FOR COMPRESSED AIR ENERGY STORAGE

by

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December 2018

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13. ABSTRACT (maximum 200 words)

The goal of this thesis was to improve on the concept of using compressed air as an energy storage medium to generate electrical power. By using compressed air as energy storage, the cost to store power is significantly reduced.

An air ejector was used to increase the airflow through a small turbine to maximize the power extraction from the compressed air. The turbine shaft rotation was coupled to a three-phase, permanent magnet generator, to produce three-phase alternating current (AC). A three-phase AC transformer bank was incorporated in one of three modes to optimize the turbine speed: step down, bypass, or step up. The AC was then rectified into direct current (DC) for storage in a super capacitor.

Computational fluid dynamics simulation was used to explore entrainment scenarios and their effect on airflow into the turbine. With the obtained entrainment airflows, the internal energy of the expanded air was proven to rise before use by the turbine. This system, if fully developed, could use existing air storage infrastructure at many Department of Defense installations to harness the full potential of renewable energy and provide for more resilient and secure energy.

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SMALL-SCALE POWER EXTRACTION SYSTEM FOR COMPRESSED AIR ENERGY STORAGE

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ABSTRACT

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An air ejector was used to increase the airflow through a small turbine to maximize the power extraction from the compressed air. The turbine shaft rotation was coupled to a three-phase, permanent magnet generator, to produce three-phase alternating current (AC). A three-phase AC transformer bank was incorporated in one of three modes to optimize the turbine speed: step down, bypass, or step up. The AC was then rectified into direct current (DC) for storage in a super capacitor.

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LIST OF ACRONYMS AND ABBREVIATIONS

A	amps
A/R	area ratio
AA-CAES	advanced adiabatic compressed air energy storage
AC	alternating current
A-CAES	advanced compressed air energy storage
ATM	atmospheres
BESS	battery energy storage system
CAES	compressed air energy storage
C-D	converging diverging
CES	cryogenic energy storage
CFD	computational fluid dynamic
CHRA	center housing rotating assembly
DC	direct current
DG	diesel generator
DoD	Department of Defense
EESS	electrical energy storage systems
ESR	equivalent series resistance
FES	flywheel energy storage
HPC	high pressure compressor
HPT	high pressure turbine
Hz	hertz (cycles/second)
IC	integrated circuit
in	inch
IPC	intermediate pressure compressor
kPa	kilo pascal
LPT	low pressure turbine
MEG	micro energy grid
NAS	sodium Sulphur battery
NO	normally open
NS	normally shut

NYSERDA	New York State Energy Research and Development Authority
Pa	pascal
PCM	phase change materials
PLC	programmable logic controller
PSIG	pounds per square inch gage
PTC	parabolic trough collectors
RPM	rotations per minute
SC-CAES	small-scale compressed air energy storage
SCFM	standard cubic feet per minute
SMES	superconducting magnetic energy storage
SSR	solid state relay
ST-CAES	solar thermal compressed air energy storage
TES	thermal energy storage
VDC	volts direct current
VRB	vanadium redox batter
W	watt
Wh	watt hour
ZEBRA	sodium nickel chloride battery

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I. INTRODUCTION

This thesis aims to use compressed air as a form of potential energy storage for later conversion to efficiently charge a 56VDC supercapacitor. A fully charged supercapacitor is able to power a microgrid when renewable or grid electricity is not available. A background of compressed air as an energy storage method and current technologies in generating power from the compressed air will be explored as a backdrop to the research being conducted for this thesis.

A. CURRENT ELECTRICAL ENERGY STORAGE SYSTEMS

Electrical energy storage systems (EESS), which convert electrical power to a storage medium for later use, vary significantly depending on the scale and needs of the end user. Reasons for storing energy include

> helping in meeting peak electrical load demands, providing time varying energy management, alleviating the intermittence of renewable source power generation, improving power quality/reliability, meeting remote and vehicle load needs, supporting the realization of smart grids, helping with the management of distributed/standby power generation, and reducing electrical energy import during peak demand periods. [1]

Each of these reasons for EESS have driven engineers to develop many different solutions. Research into EESS has increased over the past decade, with the main interest focused on storing intermittently generated renewable energy [1]. Renewable power sources like wind, solar, and tidal produce power which varies over the course of a day. As seen in Figure 1, the wind power generation in Hudson, New York, tends to peak when electrical demand was lowest [2]. If this excess capacity is not stored until it is later needed, it is lost. The most common EESS are grouped based on energy form in Figure 2. The selection of the optimum EESS for any given application depends on a variety of factors, many of which are summarized in Table 1.

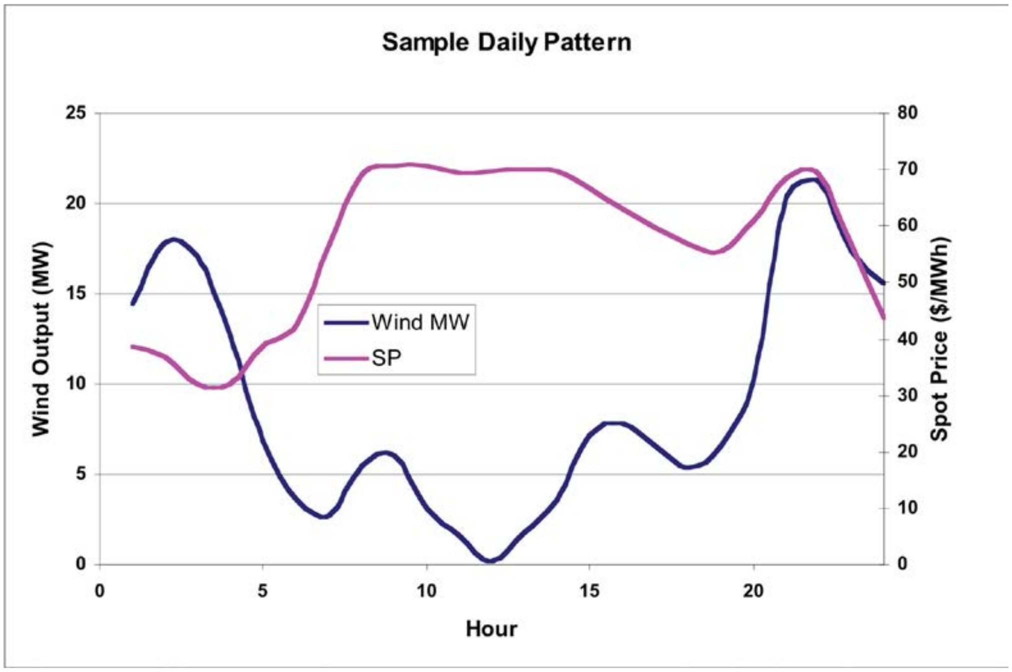


Figure 1. Wind Generation Compared to Energy Value for Hudson, New York. Source: [2].

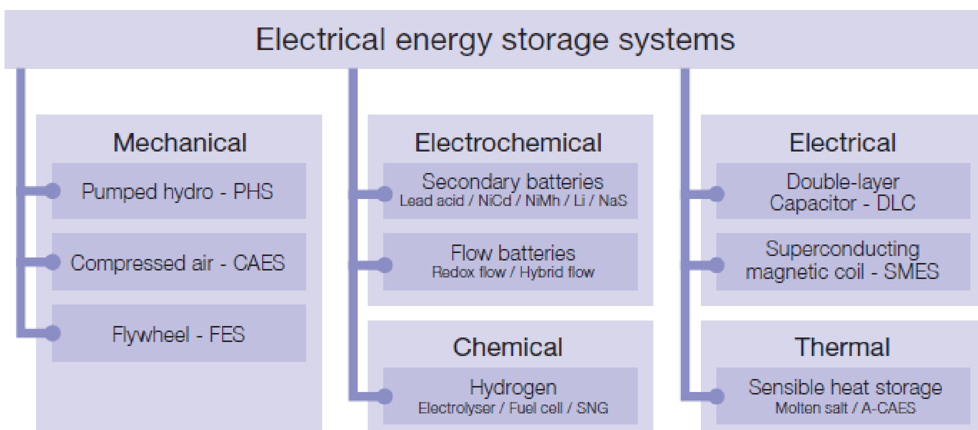


Figure 2. Classification of Electrical Energy Storage Systems According to Energy Form. Source: [3].

Table 1. Technical Characteristics of Electrical Energy Technologies. Source: [4].

Technology	Energy Density (Wh/L)	Power Rating (MW)	Suitable Storage Duration	Lifetime (years)	Discharge Time	Cycling Times (cycles)	Maturity
PHS	0.5–2	30–5000	H-Mon	40–60	1–24 H+	10,000–30,000	Mature
Flywheel	20–80	0.1–20	Sec-Min	15–20	Sec-15 Min	20,000	Early Com
CAES	2–6	≥300	H-Mon	20–40	1–24 H+	8000–12,000	Early Com
Capacitor	2–6	0–0.05	Sec-H	1–10	Millis-1 H	50,000+	Com
SMES	0.2–6	0.1–10	Millis-H	20–30	≥30 Min	10,000+	Demo/Early Com
TES	80–500	0.1–300	Min-Days	5–30	1–24 H+	-	Demo/Early Com
Solar fuel	500–10,000	0–10	H-Mon	-	1–24 H+		Developing
Hydrogen fuel cell	500–3000	0–50	H-mon	5–20	Sec-24 H+	1000+	Developing/Demo
Li-ion	150–500	0–100	Min-Days	5–15	Min-H	1000–10,000	Demo
Lead-acid	50–90	0–40	Min-Days	5–15	Sec-H	500–10,000	Mature

Abbreviations: SMES, Superconducting magnetic energy storage; TES, Thermal energy storage.

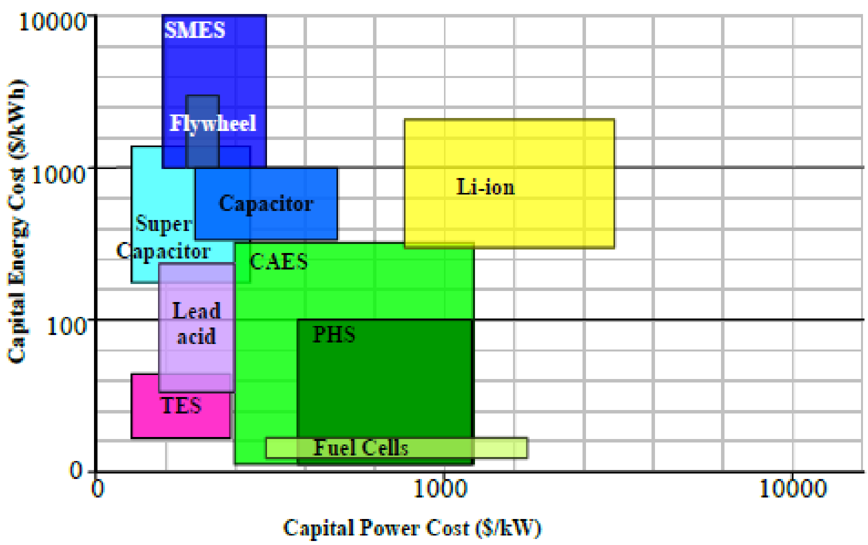


Figure 3. Capital Energy Cost versus Capitol Power Cost. Source: [4].

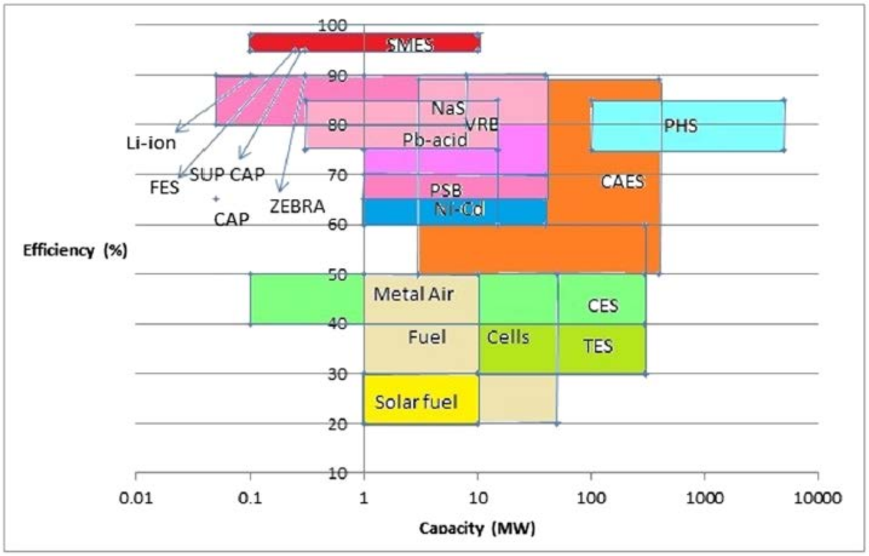


Figure 4. Round Trip Efficiency versus Capacity. Source: [5].

To understand why compressed air energy storage (CAES) is being extensively researched, attributes of other EESS should be understood. Pumped hydraulic storage (PHS), although a mature and efficient form of energy storage (70%-85% efficient), requires a significant amount of land and is reliant upon the topographic land features required for water reservoirs [3]. Superconducting magnetic energy storage (SMES), flywheel energy storage (FES), and capacitor energy storage systems have capital costs that exceed CAES [4] and discharge times that do not exceed one hour [1]. Battery energy storage systems (BESS) also have high capital costs [4], do not exceed one day of discharge capacity [1], and have much shorter lifetimes [4]. BESS also have inherent environmental concerns based on the chemicals used and shorter lifetimes [4]. CAES systems can store in excess of 24 hours of power at capacities exceeding 100's of MW without using any carbon based fuels when combined with renewable energy sources as a hybrid system [6]. CAES systems are an obvious solution for EESS because of their low capital costs, long lifetimes, lack of restriction to topographic features, and low environmental impacts.

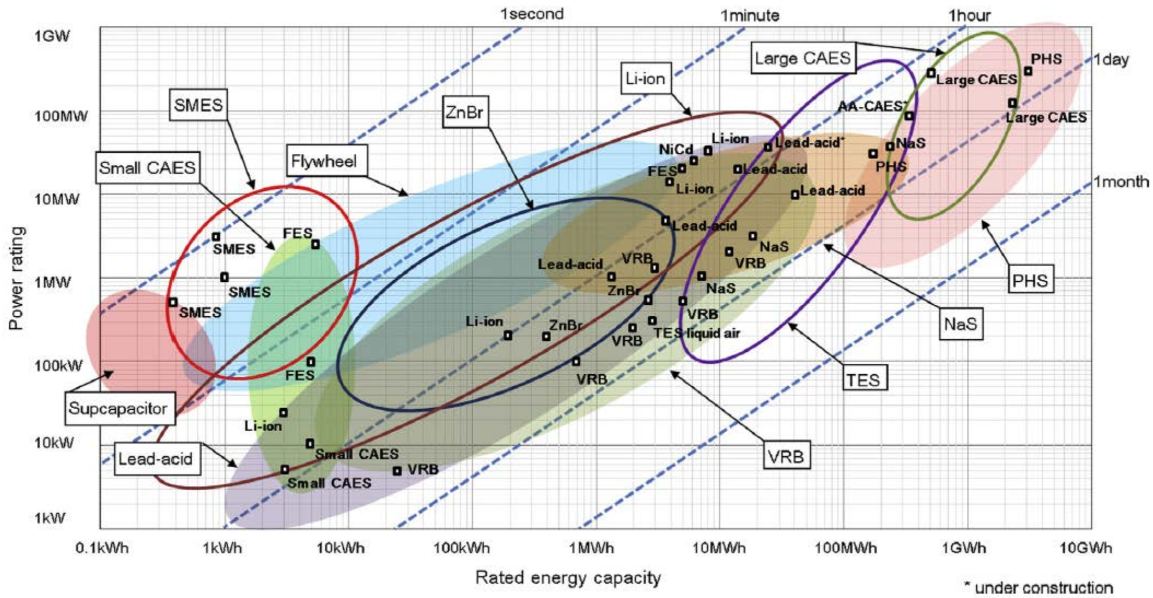


Figure 5. Comparison of Power Rating and Rated Energy Capacity.
Source: [1].

B. CURRENT CAES SYSTEMS

There are currently two CAES systems employed for commercial utility services. They are both restricted by geographic features because they use salt caverns underground as their compressed air reservoir [1].

> The world's first utility-scale CAES plant, the Huntorf power plant, was installed in Germany in 1978. …it runs on a daily cycle with 8 h of compressed air charging and 2 h of operation at a rated power of 290MW. This plant provides black-start power to nuclear units, back-up to local power systems and extra electrical power to fill the gap between the electricity generation and demand. Another commercial CAES plant started operation in McIntosh, Alabama, in 1991. The 110MW McIntosh plant can operate for up to 26 h at full power. … A recuperator is operated to reuse the exhaust heat energy. This reduces the fuel consumption by 22–25% and improves the cycle efficiency from 42% to 54%, in comparison with the Huntorf plant [1].

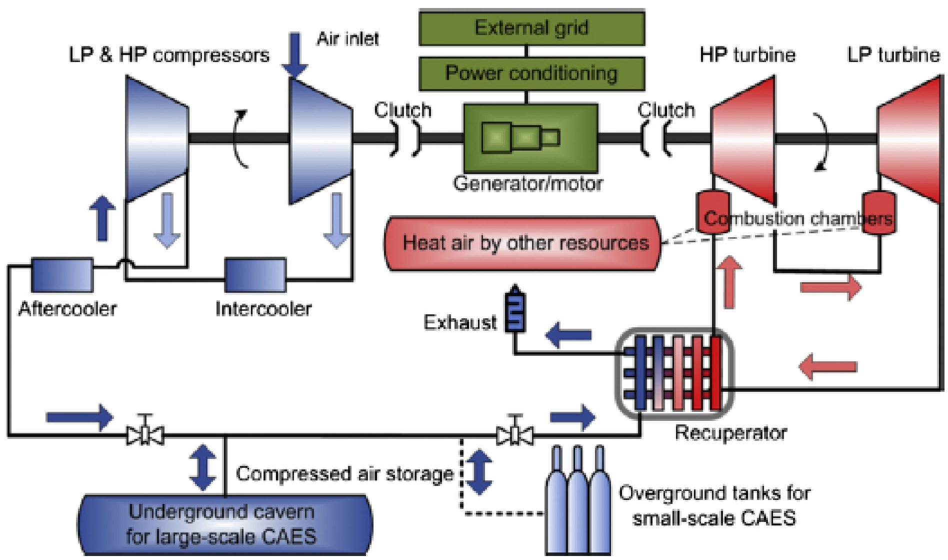


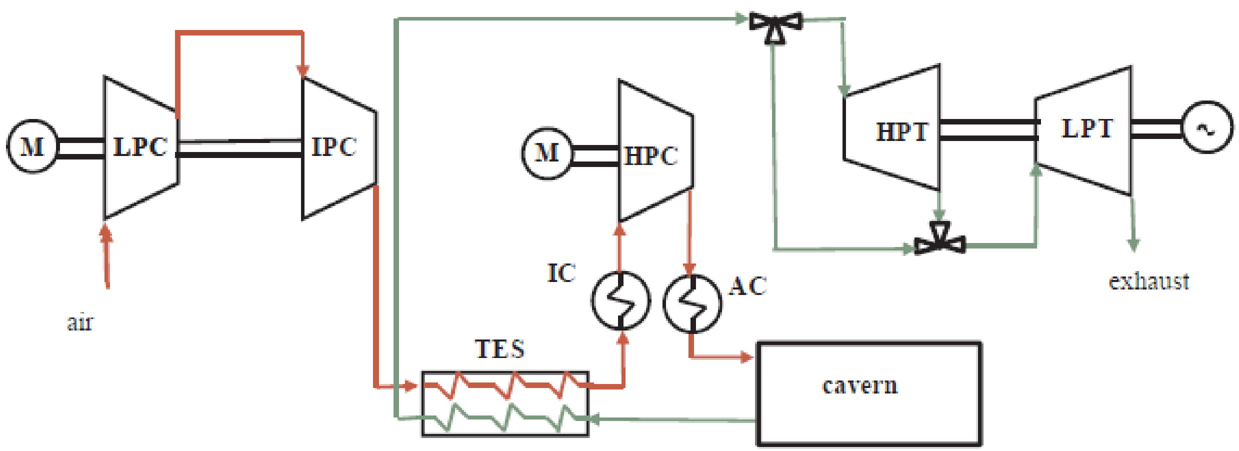
Figure 6. Schematic of a CAES Plant. Source: [1].

The low efficiency of Huntorf and the McIntosh plant is due to a number reasons. Firstly, these two plants use a gas turbine generator that requires fossil fuels to heat the compressed air [4]. Secondly, the heat generated from compressing the air is exhausted to the atmosphere (shown as the aftercooler and intercooler in Figure 6) instead of being stored for later reuse in a thermal energy storage (TES) system [4]. If this heat of compression were stored and reused upon expansion, fossil fuels would not be required to reheat the air as it expands. Lastly, as the cycle charges and extracts compressed air from the cavern, the air pressure decreases. The changing pressure "leads to a change of the pressure ratio of the compressors causing an increase in irreversible losses. Also, at the end of the discharge, there will be remnant air, which will reduce the efficiency of the whole system." [4] Current research into CAES systems aims to address these inefficiencies.

C. THEORETICAL UTILITY SCALE CAES SYSTEMS

One major obstacle of CAES systems is "when air is compressed, approximately half of the exergy created is in the form of heat…energy that is lost if not properly stored and recovered." [7] New research aims to increase the system efficiency by recovering and reusing this heat. These new designs are called advanced compressed air energy storage

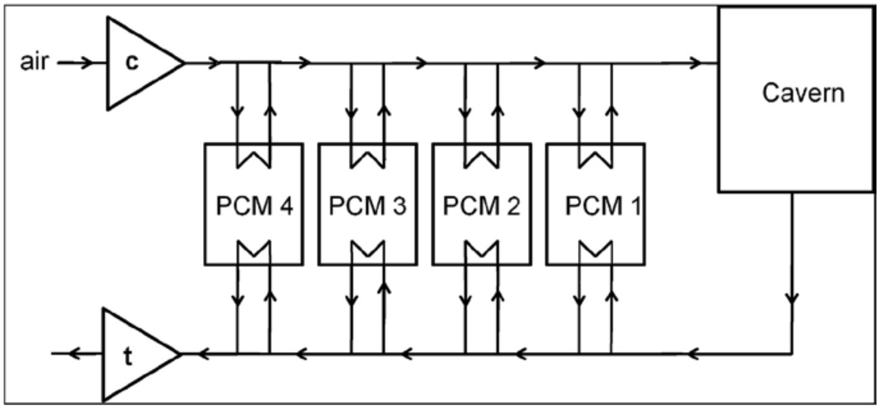
(A-CAES) or advanced adiabatic compressed air energy storage (AA-CAES) systems, depending on the heat recovery mode used [8]. One A-CAES concept uses a gravel bed TES system to recover heat from the intermediate pressure compressor (IPC) prior to the high pressure compressor (HPC). This heat is then transferred back to the compressed air prior to expansion in the high and low pressure turbines (HPT/LPT) [8]. This TES scheme increased efficiency to 77% without the use of fossil fuels to reheat the air [8].



The following acronyms explain the nomenclature in the above figure: low pressure compressor (LPC), intermediate pressure compressor (IPC), motor (M), high pressure compressor (HPC), intercooler (IC), aftercooler (AC), high pressure turbine (HPT), low pressure turbine (LPT), and generator (~).

Figure 7. Simplified Scheme of an A-CAES Plant. Source: [8].

Another approach studied used a series of phase change materials (PCM), which use the "latent heat of a first order phase transition" [7], to isothermally store the heat. To store the heat from the compressed air, "the air passes through a series of PCM's with decreasing melting temperatures to strip heat from the air, increasing the compressibility. Prior to decompression, the air again passes through the PCMs in the opposite direction, with increasing melting temperatures prior to decompression." [7] The use of PCM's raises the theoretical efficiency of CAES to 85% [7].



The following acronyms explain the nomenclature in the above figure: compressor (c) and turbine (t).

Figure 8. Cascade CAES Storage Scheme, for Case of Four PCM Stages. Source: [7].

D. FUTURE UTILITY SCALE CAES SYSTEMS

Canadian company Hydrostor aims to improve efficiency by eliminating the pressure change associated with charging and discharging a fix volume pressure storage vessel while also removing the previous geographic constraints of fixed volume, underground features. They have instead pioneered two new storage concepts that use the hydrostatic force of water to maintain a constant pressure while charging and discharging. This maintains the compressor and expander at their most efficient pressure ratio, which increases the cycle efficiency. This concept has been proved using underwater salvage bags to store air in Lake Ontario. The system has a 1 MW capacity with the air storage at 55 meters (180 feet) in depth. Future mature designs plan for placement of air storage at a depth of 198 meters (650 feet) to increase the storage pressure [9].

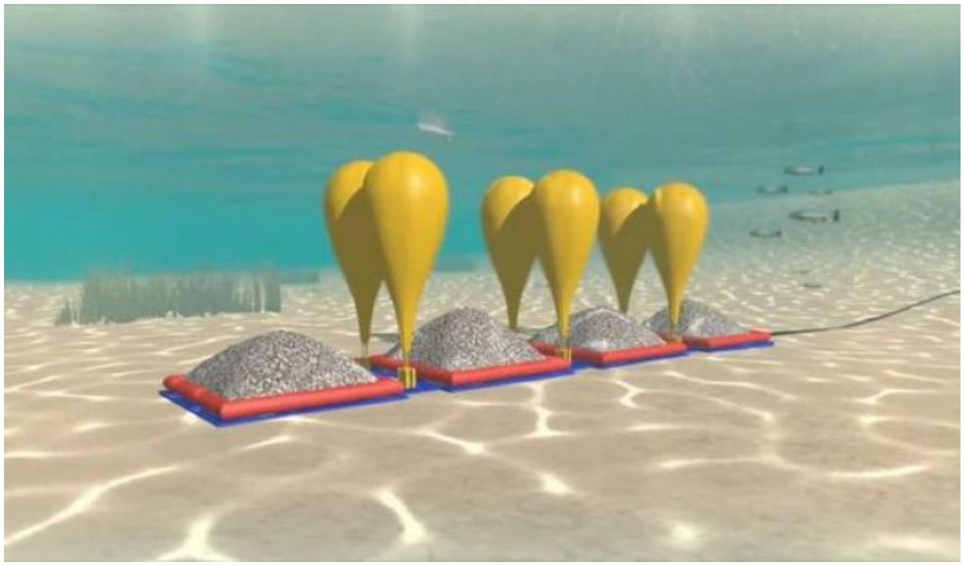


Figure 9. Hydrostor's Use of Salvage Bags for U-CAES Pilot Project. Source: [9].

Hydrostor has also developed a land-based concept that can be installed with a small surface footprint. It uses static water pressure to maintain a constant air pressure. As shown in Figure 10, the static pressure developed by the water is countered by the air pressure. As the compressor fills the air accumulators, the water is displaced to the reservoir. The process works in reverse when discharging the air accumulators to generate electricity. Hydrostor advertises storage capacity of 50-500+ MW, with 6+ hours of discharge capacity [10]. Hydrostor currently has projects under construction in Canada and Australia with 1.5GW+ of projects in advanced development in the US, Australia, Canada, and Chile [10].

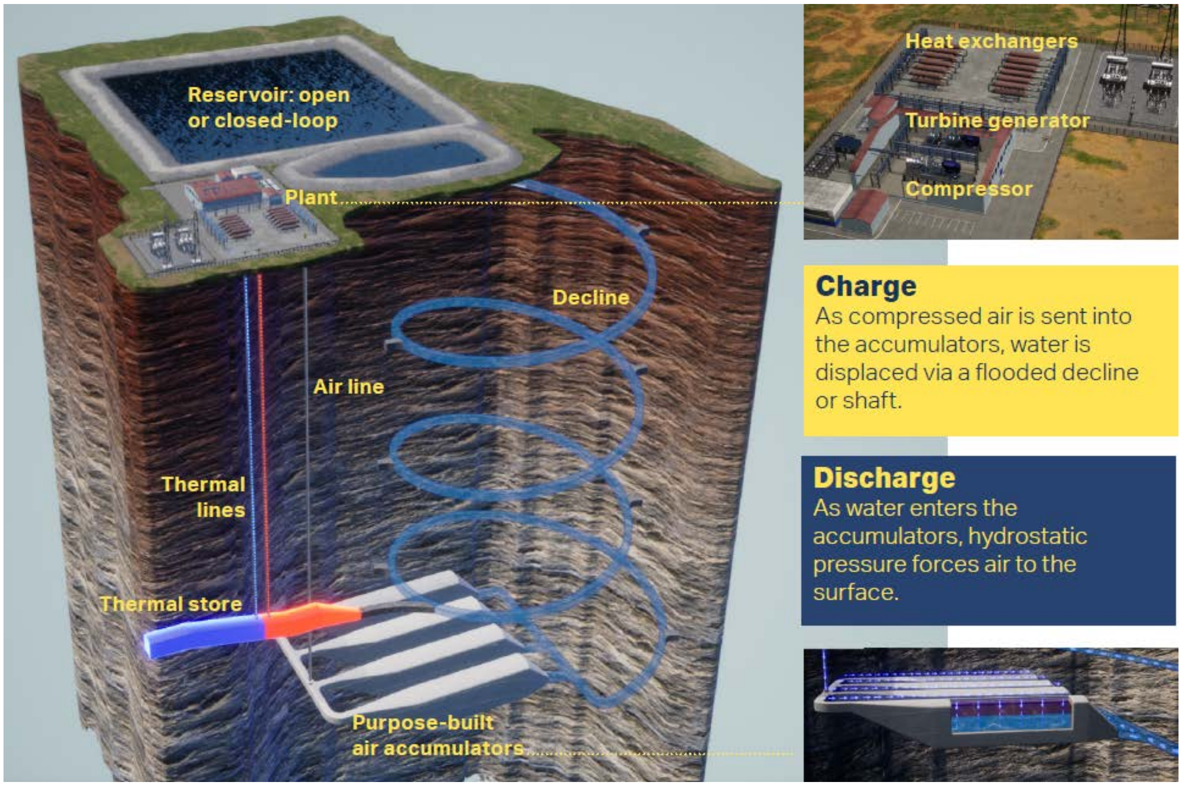


Figure 10. Land-Based, Constant Pressure A-CAES System by Hydrostor. Source: [10].

With all the benefits of CAES, there has been little interest in construction of actual plants. Other than Hydrostor's two projects currently under construction, the DOE only lists one CAES plant under construction, the Jiangsu Jintan National AA-CAES Demonstration Project being built in Jintan, Jiang Su, China. Although it has a capacity of 60MW, it is designed only as a demonstration project [11]. There are, however, two plants announced to be built by utility companies. The first is the PG&E advanced underground compressed air energy storage (CAES) in San Joaquin County, California, with a capacity of 300MW [11]. The other is the Bethel Energy Center - Apex compressed air energy storage in Tennessee Colony, Texas, with a capacity of 317 MW [11]. Both of these projects rely on underground geologic formations to store air instead of new air storage concepts.

E. SMALLER-SCALE CAES SYSTEMS

The use of CAES for utility scale projects typically focuses on the cost and efficiency, but there are other costs, not measured in strictly efficiency terms, that can be saved in smaller scale CAES systems (SC-CAES). The New York State Energy Research and Development Authority (NYSERDA) performed an analysis in 2008 looking at the potential of using a mini CAES system with capacity of 10-20MW, to potentially save money from the off-peak to on-peak electricity price difference. They found the value of the mini CAES system did overcome the cost of the system based strictly off the costs saved by using low cost electricity to offset high cost energy [2].

Another use of SC-CAES to save costs was studied for use in a remote telecom station in Canada. Typically, remote telecom stations are powered by a diesel generator (DG) with a typical constant load of 5kW. The DG requires a constant fuel supply in a remote location, as well as constant maintenance and upkeep costs. The DG currently used at one example sight is only 13% efficient at an expected partial load of 5kW. Its operating curve shows an increased efficiency of 33% as the load approaches 100% load of 30kW. The study explored three different scenarios to reduce DG fuel consumption. They are the use of a Bergey 10kW wind turbine, the use of a PGE 35kW wind turbine, and incorporation of a SC-CAES system in tandem with either of the two wind turbines. As shown in Figure 11, the use of a hybrid power system incorporating a 35kW wind turbine and SC-CAES reduced the DG fuel consumption by approximately 98% (1491 liters saved) of fuel in one month. Since this fuel has to be delivered to remote sights, sometimes only accessible by helicopter, there are many other costs saved as well. The same SC-CAES hybrid system reduced the DG run time from 668 hours to only 15 hours in one month. The savings in DG runtime can lengthen the engine life and reduce maintenance costs as well [12].

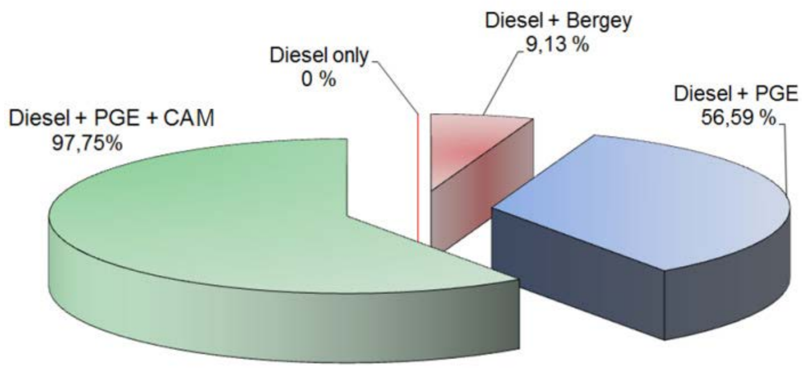


Figure 11. Fuel Saving According to Different Scenarios. Source: [12].

The use of SC-CAES systems will find additional utilization as research and development into micro energy grids advances. Qinghai University in China designed and built a Micro-Energy Grid (MEG) that utilizes a 100kW solar-thermal compressed air energy storage (ST-CAES) system in quite novel ways. As with traditional CAES systems, renewable electricity is used to compress air for energy storage. The heat of compression is captured with a TES system, while parabolic trough collectors (PTCs), or curved mirrors, are used to add additional heat to the TES. The stored heat is used to reheat the expanding air in an adiabatic process while extra stored heat can he used in the site wide distributed heating network. The turbine exhaust is then additional utilized to generate cooling energy with an attached absorption refrigerator [13]. The more holistic approach to energy generation, storage, and utilization of typically waste energy decreases a MEG's self-reliance on traditional energy sources.

II. DESIGN IMPROVEMENTS

As demonstrated in many large and small-scale CAES systems, the ability to store energy as compressed air has many practical applications. As part of the micro energy grid project, efforts have focused on improving a small-scale energy extraction device based on the conceptual demonstration of thesis work by McLaughlin [14]. Improvements were made to simplify the automated control system developed by Vranas [15], which controls when air is admitted to the turbine based on the state of charge of the supercapacitor. A 3-phase alternating current (AC) transformer bank was integrated to allow charging to higher voltages. The 3-phase AC signals generated by the turbine and generator are rectified to a direct current (DC) signal. That power is then used to charge a super-capacitor. The energy stored in the supercapacitor can be inverted for later use in an AC system.

The previous design concept can be seen in Figure 12. The overall design concept will remain unchanged, but significant changes to many components have been made to increase power output.

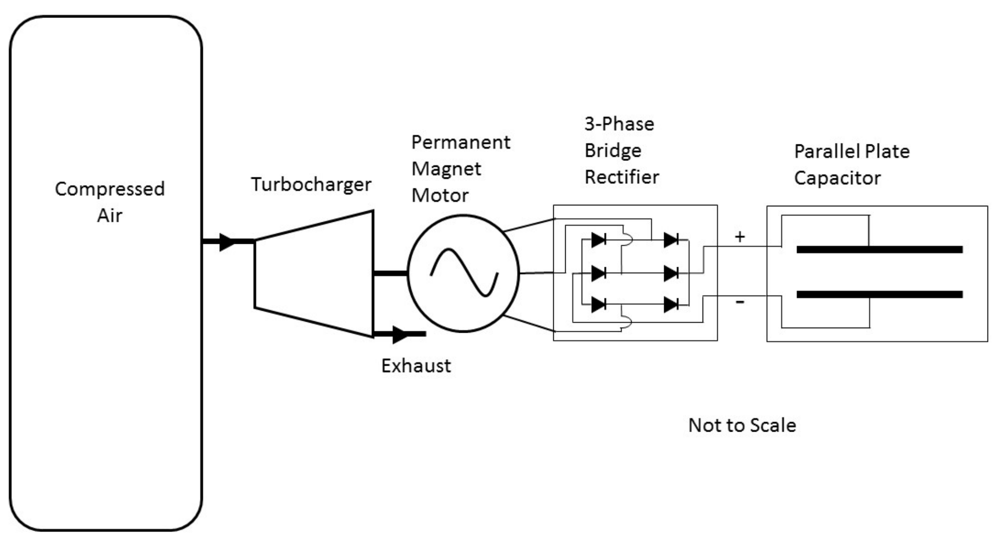


Figure 12. Proposed Design Concept. Source: [14].

A. COMPRESSED AIR DRIVE UNIT

The two mechanical elements that expand the compressed air and convert it to shaft, rotational energy are broken into two parts in this system. The first expands, accelerates, and entrains atmospheric air. The second takes the high velocity air stream and outputs a shaft rotational energy for use by the generator. This section delves into selection and design criteria for improving both parts of the compressed air drive unit.

1. Compressed Air Expansion

The first step in designing a more efficient drive unit for the generator was to understand the current design, operation, and where it was to fit into the system. McLaughlin [14], made a number of observations and suggestions that would be considered during the design selection. Before any new components could be decided upon, the expected airflow rate at the outlet was required. Since the pressure ratio of the supply or stagnation pressure (P_o) to atmospheric pressure (P) was less than 0.5283, a choked flow was assumed and Equation (1) utilized to determine a nominal airflow of 0.17487 kg/s [16]. Fluid flow is said to be choked when for specific stagnation conditions, the maximum mass flow has been reached due to the fluid achieving a sonic flow state [16]. Equation 1 uses the heat capacity ratio of air as 1.4, P_o as 689kPa, critical area (A^*) of the outlet as 93.66mm^2 (based on 10.92mm diameter), T_o as 293°K, and R is the universal gas constant. This airflow was a conservative initial estimate due to upstream flow constrictions that were more constrictive than the pipe outlet. Future testing will be conducted with airflow meters installed to determine flow rate during testing.

$$\dot{m}_{max} = \frac{0.6847 * P_o * A^*}{\sqrt{R * T_o}} \tag{1}$$

Early in experimentation by McLaughlin [14] found that with the flange mounted flush with the turbo inlet, and compressed air allowed to expand from an open pipe freely into the turbo inlet, the turbine was unable to turn against the resistance of charging a supercapacitor. McLaughlin [14] the discovered that by creating a space between the installed flange and the inlet of the turbo, and opening the turbo wastegate to atmosphere, additional air was entrained into the inlet air stream. This increase in airflow made it possible to run the turbine and charge a supercapacitor.

The reasons that additional air was entrained into the turbo inlet when opened to atmosphere must be understood to design a new power drive unit. The free expansion of compressed air into the turbo inlet created a static pressure that was less than atmosphere pressure. This was proved by McLaughlin [14] when he observed that opening the wastegate, which is normally used to release excess pressure in the turbine housing, actually drew in atmospheric air. Since the turbine outlet exhausts to atmospheric pressure, there was a negative pressure ratio from the inlet to the outlet, that was partially relieved when parts of the inlet where opened to the atmosphere.

McLaughlin [14] also theorized and modeled the entrainment of atmospheric air by the high velocity air stream at the turbo inlet. The compressed air exited the open pipe at the turbo inlet flange at sonic speeds with a large drop in enthalpy. As atmospheric air was drawn into the turbo inlet, it was accelerated by the sonic airflow. The addition of this entrained air raised enthalpy of the total airstream. The lack of a large positive pressure ratio and observed performance improvement with an increase in airflow proves the turbo acts as a reaction turbine. A reaction turbine converts the working fluid’s kinetic energy into work with no pressure drop across the rotating element [16]. To maximize the velocity into the turbine and provide a neutral pressure ratio across the turbine, design will focus on air entrainment and pressure neutralization.

The first design iteration to increase air entrainment was the installation of an EXAIR Super Air Nozzle onto the original power unit to focus the air exhaust and maximize air entrainment. The inlet flange was also spaced further away from the turbo inlet to neutralize the pressure across the turbine. The experimental gain was better than the original design, but additional effort was made to better utilize supersonic airflow concepts to increase the velocity.

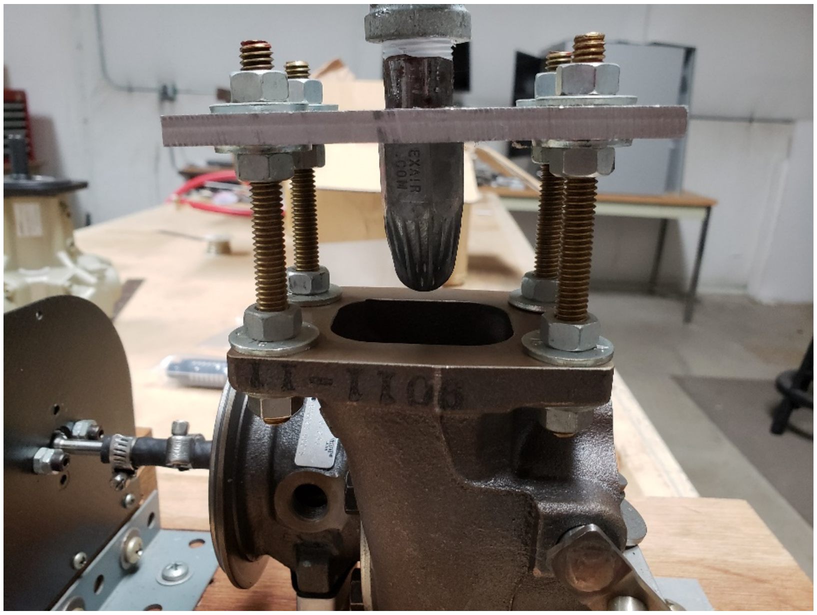


Figure 13.   Installation of EXAIR Super Air Nozzle on Original Power Unit

The use of an air mover made by Nortel Manufacturing Limited was also tested for the potential to use compressed air and boost the airflow at a boost ratio of 16:1 with an air supply line of 0.9525 cm (3/8in) [17]. The specified airflow increase, distributed in a circumferential manner, fit the desired design criteria. Figure 14 shows how compressed air is supplied in a circumferential manner near the main inlet. As the compressed air is expanded and travels through the center converging section, atmospheric air is induced and an output, with a much larger flow rate at atmospheric pressure, is produced. The device was unable to run the turbine and charge a supercapacitor, so an air entrainment method that utilized supersonic flows was explored.

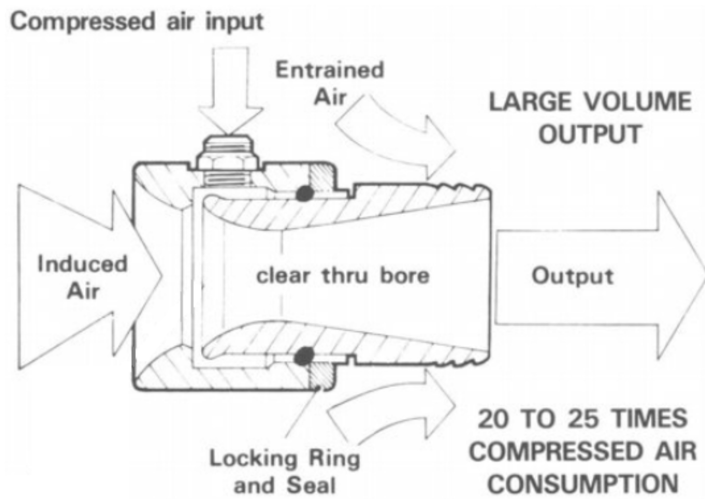


Figure 14. Diagram of Air Booster. Adapted from [18].

An air ejector uses two sets of converging-diverging nozzles to manipulate a high pressure, low mass flow inlet, into a low pressure, high mass flow outlet as shown on Figure 15. The first converging-diverging (C-D) nozzle accelerates the primary fluid (compressed air) to supersonic speed. This high-speed airflow entrains secondary fluid (atmospheric air) at the suction, which mixes with and raises the enthalpy of the overall stream. The new, mixed airflow, then proceeds through the second C-D nozzle. The converging portion slows the supersonic flow to near sonic speed. The long constant area section allows the near sonic flow to slow and shock back to a subsonic velocity. Across this shock wave pressure rises and the speed is lowered to subsonic speeds as shown by point 4 of Figure 15. In the diverging portion this pressure recovers further, rising above the secondary fluid pressure (atmospheric pressure in this application), but below the primary motive fluid pressure. Velocity lowers in the diffuser, but at the exit, remains above the inlet velocity of both fluids. The use of supersonic airflow concepts will ensure the turbine is supplied with a high velocity, positive pressure airflow.

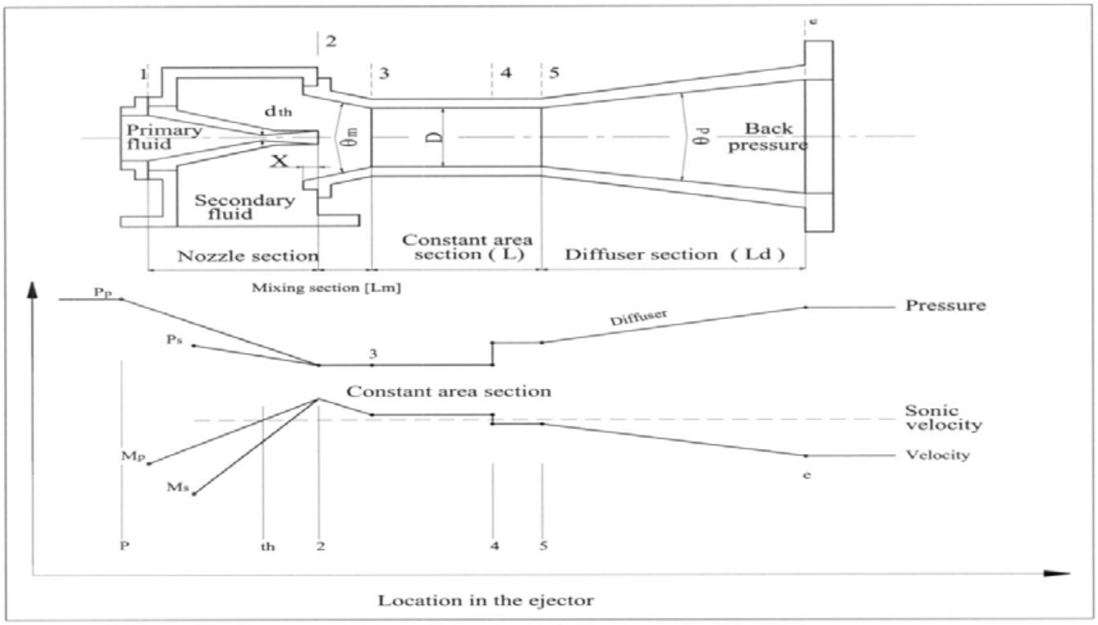


Figure 15. 2-D Schematic of Typical Steam Ejector with Pressure and Velocity Distribution. Adapted from [19].

Three different sized, GH series, air ejectors were procured for testing. The GH series inlet operating medium pressure range was 239-653kPa (20-80 psig), allowing for a large range of pressure variations while still being able to effectively to operate [20]. The GH series air ejector was designed to operate with steam as the motive fluid, but technical documentation stated that when operated with air, it would entrain at higher rates [20]. The outlet of the air ejector was smaller than the inlet of the turbine, allowing an opening to atmosphere at the turbo inlet. Through early experimentation and CFD analysis, the opening between the outlet of the air ejector and inlet of the turbo entrained additional atmospheric air through a process called thrust augmentation.

The decision to use the 1.905 cm (3/4in) compressed air supply inlet air ejector was made to maximize the compressed air supply for power production within the capabilities of the shop air supply lines and smaller turbine inlet size. If a larger capacity air compressor and supply line were available, it would be possible to use the 2.54cm (1in) inlet air ejector with the larger turbine shown in the bottom of Figure 16. The 1.27 cm (1/2in) inlet air ejector, shown above the 2.54cm (1in) inlet air ejector in Figure 16, was decided to be too small for the application.

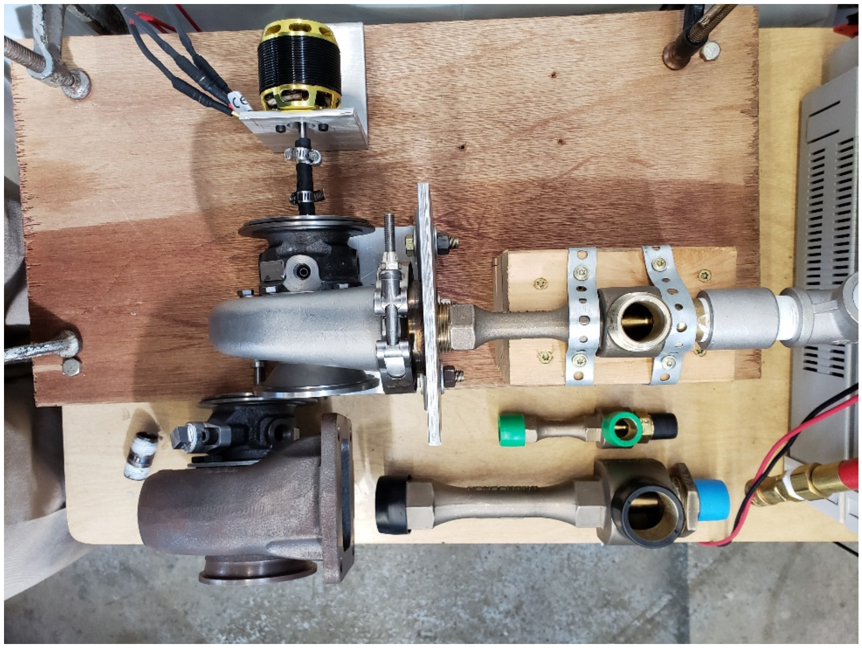


Figure 16. Experimental Setup with 3/4in Inlet Ejector Installed

2. Turbo Selection

McLaughlin [14] found turbos with ball bearings had less internal friction than turbos with a journal bearing. The reduced internal friction allowed more torque to be transmitted to the generator, producing more electrical power. This decision was incorporated by only using ball bearing turbos for further development. The turbo McLaughlin [14] chose also included a wastegate. The purpose of the wastegate in automotive applications is to allow exhaust gases to bypass the turbine, thus admitting less exhaust gas through the turbine. This allows control of the desired output speed. This application for automotive engines uses high temperature, pressurized gases and works effectively [21]. He also found that by opening the wastegate of the turbine, he was able to entrain more air and create additional power. The reason he entrained more air by opening the wastegate was that the static pressure in the turbine casing was less than atmospheric pressure.

The rapid expansion of air and entrainment at the inlet to the turbine created a pressure less than atmospheric pressure at the entry of the turbine wheel. When the wastegate valve was opened to atmosphere, additional air entrainment occurred at the wastegate. This observation confirms that there was a slight negative pressure gradient across the turbine, which was restored to a neutral pressure ratio when the wastegate was opened. This was confirmed by his observation "that more shaft power would be produced" as the wastegate was opened [14].

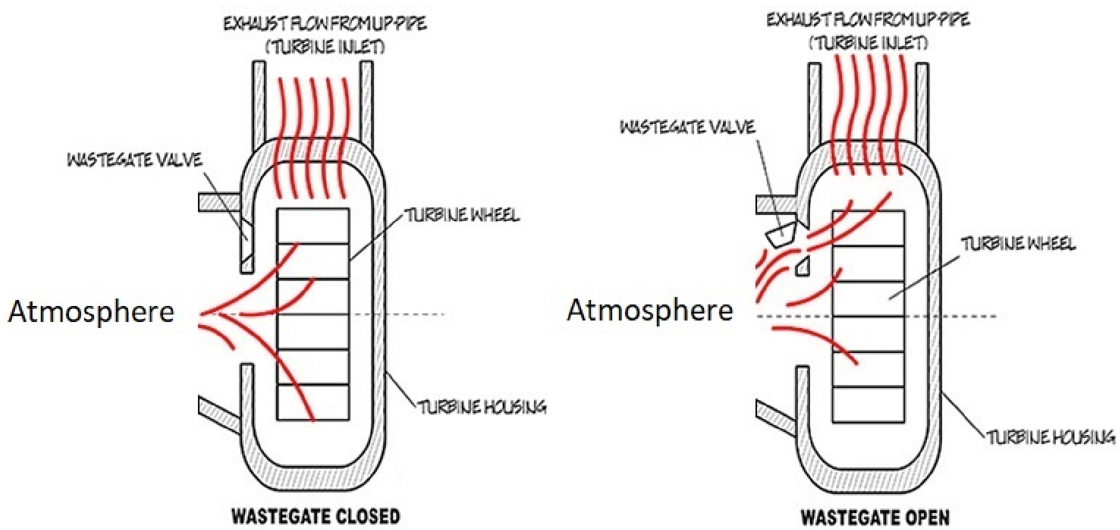


Figure 17. Function of an Internal Wastegate. Adapted from [21].

In order to simplify the turbine and improve the previous design, a turbine housing with no internal wastegate was selected. Focus was placed on fully expanding and entraining air prior to entering the turbine. This served to remove any flow restriction or discontinuity inside the turbine and created the most neutral, if not positive, pressure ratio across the turbine. Figure 18 shows a comparison of the two turbine housings. Internal housing discontinuities are removed with no wastegate present.

A turbine housing with an internal wastegate is shown on the left, and a turbine housing without an internal wastegate is shown on the right.

Figure 18. Comparison of Turbine Housings. Sources: [22], [23].

The selection of the correct size turbine was initially made by taking the calculated chocked flow maximum mass flow rate and comparing to the exhaust flow charts for different sized center housing rotating assemblies (CHRA). The CHRA is the center rotating element with the compressor and turbine wheels. Converting calculated choked airflow of 0.17487 kg/s to lbm/min for use on turbine flow charts, gave a value of 23.13 lbm/min (10.4922 kg/min). Using Figures 19 through 21, a low pressure ratio of approximately 1.25 was assumed to find an operating point for the turbine gas flow. The static pressure at the turbine inlet and outlet was assumed to be atmospheric pressure. The charts did not state if the pressure was based on static or total pressure, so the pressure ratio was expected to be above 1 due to the dynamic pressure increase caused by the high velocity of the air exiting the air ejector. With these assumptions, the Garrett GTW3884R turbo was the most promising candidate. However, since McLaughlin [14] had proven the GT2554R turbo could be successfully operated, the decision was made to continue testing with the proven size CHRA and obtain the Garrett GT3071R turbo as the next size larger for follow on testing. The GT2554R and GT3071R turbos are shown in Figure 23.

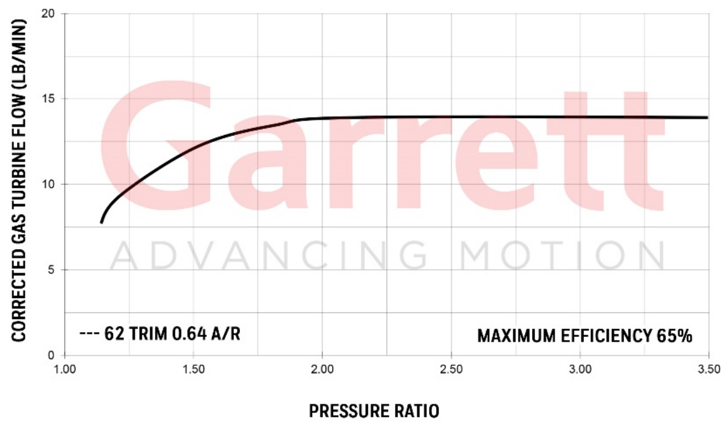


Figure 19. Flow Chart for GT2554R Turbine. Source: [24].

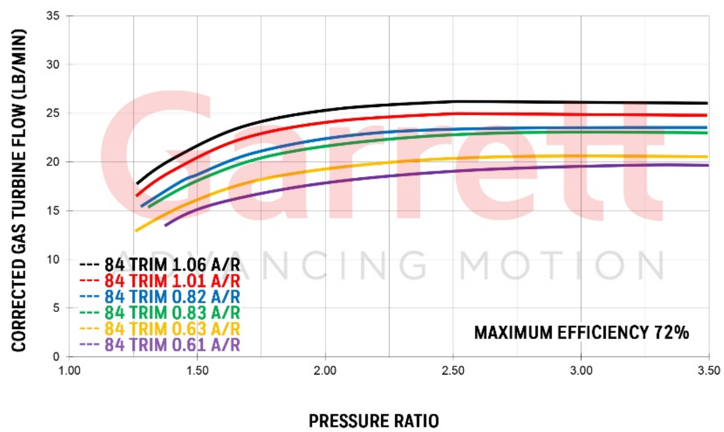


Figure 20. Flow Chart for GT3071R Turbine. Source: [25].

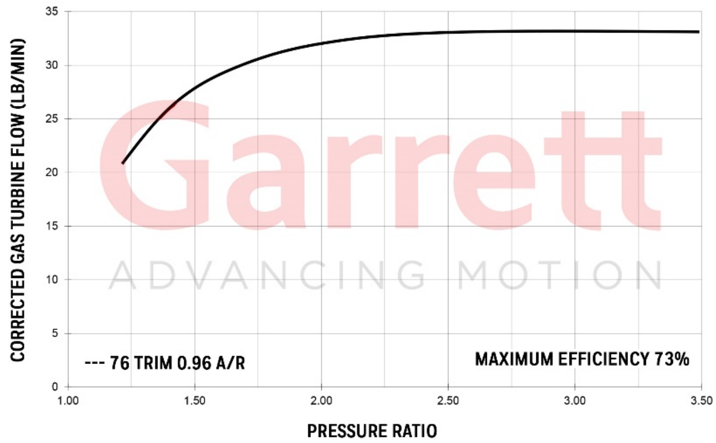


Figure 21. Flow Chart for GTW3884R Turbine. Source: [26].

The selection of the GT3071R turbine also required a decision on the turbo housing area/radius (A/R) ratio. The A/R is "defined as the inlet cross-sectional area divided by the radius from the turbo centerline to the centroid of that area." [27] As shown in Figure 20 and 22, the turbine performance will be affected by the A/R ratio. A larger A/R ratio housing allows flow to "enter the wheel in a more radial fashion, increasing the wheel's effective flow capacity, resulting in lower backpressure…" [27] Since the turbine is operating with the inlet and outlet open to atmosphere, the backpressure should be reduced as much as possible. This led to the selection of the 1.06 A/R ratio turbine housing.

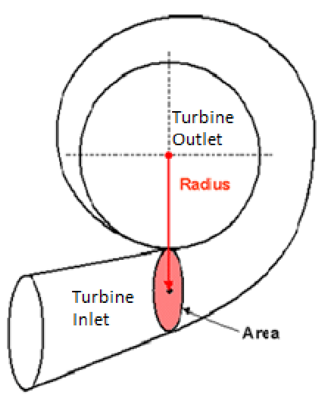


Figure 22. Illustration of Turbine Housing to Show A/R. Adapted from [27].

Figure 23. GT2554R (background) and GT3071R (foreground) with Compressor Wheels Removed

Garrett turbo CHRA's are supplied with ports for oil lubrication of the ball bearings and cooling water to remove heat. Since the present application does not use high temperature gas and is internally cooled by a constant flow of atmospheric air, the water cooling ports were not used. As seen in Figure 24, the oil outlet port had a oil drain flange, gasket, and plug installed so oil could be added and to the oil supply fitting prior to operation to reduce the ball-bearing friction.

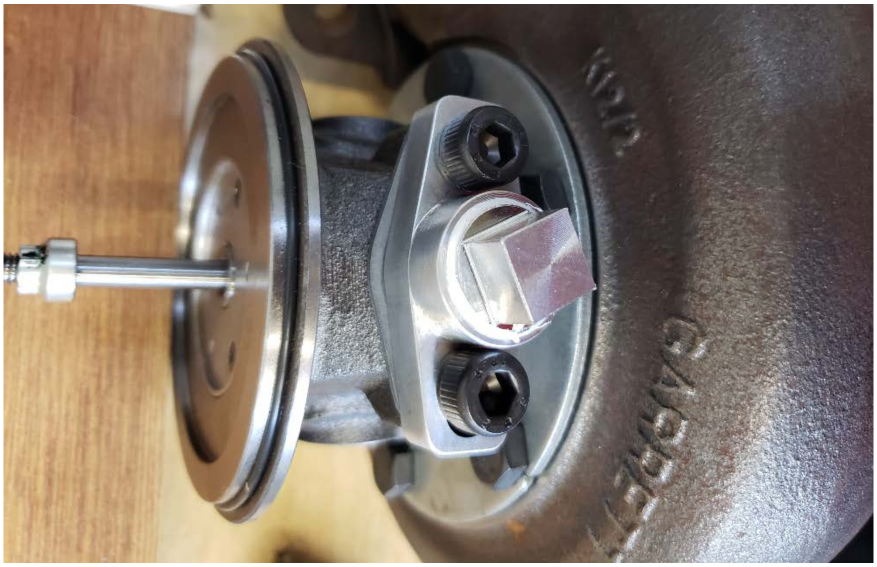


Figure 24. Oil Outlet Port of GT3071R with Installed Gasket, Oil Drain Flange, and Plug

B. ELECTRICAL EQUIPMENT

The electrical system takes a shaft rotational power and produces a DC output to charge a supercapacitor. The requirements for this system are complex due to the desire to maintain the turbine at an optimum speed and be able to start with an uncharged supercapacitor with low or no energy stored. The design and evolution of the electrical system are explored in detail in this section.

1. Permanent Magnet Generator

The conversion of stored energy to usable electrical energy is the focus of this thesis, and the equipment used to convert the mechanical energy of the compressed air drive unit to electrical energy is important. Permanent magnet motor act as generators for this project. They are simple, do not have brushes that need replacement or cleaning, and do not require magnetic field excitation voltage. If a generator that required a field excitation was used, it would require a power source to initially startup. Due to the nature of being a backup power supply, this system should function to startup without any external power supply.

Anticipating an increase in output power of the new drive unit, a motor that would be better suited to the current project was found. The Scorpion HK-4525-520 motor, pictured in Figure 25, was used instead of the HKIII-4035-560 motor for the following reasons outlined in Table 2: less internal motor resistance, higher max continuous power rating, and larger peak current to better absorb any transient without damage [28].

A maintenance regimen of lubricating the motor bearings every 2-3 uses was incorporated with a manufacturer recommended lubricant. The coupling device from the motor to the turbine was upgraded. Instead of using a flexible polymer, a nylon reinforced rubber tube, typically used as automotive fuel line, was used for added strength.

Table 2. Comparison of Current (green) and Previous (red) Permanent Magnet Generators. Adapted from [28], [29].

Scorpion HK-4525-520 Ultimate Motor Specifications		Scorpion HKIII-4035-560 Motor Specifications	
Number of Magnet Poles	10	Number of Magnet Poles	10
Motor Wind	5+6 Turn YY	Motor Wind	8 Turn Delta
Motor Kv Value	520 RPM per Volt	Motor Kv Value	560 RPM per Volt
Motor Resistance per Phase	0.012 Ohms	Motor Resistance per Phase	0.014 Ohms
Max. Continuous Current	100 Amps	Max. Continuous Current	100 Amps
Max Continuous Power	4450 Watts	Max Continuous Power	4200 Watts
Peak Current	230 Amps (2 sec)	Peak Current	120 Amps (5 sec)
Peak Continuous Power	10,200 Watts (2 sec)	Peak Continuous Power	5200 Watts (5 sec)

Figure 25. Scorpion HK-4525-520 Ultimate Motor. Source: [28].

2. 3-Phase Transformer Bank

A transformer offers the advantages of electrical isolation of one circuit to another, and allows the ability to step up or step down AC voltage. The primary coil windings around a magnetic iron core induce a magnetic field in the transformer core. When AC is applied to the primary core, this magnetic field in the transformer core alternates at the same frequency as the applied AC. This alternating magnetic field induces a voltage in the secondary winding. The ability to change the primary voltage (V_P) input to a different secondary voltage (V_S) is based on the ratio of the number of primary windings (N_P) and the number of secondary windings (N_S). The ratio of N_P to N_S is what determines if voltage will be stepped up or down [30].

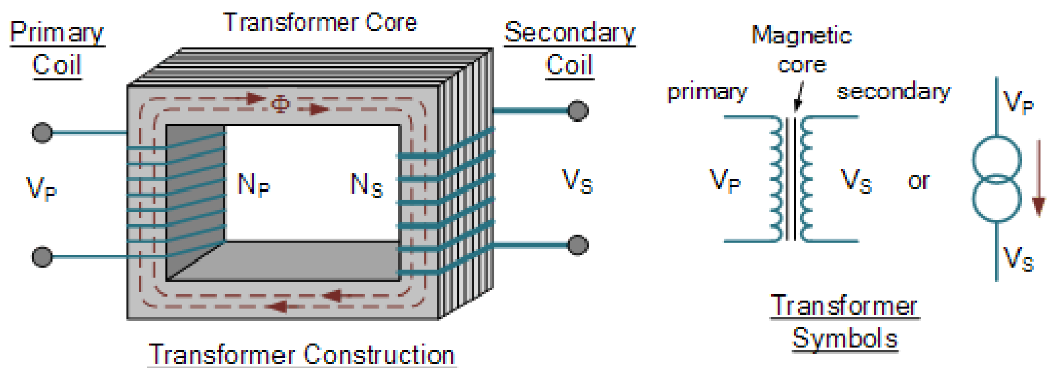


Figure 26. Single Phase Transformer. Source: [30].

The first goal in developing the upgrades to the power drive unit and generator was to be able to reach the 16VDC rating of the supercapacitor. The original power drive unit was only able to reach 15VDC during an endurance run [14]. As an interim design step, the addition of the Exair super air nozzle to the original setup, enabled reaching 16VDC 8 minutes sooner than McLaughlin [14] reached 11VDC. After the upgraded power drive unit and generator were installed, the 16VDC goal was reached. The next goal was to be able to charge a 56VDC supercapacitor. The simplest way to accomplish this was to use transformers to boost the AC voltage from the generator prior to rectifying it to DC. Since 3-phase AC power is the output from the generator, options for using a 3-phase transformer or 3 single-phase transformers wired as a 3-phase transformer bank were investigated. Finding a single 3-phase transformer that could function at the low power outputs of this system within design parameters proved impracticable because of the cost of these large transformers and unsuitability for the low power outputs. The use of small, single-phase transformers was decided as a solution to this problem.

Altering a system that can reach 16VDC to now reach 56VDC requires a step up of at least 3.5 times the input voltage. Three Emerson E200EWA encapsulated industrial control transformers were selected because of their 200VA rating and ability to perform a step up of 5 times the input voltage. Although the transformers were designed to take an input power of 120 VAC or 240 VAC and reduce it to 24 VAC, they can be used in reverse to step up the power at a ratio of 5:1 or 10:1 [31]. A ratio of 5:1 was chosen since it was closest to the needed 3.5 step up needed. As seen in Figure 27, by selecting the H1 and H2 connection points on the primary side, a conversion of 120VAC to 24VAC is a step of 5:1. If a larger step is needed in the future, a 10:1 option is available by using the H3 and H4 terminals instead. Figure 28 shows a single transformer from the top with fuses installed to protect the transformers in the event of an electrical fault.

The selected transformers are rated to operate at 60 Hz [31]. In this experimental application, they will be operated across a wide range of frequencies, sometimes higher than 1000Hz. This is due to the speed of the turbine being low when supercapacitor voltage is low, and increasing as the supercapacitor is charged.

The arrangement to wire the 3 single-phase transformers as a 3-phase transformer bank, was made based on keeping the system simple and ungrounded. Figure 29 provides a comparison between the connections between a star and delta connection. Another advantage to connecting the primary and secondary sides of the transformer in a Delta connection is that if one transformer faults, the other two transformers will continue to produce 3-phase power at two thirds of the full output capacity. The line diagram for a delta – delta connected transformer shown in Figure 30. The example voltages show a step up of 10 times the input voltage. The final installed transformer bank pictured in Figure 31 mimics Figure 30’s nomenclature of banks A, B, and C, with the generator output wired to the secondary windings side and the output to the rectifier wired to the primary windings in a step up configuration of 5:1.

Figure 32 shows individual wire connections to the Emerson E200EWA transformer for the A phase. This can be related to Figure 30 and applied to phases B and C for a full schematic.

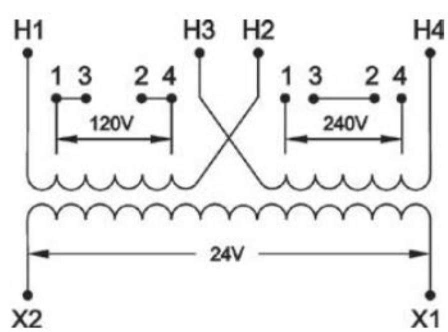


Figure 27. Transformer Line Diagram. Source: [31].

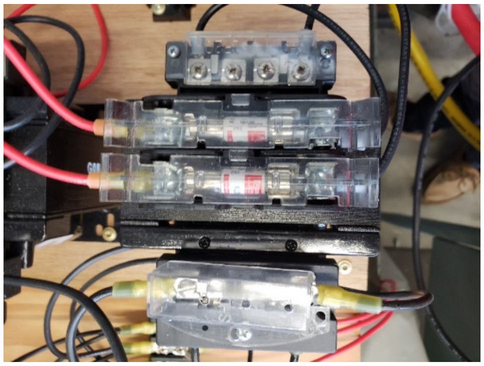


Figure 28. Emerson E200EWA with Fusing Installed

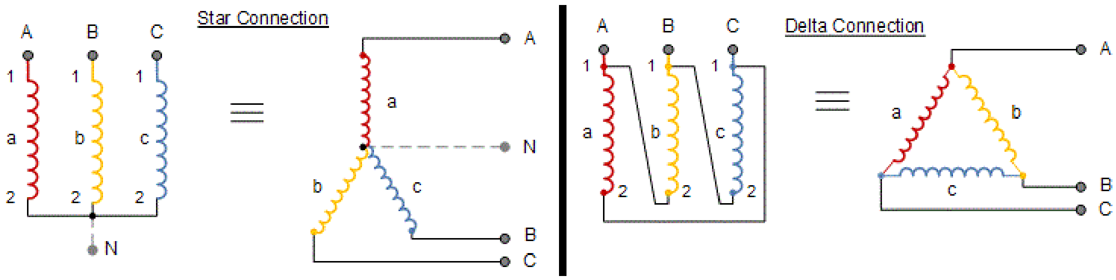


Figure 29. Comparison of Star and Delta Connections. Adapted from [32].

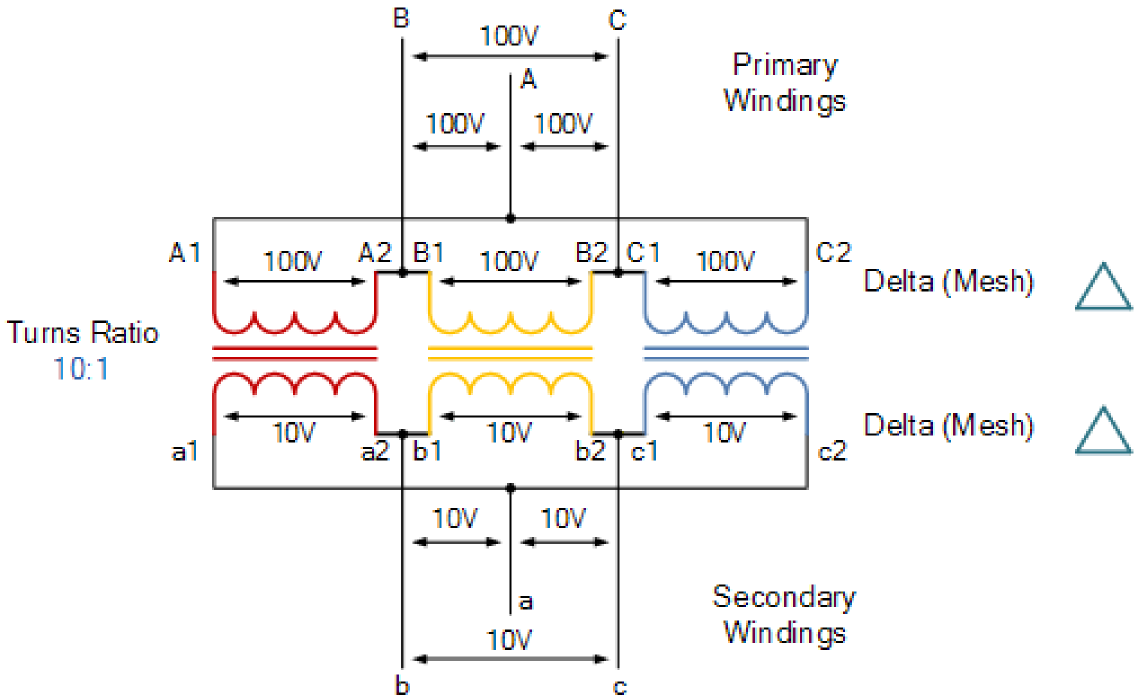


Figure 30. Transformer Connections for a Delta – Delta Connection. Source: [32].

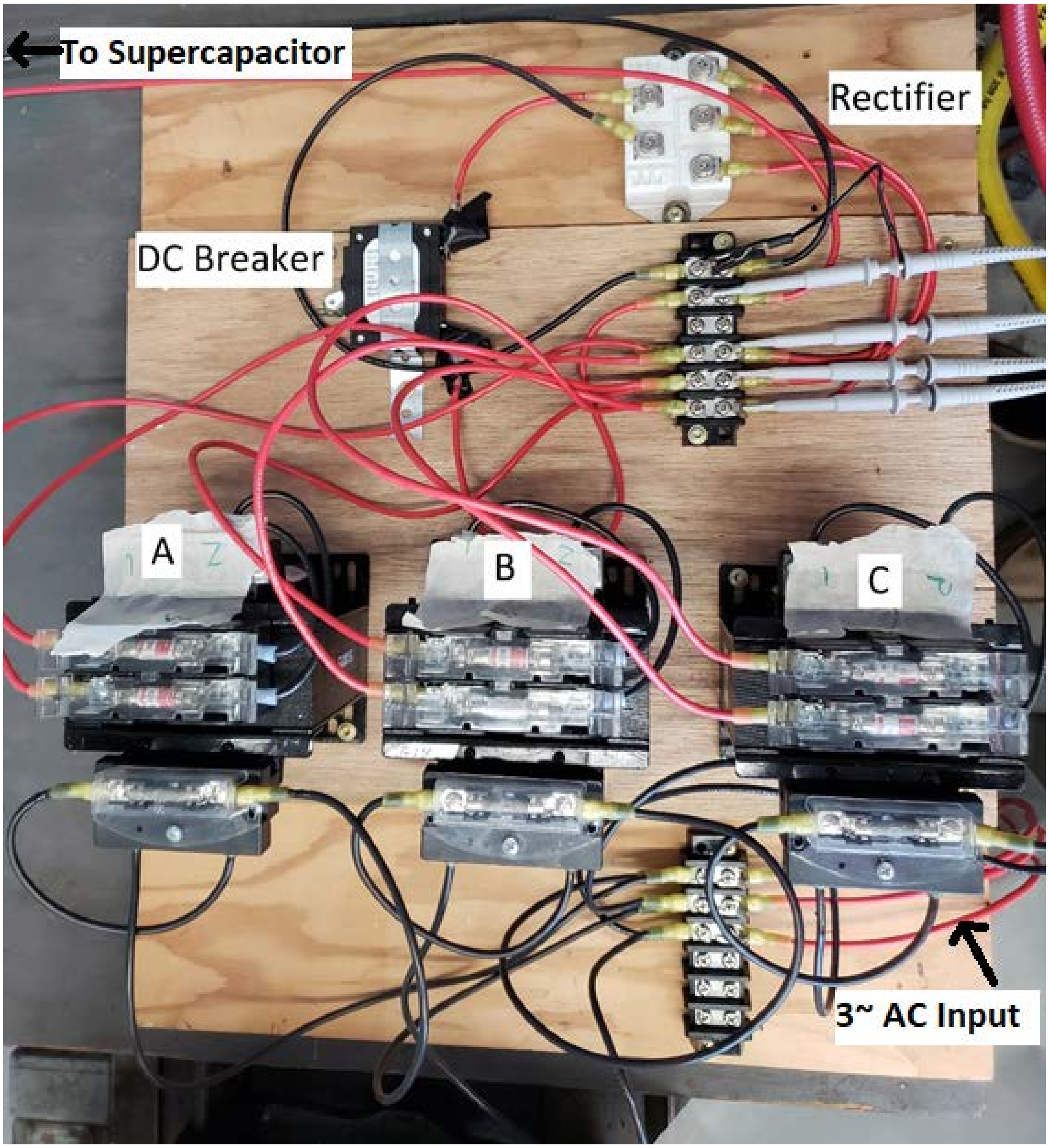


Figure 31. Final 3-Phase Transformer Bank

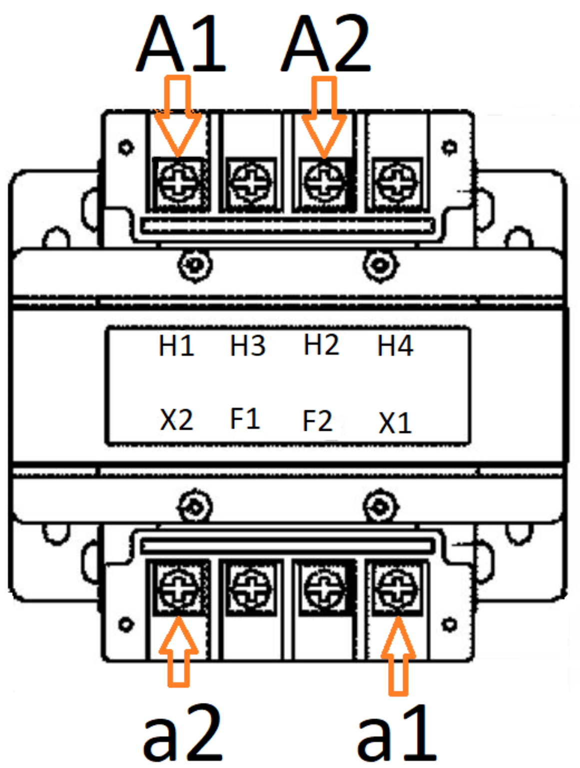


Figure 32. Transformer Connections for A Phase. Adapted from [31].

3. 3-Phase Bridge Rectifier

A diode in an electrical circuit acts to allow current in one direction only, much like a check valve in a fluid system. If six diodes are arranged as shown in Figure 33, a circuit known as a 3-phase bridge rectifier is created. A bridge rectifier takes an AC power input and converts it to a DC output to charge the supercapacitor. Figure 34, taken from an early experimental setup, shows the 3-phase voltages output from the generator (blue, green, yellow) and the DC voltage output from the 3-phase bridge rectifier (red). Figure 34 shows an early, unexpected discovery, in that the sine wave input to the bridge rectifier is flattened instead of sinusoidal shape. It was discovered that the 3-phase input to the rectifier is limited to the voltage of the supercapacitor at the output of the rectifier. This was experimentally determined by slowing down the turbine by throttling supply air. As the speed lowered and the AC voltage output lowered, the full AC sine curves resumed. As the speed was again increased, the AC curves flattened to the DC voltage of the supercapacitor. Since the supercapacitor can only charge at the voltage it is currently at, the DC current supplied pulsates. This was proved by measuring current of the DC charge wires using a clamp on current meter set to read an AC current. When reading an AC current, the meter employs the measurement of an electromagnetic induction due to the varying magnetic field. If the DC current had no pulsation, this mode of current reading would measure 0 amps. In testing, multiple readings of 0.5 amps was observed. This can be later exploited to optimize the speed of the turbine.

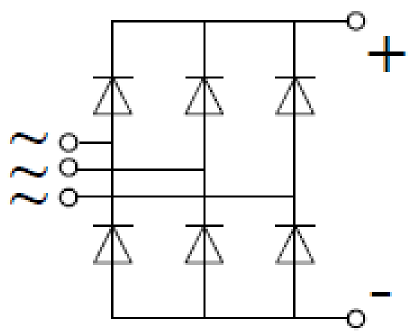
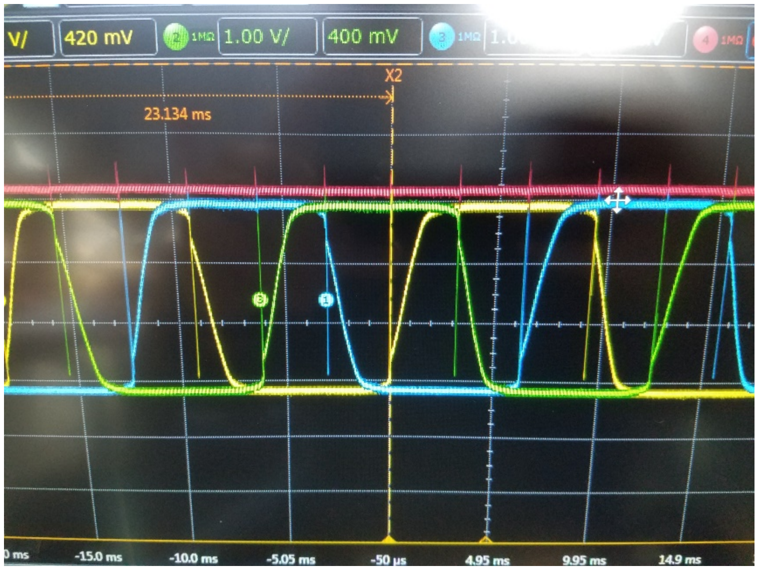


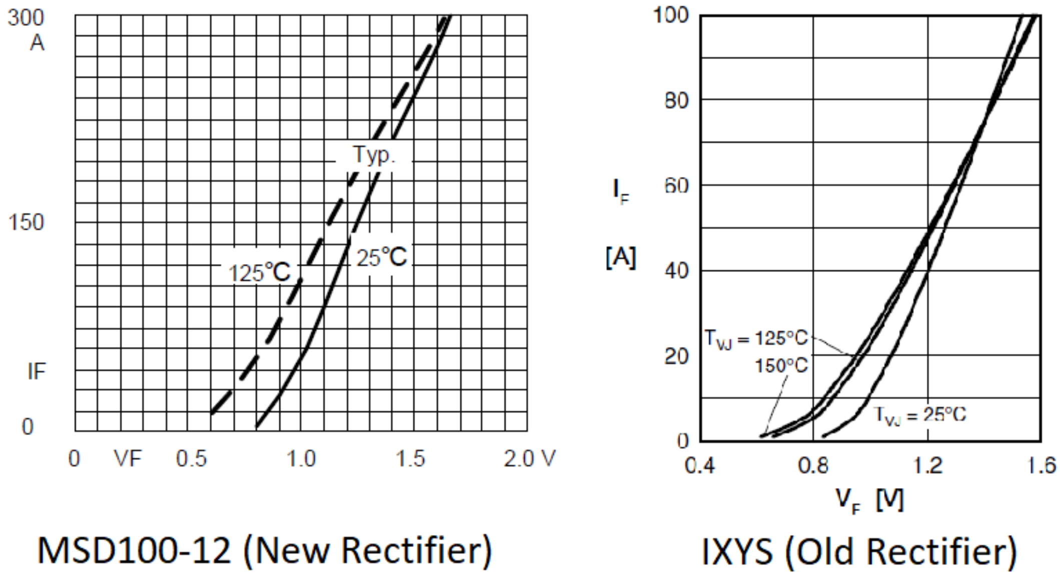
Figure 33. Three-Phase Bridge Rectifier Diagram. Source: [33].



Three Phases of VAC shown in Green, Yellow, and Blue. Rectifier VDC output shown in Red.

Figure 34. Oscilloscope Display of 3-Phase AC to DC Conversion

During testing of the original power electronics, the IXYS VUO86-16NO7-481366 3-phase bridge rectifier, ran very hot. It was theorized that the increase in temperature was because the rectifier was operating outside of the designed capability for the increased power of the drive unit. Observations made by McLaughlin [14], noticed a 0.8 VDC drop across each diode during testing. Figure 35 shows the voltage drop across the rectifier decreases as the temperature of the rectifier increases, and an expected drop of approximately 0.8VDC was correct based on current and temperature.



Forward current is abbreviated as I_F, and voltage drop per diode as V_F.

Figure 35. Voltage Drop Diode Characteristics for 3-Phase Rectifier. Adapted from [33], [34].

Due to the old rectifier's required solder mounting on an integrated circuit (IC) board, a new, higher power rated rectifier was procured with bolt on connections for ease of installation. The new rectifier's voltage drop is expected to be approximately 0.8VDC as well, so no performance gains were obtained with the new rectifier. The new rectifier is encapsulated and its temperature performance was unable to be observed in testing, so its affect upon lowering the voltage drop was not quantifiably measured.

Figure 36. MSD-100-12 3-Phase Bridge Rectifier

4. Supercapacitor Energy Storage

The use of a supercapacitor for energy storage was driven by many of the disadvantages of using batteries as an energy storage medium. Batteries take longer to charge due to the chemical reactions that occur and they have a limited life cycle. Batteries have an upper limit lifecycle of ten thousand cycles, and their storage capacity degrades as they near their end of life [4]. Supercapacitors have a much longer cycle lifespan with minimal degradation due to age and use. The 16VDC Maxwell BMOD0500 P016 B02 16VDC - 500 farad supercapacitor, used in initial testing, is shown in Figure 37. It has a 10-year life span when stored at 16 volts and is rated for one million cycles [35]. Supercapacitors also have much lower equivalent series resistance, (ESR) when compared to batteries. The ESR is a measure of the internal resistance of the storage device, and limits the max current discharge rate.

Later tests utilized a larger 56VDC Maxwell BMOD0130 P056 B03 - 130 farad supercapacitor, shown in Figure 38. This increased the energy storage rating from 18 Watt hours (Wh) to 57 Wh. The increase in energy storage capacity is ideal from an energy storage perspective, and system development should strive to use the highest VDC capacitor possible.

Figure 37. 16VDC Maxwell BMOD0500 P016 B02 - 500 Farad Supercapacitor. Source: [35].

Figure 38. 56VDC Maxwell BMOD0130 P056 B03 - 130 Farad Supercapacitor. Source: [36].

C. AUTOMATED CONTROL

The design requirement that the SS-CAES power extraction unit operate with minimal operator input requires that various functions be automated. The system was designed to be as simple as possible, so the number of automated functions were reduced to the control of air admittance to the power drive unit, and control of the transformer mode of operation.

1. Control of Air Valve

Previous thesis work by Vranas [15], developed an initial design to control the admittance of air to the power drive unit, as shown in Figure 39. It took into account the requirement to black start the system by manually opening a ball valve until the control system can power up on the power generated by the power drive unit. Once power is available, the programmable logic controller (PLC) would open the normally shut (NS) solenoid valve to control the air being admitted to the turbine. If the ball valve were accidently maintained open, the PLC would shut the normally open (NO) solenoid valve. The initial design used 3/8in air supply lines and Parker B6 series, internally piloted solenoid valves shown in Figure 40. The internal pilot allows a very small voltage to control the pilot valve, which then opens the main valve to admit air to the system.

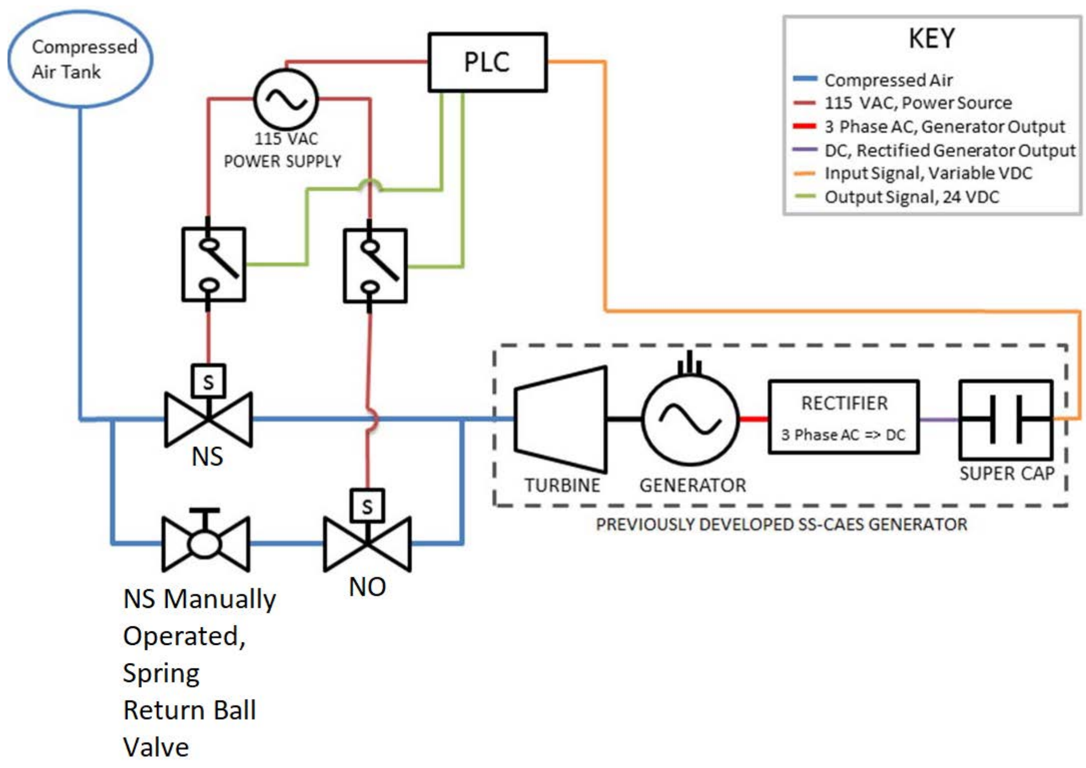


Figure 39. SS-CAES Previously Proposed Schematic. Adapted from [15].

Figure 40. Parker B6 Pilot Operated Solenoid Valve. Source: [37].

With the increase in size of the air supply line to the power drive unit from 3/8in to 3/4in, the automated control valve also had to be replaced. The overall control system was also simplified for ease of use. A ball valve was selected instead of an increased size Parker B6 series to eliminate any pressure drop across the valve. A Valworx 3/4in ball valve with a spring return to shut condition was coupled with a Valworx direct mount solenoid valve, to enable control of the ball valve with air pressure and a 24VDC control signal [38]. The ball valve with the installed solenoid is shown in Figure 41. When a 24VDC signal is applied to the solenoid valve, it opens, allowing compressed air to be admitted to the air actuated ball valve, which opens the ball valve. If the pressure of the air bank drops below a nominal 653kPa (80psig), it will no longer be able to hold the ball valve open and it will shut. This is an ideal cutoff pressure to the drive unit because below 653kPa (80psig), the efficiency drops markedly [39]. If air bank pressure recovers, the ball valve will reopen to continue power generation. Once the 24VDC control signal is removed, the ball valve will also shut. The solenoid only uses 4W of DC power, which was supplied from a DC power source for testing. The solenoid valve also has to capability to be manually operated when power is not available so the black start capability is retained. The PLC is capable of providing a 24VDC control signal when properly configured as proven in testing by Vranas [15].

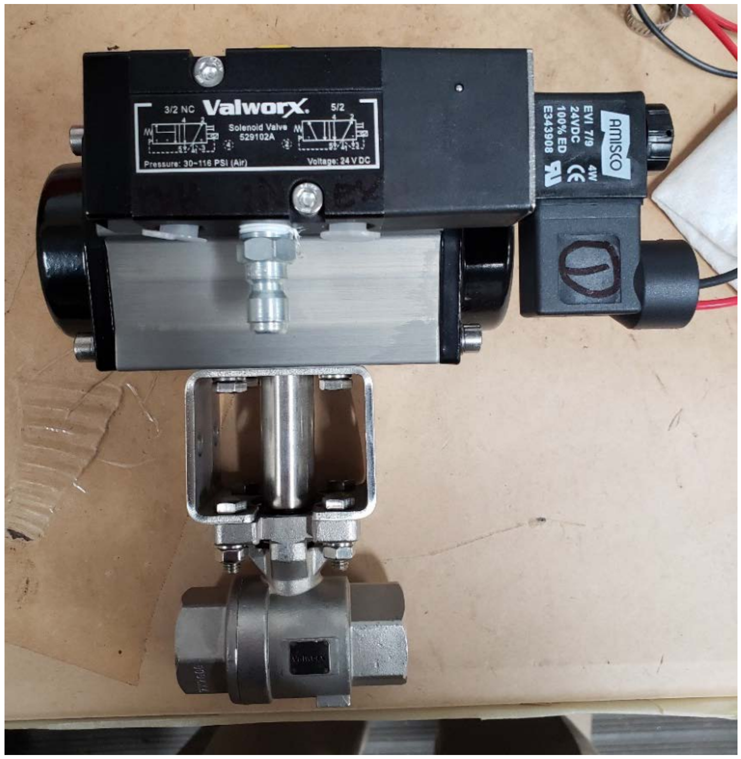


Figure 41. Valworx 523606A 3/4in Ball Valve with Valworx 529102A Direct Mount Solenoid Valve Installed

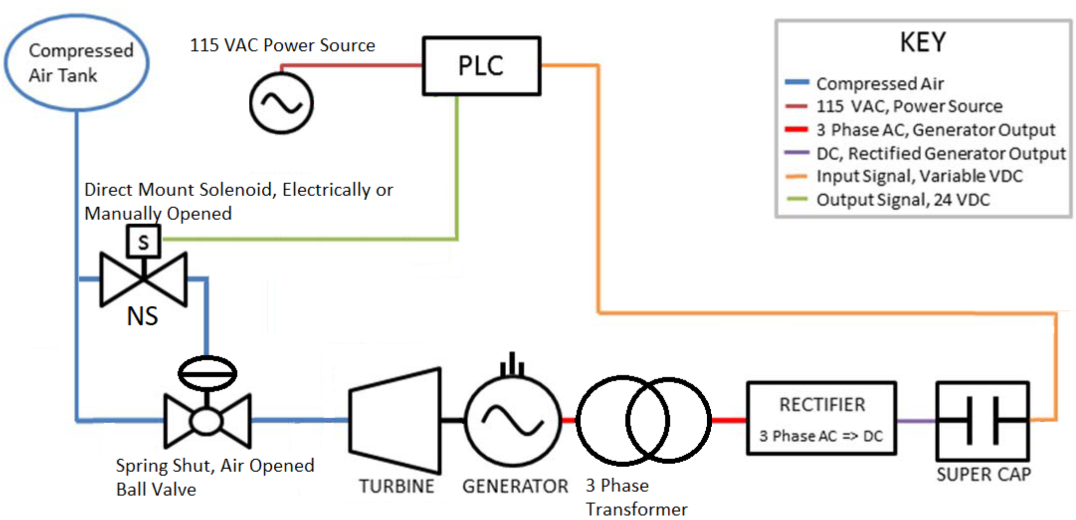


Figure 42. Current Diagram for SS-CAES System. Adapted from [15].

As shown in Figure 42, the overall design is simpler than the previous design shown in Figure 39. However, the capability of the PLC to override an operator error in holding open the solenoid valve to prevent overcharging the supercapacitor is lost. Since the manual override of the solenoid requires someone to maintain the valve open and the supercapacitor takes approximately 30 minutes to charge from a black start condition, it is unlikely that someone would hold the valve open too long. This reasoning led to the elimination of the override feature for simplicity, but this feature could easily be added back in the future. It is thought that a more advanced active control system would eventually be added to the system.

2. Control of Transformer Operation

The last design challenge was a result of the supercapacitor characteristic that it has to be charged at the voltage that it is currently at, and its voltage increases from 0VDC to rated voltage as the energy density increases. That means when the supercapacitor is nearly empty, the charge voltage is low, and the voltage supplied by the generator is also held low. The motor's RPM/volt relationship works in reverse when being used as a generator so a 520 RPM/V motor creates 1V of potential for every 520RPM. When switching motors from 560RPM/V to 520RPM/V, a 7% reduction in the turbine speed to generate the same voltage occurred. Turbines are more efficient at higher speeds so this decreases efficiency. With the transformer bank installed to increase voltage by a factor of 5, the generator output voltage and speed is now also reduced by a factor of 5 from the voltage of the supercapacitor, even further reducing efficiency.

The only ways to increase the speed of the generator is to increase the supercapacitor voltage, which can either take time from an uncharged state, or change the mode of operation of the transformer bank away from step up mode. To optimize the speed of the turbine, it was determined that the transformer bank can be dynamically utilized in 3 different modes: to step down voltage, bypass the transformer bank, and step up voltage. This gives the ability to maintain the turbine speed higher when the supercapacitor voltage is low, bypass the transformer bank to lower the turbine speed with an appropriate upper speed limit is reached, and again lower turbine speed by stepping up voltage to reach the 56VDC capacity of the supercapacitor. By stepping down voltage in a 1:5 ratio, the speed of the turbine is increased by a factor of 25 when compared to the step up mode of operation. This allows the turbine to operate at a higher, more efficient speed, while the supercapacitor voltage is low. By changing the transformer mode of operation based on supercapacitor voltage, the turbine speed can be maintained higher, efficiency improved, and the supercapacitor can be charged to higher voltages. Although a 5:1 ration was chosen for this project, the same transformers can be reconfigured for a 10:1 winding ratio, allowing for even higher voltages to be realized.

Changing the flow of power through the transformer should be done autonomously with a PLC. The switching of transformer operations will by controlled by solid state relays (SSR). A SSR acts like a mechanical relay, but instead uses semiconductor elements to perform the circuit isolation and switching functions. Figure 43 shows the three modes of operation of one phase of the 3-phase transformer bank. Since 6 switching functions for each phase are required, a total of 18 switches will be needed to control all 3 phases of the transformer bank, for 3 different modes of operation. To simplify the wiring and installation requirements, 3-phase SSR's were used. This lowered the number of SSR switches required from 18 to 6. The Crydom D53TP25D, shown in Figure 44, was used because of its lower power dissipation and ability to control three switching functions with one control input [40]. Using a 4-32VDC control signal, it controls the switching on and off of three phases of main line power. The mainline power rating is 25A, which is well below previously observed current flow to the supercapacitor [40]. The final installed SSR experimental setup is shown in Figure 45. The generator's 3-phase output is fed into this setup at the left terminal block and the control signals for the SSR's are supplied at the terminal block at the bottom of Figure 45.

The PLC and its programming were not programmed to automatically control the ball valve and SSR's due to time constraints and additional functionalities that were desired to be added in follow on thesis work. Instead, a DC voltage source was applied to simulate the control signal to operate the ball valve and SSR's.

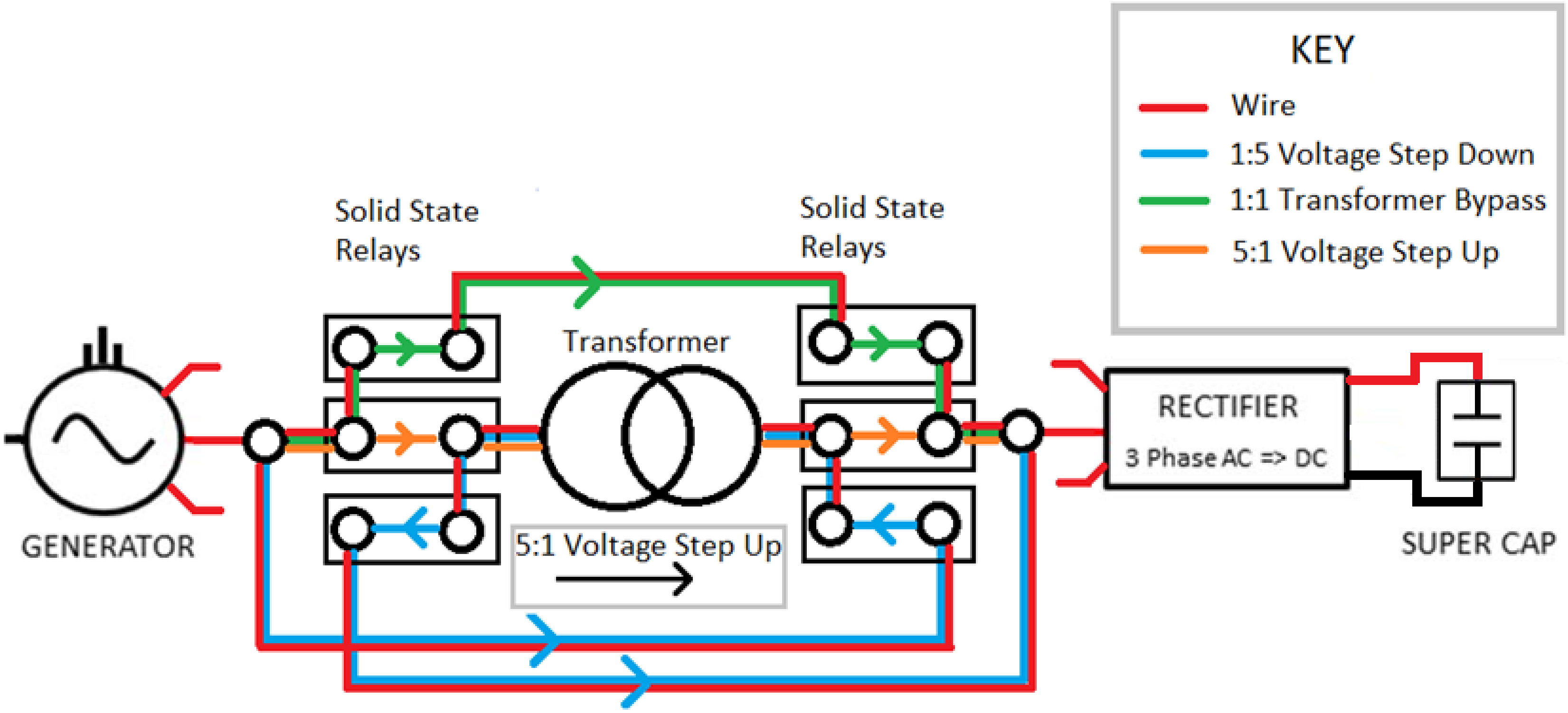


Figure 43. Single Phase of Dynamic Transformer Operation

Figure 44. Crydom D53TP25D 3-Phase Solid-State Relay. Source: [40].

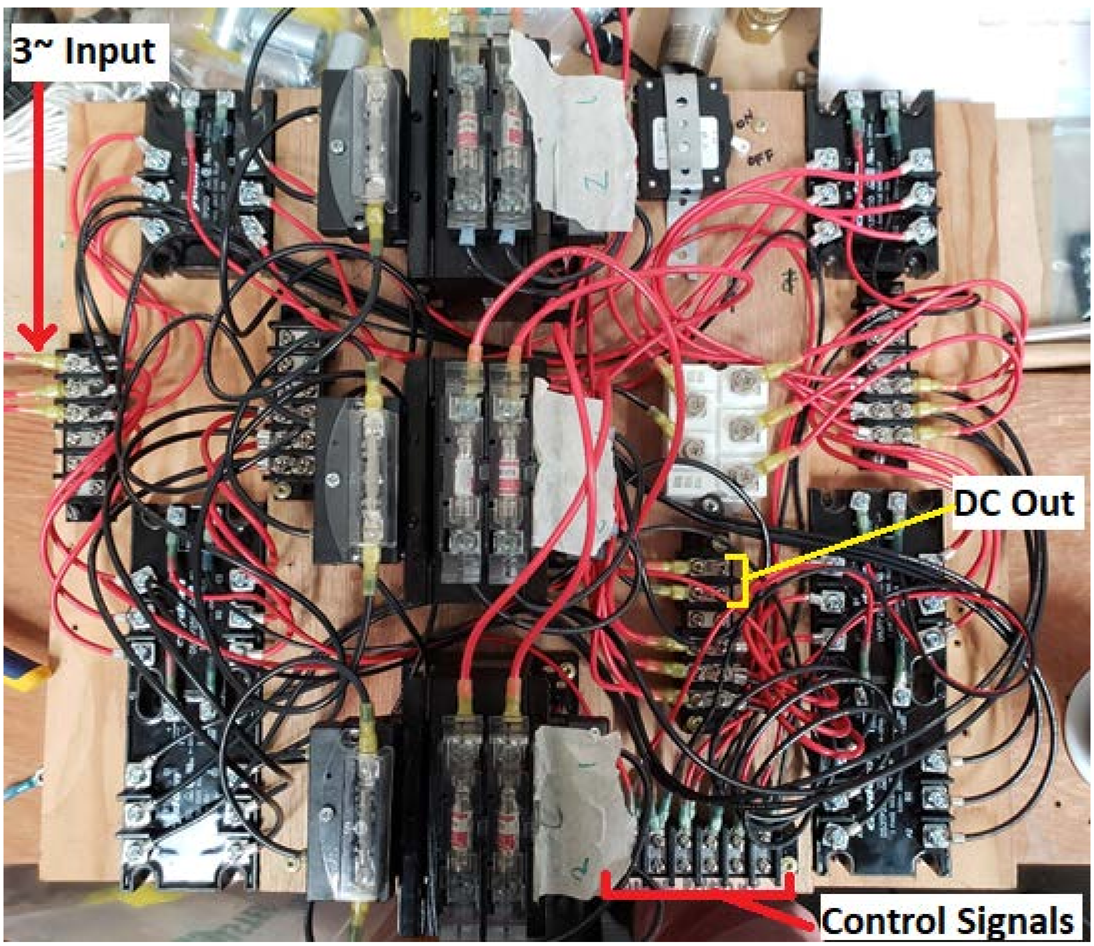


Figure 45. 3-Phase Transformer Bank with Switching Operation Option

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III. CFD ANALYSIS OF COMPRESSED AIRFLOW

A. INTRODUCTION AND OBJECTIVE

An air ejector uses two sets of converging-diverging nozzles to manipulate a high pressure, low mass flow, into a low pressure, high mass flow outlet. The first accelerates the inlet motive flow (compressed air) to supersonic speed. This high-speed airflow entrains additional air at the suction which raises the enthalpy of the overall stream. It then proceeds passes through the second nozzle, where pressure is recovered and the speed is lowered to subsonic speeds. This pressure velocity relationship for the air ejector is shown in Figure 15.

This subsonic, high velocity air exits the air ejector and enters the turbine inlet. However, the outlet of the air ejector is smaller than the turbine inlet, and there exists a potential to harness the remaining pressure of the air ejector exit stream to entrain more atmospheric air prior to entry into the turbine. This has the potential to increase the mass flow rate through a reaction type turbine and increase the enthalpy of the stream prior to energy extraction, thereby increasing the power extraction. This secondary entrainment is called thrust augmentation.

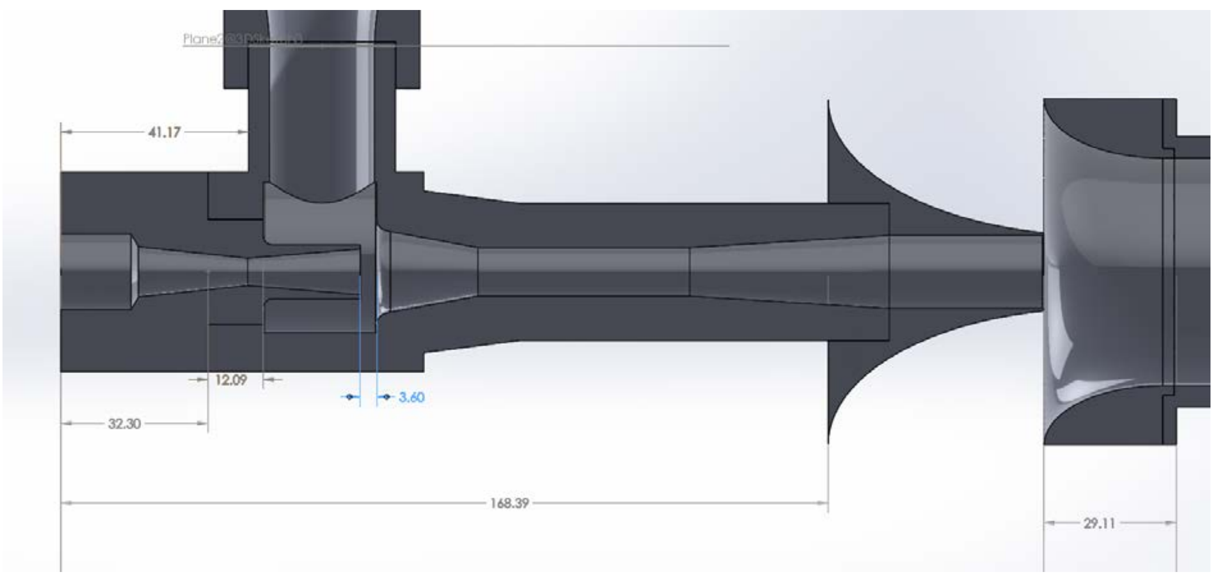
The computational fluid dynamics (CFD) analysis aims to model and analyze the primary and secondary ejection processes to investigate the feasibility of a secondary air entrainment at the exit of the air ejector into the turbine housing. By creating an accurate CFD model that reflects experimental observations, an understanding of the primary and secondary entrainments can be gleaned. This will allow for future design changes and optimization of the current design selection.

B. CFX PROBLEM SETUP

The general solution development approach is to model the physical domain in Solidworks, create the fluid flow domain in the ANSYS CFX software suite from the physical domain, generate an appropriate mesh, apply boundary conditions and solver options, run the solver, and analyze the results.

1. Physical and Fluid Flow Domain

A physical model of the air ejector must be rendered in Solidworks in order to build the required fluid domain in ANSYS CFX. The Solidworks model was created by measuring the air ejector with a micrometer, gauge pins, and depth micrometer. The geometry of the turbo inlet flange was also measured for physical modeling of the thrust augmenter and to create a smooth entry surface, which makes airflow analysis easier. Sharp edges at air entry points creates calculation discontinuities, and in physical applications, cause unneeded losses. A smooth inlet was added to the primary suction for the same reasons. As shown in Figure 46, the air ejector and turbine inlet were fitted with smooth surfaces where air is entrained. The file was saved as a parasolid file format for ease of importing into ANSYS CFX.



All dimensions are measured in mm.

Figure 46. Physical Rendering of Air Ejector and Turbo Inlet

To model the fluid flow domain from the physical model shown in Figure 46, another shape has to be generated. It encompasses the fluid flow path and includes a control volume extending outward from the suctions to allow variations to dissipate and obtain accurate results of overall mass. This encompassing shape is shown in Figure 47.

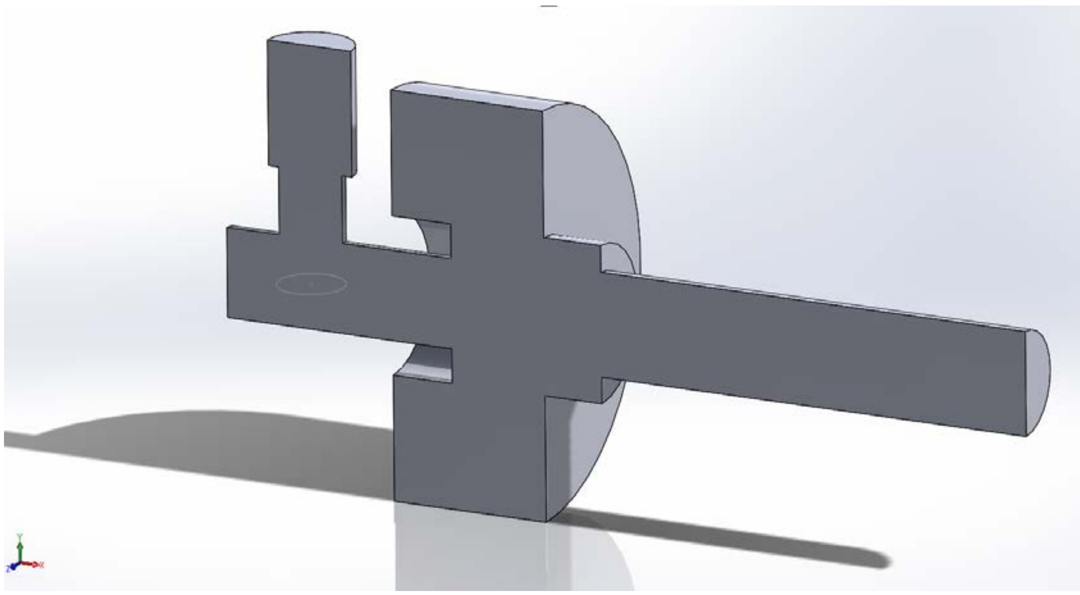


Figure 47. Fluid Flow Encompassing Shape

The two shapes are imported into ANSYS CFX, the encompassing shape treated as a positive area, the physical model is treated as a negative area, and the left over shape is the volume that is analyzed for fluid flow characteristics. The fluid flow domain is shown in Figure 48.

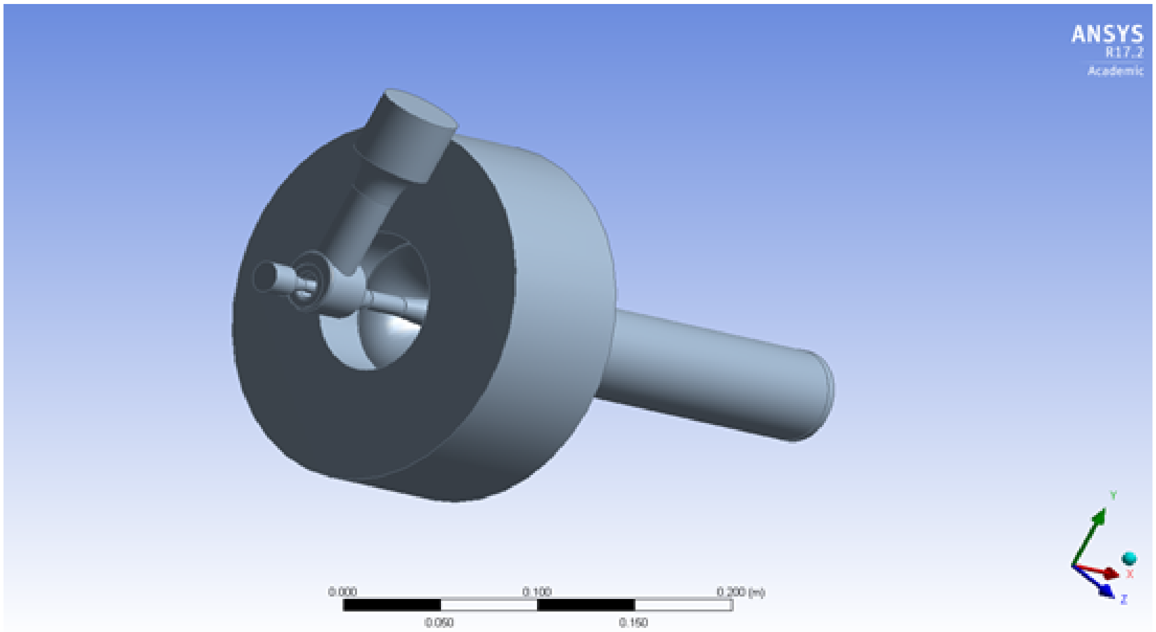


Figure 48. Fluid Flow Domain

To remove computational difficulties that arise from the complex internal flow path at the primary ejection and determine the highest achievable airflow, the primary nozzle ejection volume was refined to be modeled as an open volume. The physical representation of the open flow model is shown in Figure 49. This physical model represents the most open airflow path possible and could be used to improve the commercially available air ejector or used to design a new air ejector. All remaining sharp edges in the fluid flow path were rounded slightly to assists in solution computation.

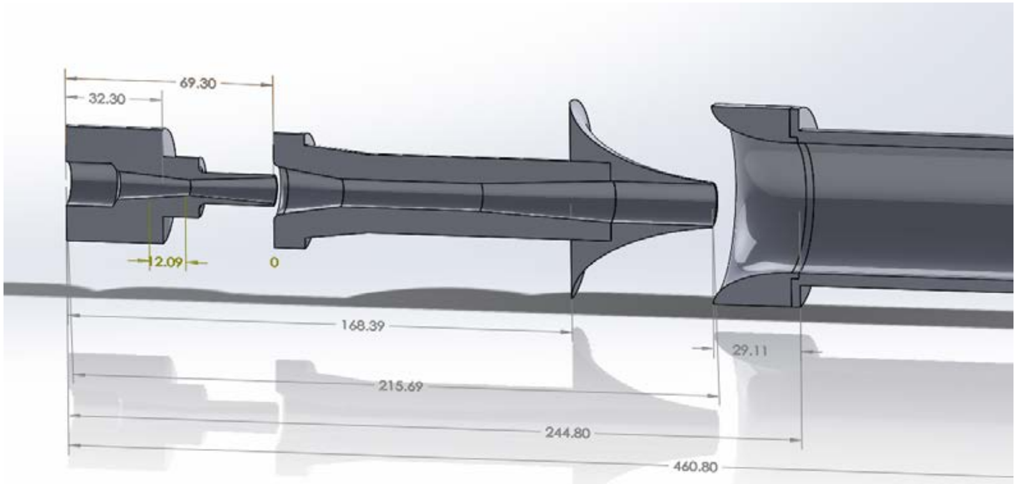


Figure 49. Physical Representation of Open Flow Model

2. Computational Mesh Creation

A computational mesh must be applied to the fluid flow domain to define the number of points that the ANSYS CFX software analyzes to calculate expected fluid flow characteristics. A mesh with more points can lead to a more accurate solution, but takes longer to calculate. As shown in Figure 50, areas with laminar flow require less nodes to create an accurate solution, while areas with turbulent flow require more nodes since the boundary layer is much smaller. Creating an adequate mesh is an iterative process, and should be refined as interim results are analyzed.

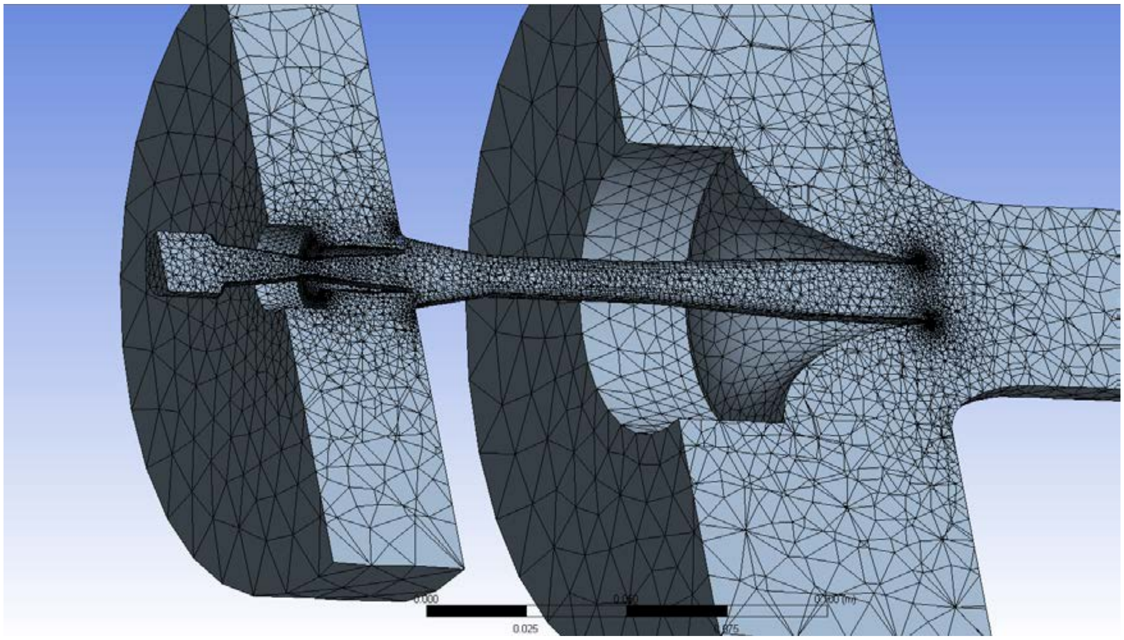


Figure 50. Open Flow Model Fluid Domain with Mesh Applied

Fluid flow which is supersonic requires especially detailed solution development near the wall, and thus a finer mesh with more points to develop a solution must be employed. Initial solutions revealed inaccuracies evident by the presence of oblique shocks and Y+ values greater than 200 in critical throat regions. Inflation layers were added as early analysis of the visual cross section of Mach number revealed oblique shocks at many walls due from a too course mesh, and later upon analysis of high Y+ values. Adding inflation layers creates more computational points as the wall is approached in an attempt to accurately resolve the viscous sublayer flow. Due to the supersonic airflow, particular attention was paid to the inflation layers in critical regions by slowing the growth rate and adding additional layers. This allows ANSYS CFX more computational points where the fluid flow is the most difficult to solve, aids in resolving the viscous sublayer, which leads to a reduced the Y+ value. Figure 51 shows the use of inflation layers, especially at the throat of the primary nozzle. Similar inflation layers were also used on the secondary nozzle of the air ejector. The final solution mesh contained 146,077 nodes and 461,913 elements.

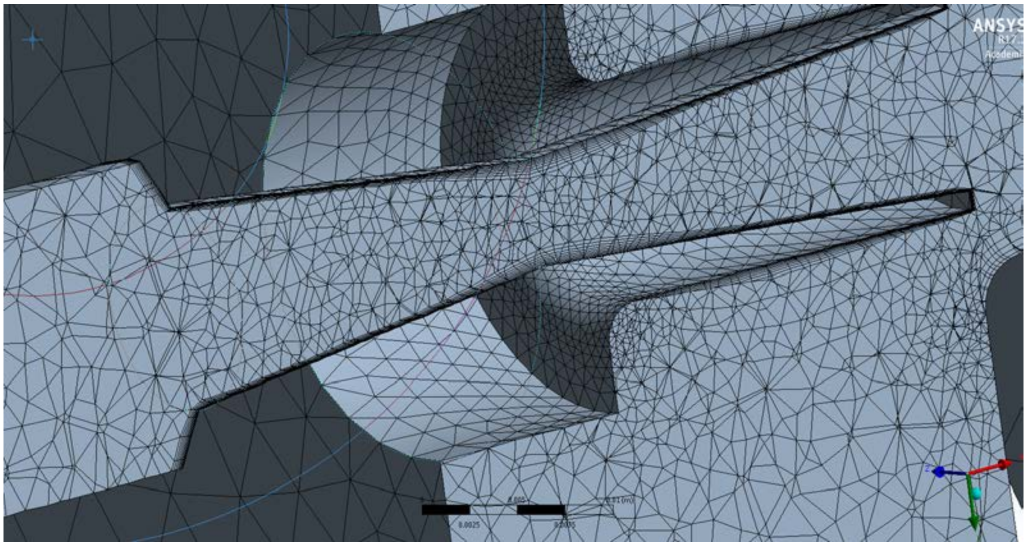


Figure 51. Inflation Layers in Primary Nozzle

3. Boundary Conditions and Solver Options

Initially, all pressures were referenced to 0 Pa as an absolute scale, but they were modified to remove the possibility of being divided by zero and referenced to one atmosphere. This did not have a noticeable effect on the solution, but removed a possible source of error. Boundary conditions had to be varied to obtain a working solution, and the final conditions are listed in Table 3. Turbulence was varied in two regions beyond the default 5% intensity due to expected high turbulence, which resulted in better convergence.

Table 3. CFX Solution Boundary Conditions.

	Inlet (INLET)	Primary Ejection (INLET)	Thrust Augmenter (INLET)	Outlet (Opening)
Flow Regime	Subsonic	Subsonic	Subsonic	Subsonic
Mass and Momentum	Total Press. 689 kPa	Total Press. 0 Pa	Total Press. 0 Pa	Opening Press. And Dirn 0 Pa
Flow Direction	Normal to B.C.	Normal to B.C.	Normal to B.C.	Normal to B.C.
Turbulence	High (Intensity =10%)	High (Intensity =10%)	Medium (Intensity = 5%)	Medium (Intensity = 5%)
Heat Transfer	Total Temp 300K	Total Temp 300K	Total Temp. 300K	Opening Temp 300K

The default domain used air as an ideal gas with reference pressure set to 1 atm. A no slip wall was imposed. Heat transfer was set to total energy and viscous work terms were included. The selected turbulence option was k-epsilon with a scalable wall function, including high-speed (compressible) wall heat transfer model and turbulent flux closure with default options selected. The k-epsilon model was demonstrated to provide the most accuracy by Su [19] in ejector analysis and was used for this simulation.

Solver control options used a high-resolution advection scheme and turbulence numerics. Convergence control was set to a max of 1000 iterations, auto timescale control, conservative length scale, and residual target of $1e^{-5}$. Solver advanced controls included global dynamic model control, velocity pressure coupling with the Rhie Chow option set to high resolution, compressibility control, and high speed numerics with the total pressure option set to automatic. The velocity pressure coupling scheme was added due to residual variations in mass, momentum, and velocity that could not be resolved. By using this option, residuals dropped an additional 3-4 orders of magnitude and residual stability was much better. Expert parameters was used to set the max continuity loops to three since the ANSYS CFX documentation recommends at least two continuity loops when Mach numbers above 2 are expected to help convergence and resolving areas near a shock [41].

4. Solver Running

The solver was run using double precision and large problem options to ensure the most accurate answer was calculated. The problem was also set to solve for a steady state solution. Getting the problem to run took multiple steps to prevent the solution from diverging. Initially, all advanced options were turned off and the thrust augmenter boundary conditions were changed to a wall vice an inlet, effectively turning off the secondary entrainment. The solver was run until residuals trended down, indicating a converging solution. This produced an approximate solution for the first and second nozzles of the air ejector, and the primary entrainment. Since the airflow is choked at the first nozzle, this solution is accurate enough to re-enable the secondary entrainment. The thrust augmenter's boundary condition was changed back to an inlet and the solver was allowed to run 1000 iterations. Once this solution was developed, all the options mentioned before were added in one at a time, and the solver ran until the residuals reached a steady state value (or 1000 iterations). Figure 52 shows the residuals over the course of the solution development as individual options were added. The highly oscillating nature was damped out near the end with the addition of pressure velocity coupling.

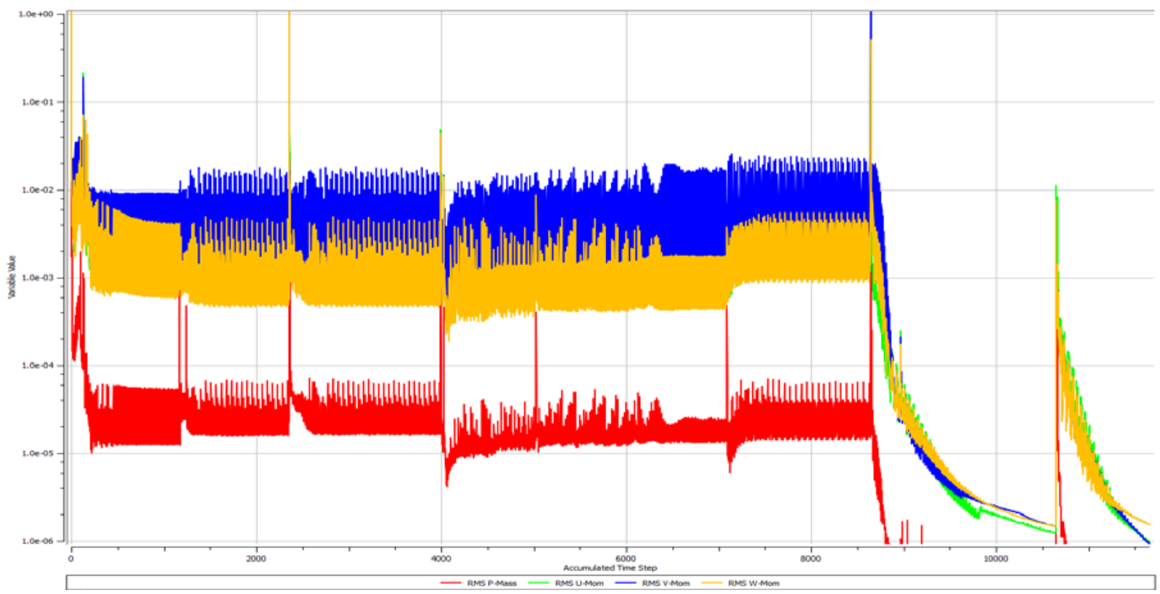


Figure 52. Residual Convergence Trends

C. ANALYSIS

Convergence of the solution was based on residuals dropping at least three orders of magnitude, all inlet mass flows equaling the outlet mass flow, and the solution modeling observed conditions during testing. Residuals in Figure 53 show a converged solution with residual oscillations damped out and residuals on a downward trend below 10^{-6}.

The results of the final CFX solution are given in Table 4. The difference between the total of the inlet and outlet mass flows is negligible, and the entrained flow of the thrust augmenter is 3 times the mass flow of the inlet motive flow. It also shows improvement in reducing the airflow supplied when compared to the calculated choked flow use of 0.17487 kg/s of the original power drive unit.

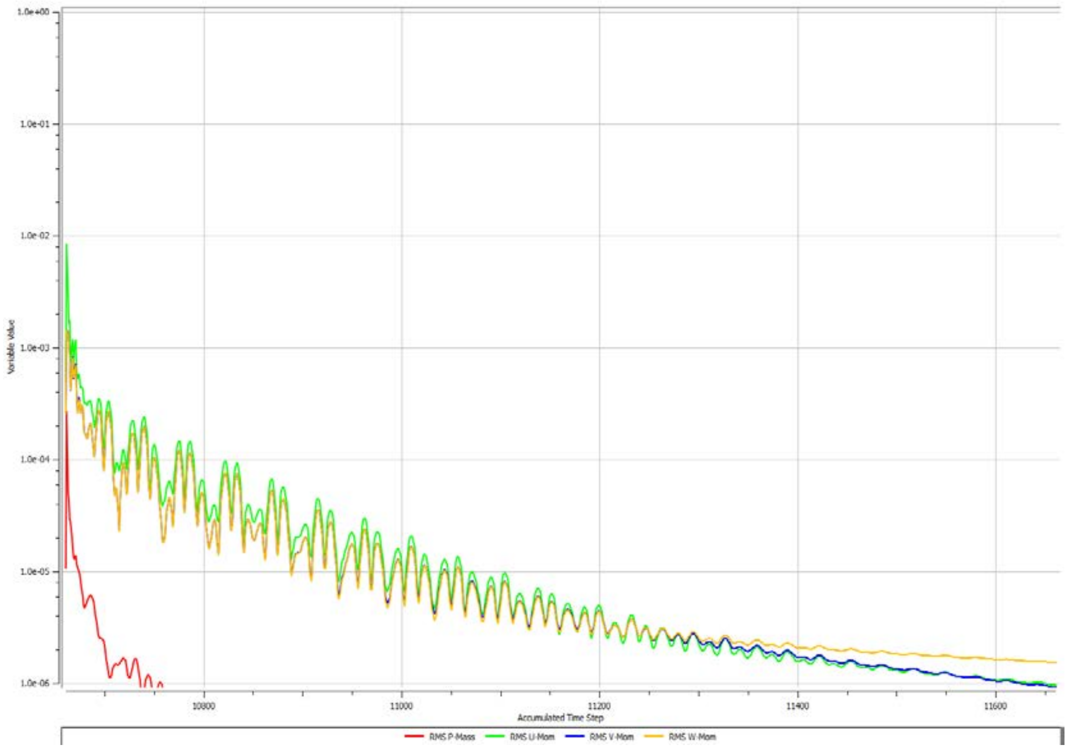


Figure 53. Final Solution Residuals

Table 4. CFX Calculated Values of Mass Flow

	Inlet	Primary Ejection	Thrust Augmenter	Total of Inlet Flows	Outlet
Mass Flow (kg/s)	0.0512173	0.00502605	0.154566	0.21080935	-0.210805

Y+ values for the final solution trended as high as 120 in the critical throat regions. Although Y+ values in excess of 100 gives an indication that the CFX solution has not completely reached an accurate solution near the wall, it is only an indicator that the boundary layer has not been completely resolved. Based on the amount of near wall mesh refinement already performed, mass flow totals, and residual trends, the final solution is probably close to reality.

Figure 54 shows the cross sectional pressure distribution with 0 Pa reference to atmospheric pressure. As expected, pressure at the outlet of the primary nozzle drops below atmospheric pressure, aiding in the entrainment of air into the secondary nozzle. The outlet of the thrust augmenter is at atmospheric pressure, which meets the goal of supplying fully expanded, high velocity, and at or above atmospheric pressure air to the turbine.

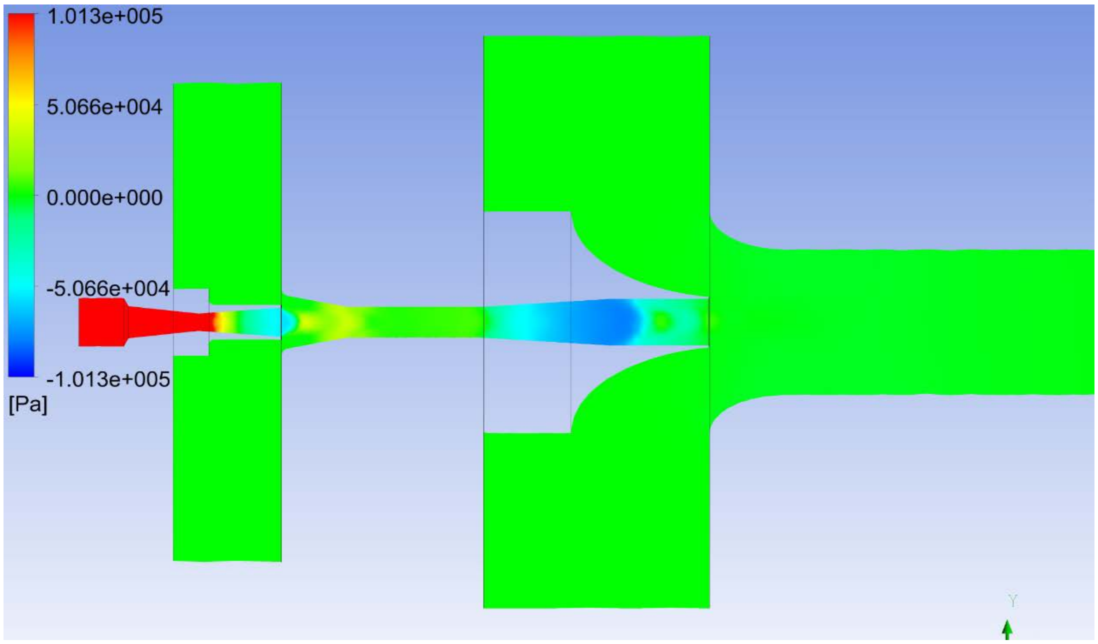


Figure 54. Cross Sectional Pressure Distribution

Figure 55 shows the Mach number distribution. As expected, Mach 1 is reached by the throat of the primary nozzle, as evident by the further acceleration of the flow as the nozzle diverges. Based on the idealization of an air ejector as shown by Figure 15, the supersonic flow should slow to subsonic speed prior to exiting the diverging portion of the secondary nozzle. However, in this simulation, the flow maintained supersonic velocity through the throat of the secondary nozzle of the air ejector, and thus accelerates back above Mach 2 when it meets the second diverging portion of the air ejector. This could be due to a number of reasons. In a steam application for which this air ejector was primarily designed, densities vary from air and affect where the flow will go subsonic. Additional sources of difference may also include inaccurate or incomplete measurements of the air ejector and poor manufacturer design or manufacture if we assume the CFD results are incorrect. If the CFD results are accurate, this deviation from ideal air ejector operation seems to aid the desired effect of supplying the highest velocity air possible with a high mass flow as evident by the successful thrust augmentation.

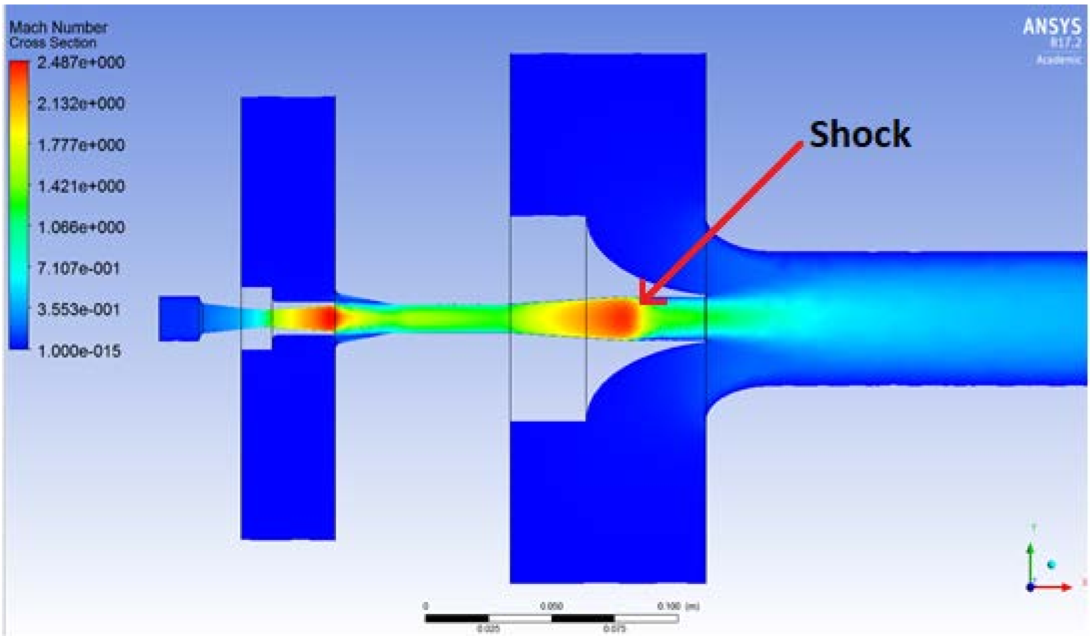


Figure 55. Cross Sectional Mach Number Distribution

The last way to validate the CFD results is to compare to experimental data. During the last experiments, air consumption was a constant 0.057119kg/s throughout the entire test. This is expected since a constant pressure was maintained throughout the experiment, and the choked condition in the primary nozzle prevents variations in the mass flow. The variation of the CFD solution inlet value mass flow of 0.0512173 kg/s to the experimental value is 9.11%, which validates the geometry measured of the primary nozzle throat. Although not performed, measuring the primary suction and thrust augmenter flows would validate the CFD model fully and allow for further, confident development of design changes before implementation.

IV. TESTING AND RESULTS

A. EARLY TESTING

Initial testing sought to identify power drive unit weaknesses and understand where gains could be made to extract more power. The modified power drive unit shown in Figure 56, and the new power drive unit, shown in Figure 57, were first tested and compared. Additionally, the RPM to volt relationship that McLaughlin [14] proposed was validated with using a Genrad 1531-A stroboscope in early testing. The stroboscope measured the RPM of the generator and was compared to the calculated RPM based on voltage and frequency measurements using relationships given by McLaughlin [14] across a range of speed. Electrical conversion during this testing only used a 3-phase rectifier without the assistance of AC transformers.

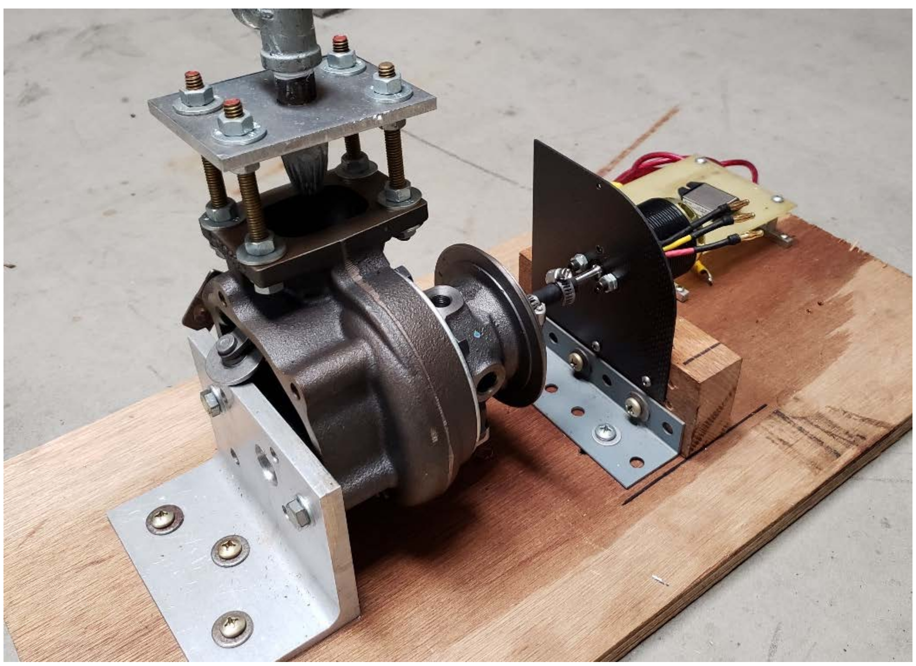


Figure 56. Modified Power Drive Unit

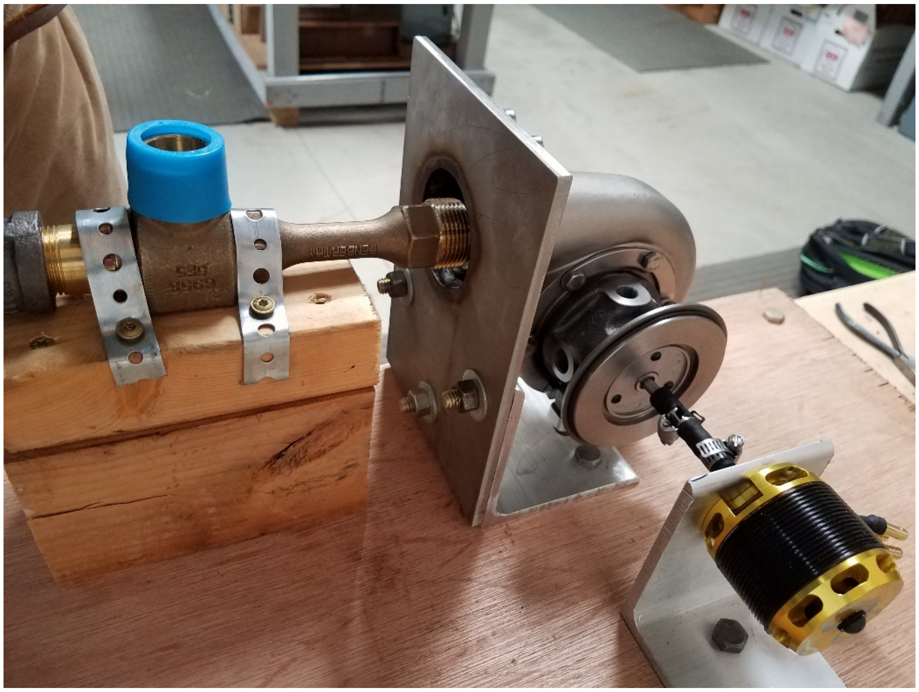


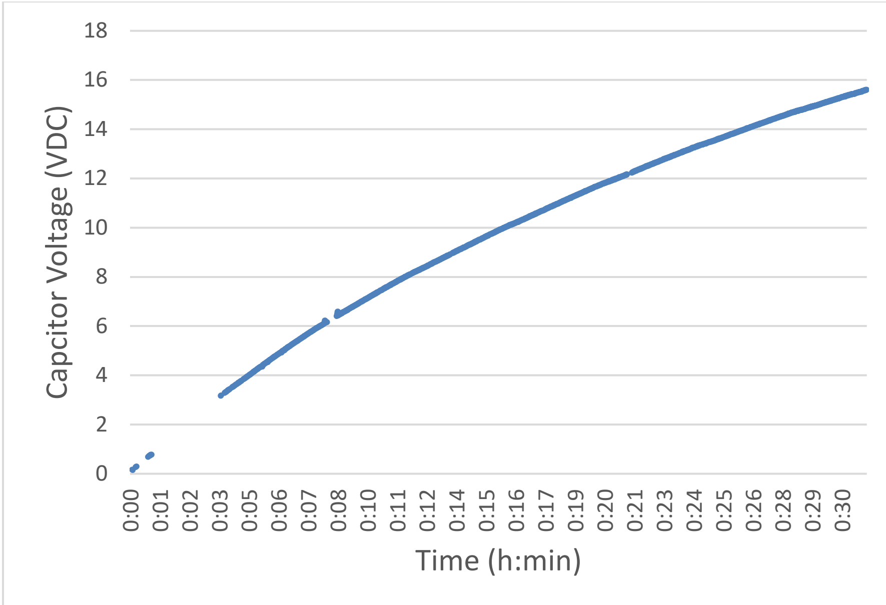
Figure 57. Final Power Drive Unit Installation

The air supply used in initial testing, a shop air supply with 1in. supply lines, proved to be insufficient to maintain pressure at the air consumption rate of both power drive units. The shop air compressor nominally maintains air pressure at 791 kPa (100 psig) for small air consumption loads, but is unable to maintain this pressure for large loads. Airflow was measured with an Orange Research Inc. 2321-S1035 airflow gage with 1/2in connections. Since the inlet to the new power drive unit is 3/4in, this was an airflow restriction that will be upgraded to a larger diameter airflow meter in later testing. Data collection was performed with a Keysight MSOS104A oscilloscope with a laptop interface recorded at one second intervals. Some data was not properly recorded by the instrument due to intermittently lost lead connections, but the fidelity of the measurements was excessive for early testing.

The first comparison made was the modified power drive unit to the original testing done by McLaughlin [14]. The original power drive unit was able to reach 11.73VDC in 45 minutes on the second charge cycle. The third charge cycle, an upper limit run, was only able to reach 15.03VDC in an unspecified amount of time. As Figure 58 shows, the modified power drive unit was able to reach 15.61VDC in 32 minutes. This is an improvement over the original design since a higher voltage was reach in a shorter time. It 42 SCFM of air while the air compressor was able to maintain pressure at 584 kPa (70 psig). Better results may be possible with constant air pressure maintained at 791 kPa (100 psig) throughout the experiment.

Airflow was read as 42 SCFM from the Orange Research flow gage, but must be corrected for conditions different from the calibration setpoint using Equation 2 [42]. All input values to Equation 2 must be in English units. The Orange Research gage plate data flow meter gives P_c as 790 kPa (100psig) and T_c as 21°C (70°F). Using Equation 2, actual pressure of 584 kPa (70psig) and actual temperature of 20°C (68°F), K was calculated as 0.86095. This corrects measured airflow to 36.62 SCFM at 101 kPA (14.7psia) and 20°C (68°F). Using the density of air (1.1839kg/m^3) at 1 atm and 20°C, a final mass flow of 0.0202 kg/s is obtained for the modified power drive unit.

$$K = \sqrt{\left(\frac{(P_a + 14.7)}{(P_c + 14.7)}\right) * \left(\frac{(T_c + 460)}{(T_a + 460)}\right)} \qquad (2)$$

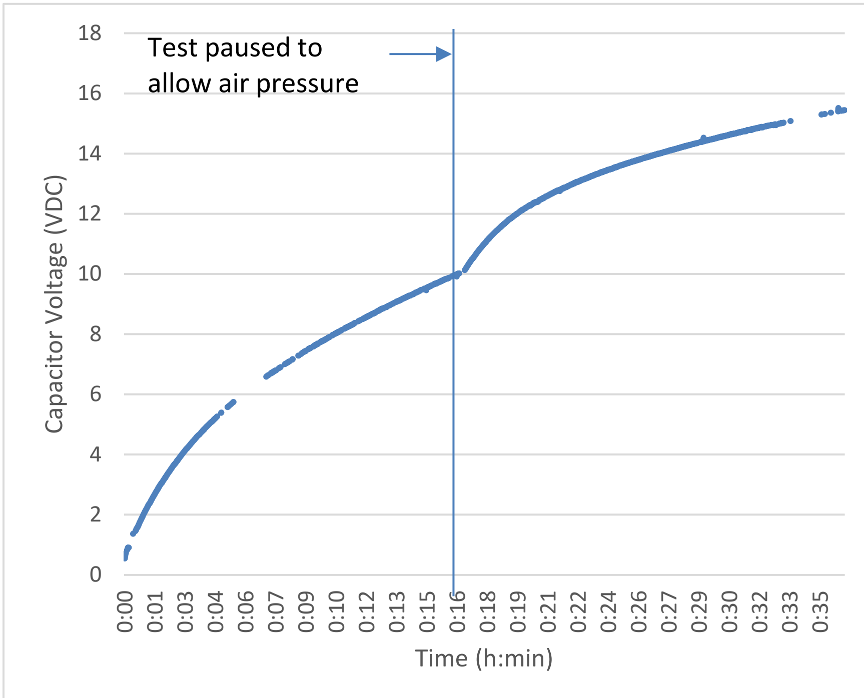


Missing values are due to erroneous readings from oscilloscope, and were deleted.

Figure 58. 16VDC Supercapacitor Voltage for Charge Cycle Charge Cycle Using Modified Power Drive Unit

As Figure 59 shows, the new power drive unit was able to reach 15.45 VDC in 37 minutes. It used 80 SCFM of air while the air compressor was only able to maintain 515 kPa (60psig) at steady state. With updating the actual pressure in Equation 2, the new K value is 0.8085. This corrects measured airflow to 64.68 SCFM at 101 kPa (14.7psia) and 20°C (68°F). Using the density of air (1.1839kg/m3) at 1 atm and 20°C, a final mass flow of 0.03614 kg/s is obtained for the new power drive unit.

While the new system took 5 minutes longer to reach a similar voltage of 15.45VDC, the shape of the voltage curve of Figure 59 offered promise of better performance. When the supercapacitor charge test was initially started with air bank pressure of 790 kPa (100 psig), the rate of voltage change was greater than the modified power drive unit. This was verified by pausing the experiment around the 17-minute point, allowing the air bank pressure to recover to 790 kPa (100 psig), and then continue the supercapacitor charge. The rate of voltage change, again started off higher, but then lessoned as the air bank pressure fell to its steady state value of 515 kPa (60psig). This pressure was maintained as the supercapacitor reached full charge.



Missing values are due to erroneous readings from oscilloscope and were deleted.

Figure 59. 16VDC Supercapacitor Voltage for Charge Cycle Using New Power Drive Unit

Other experimentation tested the ability of the 3-phase transformer bank to step up and step down voltage. Figure 60 shows two phases of the 3-phase generator output in blue and yellow, the stepped down voltage in green, and the DC output voltage in red. A steady output DC voltage is produced from the 3-phase DC up to approximately 995Hz. After 995Hz, the DC output became unstable due to exceeding the reverse-recovery time of the diodes. The unstable DC voltage also affected the stepped down input AC voltage to the rectifier, shown in green in Figure 61. This effect was isolated to the rectifier since it was also seen with the transformers removed.

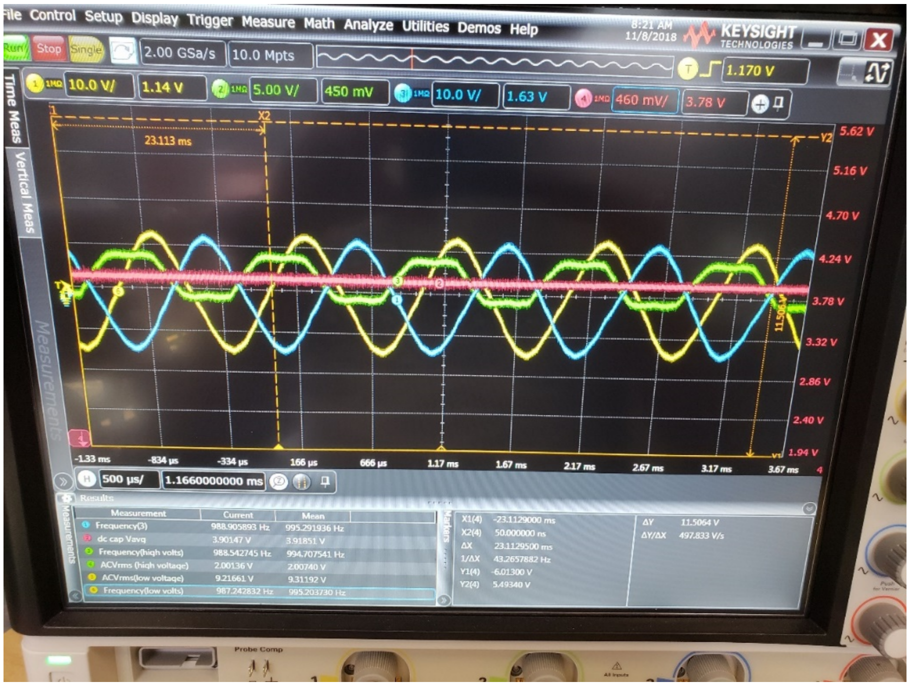


Figure 60. Step Down Transformer Configuration

Figure 61. Breakdown in Rectifier Output

The automated switching of the transformer bank through the use of solid state relays was found to not work with the current system configuration. Although the SSR's act as a switch, they also have diodes built into the circuitry which are susceptible to their reverse-recovery time being exceeded. In addition, the SSR's selected contain current limiting, transient protection circuitry, which when exposed to the operating frequencies of this system, would not allow power to be transmitted through the transformer bank. This was audibly noted from rapid turbine speed changes from the unpredictable transient loading the SSR introduced.

B. FINAL TESTING

Final testing was accomplished with a different air supply with an air compressor able to provide the required airflow at a constant 130 psig (896Kpa). All air lines used were the same size as the air ejector or larger. A 2.54cm (1in) Flo-Gage, part number 1-71-L-300-I, was used to measure the airflow. This data was taken manually at 15 second intervals for the first two minutes and at 30 second intervals for the rest of the run. The same oscilloscope was used for visual analysis of the waveform and frequency analysis. Tests were performed on both the 16VDC and 56VDC supercapacitors. The 16VDC supercapacitor was charged without the use of the transformer bank. The 56VDC supercapacitor was charged without, and later in the charge cycle, with a step up transformer configuration.

The 16VDC test took 6 minutes to charge to 16VDC, and produced a max power of 293 watts. The 16VDC charge cycle found one mechanical limitation as the coupling tube from the turbine to generator was broken. A stronger replacement was made with a steel reinforced hydraulic line. There were no limits to either the turbine or charging system. As shown in Figure 62, the voltage increase was near linear, while as shown in Figure 63, the DC charging current was constant. By multiplying the voltage and current, output power was obtained. Because the turbine operates more efficiently at higher RPM, it was expected that the power drive unit would produce more power as the RPM and voltage increased.

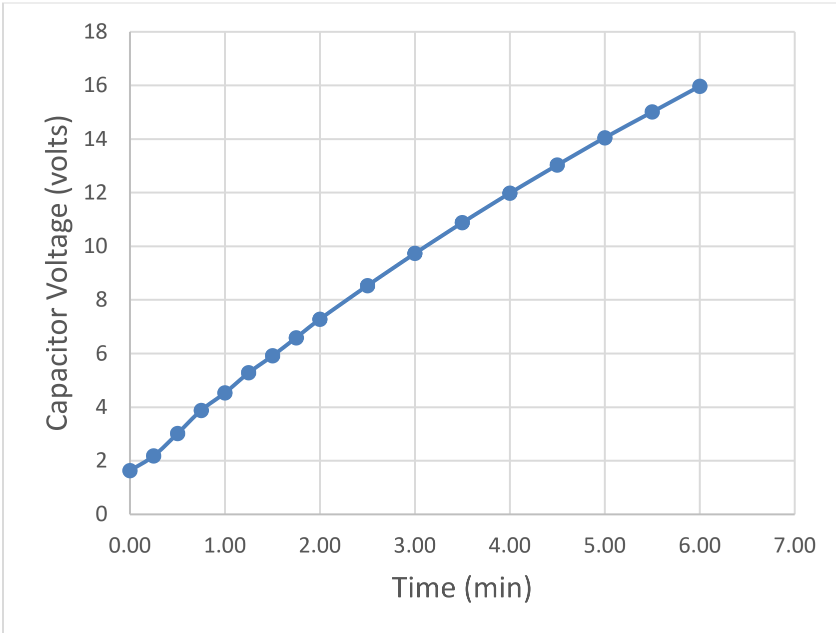


Figure 62. 16VDC Supercapacitor Voltage for Charge Cycle

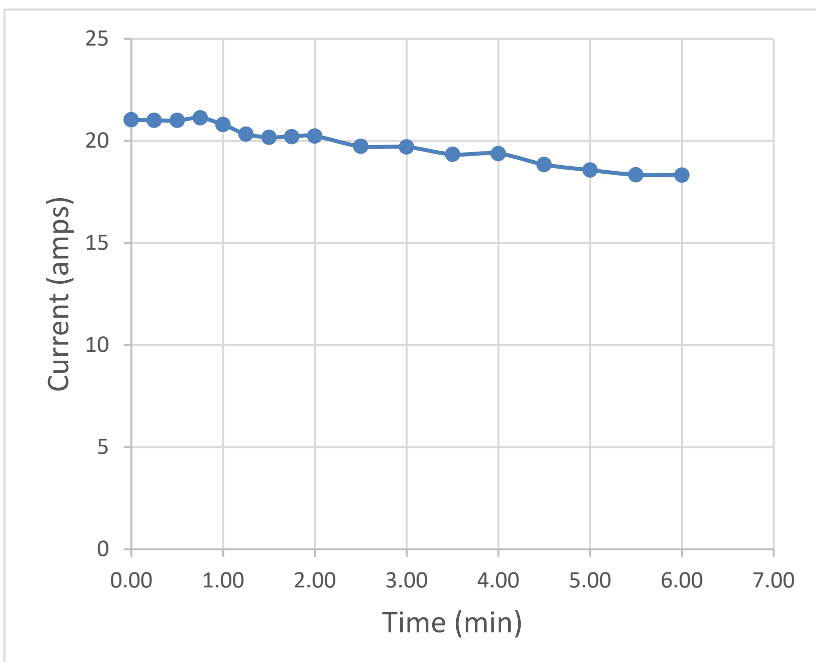


Figure 63. 16VDC Supercapacitor DC Current for Charge Cycle

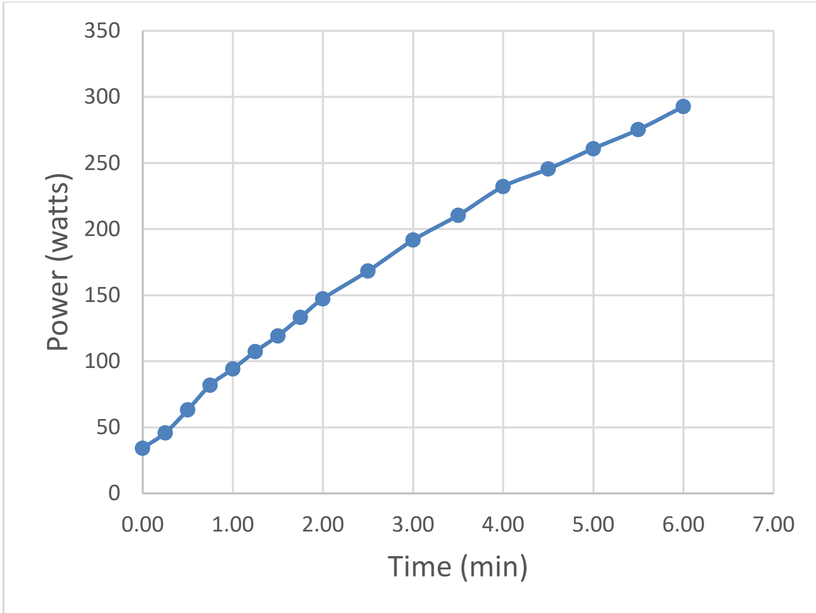


Figure 64. 16VDC Supercapacitor Power for Charge Cycle

The 56VDC supercapacitor charge cycle took 16 minutes to reach 56VDC, and produced a max power of 448 watts. The charge cycle began without the transformer bank, but was shifted to the step up transformer mode of operation at the 4.5 minute point because an operational limit of the generator was reached. Using the power rating of 4450 watts and current rating of 100 A of Table 2, an operational voltage limit of 44.50 volts can be calculated using the power equation. In testing, the motor began to issue sparks around 37.24VDC at 4.5 minutes, at which the experiment was paused. The transformer bank was then introduced to step up the voltage. This lowered the turbine speed and continued to charge the supercapacitor to its limit of 56VDC. This point was annotated on Figures 65, 66, and 67. However, looking at Figure 67, the generator might have reached its max operational capability at the 4 minute point, where the peak power output occurred and began to decrease after.

The 56 VDC charge cycle had different voltage rise characteristics due to the fact that the 56VDC supercapacitor has a 130 farad capacity vice the 500 farad capacity of the 16VDC supercapacitor. Due to this, it charged to higher voltages in a shorter amount of time. However, higher voltages in a lower farad rated supercapacitor allow more energy to be stored. Comparing the 16VDC supercapacitor to the 56VDC supercapacitor with Equation 3, it can be noted that the 56VDC supercapacitor stores 3.185 times more energy with less capacitance at its rated voltage [43].

$$E = \left(\frac{1}{2}\right) CV^2 \tag{3}$$

Other than reaching the voltage limit of the generator, which was corrected stepping up voltage with a transformer in turn lower the turbine speed, the power drive unit demonstrated reliable power delivery to the 56VDC supercapacitor. If the transformer bank step were implemented at the 35VDC point, safe operation of the generator could be assured.

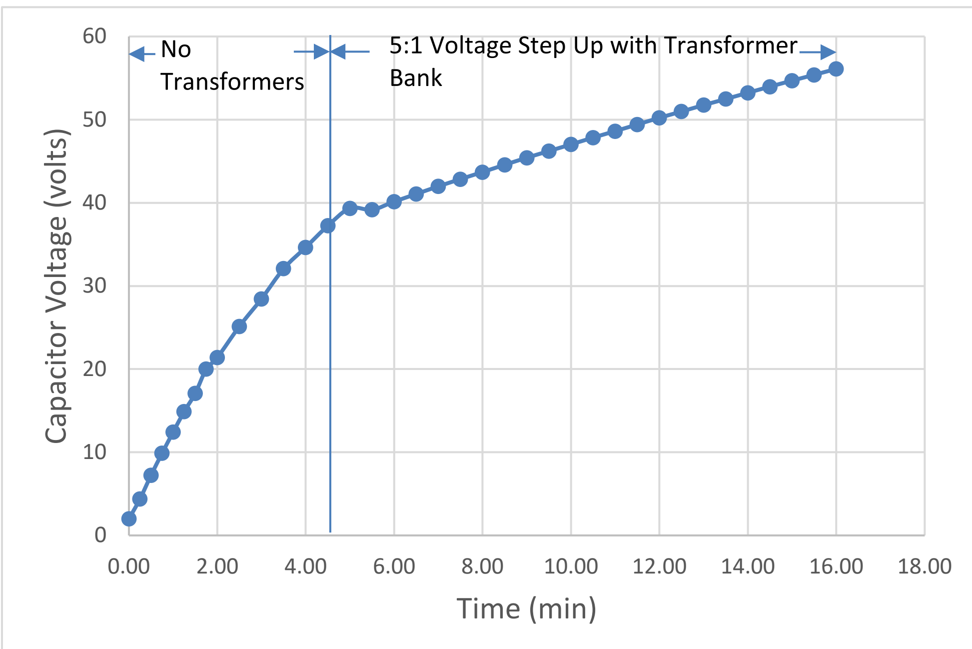


Figure 65. 56VDC Supercapacitor Voltage for Charge Cycle

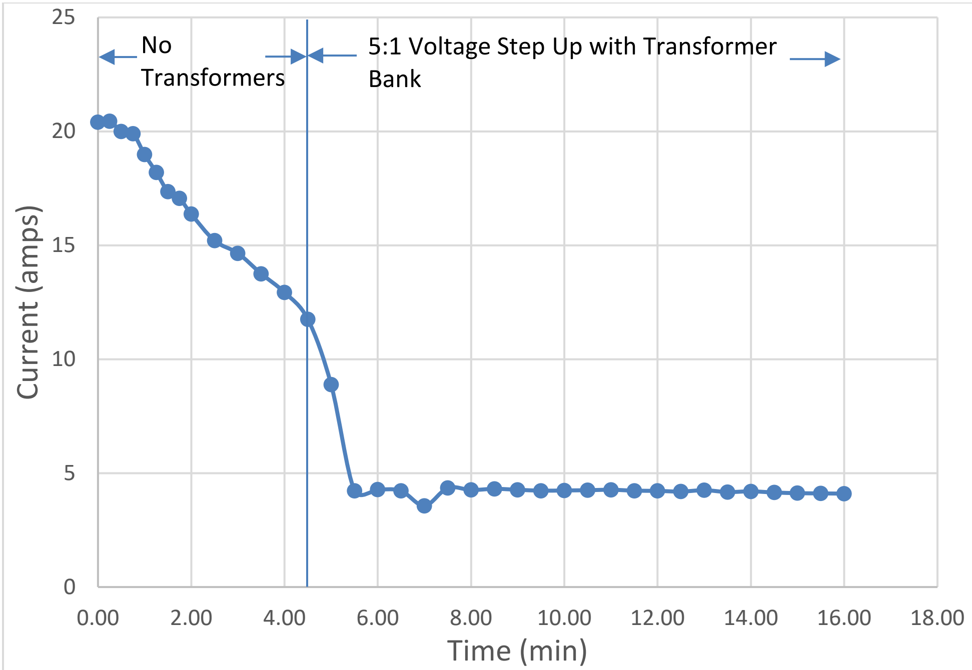


Figure 66. 56VDC Supercapacitor DC Current for Charge Cycle

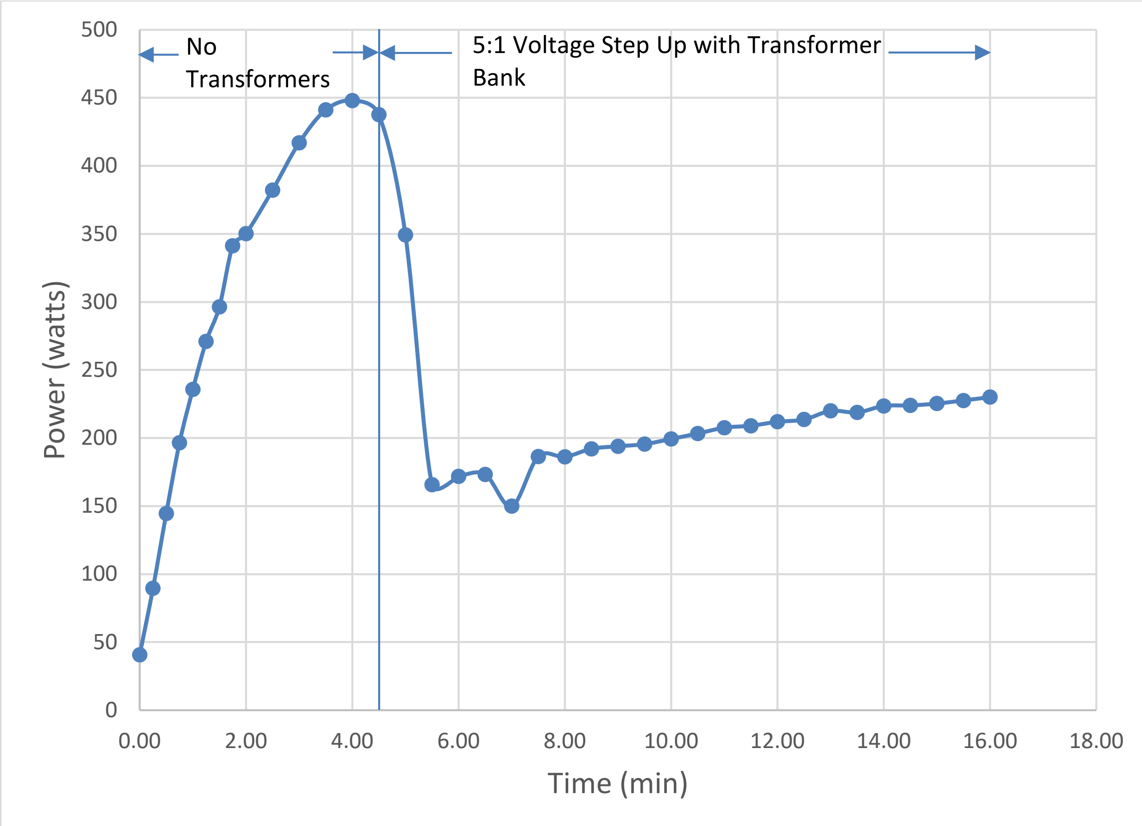


Figure 67. 56VDC Supercapacitor Power for Charge Cycle

Airflow was as a constant 90 SCFM for the 16VDC and 56VDC supercapacitor charging cycles. This measured airflow must be corrected for conditions different from the calibration setpoint using Equation 3 [42]. The RCM gage plate data for the new flow meter gives P_c as 791 kPa (100psig) and T_c as 26.7°C (80°F). Using Equation 3, actual pressure of 998 kPa (130psig), and environmental temperature of 20°C (68°F), K was calculated as 1.13588. This corrects measured airflow to 102.23 SCFM at 101 kPa (14.7psia) and 20°C (68°F). Using the density of air (1.1839kg/m^3) at 1 atm and 20°C, a final mass flow of 0.057119kg/s is obtained.

V. CONCLUSIONS

The benefits of CAES systems make it applicable for large, utility scale projects, and small, off grid applications. The goal of this work was to extract energy from compressed air and charge a 56VDC supercapacitor. Improvements to the airflow of a previous proof of concept, were made by incorporating supersonic fluid flow concepts and changing the automotive turbine design. Electrical generation and conversion elements were improved as well to enable reaching the 56VDC goal. Additional design selections were made to enable automation of the system through control of the supply air and changing the AC flow path through a transformer. CFD simulation showed great potential for thrust augmentation and demonstrated the potential for supplying high velocity air at atmospheric pressure to the turbine. Testing determined 16VDC, 500 farad supercapacitor could be charged in 6 minutes with a maximum power output of 293 watts. Testing also showed the 56VDC, 130 farad supercapacitor could be charged in 16 minutes with a max power output of 448 watts. During the 56VDC supercapacitor charge cycle, it was identified that the AC voltage had to be stepped up in a 5:1 ratio with a transformer because the generator was unable to safely charge past 35VDC without a transformer. Compressed airflow, measured during testing, was within 10% of the value calculated from the CFD simulation. The ability to charge high voltage supercapacitors with compressed air provides an inexpensive, capable solution to store energy in support of DoD energy security and resilience goals.

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VI. RECOMMENDATIONS

A. AC TO DC CONVERSION

It was evident that the full wave bridge rectifier operational limits due to the reverse-recovery time were exceeded as shown in Figure 61. Diodes can only switch modes of operation reliably at frequencies less than what this system is operated at. The inefficiency could be rectified by selection a power conversion module capable of operating over variable and high frequencies.

B. GENERATOR SELECTION

Although, the current generator was only capable of a theoretical output voltage of 44.50VDC, it reached an observed peak power output near 35VDC and by 37VDC had to be stopped due to sparks. To find and allow the turbine to operate at its most efficient speed, a generator with a higher speed rating must be identified and installed to increase the efficiency of the power drive unit.

C. TURBINE SELECTION

Larger turbines are able to more efficiently utilize a given airflow across the entire range of operation. The power drive unit used in this thesis was the smallest ball bearing turbine commercially available due to air supply constraints early in the design phase and since it was a proven design. The turbo machinery lab now has equipment capable of supplying adequate pressurized airflow to test larger turbines, and the design has been proven. By scaling up the power drive unit, larger power outputs will be realized.

D. VIBRATION ISOLATION

As the turbine reached higher speeds, vibration became an issue that had to be accounted for. The turbine and generator were rigidly mounted to a testbed, and caused a number of issues that had to be fixed prior to further testing. Once the turbine mounting bolts all vibrated loose. Lock washers corrected this. Higher RPM, caused the table the test bed was mounted on, to start moving around. Additionally, a wire from the generator vibrated to the point of mechanical failure. To correct these failures, the test bed was isolated from the table using rubber and dense foam, while the wires near the failure point were damped by wrapping in a large piece of foam. As higher speeds are reached in future design iterations, vibration isolation must become part of the design considerations.

E. MOTOR TO GENERATOR COUPLING

The original power drive unit used a Tygon tube as a coupling device. This was changed to nylon reinforced rubber tubing, which proved adequate for initial testing. Once airflow was adequate and larger power outputs accomplished, the upgraded coupling would not last for one charge cycle. A steel reinforced hydraulic line with the appropriate inside diameter was then used to accomplish all final testing with success. With further development and larger power outputs, the coupling mechanism must also be examined for improvements.

F. DYNAMIC TRANSFORMER OPERATION

The SSR's selected to perform the switching of the transformer bank were not capable of operating with the system due to protective internal circuitry. Other options should be explored if future design iterations require changing transformer modes of operation. The simplest option would be to use a solenoid operated contactor, which mechanically operates a switch to open or close the desired circuit.

G. TEST INSTRUMENTATION

Initial testing was accomplished using a data link to the oscilloscope, but during final testing, this interface had problems that could not be remedied with the manufacturer. Instead, manual data collection was used for the final testing, and human error was introduced into the data acquisition process. To gain the best fidelity in the future, this communication error between the oscilloscope and computer should be corrected.

The current readings DC charging current were read using a Fluke clamp on current instrument. The readings obtained were accurate enough to understand the magnitude of current flow, but not precise. Follow on testing would benefit from current measurements that can be acquired automatically.

H. CAPACITOR SIZING

Higher voltage capacitors store more energy, and thus should be used. This system safely reached 34.65VDC before the power curve started to decrease without the step up transformer. Assuming a safety margin of switching to a 5:1 step up at 30VDC, a 150VDC supercapacitor could currently be charge. The same transformer bank can also be reconfigured to step up 10:1. This would allow a 300VDC capacitor to be used. Future design work should strive to use the highest voltage supercapacitor that is compatible with the MEG it is installed in.

I. EXPLORE PISTON TYPE AIR EXPANSION MOTOR

Although the concepts used to develop the new power drive unit are simple, the system is complex. The ejector has to provide an optimized airflow to the turbine, the turbine has its own efficiency curves which vary based on RPM, the generator has operational limitations, and the power electronics required to reliably convert high frequency AC to DC must also be refined. One way to simplify all of the mentioned complexities would be to slow the system down. Ibrahim [12] explored theoretical efficiencies of using vane type air motors compared to piston type air motors. Although this system is not a vane type motor, piston type motors were found to be almost a constant 70% efficient across a large range of CAES pressures. Ibrahim decided to use “a piston type air motor …because it is the most mature, reliable, cheap, and allows full use of the polytropic expansion of compressed air “[12]. Piston type air motors would operate at a much lower frequency, which would simplify much of the design selection for the generator and power conversion elements.

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APPENDIX A. ANSYS CFX MODELING OF AIR EJECTOR

Date

2017/12/18 15:10:28

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Table 1 File Information for CFX
2. Mesh Report
Table 2 Mesh Information for CFX
3. Physics Report
Table 3 Domain Physics for CFX
Table 4 Boundary Physics for CFX
4. Solution Report
Table 5 Boundary Flows for CFX

1. File Report

Table 1. File Information for CFX

Case	CFX
File Path	C:\Users\nspellet\AppData\Local\Temp\5\Ejector Rev 1.tmp\Ejector Rev 1_files\dp0\CFX\CFX\Fluid Flow CFX_040.res
File Date	18 December 2017
File Time	02:53:24 PM
File Type	CFX5
File Version	17.2

2. Mesh Report

Table 2. Mesh Information for CFX

Domain	Nodes	Elements
Default Domain	146077	461913

3. Physics Report

Table 3. Domain Physics for CFX

Domain - Default Domain	
Type	Fluid
Location	B713
Materials	
Air Ideal Gas	
Fluid Definition	Material Library
Morphology	Continuous Fluid
Settings	
Buoyancy Model	Non Buoyant
Domain Motion	Stationary
Reference Pressure	1.0000e+00 [atm]
Heat Transfer Model	Total Energy
Include Viscous Work Term	On
Turbulence Model	k epsilon
Turbulent Wall Functions	Scalable
High Speed Model	On

Table 4. Boundary Physics for CFX

Domain	Boundaries	
Default Domain	Boundary - Inlet	
	Type	INLET
	Location	Air Supply
	Settings	
	Flow Direction	Normal to Boundary Condition
	Flow Regime	Subsonic
	Heat Transfer	Total Temperature

	Total Temperature	3.0000e+02 [K]
	Mass And Momentum	Total Pressure
	Relative Pressure	6.8900e+02 [kPa]
	Turbulence	High Intensity and Eddy Viscosity Ratio
	Boundary - Primary Ejection	
	Type	INLET
	Location	Primary Suction
	Settings	
	Flow Direction	Normal to Boundary Condition
	Flow Regime	Subsonic
	Heat Transfer	Total Temperature
	Total Temperature	3.0000e+02 [K]
	Mass And Momentum	Total Pressure
	Relative Pressure	0.0000e+00 [Pa]
	Turbulence	High Intensity and Eddy Viscosity Ratio
	Boundary - Thrust Augmentor	
	Type	INLET
	Location	Thrust Augmentor
	Settings	
	Flow Direction	Normal to Boundary Condition
	Flow Regime	Subsonic
	Heat Transfer	Total Temperature
	Total Temperature	3.0000e+02 [K]
	Mass And Momentum	Total Pressure
	Relative Pressure	0.0000e+00 [Pa]
	Turbulence	Medium Intensity and Eddy Viscosity Ratio

	Boundary - Outlet	
	Type	OPENING
	Location	Outlet
	Settings	
	Flow Direction	Normal to Boundary Condition
	Flow Regime	Subsonic
	Heat Transfer	Opening Temperature
	Opening Temperature	3.0000e+02 [K]
	Mass And Momentum	Opening Pressure and Direction
	Relative Pressure	0.0000e+00 [Pa]
	Turbulence	Medium Intensity and Eddy Viscosity Ratio
	Boundary - Default Domain Default	
	Type	WALL
	Location	F729.713, F730.713, F731.713, F732.713, F733.713, F734.713, F735.713, F736.713, F737.713, F739.713, F741.713, F743.713, F744.713, F745.713, F746.713, F747.713, F755.713, F756.713
	Settings	
	Heat Transfer	Adiabatic
	Mass And Momentum	No Slip Wall
	Wall Roughness	Smooth Wall

4. Solution Report

Table 5. Boundary Flows for CFX

Location	Type	Mass Flow	Momentum		
			X	Y	Z
Default Domain Default	Boundary	0.0000e+00	-1.2718e+02	-3.0411e-02	2.7658e-02
Inlet	Boundary	5.1217e-02	1.4800e+02	-1.6578e-05	9.2712e-06

Outlet	Boundary	-2.1080e-01	-2.0106e+01	3.0845e-02	-2.9160e-02
Primary Ejection	Boundary	5.0260e-03	-1.7204e-03	-3.4600e-04	1.4716e-03
Thrust Augmentor	Boundary	1.5457e-01	-7.0852e-01	-3.1238e-05	-3.9002e-05

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APPENDIX B. MODIFIED POWER DRIVE UNIT TEST DATA

NOTE: Discontinuous readings appear as blank entries.

Recorded Time (h:mm:ss)	Normalized Time (h:mm:ss)	Capacitor Voltage (VDC)
12:16:50	0:00:00	
12:16:51	0:00:01	
12:16:52	0:00:02	
12:16:53	0:00:03	
12:16:54	0:00:04	
12:16:55	0:00:05	0.170293
12:16:56	0:00:06	0.152981
12:16:57	0:00:07	
12:16:58	0:00:08	0.196712
12:16:59	0:00:09	
12:17:04	0:00:14	
12:17:04	0:00:14	
12:17:04	0:00:14	
12:17:04	0:00:14	
12:17:04	0:00:14	0.264346
12:17:05	0:00:15	0.278073
12:17:06	0:00:16	0.295218
12:17:07	0:00:17	
12:17:08	0:00:18	
12:17:09	0:00:19	
12:17:10	0:00:20	
12:17:14	0:00:24	
12:17:14	0:00:24	
12:17:14	0:00:24	
12:17:14	0:00:24	
12:17:15	0:00:25	0.410837
12:17:16	0:00:26	
12:17:17	0:00:27	
12:17:18	0:00:28	
12:17:19	0:00:29	0.467133
12:17:20	0:00:30	
12:17:21	0:00:31	0.488822
12:17:22	0:00:32	
12:17:23	0:00:33	
12:17:24	0:00:34	
12:17:25	0:00:35	
12:17:26	0:00:36	
12:17:27	0:00:37	
12:17:28	0:00:38	
12:17:29	0:00:39	0.592241
12:17:30	0:00:40	
12:17:31	0:00:41	
12:17:32	0:00:42	
12:17:33	0:00:43	
12:17:34	0:00:44	
12:17:35	0:00:45	
12:17:36	0:00:46	0.686634
12:17:37	0:00:47	0.697936
12:17:38	0:00:48	0.708432
12:17:39	0:00:49	0.731632
12:17:40	0:00:50	
12:17:41	0:00:51	0.743338
12:17:42	0:00:52	0.7615
12:17:43	0:00:53	0.769007
12:17:44	0:00:54	0.771564
12:17:45	0:00:55	0.772522
12:17:46	0:00:56	
12:17:47	0:00:57	
12:17:48	0:00:58	
12:17:49	0:00:59	
12:17:52	0:01:02	
12:17:52	0:01:02	
12:17:54	0:01:04	
12:17:54	0:01:04	
12:17:54	0:01:04	
12:17:55	0:01:05	
12:17:56	0:01:06	
12:17:57	0:01:07	
12:17:58	0:01:08	
12:17:59	0:01:09	
12:18:00	0:01:10	
12:18:01	0:01:11	
12:18:02	0:01:12	

12:18:03	0:01:13		12:18:46	0:01:56	
12:18:04	0:01:14		12:18:47	0:01:57	
12:18:05	0:01:15		12:18:48	0:01:58	
12:18:06	0:01:16		12:18:49	0:01:59	
12:18:07	0:01:17		12:18:50	0:02:00	
12:18:08	0:01:18		12:18:51	0:02:01	
12:18:09	0:01:19		12:18:52	0:02:02	
12:18:10	0:01:20		12:18:53	0:02:03	
12:18:11	0:01:21		12:18:54	0:02:04	
12:18:12	0:01:22		12:18:55	0:02:05	
12:18:13	0:01:23		12:18:56	0:02:06	
12:18:14	0:01:24		12:18:57	0:02:07	
12:18:15	0:01:25		12:18:58	0:02:08	
12:18:16	0:01:26		12:18:59	0:02:09	
12:18:17	0:01:27		12:19:00	0:02:10	
12:18:18	0:01:28		12:19:01	0:02:11	
12:18:19	0:01:29		12:19:02	0:02:12	
12:18:20	0:01:30		12:19:03	0:02:13	1.8556
12:18:21	0:01:31		12:19:04	0:02:14	
12:18:22	0:01:32		12:19:05	0:02:15	
12:18:23	0:01:33		12:19:06	0:02:16	
12:18:24	0:01:34		12:19:07	0:02:17	
12:18:25	0:01:35		12:19:08	0:02:18	
12:18:26	0:01:36		12:19:09	0:02:19	
12:18:27	0:01:37		12:19:10	0:02:20	
12:18:28	0:01:38		12:19:11	0:02:21	
12:18:29	0:01:39		12:19:12	0:02:22	
12:18:30	0:01:40		12:19:13	0:02:23	
12:18:31	0:01:41		12:19:14	0:02:24	
12:18:32	0:01:42		12:19:15	0:02:25	
12:18:33	0:01:43		12:19:16	0:02:26	
12:18:34	0:01:44		12:19:17	0:02:27	
12:18:35	0:01:45		12:19:18	0:02:28	
12:18:36	0:01:46		12:19:19	0:02:29	
12:18:37	0:01:47		12:19:20	0:02:30	
12:18:38	0:01:48		12:19:21	0:02:31	
12:18:39	0:01:49		12:19:22	0:02:32	
12:18:40	0:01:50		12:19:23	0:02:33	
12:18:41	0:01:51		12:19:24	0:02:34	
12:18:42	0:01:52		12:19:25	0:02:35	
12:18:43	0:01:53		12:19:26	0:02:36	
12:18:44	0:01:54		12:19:27	0:02:37	
12:18:45	0:01:55		12:19:28	0:02:38	

12:19:29	0:02:39	
12:19:30	0:02:40	
12:19:31	0:02:41	
12:19:32	0:02:42	
12:19:33	0:02:43	
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12:43:03	0:26:13	13.8775
12:43:04	0:26:14	13.8757
12:43:05	0:26:15	13.876
12:43:06	0:26:16	13.8867
12:43:07	0:26:17	13.898

12:43:08	0:26:18	13.8994
12:43:09	0:26:19	13.9049
12:43:10	0:26:20	13.9098
12:43:11	0:26:21	13.9244
12:43:12	0:26:22	13.9314
12:43:13	0:26:23	13.9307
12:43:14	0:26:24	13.9408
12:43:15	0:26:25	13.9367
12:43:16	0:26:26	13.9451
12:43:17	0:26:27	13.9471
12:43:18	0:26:28	13.9564
12:43:19	0:26:29	13.9607
12:43:20	0:26:30	13.9683
12:43:21	0:26:31	13.969
12:43:22	0:26:32	13.9777
12:43:23	0:26:33	13.9847
12:43:24	0:26:34	13.9925
12:43:25	0:26:35	13.9901
12:43:26	0:26:36	14.0025
12:43:27	0:26:37	14.0096
12:43:28	0:26:38	14.022
12:43:29	0:26:39	14.0284
12:43:30	0:26:40	14.0223
12:43:31	0:26:41	14.0395
12:43:32	0:26:42	14.0373
12:43:33	0:26:43	14.0386
12:43:34	0:26:44	14.0491
12:43:35	0:26:45	14.0534
12:43:36	0:26:46	14.0568
12:43:37	0:26:47	14.0614
12:43:38	0:26:48	14.0635
12:43:39	0:26:49	14.0831
12:43:40	0:26:50	14.0824
12:43:41	0:26:51	14.0959
12:43:42	0:26:52	14.0989
12:43:43	0:26:53	14.1072
12:43:44	0:26:54	14.1123
12:43:45	0:26:55	14.1042
12:43:46	0:26:56	14.1134
12:43:47	0:26:57	14.1239
12:43:48	0:26:58	14.1277
12:43:49	0:26:59	14.1306
12:43:50	0:27:00	14.1403

12:43:51	0:27:01	14.1488	12:44:34	0:27:44	14.3798
12:43:52	0:27:02	14.148	12:44:35	0:27:45	14.3873
12:43:53	0:27:03	14.1621	12:44:36	0:27:46	14.3935
12:43:54	0:27:04	14.154	12:44:37	0:27:47	14.4009
12:43:55	0:27:05	14.1673	12:44:38	0:27:48	14.4009
12:43:56	0:27:06	14.1703	12:44:39	0:27:49	14.4198
12:43:57	0:27:07	14.1841	12:44:40	0:27:50	14.4172
12:43:58	0:27:08	14.1822	12:44:41	0:27:51	14.4202
12:43:59	0:27:09	14.1842	12:44:42	0:27:52	14.4351
12:44:00	0:27:10	14.1919	12:44:43	0:27:53	14.4301
12:44:01	0:27:11	14.1933	12:44:44	0:27:54	14.4352
12:44:02	0:27:12	14.1984	12:44:45	0:27:55	14.4421
12:44:03	0:27:13	14.2197	12:44:46	0:27:56	14.4472
12:44:04	0:27:14	14.2144	12:44:47	0:27:57	14.4522
12:44:05	0:27:15	14.2212	12:44:48	0:27:58	14.4698
12:44:06	0:27:16	14.2266	12:44:49	0:27:59	14.4686
12:44:07	0:27:17	14.2359	12:44:50	0:28:00	14.4683
12:44:08	0:27:18	14.2391	12:44:51	0:28:01	14.4695
12:44:09	0:27:19	14.2546	12:44:52	0:28:02	14.4787
12:44:10	0:27:20	14.2465	12:44:53	0:28:03	14.4844
12:44:11	0:27:21	14.2559	12:44:54	0:28:04	14.491
12:44:12	0:27:22	14.2698	12:44:55	0:28:05	14.4981
12:44:13	0:27:23	14.2677	12:44:56	0:28:06	14.5128
12:44:14	0:27:24	14.2738	12:44:57	0:28:07	14.5078
12:44:15	0:27:25	14.2781	12:44:58	0:28:08	14.5127
12:44:16	0:27:26	14.2788	12:44:59	0:28:09	14.5228
12:44:17	0:27:27	14.2899	12:45:00	0:28:10	14.5202
12:44:18	0:27:28	14.2983	12:45:01	0:28:11	14.5374
12:44:19	0:27:29	14.2989	12:45:02	0:28:12	14.5419
12:44:20	0:27:30	14.3063	12:45:03	0:28:13	14.5429
12:44:21	0:27:31	14.3083	12:45:04	0:28:14	14.5439
12:44:22	0:27:32	14.3162	12:45:05	0:28:15	14.5556
12:44:23	0:27:33	14.3214	12:45:06	0:28:16	14.5522
12:44:24	0:27:34	14.329	12:45:07	0:28:17	14.5575
12:44:25	0:27:35	14.3378	12:45:08	0:28:18	14.5672
12:44:26	0:27:36	14.3417	12:45:09	0:28:19	14.569
12:44:27	0:27:37	14.3452	12:45:10	0:28:20	14.5726
12:44:28	0:27:38	14.3483	12:45:11	0:28:21	14.5863
12:44:29	0:27:39	14.3634	12:45:12	0:28:22	14.5889
12:44:30	0:27:40	14.36	12:45:13	0:28:23	14.6042
12:44:31	0:27:41	14.3739	12:45:14	0:28:24	14.6034
12:44:32	0:27:42	14.3727	12:45:15	0:28:25	14.6063
12:44:33	0:27:43	14.3758	12:45:16	0:28:26	14.6159

12:45:17	0:28:27	14.625	12:46:00	0:29:10	14.8265
12:45:18	0:28:28	14.6166	12:46:01	0:29:11	14.8284
12:45:19	0:28:29	14.6375	12:46:02	0:29:12	14.8331
12:45:20	0:28:30	14.6344	12:46:03	0:29:13	14.8408
12:45:21	0:28:31	14.6406	12:46:04	0:29:14	14.8462
12:45:22	0:28:32	14.6456	12:46:05	0:29:15	14.8505
12:45:23	0:28:33	14.6474	12:46:06	0:29:16	14.8587
12:45:24	0:28:34	14.664	12:46:07	0:29:17	14.8653
12:45:25	0:28:35	14.6638	12:46:08	0:29:18	14.8641
12:45:26	0:28:36	14.666	12:46:09	0:29:19	14.8747
12:45:27	0:28:37	14.6758	12:46:10	0:29:20	14.8693
12:45:28	0:28:38	14.68	12:46:11	0:29:21	14.8828
12:45:29	0:28:39	14.6924	12:46:12	0:29:22	14.8833
12:45:30	0:28:40	14.687	12:46:13	0:29:23	14.8871
12:45:31	0:28:41	14.6943	12:46:14	0:29:24	14.8974
12:45:32	0:28:42	14.6961	12:46:15	0:29:25	14.8933
12:45:33	0:28:43	14.7082	12:46:16	0:29:26	14.9076
12:45:34	0:28:44	14.7034	12:46:17	0:29:27	14.9004
12:45:35	0:28:45	14.719	12:46:18	0:29:28	14.9059
12:45:36	0:28:46	14.7118	12:46:19	0:29:29	14.9226
12:45:37	0:28:47	14.7189	12:46:20	0:29:30	14.9248
12:45:38	0:28:48	14.7267	12:46:21	0:29:31	14.9205
12:45:39	0:28:49	14.7283	12:46:22	0:29:32	14.9363
12:45:40	0:28:50	14.7435	12:46:23	0:29:33	14.9259
12:45:41	0:28:51	14.7415	12:46:24	0:29:34	14.9454
12:45:42	0:28:52	14.753	12:46:25	0:29:35	14.9432
12:45:43	0:28:53	14.7521	12:46:26	0:29:36	14.9468
12:45:44	0:28:54	14.7468	12:46:27	0:29:37	14.9495
12:45:45	0:28:55	14.7608	12:46:28	0:29:38	14.9556
12:45:46	0:28:56	14.7616	12:46:29	0:29:39	14.9597
12:45:47	0:28:57	14.7767	12:46:30	0:29:40	14.9618
12:45:48	0:28:58	14.7789	12:46:31	0:29:41	14.9637
12:45:49	0:28:59	14.7858	12:46:32	0:29:42	14.9815
12:45:50	0:29:00	14.7812	12:46:33	0:29:43	14.9797
12:45:51	0:29:01	14.7828	12:46:34	0:29:44	14.9825
12:45:52	0:29:02	14.7996	12:46:35	0:29:45	14.9923
12:45:53	0:29:03	14.7879	12:46:36	0:29:46	14.9976
12:45:54	0:29:04	14.7977	12:46:37	0:29:47	15.002
12:45:55	0:29:05	14.7969	12:46:38	0:29:48	15.0008
12:45:56	0:29:06		12:46:39	0:29:49	15.0045
12:45:57	0:29:07	14.8146	12:46:40	0:29:50	15.0147
12:45:58	0:29:08	14.8132	12:46:41	0:29:51	15.0178
12:45:59	0:29:09	14.8223	12:46:42	0:29:52	15.0309

12:46:43	0:29:53	
12:46:44	0:29:54	15.0317
12:46:45	0:29:55	15.0419
12:46:46	0:29:56	15.0508
12:46:47	0:29:57	15.054
12:46:48	0:29:58	15.0589
12:46:49	0:29:59	15.0596
12:46:50	0:30:00	15.0679
12:46:51	0:30:01	15.0732
12:46:52	0:30:02	15.077
12:46:53	0:30:03	15.0884
12:46:54	0:30:04	15.0848
12:46:55	0:30:05	
12:46:56	0:30:06	15.1058
12:46:57	0:30:07	15.0969
12:46:58	0:30:08	15.1066
12:46:59	0:30:09	15.1072
12:47:00	0:30:10	15.1119
12:47:01	0:30:11	15.1172
12:47:02	0:30:12	15.1283
12:47:03	0:30:13	15.1293
12:47:04	0:30:14	15.1343
12:47:05	0:30:15	15.1401
12:47:06	0:30:16	15.1525
12:47:07	0:30:17	15.1569
12:47:08	0:30:18	15.152
12:47:09	0:30:19	15.1538
12:47:10	0:30:20	15.1593
12:47:11	0:30:21	15.1724
12:47:12	0:30:22	15.1762
12:47:13	0:30:23	15.1832
12:47:14	0:30:24	15.188
12:47:15	0:30:25	15.1903
12:47:16	0:30:26	15.1914
12:47:17	0:30:27	15.1968
12:47:18	0:30:28	15.2131
12:47:19	0:30:29	15.2096
12:47:20	0:30:30	15.2183
12:47:21	0:30:31	15.2126
12:47:22	0:30:32	15.223
12:47:23	0:30:33	15.2384
12:47:24	0:30:34	15.2306
12:47:25	0:30:35	15.2362

12:47:26	0:30:36	15.2389
12:47:27	0:30:37	15.2471
12:47:28	0:30:38	15.2629
12:47:29	0:30:39	15.2567
12:47:30	0:30:40	15.2704
12:47:31	0:30:41	15.2676
12:47:32	0:30:42	15.2691
12:47:33	0:30:43	15.283
12:47:34	0:30:44	15.292
12:47:35	0:30:45	15.2882
12:47:36	0:30:46	15.2907
12:47:37	0:30:47	15.3032
12:47:38	0:30:48	15.3135
12:47:39	0:30:49	15.3104
12:47:40	0:30:50	15.3158
12:47:41	0:30:51	15.3211
12:47:42	0:30:52	15.3214
12:47:43	0:30:53	15.3232
12:47:44	0:30:54	15.3397
12:47:45	0:30:55	15.3422
12:47:46	0:30:56	15.3498
12:47:47	0:30:57	15.3355
12:47:48	0:30:58	15.346
12:47:49	0:30:59	15.3538
12:47:50	0:31:00	15.3674
12:47:51	0:31:01	15.3707
12:47:52	0:31:02	15.3754
12:47:53	0:31:03	15.3808
12:47:54	0:31:04	15.3871
12:47:55	0:31:05	15.3914
12:47:56	0:31:06	15.3842
12:47:57	0:31:07	15.3943
12:47:58	0:31:08	15.4038
12:47:59	0:31:09	15.4087
12:48:00	0:31:10	15.4052
12:48:01	0:31:11	15.4135
12:48:02	0:31:12	15.4179
12:48:03	0:31:13	15.4317
12:48:04	0:31:14	15.4258
12:48:05	0:31:15	15.4307
12:48:06	0:31:16	15.4333
12:48:07	0:31:17	15.4338
12:48:09	0:31:19	15.4338

12:48:10	0:31:19	15.4338
12:48:10	0:31:20	15.4513
12:48:13	0:31:22	15.4513
12:48:13	0:31:22	15.4513
12:48:13	0:31:23	15.4696
12:48:16	0:31:25	15.4696
12:48:16	0:31:25	15.4696
12:48:16	0:31:26	15.4823
12:48:18	0:31:28	15.4823
12:48:18	0:31:28	15.4823
12:48:19	0:31:29	15.4972
12:48:21	0:31:31	15.4972
12:48:21	0:31:31	15.4972
12:48:22	0:31:32	15.5172
12:48:24	0:31:34	15.5172
12:48:24	0:31:34	15.5172
12:48:25	0:31:35	15.5261

12:48:29	0:31:39	15.5261
12:48:29	0:31:39	15.5261
12:48:29	0:31:39	15.5261
12:48:29	0:31:39	15.5261
12:48:30	0:31:40	15.5515
12:48:31	0:31:41	15.5559
12:48:32	0:31:42	15.5648
12:48:33	0:31:43	15.5639
12:48:34	0:31:44	15.5677
12:48:35	0:31:45	15.568
12:48:36	0:31:46	15.5746
12:48:37	0:31:47	15.5923
12:48:38	0:31:48	15.5871
12:48:39	0:31:49	15.5968
12:48:40	0:31:50	15.5901
12:48:41	0:31:51	15.6009
12:48:42	0:31:52	15.6074

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APPENDIX C. NEW POWER DRIVE UNIT INITIAL TEST DATA

NOTE: Discontinuous readings appear as blank entries.

Recorded Time (h:mm:ss)	Normalized Time (h:mm:ss)	Capacitor Voltage (VDC)
13:59:48	0:00:00	
13:59:49	0:00:01	
13:59:50	0:00:02	0.546905
13:59:51	0:00:03	0.66819
13:59:52	0:00:04	0.702486
13:59:53	0:00:05	0.73224
13:59:54	0:00:06	
13:59:55	0:00:07	
13:59:56	0:00:08	0.826348
13:59:57	0:00:09	0.832438
13:59:58	0:00:10	0.868167
13:59:59	0:00:11	0.909986
14:00:02	0:00:14	
14:00:02	0:00:14	0.909986
14:00:02	0:00:14	0.909986
14:00:04	0:00:16	
14:00:04	0:00:16	
14:00:05	0:00:17	
14:00:06	0:00:18	
14:00:07	0:00:19	
14:00:08	0:00:20	
14:00:09	0:00:21	
14:00:10	0:00:22	
14:00:11	0:00:23	
14:00:12	0:00:24	
14:00:13	0:00:25	
14:00:14	0:00:26	
14:00:15	0:00:27	1.37016
14:00:16	0:00:28	1.37955
14:00:17	0:00:29	
14:00:18	0:00:30	
14:00:19	0:00:31	
14:00:22	0:00:34	
14:00:22	0:00:34	
14:00:22	0:00:34	
14:00:23	0:00:35	1.46417
14:00:24	0:00:36	1.49032
14:00:25	0:00:37	1.50818
14:00:26	0:00:38	1.53665
14:00:27	0:00:39	1.55919
14:00:28	0:00:40	1.58386
14:00:29	0:00:41	1.60275
14:00:30	0:00:42	1.63135
14:00:31	0:00:43	1.64714
14:00:32	0:00:44	1.67485
14:00:33	0:00:45	1.69706
14:00:34	0:00:46	1.72367
14:00:35	0:00:47	1.74735
14:00:36	0:00:48	1.76711
14:00:37	0:00:49	1.79565
14:00:38	0:00:50	1.81367
14:00:39	0:00:51	1.83706
14:00:40	0:00:52	1.86384
14:00:41	0:00:53	1.87739
14:00:42	0:00:54	1.9038
14:00:43	0:00:55	1.9206
14:00:44	0:00:56	1.94383
14:00:45	0:00:57	1.97004
14:00:46	0:00:58	1.98996
14:00:47	0:00:59	2.01168
14:00:48	0:01:00	2.0331
14:00:49	0:01:01	2.05303
14:00:50	0:01:02	2.07454
14:00:51	0:01:03	2.09315
14:00:52	0:01:04	2.11852
14:00:53	0:01:05	2.13803

14:00:54	0:01:06	2.16397
14:00:55	0:01:07	2.17906
14:00:56	0:01:08	2.1954
14:00:57	0:01:09	2.21696
14:00:58	0:01:10	2.23763
14:00:59	0:01:11	2.25587
14:01:00	0:01:12	2.282
14:01:01	0:01:13	2.29474
14:01:02	0:01:14	2.32273
14:01:03	0:01:15	2.34278
14:01:04	0:01:16	2.35517
14:01:05	0:01:17	2.37466
14:01:06	0:01:18	2.39385
14:01:07	0:01:19	2.41531
14:01:08	0:01:20	2.42655
14:01:09	0:01:21	2.45607
14:01:10	0:01:22	2.47988
14:01:11	0:01:23	2.5046
14:01:12	0:01:24	2.51613
14:01:13	0:01:25	2.53649
14:01:14	0:01:26	2.55434
14:01:15	0:01:27	2.57988
14:01:16	0:01:28	2.59777
14:01:17	0:01:29	2.60897
14:01:18	0:01:30	2.63181
14:01:19	0:01:31	2.65548
14:01:20	0:01:32	2.66831
14:01:21	0:01:33	2.68386
14:01:22	0:01:34	2.70327
14:01:23	0:01:35	2.72485
14:01:24	0:01:36	2.7486
14:01:25	0:01:37	2.75762
14:01:26	0:01:38	2.78107
14:01:27	0:01:39	2.79272
14:01:28	0:01:40	2.81712
14:01:29	0:01:41	2.83284
14:01:30	0:01:42	2.84886
14:01:31	0:01:43	2.8656

14:01:32	0:01:44	2.89209
14:01:33	0:01:45	2.9006
14:01:34	0:01:46	2.92048
14:01:35	0:01:47	2.93845
14:01:36	0:01:48	2.9569
14:01:37	0:01:49	2.96681
14:01:38	0:01:50	2.98847
14:01:39	0:01:51	3.00657
14:01:40	0:01:52	3.02443
14:01:41	0:01:53	3.04051
14:01:42	0:01:54	3.05392
14:01:43	0:01:55	3.07187
14:01:44	0:01:56	3.09215
14:01:45	0:01:57	3.10727
14:01:46	0:01:58	3.1312
14:01:47	0:01:59	3.14272
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14:46:51	0:36:29	15.4412
14:46:52	0:36:30	15.4432
14:46:53	0:36:31	15.445

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APPENDIX D. FINAL TEST 16VDC CAPACITOR CHARGE DATA

Time (min)	Capacitor Voltage (VDC)	DC Current (A)	Power (W)
0.00	1.63	21.03	34.2789
0.25	2.18	21.01	45.8018
0.50	3.01	21	63.21
0.75	3.88	21.13	81.9844
1.00	4.53	20.8	94.224
1.25	5.28	20.33	107.3424
1.50	5.91	20.18	119.2638
1.75	6.59	20.21	133.1839
2.00	7.28	20.24	147.3472
2.50	8.53	19.73	168.2969
3.00	9.73	19.7	191.681
3.50	10.88	19.34	210.4192
4.00	11.98	19.38	232.1724
4.50	13.03	18.84	245.4852
5.00	14.05	18.57	260.9085
5.50	15.01	18.34	275.2834
6.00	15.97	18.33	292.7301

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APPENDIX E. FINAL TEST 56VDC CAPACITOR CHARGE DATA

Time (min)	DC Capacitor Voltage (VDC)	DC Current (A)	Power (W)
0.00	1.99	20.4	40.596
0.25	4.38	20.45	89.571
0.50	7.23	20	144.6
0.75	9.88	19.9	196.612
1.00	12.42	18.98	235.7316
1.25	14.89	18.2	270.998
1.50	17.08	17.36	296.5088
1.75	20	17.06	341.2
2.00	21.39	16.37	350.1543
2.50	25.15	15.2	382.28
3.00	28.46	14.65	416.939
3.50	32.08	13.75	441.1
4.00	34.65	12.93	448.0245
4.50	37.24	11.75	437.57
5.00	39.34	8.88	349.3392
5.50	39.17	4.23	165.6891
6.00	40.14	4.28	171.7992
6.50	41.06	4.22	173.2732
7.00	41.98	3.57	149.8686
7.50	42.85	4.35	186.3975
8.00	43.7	4.26	186.162
8.50	44.57	4.31	192.0967
9.00	45.42	4.27	193.9434
9.50	46.22	4.23	195.5106
10.00	47.02	4.24	199.3648
10.50	47.84	4.25	203.32
11.00	48.62	4.27	207.6074
11.50	49.42	4.23	209.0466
12.00	50.22	4.22	211.9284
12.50	50.98	4.19	213.6062
13.00	51.75	4.25	219.9375
13.50	52.48	4.17	218.8416
14.00	53.23	4.2	223.566
14.50	53.97	4.15	223.9755
15.00	54.69	4.12	225.3228
15.50	55.39	4.11	227.6529
16.00	56.1	4.1	230.01

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