Heuristic Approach to Designing a Unique Ships Grid with Energy Storage for the Future Fleet of River Tender Ships

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(ABSTRACT)

This work discusses the implementation of a Unique Ships Grid design that utilizes Energy Storage. This Unique Ships Grid is used to enhance the efficiency of a Construction Single-Hull River Tender previously discussed and assessed by the Army Corps of Engineers and the United States Coast Guard (USCG). This Grid Design is shown to be both in compliance with applicable regulations and reliable due to built-in redundancy. Compliance with regulations and redundancy are both prized by the Maritime Community and the USCG. An applicable Heuristic Design Methodology is provided in conjunction with the Unique Ships Grid. This Design Methodology can be used with a simple load analysis and results in a Load Center breakdown and the sizing of Cables, Generators, Inverter, and required Energy Storage. This design process is shown to provide an inherent margin for growth and safety. This design process is quick and results in values necessary to do a cost analysis, environmental impact survey, and stability analysis (Ship Stability not Electrical Stability).

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GENERAL AUDIENCE ABSTRACT

This work discusses a unique way to power the electric equipment onboard a small ship by using lithium-ion batteries or another safe form of energy storage. The goal of this shipboard power system is to reduce emissions and wear and tear on a small ship. This work demonstrates that the shipboard power system adheres to U.S. Code and is reliable due to inherent redundancy. Reliability and adherence to U.S. Code are necessary for a system to be adopted for maritime applications. The power system is implemented at the level of the controls system and partially relies on conventional methods, such as diesel generators, for powering shipboard electric equipment. This partial reliance on conventional methods for ships power provides for an easy way for industry to transition to more renewable sources of energy. Additionally, this power system is provided with guidance on how to design and customize the system for many applications. The guidance provided on the design methodology is simple, can be easily implemented, and is shown to provide estimates for the power system that provide for reliability and redundancy. The design methodology can be implemented very early in the construction of a ship and provides valuable information needed when building this unique power system.

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Chapter 1 – Review of Ships, Their Power Systems, and Applicable Regulations

1-1 General Information on Ships and the Maritime and Shipbuilding Industries

The electrical engineering (EE) community prides itself on being at the forefront of technological advancement, for good reason. The EE community and, specifically, the Power Systems community have been the recipients of a great number of advancements within communications, computing, and steady state electronic devices. This willingness to be on the bleeding edge stands in contrast to the collective personality of the maritime community. Within the maritime community, safety and reliability take a front seat to efficiency and novelty. This is especially true of the military seagoing services.

On-the-ocean accidents can have enormous consequences. Most Americans can easily recall the Exxon Valdez or Deepwater Horizon disaster oil spills, yet the American public is not nearly as concerned about the level of technology that oil tankers contain. With the dire consequences of mishaps, the shipbuilding and operating communities focus resources on technologies that result in reliability and redundancy. It is with this reliability and redundancy context that the solutions proposed in this thesis must be weighed.

1-2 Ships Power Systems

In general there are four different types of ship drives. *Mechanical-drive ship* refers to a setup where a prime mover is mechanically coupled to the propellers of the ship. This is a conventional setup for ships, resulting in the generation capacity onboard going towards providing for a ship's service loads. *Electrical-drive ships* are ships that have dedicated generators for propulsion and generators dedicated to ship's service loads. *Integrated-drive ships* have a single power grid and generators that are not differentiated between the ship's service and propulsion loads [1]. This type of ship is becoming more prevalent within naval forces. Older ships in the U.S. Coast Guard (USCG) are mechanically-driven, but recently electrical and integrated-drive setups are becoming more prevalent.

When a ship's power grid and generators are being designed and considered, numerous tasks must be undertaken: the power system configuration and voltage level must be selected for; a load analysis must be completed; sizing of the power cables must be completed in order to reduce voltage drops; and a fault current analysis must be completed [1].

For the purposes of this thesis, a load analysis will be the most important of the design tasks. The generator rating, determined by this load analysis, depends on an assessment of the peak power and load timing. Load factors of different load categories for different steaming conditions must be determined. *Load factor (LF)* is defined as the following:

$$Load\ factor = \frac{kWh\ used\ during\ \boldsymbol{T}}{Rated\ kW\ \times \boldsymbol{T}\ in\ hours} = \frac{\int_0^T p(t)dt}{Rated\ kW\ \times \boldsymbol{T}\ in\ hours} \qquad (1)$$

LF is also known as the diversity factor. Based on Equation 1, an LF would be equal to one when a load is continuously demanding rated power, and an LF would be equal to zero for a load that will remain offline for the time in question. Usually, an LF will be somewhere between zero and one. LF can be determined for specific situations (i.e. in-port or maneuvering) and for different periods of time (i.e. daytime, meals, or nighttime).

One of the most crucial tasks to complete when doing a load analysis is drafting up and analyzing the *Load Table Compilation* [1]. This requires a table of all connected loads that gives a kilowatt (KW) value for all connected loads of specific types, such as propulsion machinery, auxiliary machinery, cargo equipment, deck machinery, shop loads, electronics, communications, hotel loads, and HVAC equipment.

A ship has numerous operating modes that all produce differing demands on the system. The typical operating modes are in-port loading, maneuvering, cruising at sea, in-port unloading, anchor, and emergency operation [1]. Each of these conditions will result in different LFs for the groupings of equipment listed in the previous paragraph. This information is organized in the Load Analysis Table for Ships shown below.

Table 1.1: Example of Load Analysis

		Towing		**Construction**		**Standby**	
	Total	**Winter**		**Winter**		**Winter**	
Load Group	**KW**	**D.F.**	**KW**	**D.F.**	**KW**	**D.F.**	**KW**
Propulsion							
Auxiliary							
Construction Equipment							
Deck Equipment							
Electronics and Navigation							
Hotel Loads							
HVAC							
	Sum(Nameplate Loads) = Power of Total Rated Loads		Sum(Nameplate Loads x Diversity Factors) = Typical Loading for Winter Towing		Sum(Nameplate Loads x Diversity Factors) = Typical Loading for Winter Construction		Sum(Nameplate Loads x Diversity Factors) = Typical Loading for Winter Standby

The bottom of **Table 1.1** shows a row in which the typical loading of the grid is given in aggregate for the different operation conditions. The generation capacity is then determined from Equation 2. This generation capacity is equivalent to the worst loading condition in the most demanding operating condition.

$$P_{gen} = \text{Maximum of } \{P_{construction\ winter}, P_{construction\ summer}, P_{standby} \cdots\} \quad (2)$$

From the required generating power, the kVA rating and the HP rating of the prime movers can be determined from Equation 3.

$$Power\ Rating\ of\ Generator\ (kVA) = \frac{P_{gen}(kW)}{Generator\ pf} \quad (3)$$

$$Generator\ Prime\ Mover\ Rating\ (HP) = \frac{P_{gen}(kW)}{.746 \times Generator\ Efficiency} \quad (4)$$

The Generator kVA rating and Prime mover HP rating will be provided some margin for future growth in load and for safety/security [1].

The power system configuration on a ship is in some ways similar to a small land-based distribution system. Key differences are present, however. These key differences are that many ships still have 450- V as the highest voltage on the grid. Onboard Ship's Grids, Motor Generators (MG) sets are still common because they represent a reliable way to convert to 400Hz power without too much distortion from harmonics. It is also typical for the distribution system to have parts where power is converted to 24VDC to power DC loads through the use of chargers and batteries. The use of radial distribution networks on ships is becoming less common. However, a noted exception to this is radial architecture, used on military ships to provide a degree of redundancy.

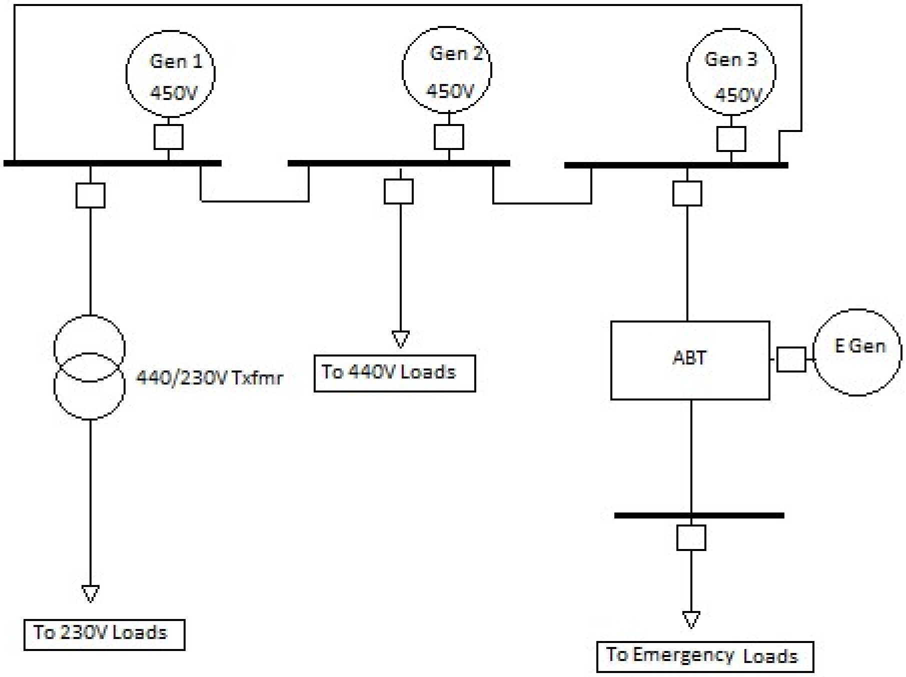


Figure 1.1 Example of Standard LV Ships Distribution Layout

Figure 1.1 above shows a low voltage ships grid that relies on more standard radial architecture with an emergency generator for backup. In order to improve redundancy some ships grids increasingly use redundant radial architecture, as shown in **Figure 1.2.**

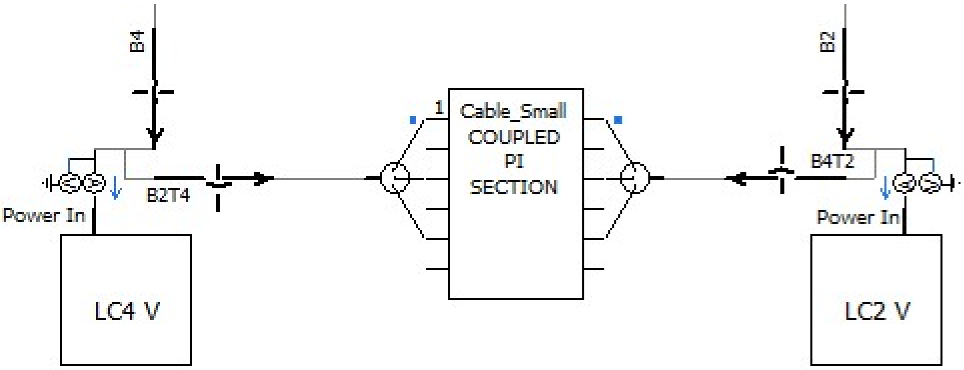


Figure 1.2 Improving Redundancy of Radial Architecture by Multiple Paths for Power Flow

1-3 Grounding

Another unique difference between terrestrial and afloat grids is in the grounding of the system. Although it is not explicitly forbidden, shipbuilding standards recommend an ungrounded distribution system for increased reliability. The exception to this is Naval ships, which typically require ungrounded systems [1].

There are three main options when installing the neutral line on a ship: the neutral can be solidly grounded; the neutral can be grounded through a resistance or reactance, in order to control the ground fault current; or the neutral can be left ungrounded [1].

The advantage of the ungrounded neutral is that the power system requires faults from two different phases before experiencing a large fault current. This gives the engineers a period of time to clear the fault without suffering damage to the equipment or personnel. Having an ungrounded neutral also reduces the harmonic and zero sequence currents that the neutral can experience [1]. This is beneficial to low frequency electronics measuring equipment.

1-4 N – 1 Criterion

Ship's service loads are defined as electrical equipment for all auxiliary services necessary for maintaining the vessel in a normal, operational, and habitable condition [2]. *Ship's service loads* include all safety lighting, ventilation, navigational communications, habitability, and propulsion auxiliary loads. *Essential services* are defined as those services considered necessary to maintain propulsion and steering and a minimum level of safety for the vessel's navigation and systems including safety for dangerous cargoes to be carried and emergency services [3]. Examples of essential Services include steering gears, ventilation necessary for propulsion, lubricating oil plants, and a number of other electrical loads that, when lost, would result in a loss of propulsion, steering, safety or navigation capability [3]. *Minimum Comfortable Condition of Habitability* is a condition where, at a minimum, services such as cooking, heating, domestic refrigeration, mechanical ventilation, sanitary and fresh water are adequately provided.

The minimum number of generating sources is two for all applicable vessels. The aggregate capacity of the aforementioned generating sources must be sufficient to supply power to the ship's service loads. The N – 1 criterion is described in both [2] and [3]. "With the ship's service generating source of the largest capacity stopped, the combined capacity of the remaining electric ship's service generating source or sources must be sufficient to supply those services necessary to provide normal operational conditions of propulsion and safety, and minimum comfortable conditions of habitability. Habitability services include cooking, heating, air conditioning (where installed), domestic refrigeration, mechanical ventilation, sanitation, and fresh water [2]." Reference [3] Further elaborates on the *N – 1 criterion,* stating, "In selecting the capacity of a generating set, particular attention is to be given to the starting current of motors forming part of the system. With any one generator held in reserve as a standby, the remaining generator sets, operating in parallel and initially carrying the loads in 4-8-2/3.1.1, are to have sufficient capacity with respect to the largest idle essential motor on the vessel so that the motor can be started and the voltage drop occasioned by its starting current will not cause any already running motor to stall or control equipment to drop out. The limits of transient voltage variation under suddenly-applied loads are to be in accordance with 4-8-3/3.13.2(c)." The regulations that govern AC voltage and frequency onboard ships, specifically [3] and [2], require that voltage regulation be sufficient to maintain transient voltage levels between +20% and -15% of rated voltage. This voltage must be brought within +/-3% of rated voltage within 1.5 seconds.

The previously mentioned criterion must be met without the use of a generating sources that rely on the speed or direction of the main propulsion plant. The operating generators must also provide continuous and uninterrupted power during normal operating conditions. Generators also have to be set up so that the failure of one any energy source (i.e. boiler, diesel, gas turbine, or steam turbine) must not cause all generating sets to become inoperable. In addition to the regulations on power generation, the *N – 1 criterion* also applies to power transformers, meaning that with the largest power transformer out of service, the remaining power transformers should be capable of supplying the ship's service load.

1-5 Generator Regulations

With generators, there are a few definitions worth noting. There is the *periodic duty rating*, which is the rated kW load at which the machine can operate repeatedly for a specified period (N) at the rated load followed by a specified period (R) of rest and de-energized state, without exceeding a specific temperature. N and R are such that N+R = 10 minutes, and cyclic duty factor is given by N/ (N+R) % [3]. The *short-time rating* of a rotating electrical machine is the rated kW load at which the machine can operated for a specified time period without exceeding another specific temperature. A rest and de-energized period sufficient to re-establish the machine temperature to within 3.6º Fahrenheit of the coolant prior to the next operation is to be allowed [3]. *Non-periodic Duty Rating* revers to the kW load at which the machine can operate continuously for a specific period of time, or intermittently under the designed variations of the load and speed within the permissible operating range, respectively. The temperature rise, measured when the machine has been run until it reaches a steady temperature, is not to exceed the values provided in reference [3]. *Continuous Rating* refers to the rated kW load at which the machine can continuously operate without exceeding the steady state temperature rise given in reference [3]. Generators are to be of continuous rating. Additionally, AC generators are to be capable of withstanding a current equal to 1.5 times the rated current for not less than 30 seconds [3].

Both ships' service generators and emergency generators must be protected by an individual, trip-free air circuit breaker [2]. The circuit breaker must contain the following trips:

1. Open when the prime mover is shut down

2. Have longtime overcurrent trips or relays set to coordinate with the trip settings of the feeder circuit breakers
3. Not have an instantaneous trip, with the exception that an instantaneous trip is required if there are more AC generators that can be paralleled or the circuit breaker is for a direct current generator.

The setting of the longtime overcurrent protection must not be larger than 115% percent of the generator rating for a continuous rated machine or 115% of the overload rating for a machine with a 2-hour or greater overload rating. The setting for an instantaneous trip of a generator circuit breaker must be set above, but as close as practicable to, the maximum asymmetrical short circuit available from any one of the generators that can be paralleled. All generators arranged to operate in parallel must have reverse current and reverse power trips. Generator circuit breakers also must not automatically reclose after tripping [3].

Load shedding of nonessential services and secondary essential services (when necessary) should be provided to protect the generators from sustained overload [2]. Where electrical power is normally supplied by more than one generator set simultaneously in parallel operation for propulsion and steering of the vessel, upon the failure of one of the parallel running generators, the total connected load exceeds the total capacity of the remaining generator(s). Services that are not allowed for shedding are primary essential services that, when disconnected, will cause immediate disruption to propulsion and maneuvering of the vessel. Emergency services include but are not limited to, emergency lighting, emergency communications, and steering/navigational services.

1-6 Construction Single Hull Tender

The U.S. Coast Guard has an aging fleet of inland river tenders. This fleet will soon have to be replaced, so the USCG sent out a request to the U.S. Army Corps of Engineers Marine Design Center (MDC) to do some analysis on early designs for the replacement fleet [4]. The USCG is still early on in the designing of the new river tenders. This means that there is still great flexibility in the modeling, testing, and design of these ships. Additionally, river tenders only go underway for small periods of time and are therefore ideal for implementation of a hybrid power grid.

Numerous designs were proposed for the new river tenders, but the design that has been chosen for the purposes of this research is the Construction Single Hull Tender. This means that there will be no barge/tugboat design and that the focus will not be on buoy tending. Using this design provides for a simple platform around which a more complex power grid can be based [4].

Part of the U.S. Army Corps of Engineers Marine Design Center's (MDC's) job was to analyze certain diesel electric battery power systems. The specifics of the different systems analyzed will be contained in section 2-2. The "unique ships power grid with energy storage" idea that is proposed in the next chapter is an attempt to solve two problems. The first problem is the wear and tear that occurs to diesel engines when they are forced to operate for longer hours than necessary or to operate at sub-optimal loading conditions. Both of these conditions result in unneeded wear and tear on the engines. The next problem is the problem of excessive greenhouse gas emissions. Having energy storage should reduce the amount of fuel burned onboard the ship and would therefore result in a reduced greenhouse gas emission. These reduced emissions would be the result of both energy storage that is provided to the CONSHT through the shore tie connection and won't need to be produced by the Ships Service Diesel Generators (SSDGs), and the SSDGs operating at 90% of the continuous rated load, which is typically condition where the fuel efficiency is highest.

Chapter 2 – Single Hull Construction Tender Hybrid Grid and Associated Heuristic Design Process

2-1 Description of Conventional Ships Power Grid

The simplest description of the power systems on newer Ships is that they are isolated microgrids that, ironically, increasingly display a radial architecture [5] [4]. The fact that power grids on ships are centrally planned, well understood, and geographically small (loads in almost all cases are so close to the generation that differential protection can be used in many cases) allows for the accuracy of many assumptions that would be impossible to make on terrestrial power distribution systems.

The nature and size of loads onboard a ship are preplanned and well known to Naval engineers. The totality of equipment connected to the power system can be summed up, and load factors are determined for almost every operating condition [1]. Even on larger ships, there are few enough large loads (such as large induction motors) that specific solutions can be presented to solve problems that arise from inrush currents that are produced when these motors energize. The load factors of these motors, and all loads for that matter, are well understood and can be used to predict power demand for a number of operating modes.

2-2 Description of the Construction Single Hull Tender

The specific Ship that is the focus of this work is a 160' river construction tender. For the rest of this thesis the aforementioned river construction tender will be referred to as CON SHT (construction single hull tender concept). This ship was specifically chosen for several reasons. A river tender will typically have a rather short underway duration (CON SHT has enough fuel and consumables for three days duration). This means that energy storage can be kept relatively low and the risk of losing power or propulsion can be mitigated by being so close to homeport. Some of the larger ships, were they to use a hybrid energy storage concept, would require tons of lead acid battery storage [6]. The CON SHT is also a ship that has well planned-out work schedules and work days. This allows for a well understood "worst case scenario" for the loading. This "worst case" would be the case where the CON SHT would encounter the most taxing possible loading situation over a 72-hour period. The worst case loading would be almost impossible to predict with a law enforcement vessel, because a law enforcement vessel can sometimes be at high alert for days on end.

This CON SHT concept has already been tossed around by the USCG, and a few novel hybrid power systems were proposed. These systems were as follows:

1. Conventional Diesel with Constant Speed Ship Service Gensets – this describes a conventional ship in which mechanical energy is produced by internal combustion then mechanically coupled to propulsion. And the ship's grid is fed by constant RPM generators [4].

2. Diesel Electric with Constant RPM Gensets and Battery Buffer – this describes a system in which generators directly feed the ship's grid and propulsion is powered by the grid through a variable frequency drive. There is also a battery buffer that allows you for the ability to keep a minimum number of generators online when the load slightly exceeds the limits of the generators already online [4].

3. Diesel Electric with Variable RPM Gensets and Battery Buffer - this describes a system in which generators produce power at variable RPM (dictated by the load and its corresponding most efficient fuel curve) and then are converted to 60 Hz power through power electronics. Propulsion is powered by the grid through a variable frequency drive. There is also a battery buffer that allows for the ability to keep a minimum number of generators online when the load slightly exceeds the limits of the generators already online [4].

4. Diesel Electric, Propulsion Prime Mover Hybrid with Standby Gensets – this is an interesting concept where large diesel engines directly power a ship's propulsion. The ship's power is delivered through two permanent magnet alternators and inverters. The fact that this design was proposed shows that the USCG is willing to entertain inverters in the service of providing ships service electrical power [4].

2-3 Brief Description of the Novel CONSHT Hybrid Grid

The hybrid power grid concept is a little different than the concepts proposed in **Section 2-2**. Propulsion power would be provided by mechanically coupling the propulsion to diesel engines. In this sense, the CON SHT concept proposed here would rely on conventional methods for propulsion. Not supplying the propulsion from the power grid simplifies the modeling immensely and avoids the need to model an accurate variable frequency drive. However, if the hybrid power gird concept is proven reliable, then it can and should be applied on a larger scale to a hybrid diesel electric concept (where propulsion is powered from the grid.) A relatively large amount of electric storage would be provided on board. This electric storage will be recharged in-port from the shore tie or whenever the power generated exceeds the load.

While the generating power would be sufficient to provide the average power during the most demanding workday (around 140 kW potentially taking place from 0700 – 1700), the inverter should be able to provide whatever power is not provided by the online generators. This would mean that at almost all times, only half of the generators (in this case, one) would need to be energized. Additionally, the load would substantially drop at night.

The specific layout of this ship will be illustrated in the modeling section, but the general description is as follows: the grid will be fed by two generators that, in addition to the inverter, would be sufficient to provide energy to the two largest motors onboard, as well as to other equipment operating at expected levels during the most demanding loading conditions. Energy storage in the form of batteries will be provided to power the inverter. The power that will be available from the inverter will be enough that under average loading conditions for all modes of operation, only one generator will need to be online. The generators will also be sized so that limited recharging can occur during non-peak load hours. And the energy storage onboard the ship will be sized so that this can occur over the period of 72 hours.

The inverter when online will supply enough power that the generators will always provide 90% of their continuous operating power level. The exception to this is that, if in order to fill this requirement, the inverter must sometimes supply between 0-10% of its full rated power, the inverter will instead supply 10%+ of its rated power. This is because below 10%, efficiency drops off precipitously on the inverter.

This hybrid energy storage grid concept would have a few expected benefits and costs. The costs would include the following:

1. Increased risk – risk is likely to be increased when any new concept is implemented. Many USCG personnel are well adapted to conventional diesel power ships where power electronics and energy storage is nonexistent or, at least, minimized. This increased risk, however, could be curtailed. Proper training, stringent testing, and the small size and short duration of the CON SHT will help to minimize this added risk.
2. Batteries storage and weight issues – this storage space and weight will be calculated in the simple modeling section and will likely result in an increase to ships' tonnage and will take up a few thousand cubic feet.
3. Power losses due to conversion between DC and AC – there will be inevitable losses in the conversion of power from DC to AC, and vice versa.

However, there are benefits to this system as well. They are as follows:

1. Generators can be run at 90% continuous rated load for long periods of time. Running generators at 90% of their rated load will improve fuel efficiency. This can also reduce the amount of preventative maintenance required on them.
2. Generator usage can be reduced. Allowing for, at most, half the generators to be run at any time will reduce the run time and therefore the wear and tear. This, in addition to increased rated load operation, will hopefully further reduce the preventative and conditional maintenance. This will result in cost reductions both from equipment costs and from personnel work hours.
3. Energy to power the ships' loads can come from the utility. A certain amount of energy that would otherwise be extracted from diesel fuel in an internal combustion engine will now come from the utility in the form of energy stored in the batteries that are charged from the shore tie. This will reduce the cost of energy and the greenhouse emissions from the ship.
4. The total capacity of generators can be reduced. The power rating of the inverter will allow for the power capacity of the combined generators to be reduced. This will result in fewer or smaller generators that can be repaired and brought online easier and faster.

Once the system is modelled, the amount of energy storage and the reduction to fuel consumption and generator size can be calculated. This cost analysis in conjunction with the factors of risk and complexity can be taken into account in order to determine whether this hybrid ship's grid concept can be useful to the USCG and other inland ships. This course of action is suggested in the future work section.

The USCG and the maritime community generally lean more on the side of reliability than efficiency. It is for this reason that all increases in the ship's efficiency should be properly managed to reduce the increase to risk. For this reason lithium ion batteries were chosen as the medium for energy storage. Lithium ion batteries are both high performing and sufficiently matured for minimizing risk [6]. Also, the proposed power grid has enough generation capacity to manage the average load during the most taxing working conditions if the batteries fail. This has all been done in the name of reducing risk.

2-4 Description of the Heuristic Design Process Used on the CONSHT

Often times in initial reports and design proposals for new ships rely on approximate methods for determining values of Generation Capacity, Number of Generators, and efficiencies in the energy conversion process. This Heuristic Design Process is intended to compete against other methods for sizing and determining basic values for a ship's electric grid. The design process does not need to address every issue with the building of a ship's grid but should produce results that, when applied intelligently, should lead to reliable ships' grids.

This design process should be simple enough to be implemented by a reasonably competent technician or someone with a technical degree not in engineering. The design process can't rely on expensive software. The simplified model is implemented in Matlab but it could just as easily be implemented in R or Excel. This design process should be quick and provide values that can be used in initial reports for cost and environmental impact analysis.

With this design process, implementation difficulty, man-hours needed, and an inherent margin for safety are all important factors. Accuracy, while important, is less so. One big reason that these other factors are more important than accuracy is that, regardless of how accurate the results are, an additional margin for safety and future growth will inevitably be added to these estimated values. With a preliminary power system design, a 30% margin for growth and power uncertainties is common [1]. In heritage designs, a 10% margin can be applied [1]. The effect of this is that if two competing methods for estimating energy storage capacity each have errors of 1% and 4%, respectively, then after an added margin of 20% the respective "errors" would be 21% and 24%. This means that the returns expected from increased accuracy have been greatly diminished. Another factor that increases the premium on overestimation is the fact that the less depleted the Li-Ion batteries are, the greater the life expectancy of the batteries [6]. This can be illustrated by the fact that Li-Ion batteries can withstand discharging to 50% 1000 times but can only be discharged to 5% 500 times [8].

The design process expounded upon above is specifically intended for is sizing and initial design of the power plant on a ship similar to the CON SHT. The assumptions are validated and tested for a ship design that is radial, organized in load centers (LCs), and has an inverter that controls power output as a function of generator output. Assuming these factors are all kept similar, the design process used here should be applicable to larger and smaller vessels.

2-5 Selection and Sizing of the SSDGs

2.2.1 IEEE Std 45-2002, 7.4.2, states as follows:

> *"In determining the number and capacities of generating sets to be provided for a vessel, careful consideration should be given to the normal and maximum load demand (i.e., load analysis) as well as for the safe and efficient operation of the vessel when at sea and at port. The vessel must have at least two generating sources. For ships, the number and rating of the main generating sets should be sufficient to provide one spare generating set (one set not in operation) at all times to service the essential and habitable loads. For MODUs, with the largest generator off-line, the combined capacity of the remaining generators must be sufficient to provide normal (non-drilling) load demands.*

> *In selecting the capacity of an AC generating plant, particular attention should be given to the starting current of AC motors supplied by the system. With one generator held in reserve and with the remaining generator set(s) carrying the minimum load necessary for the safe operation of the ship, the voltage dip resulting from the starting current of the largest motor on the system should not cause any motor already running to stall or control equipment to drop out. It is recommended that this analysis be performed when total horsepower of the motor capable of being started simultaneously exceeds 20% of the generator nameplate kVA rating. The generator prime-mover rating may also need to be increased to be able to accelerate motor(s) to rated speed. Techniques such as soft starting (i.e., reduced voltage autotransformer starters, electronic soft starters, and variable frequency drives) may be utilized to reduce the required capacity of generators when motor starting is of concern [7].”*

With this guidance in mind, the CONSHT will have three generators. Two of these SSDGs will be for the ship’s service to the grid. The third generator will be an emergency generator that will not be detailed here. The two SSDGs will be the same size. Under taxing loading conditions, such as construction during the winter, the vital loads average about 79 kW [5]. With intelligent load management, achieved through the use of a programmable logic controller or some other industrial control device, the load can be held around 79 kW with little variation. Thermal loads, such as the air conditioning, refrigeration, and heating, can be reduced and will further reduce the demand from the vital and minimum habitable loads.

The total generating capacity will be selected so that when CON SHT is experiencing the average load during the most demanding condition (i.e. during construction winter conditions), the two largest motors should be able to run simultaneously, assuming both generators and the inverter are online. With the two largest motors running at rated load during construction winter, the demand will be 283kW. Once the assumed 3% losses are factored in, the generators and inverter will have to supply 291.5kW of power. The inverter in this example is assumed to be rated at 75kW (26% of total power capacity). Therefore, the generators will need to supply 216.5kW of power. For the best chance of compliance with the N – 1 criterion, the generators should both be the same size. Therefore, the minimum generator rating will be 110kW. However, to provide for another small margin, the generators were instead chosen with a rating of 115kW. In order for 115kW to be compliant with the CFR and IEEE std 45, one generator will need to be able to supply the minimum habitable load and bring on the largest motor. A possible relaxation in the regulations could occur by allowing the inverter to function as a generator in these regulations. Allowing the inverter to supply a percentage of the load while a motor is started.

2-6 Estimation of Losses

Data was given for the power drawn by individual loads, meaning that the losses in the motors and other loads are already factored in. With the modeling and estimates here, losses in generation are already factored in with the sizing of generators and prime movers. For this reason, the losses will be simplified down to the losses that result from transforming and distributing power. Approximations were made in the estimation of ship's losses due to both line losses (in the form of $\boldsymbol{I^2 R}$) and the various forms of transformer losses. The loads of the ship are provided in **Appendix A**. Those loads were then taken and added to eight different load centers supplied by three-phase cable. Each load center could be vital or nonvital and $440V_{LL}$ or $208V_{LL}$. The cables were sized as appropriate for a ship that requires redundancy in the power supply to its load centers. The loading of the cables was assumed to be rated nameplate plus 100% of the corresponding load center for vital loads and nameplate plus 50% of corresponding nameplate value for nonvital loads. Certain cables were then sized up to either 3 AWD SLD or 1/0 7STRD to limit the different types of cables that would be needed. The resistance values were then calculated for 120ft of those given cables, and then I^R losses were calculated for worst case loading (demand factor of 1 for all equipment). 120ft was chosen, assuming the SSDGs were near the center of the cutter and that the cables had to travel 80ft (half of the boat's length) longitudinally and then 20ft out of their way in both other directions. The worst line losses were 1.629% for LC12.

Transformer losses would only factor in to losses for LC16 and LC6. Both of these load centers have relatively small loads when looking at the nameplate value. So assuming transformer losses of 2-3% on LC6 and LC16, LC6 would experience total losses of 3.54% when factoring in-line and transformer losses. 3.54% losses applies to only a small portion of the load when loading conditions are the worst. For this reason, losses will be calculated as 3% of the total load. This should provide ample margin for losses incurred during distribution of the power on the grid.

Table 2.1: Estimated Line Losses with Simple Calculations

Load Center	Amps Per Phase	Amps x120%	Cable Selection	Cable Resistance 1 mi	Cable Resistance 120ft	Nameplate loading	I^2 R losses	Percentage Losses
DC	5.68814347	6.82577217				5.688143471	0	0
LC 1	84.9971153	101.996538	3 AWG SLD	1.192	0.027090909	84.9971153	195.7185	1.12266845
LC 11	134.662734	161.59528	1/0 7STRD	0.607	0.013795455	134.6627337	250.1675	0.9057476
LC 12	242.152393	290.582872	1/0 7STRD	0.607	0.013795455	242.1523935	808.9349	1.62872789
LC 16	30.7484784	36.8981741	3 AWG SLD	1.192	0.027090909	30.74847842	25.61361	0.40613551

LC 2	84.3795454	101.255455	3 AWG SLD	1.192	0.027090909	84.37954544	192.8848	1.11451139
LC 3	82.7381097	99.2857317	3 AWG SLD	1.192	0.027090909	82.73810975	185.4534	1.0928308
LC 4	81.7142439	98.0570927	3 AWG SLD	1.192	0.027090909	81.71424392	180.8919	1.07930726
LC 6	40.7596109	48.9115331	3 AWG SLD	1.192	0.027090909	40.75961093	45.00737	0.53836567

2-7 Assumptions Inherent in the Simplified Matlab Model

The simplified Matlab Model is meant to emulate models used in the design process on traditional ships' power grids (mentioned in **Section 1-2**). To determine energy storage (in kWh) that is needed, the strict function of this Matlab model is given generation capacity, inverter capacity, loading assumptions, and generation schedule. It is important to note that the nautical community is more concerned with reliability than efficiency in most cases. (Anecdotally, a sailor would rather have a generator that consumes too much fuel but rarely overloads, rather than vice versa.) For these reasons, the assumptions made in this simplified model erred on the side of caution when accuracy was reduced.

The most consequential assumptions made in this simplified model are the timeframe of change in the grid and the constancy of the power supplied by the generators and batteries. The timeframe within this model is hour-by-hour. In order for this model to be reliable, the steady state losses in the system should be less than assumed. During times of change within the system (for instance, when an induction motor is energized), the losses can exceed the steady state assumption, but not so much more that they cannot be factored into the steady state assumption—meaning, assuming the motor is to be energized, say, multiple times an hour for the entire work day every day (a very liberal estimate on the number of times this motor will be energized), the total losses due to this energizing plus the losses in the steady state must not exceed 3% for the whole day. This assumption, though not accurate, will be shown to be a safe assumption through simulations in PSCAD in the time-domain.

The generators are assumed to supply a constant power during that time, and from there the power to or from the battery is assumed to remain constant. This is another large assumption, but the inverter's controls are designed to maintain rated power for the generators below 90% continuous rated power of the generator and to maintain rated output of at least 15% from the inverter. This means that the assumption that the generators maintain rated power should be somewhat accurate. The converse assumption—that this will result in a given power supplied by the battery—is harder to rectify. During times of great change or fluctuation in the load, the inverter's controls systems will take time to respond to these changes. This means that the inverter will be asked to supply more and less power than is assumed depending on whether the load quickly increases or decreases. If during simulation, it is determined that the inverter during times of change reliably supplies more power than the simple model assumes, then there will need to be an inverter correction factor based off of the difference between the assumed power supplied and the simulated power supplied. If shown to be nonexistent, an inverter correction factor will not be needed.

There are also many assumptions made on the variation and the nature of the ship's load. The information on the ship's load is given in the previously mentioned load analysis. The information contained in the load analysis is the rated or nameplate load usually in W or kW but sometimes in hp for larger motors. Load factors are given for all loads in all common loading conditions. Next to the load factors are the average loads in these same loading conditions. From these average loads, the average total load can be determined [8].

With the limited information provided with this load analysis, the assumption was that the loading of the ship follows a normal distribution. The reason for this assumption is that the average load is known and well-studied, but the variation is unknown. There will be deviation from the assumed average load from hour to hour. In some cases these deviations may accumulate if the day has been particularly demanding on the ship. This would result in more power supplied by the batteries than usual. It is for this reason that variation is introduced. Even though the true loading distribution is likely not perfectly normal, it is important to include variation to increase the calculated battery storage so that the storage can handle worse than usual demand from the batteries over the course of a 72-hour at-sea period. In this specific model, the variation is assumed to be 15% of the estimated load.

The reasoning behind the normal assumption is that, frankly, there was no data on the loading distribution for this type of ship that could be found. However, loads on a ship are most likely less correlated than on land because much of the large equipment onboard a ship gets energized and de-energized at unplanned times. If you look at the energy consumed by the load over an hour as basically a summation of the energies consumed over various 5-minute periods and assume these different five-minute periods are uncorrelated (This assumption is not proven here; however, loads on ships change very frequently), then the energy over the hour would likely start to look like a normal distribution. The average load from hour to hour is well understood; it's just that the deviation from that average is unknown and assumed to be normal.

Another assumption in the simplified model is the assumption of line and transformer losses. The assumption is that transformer and cable losses account for 3% of the load. This assumption is inaccurate in many of the lower loading situations. This assumption is shown to be safe in the results section. In addition to the 3% loss assumption, efficiencies of both the inverter and the charger are assumed to be constant.

2-8 Simple Modelling of the System in Matlab

The purpose for this initial simplified design and specification methodology is that energy storage requirements can be estimated, and generated capacity factors can be experimented with. As of now, it is difficult to estimate the amount of batteries storage required and the resulting reduction in generating capacity without doing a somewhat in-depth analysis of the specific design of the hybrid grid. The Matlab model developed is simple enough to be implemented in Excel and is shown to provide safe estimates for energy storage requirements.

The purpose of using the simple Matlab model is to provide a repeatable methodology for Naval or electrical engineers to use when sizing energy storage. This model makes many assumptions that have been expounded upon in **Section 2-7**. This model is intended to be useful even when the only data available on a ship design is the load analysis, description of the ship's worst case workday, and the ship's underway duration.

Apart from the assumptions mentioned in **2-7**, this model is based off the conservation of energy theorem. This model assumes that the inverter and therefore the battery will require a certain amount of energy based off of loading predictions and an assumed generator schedule. The model ignores transient phenomena. The losses that result from the transient phenomena will be covered by the generous estimate of 3% steady state line and transformer losses. The losses are assumed to be limited to line $\mathbf{I^2\,R}$ losses, transformer losses (total, calculated from efficiency of a typical transformer of this given size), and losses from the inverter and battery charger. The system requires that the inverter supply 15% rated load, which means the minimum inverter efficiency would be 95% [9]. However, the assumed efficiency for the inverter is 96.5%, which is still a safe assumption as shown in simulation.

Because this model assumes all losses are a fixed percentage of either the total load or the power going to or coming from the batteries, the calculations are very simple. The model described here can be made within an Excel spreadsheet (although for the purposes of this research it has been done in Matlab). This may seem strange to some within academia, but the hope is that this simple method for estimating the requirements on the hybrid power grid will be used in industry. The Maritime Industry has access to accurate modeling software, but this modelling software is typically used only once there is a funded and mature idea on how the ship will be designed. This model will provide industry with not only a concept for the particular design and protocol used for a hybrid power grid with energy storage, but will also provide a simple yet accurate way to estimate requirements and constraints that act on that design. By integrating these requirements and constraints, environmental impact, long-term costs, weight change, battery size and a number of other important values and design aspects can be estimated with limited information.

The Matlab code for this model is attached in **Appendix B.** There are two functions in this code. One produces the hour-by-hour load profile for the entire ship, while the other produces the hour-by-hour generation capacity of the ship. The load profile is developed by taking data from the load analysis attached in **Appendix A.** A "worst case loading" is developed where the work hours are assumed to be filled with the work that has the highest load. In this particular case the worst loading is "construction winter." Therefore, it is assumed that for three days (the ship's at-sea duration) ten hours a day is taken up by "construction winter" loading. During the nonworking hours, "standby winter" loading is assumed. Variation is assumed to be random Gaussian with a variation of 15% of that given hour's load. From the preceding assumptions, the hour-by-hour load profile is calculated.

The hour-by-hour generation capacity is much easier to calculate. The ratings of the generators are given, and an hour-by-hour condition of the power plant is determined by the user. This gives the user a tremendous amount of flexibility when determining battery capacity and how the system will be run. The user can decide to use a certain amount of battery storage and see what capacity factor on the generators would be needed to power the ship. The user can also use a capacity factor on the generators and determine how much energy storage is needed. On the CON SHT, the largest motor will usually be run two hours a day. Because both SSDGs must be run when the largest motor is online, the capacity factor of the second generator on a typical day will be at least (2 hours a day X 90% Capacity) ÷ 24 hours a day, so 7.5%. Below is the expected battery charge over 72 hours when the second generator is assumed to be run four times a day for 30-minute periods during a 50th percentile loading scenario.

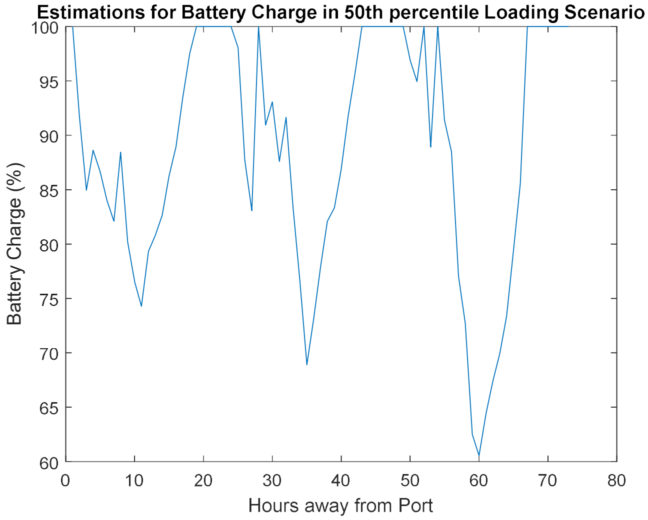


Figure 2.1: Depiction of Charge Over Time

The way this curve is generated is by simulating the generator capacity and load curves 100 times. In each simulation each hour in the load curve is assumed to be from a Gaussian distribution with the mean given in reference [5] and a variation of 15%. This 15% can easily be changed when and if more information on the distribution of the load is provided. The losses equating to 3% of the load are also then factored in. The difference between the generating capacity and the load is then calculated to determine the power coming from the inverter and going to the charger. Certain limits are then enforced. The lower limit for the inverter is 11.25 kW (15% inverter rating to maintain good efficiency) and the upper is 75 kW (inverter rating). From the power going to and from the charger/inverter the efficiency is then used to determine the power going to and from the batteries. Once the power from the battery is calculated, a simple summation provides the level of charge in the battery. However this level of charge might have values that exceed a full charge. Therefore when the batteries are fully charged, no more power can be delivered to them and the energy level stays at 100% (indicating full charge.)

Since this simulation is run 100 times, there are 100 different battery charge curves. These curves are then sorted based off of their minimum values (indicating the point during the ships voyage at which the battery charge is the lowest.) from these sorted curves the 1st, 5th, 25th, 50th, 75th, 95th and 99th curves are taken. These curves correspond to percentile scores for minimum values within the curves. This is important because the battery capacity should be calculated from both an average case and worst case scenario.

Figure 2.2 represents the 99th percentile most demanding load out of 100 simulations. Therefore, with running the second generator for only six hours total, accounting for a 7.5% capacity factor, the charge gets down to 40% only once. Because this curve represents a very demanding load, the capacity factor on the second generator will likely be greater than 7.5%, and the charge will likely find its minimum at a value much greater than 40%.

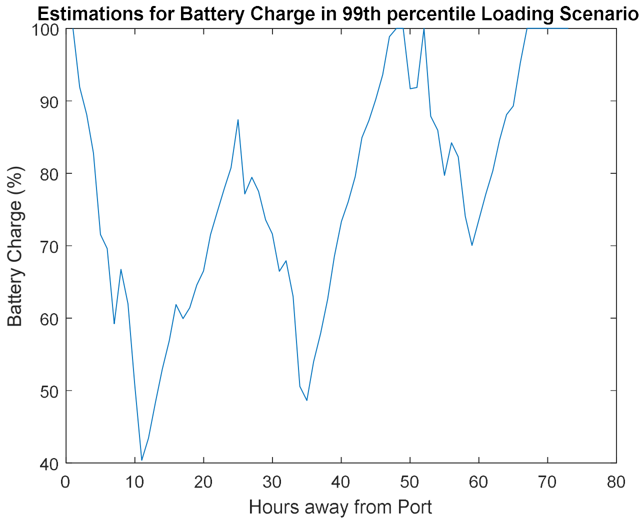
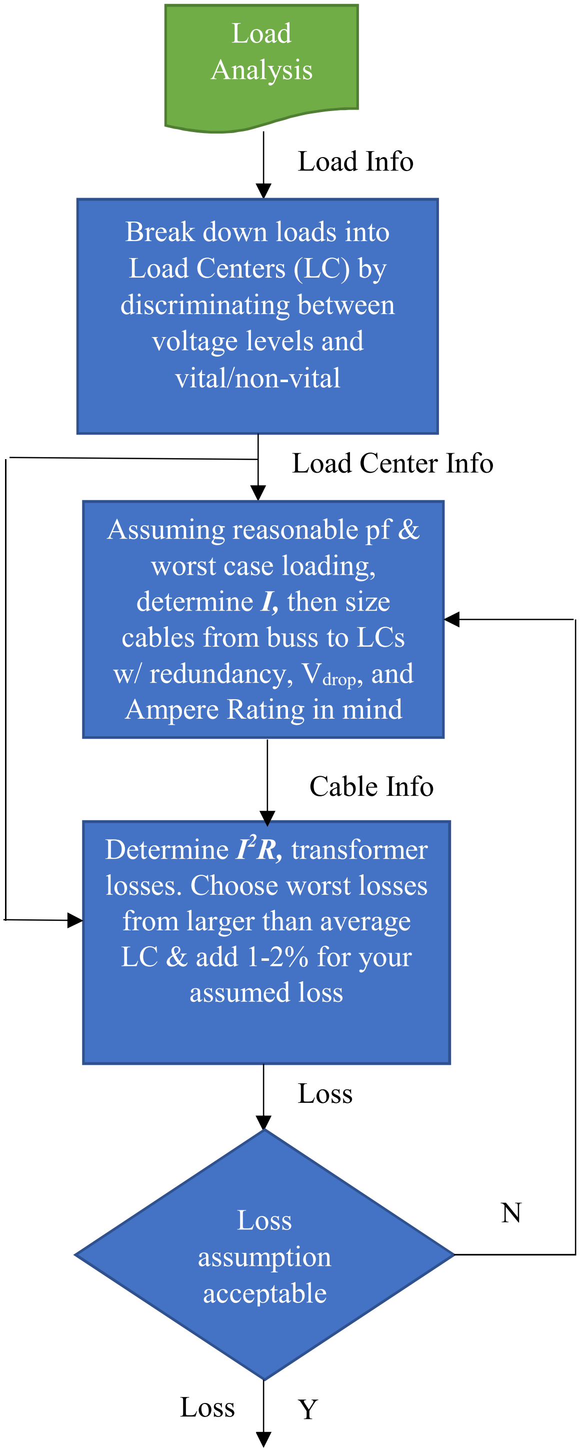
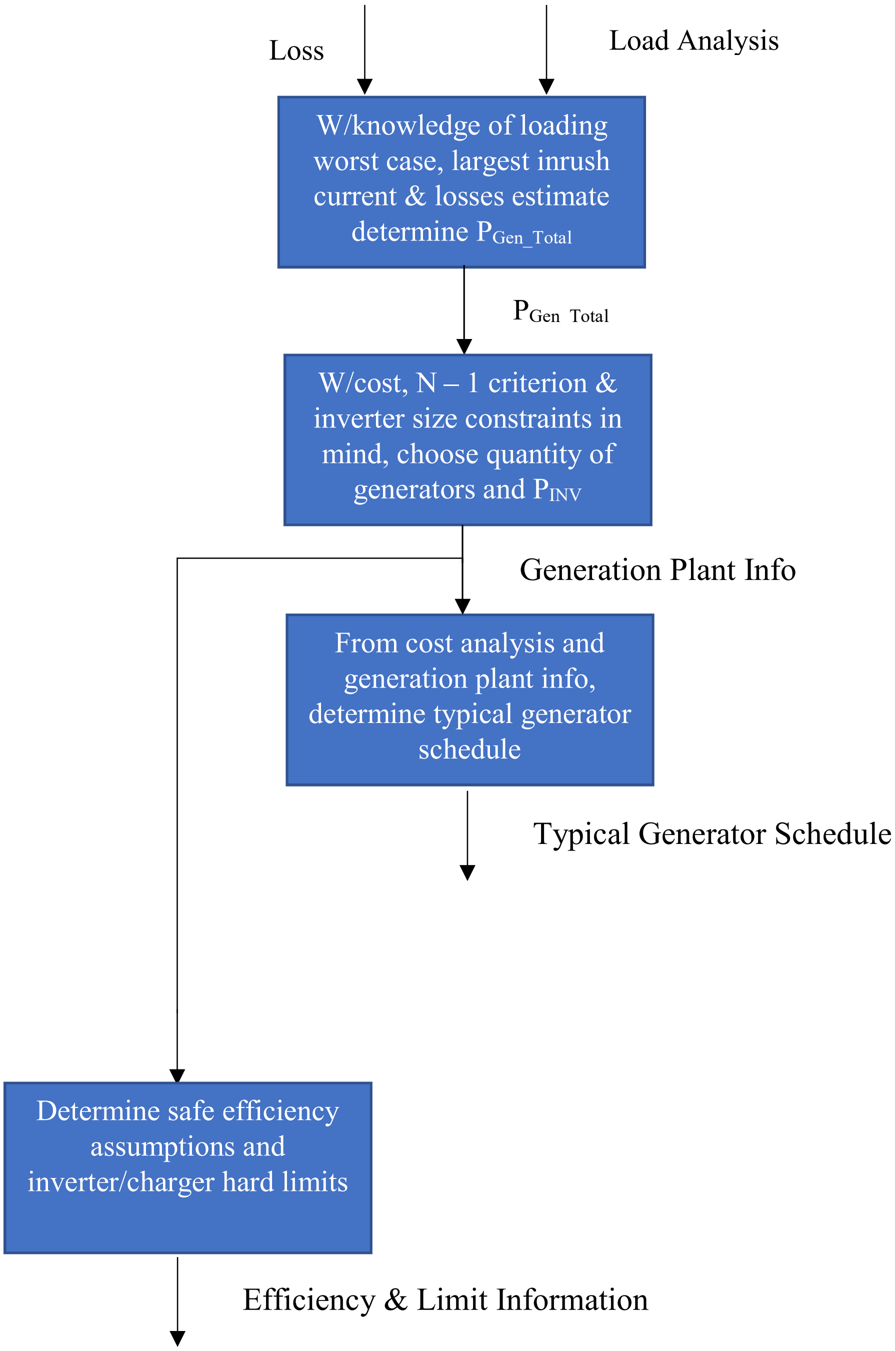


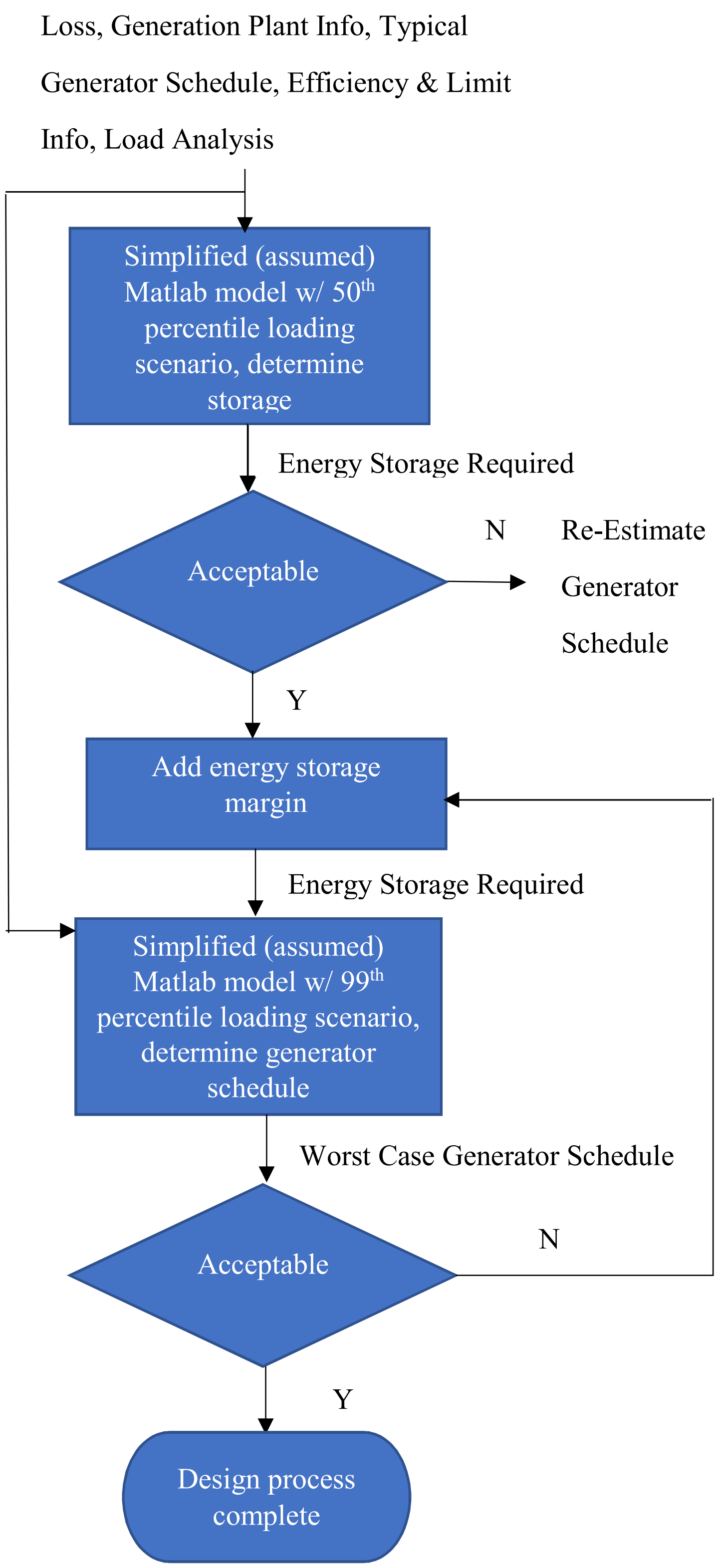
Figure 2.2: Depiction of Charge Over Time

2-9 Flow Chart Overview and Results of the Heuristic Design Process

2-9-1 Flow Chart Overview




Loss
Load Analysis
W/knowledge of loading worst case, largest inrush current & losses estimate determine P_{Gen_Total}
$P_{Gen\ Total}$
W/cost, N – 1 criterion & inverter size constraints in mind, choose quantity of generators and P_{INV}
Generation Plant Info
From cost analysis and generation plant info, determine typical generator schedule
Typical Generator Schedule
Determine safe efficiency assumptions and inverter/charger hard limits
Efficiency & Limit Information


Loss, Generation Plant Info, Typical Generator Schedule, Efficiency & Limit Info, Load Analysis
Simplified (assumed) Matlab model w/ 50th percentile loading scenario, determine storage
Energy Storage Required
Acceptable
N
Re-Estimate Generator Schedule
Y
Add energy storage margin
Energy Storage Required
Simplified (assumed) Matlab model w/ 99th percentile loading scenario, determine generator schedule
Worst Case Generator Schedule
Acceptable
N
Y
Design process complete

2-9-2 Results of the Application of Design Process on CON SHT

When assuming a capacity factor of just 13.125% or 3.5 hours online a day for the second SSDG, the battery capacity can be reduced to 200 kWh and rarely dip below 40% charge in the typical loading scenario, as shown in **Figure 2.3**.

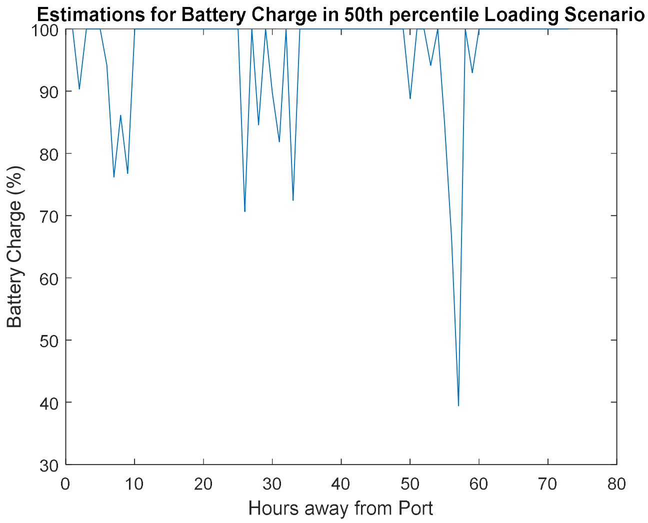


Figure 2.3: Charge over Time for Typical Conditions

Even in worst case loading situations, the batteries rarely drop below a 20% charge when maintaining a 15% capacity factor on the second generator.

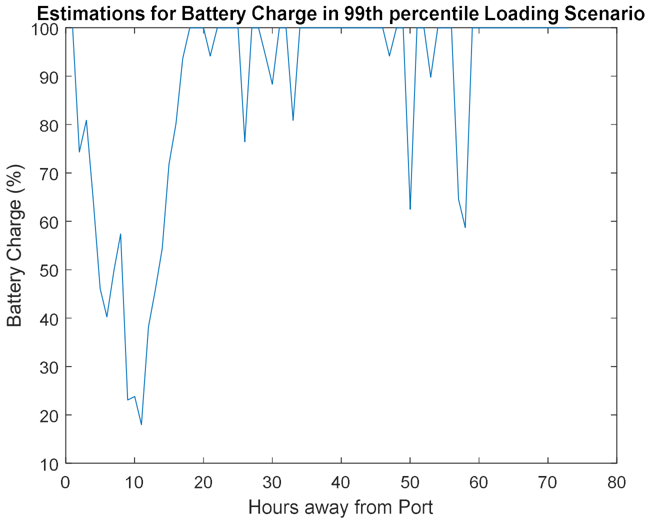


Figure 2.4: Worst Case Loading with 15% CF

200 kWh worth of batteries will weigh around 2,960 lbs. This is a heavy weight, but when taken in the context of shipboard systems, it is very manageable. For example, the USCG Keeper-Class Cutters are only 15ft longer than the CON SHT, perform similar work, and displace 850 tons of water. (The batteries mentioned here would account for only .17% of the displacement.)

Chapter 3 – PSCAD Model and Methodology Used to Validate the Design Process

3-1 Purpose for Detailed Model in PSCAD

Assumptions about the physical world are inherent in any model. However, certain models with more detail and variables can have fewer inherent assumptions. The goal with the PSCAD model is to build a more detailed model of the CON SHT in order to validate some of the assumptions made in the simple model. Additionally the design of the CONSHT must be shown to be reliable and stable, with aspects of redundancy that would be desired by the Maritime Industry.

Some of the simple model assumptions that will be verified through the detailed PSCAD model is the assumption on line/transformer losses. The line and transformer losses need not be exactly 3% of the load but need to be 3% or less than 3% of the load in all steady state loading conditions. Line and transformer losses can momentarily exceed 3% during times of great change in the grid. However it must be shown that these changes will not occur often enough to where the 3% assumption cannot be made.

The simple way to prove that this is a safe assumption is to put the PSCAD model through a battery of simulations. These situations should be designed to simulate the situation with the worst possible line losses, for example energizing the two largest motors back to back with high load. Another possible situation could be large loads occurring on particularly lossy Load Centers. These simulations would aggregate the total power consumed by the loads and then compare to the power output from the SSDGs and the Inverter and get the difference. The difference could then be integrated over a period of milliseconds and then divided by the total load over that same period of milliseconds. The purpose for integrating the losses and the load is to ignore transient phenomena. For example If the losses are integrated over .025 seconds and the integrated losses are never greater than 3% then as long as the phenomena being studied does not repeat more often than every .025 seconds, the assumption holds.

$$3\% \geq \frac{\sum_{T-.0125}^{T+.0125s}\left(\left(P_{gen}+P_{inv}\right)-P_{load}\right)}{\sum_{T-.0125s}^{T+.0125s}P_{load}} \tag{5}$$

If the above assumption doesn’t hold, then it will have to be determined over what time period that assumption holds. And then determined whether that phenomena is likely to occur more often than once in that time period.

The next assumption that must be validated is the assumption that in the steady state the energy provided by the inverter will be no greater than the demand predicted in the simple model. The simple model predicts that the inverter will supply energy equal to or lesser than the total load plus the 3% losses minus the rated energy output of the online generator over an hour. This assumption is shown in Equation 5. This should hold true in the steady state. When analyzed in quasi steady state where system variables are changing the power supplied from the inverter may differ from the simple model predictions. This is because the simple model does not factor in any of the time that it will take for the inverter or SSDG controls systems to adjust. Therefore, multiple simulations must be run at high loads where there are fluctuations in the load and motors are being brought on and offline. In these 'quasi steady state' simulations the real inverter energy output will be compared to the simple model assumptions. It must be show that the PSCAD model inverter supplies less energy than assumed with the simplified matlab (assumed) model. If this cannot be shown then an inverter fluctuation factor must be included in the simplified (assumed) model. This inverter fluctuation factor would look like the line loss factor. Where a given 1 +x% multiplier would be applied to the inverter.

$$Einverter \leq (Eload \times 1.03) - .9 \times Egencapacity \tag{6}$$

On a similar note the power supplied by the batteries will be verified in a similar fashion. The major difference between this validation and the inverter validation will be in the efficiency factor that is applied. In the assumed battery output the efficiency of the inverter is 93% when inverter output is less than 10% and 96.5% when the inverter output is greater than 10% rated power output. In the model it will be the inverter divided by the efficiency curve built from data. The power that will be summed or integrated is shown below.

$$P_{batterymodeled} = \frac{P_{modeled\ inverter}}{\mathcal{E}_{fromcurve}(P_{modled\ inverter})} \tag{7}$$

$$P_{batteryassumed} = \frac{((P_{load} \times 1.03) - P_{gencapacity})}{\mathcal{E}_{Assumed}((P_{load} \times 1.03) - P_{gencapacity})} \tag{8}$$

Certain assumptions that will not be tested through the detailed model are the assumptions on inverter and charger efficiency, and the assumptions on the load profile. The exception to this is that the three largest motors will be modeled as induction motors. For these three motors the nature of the load will be more accurately represented. With the exception of those three motors the loads will be modeled as three phase loads in PSCAD. Gaussian assumption will not be validated.

It must be shown that the SSDG, motors, and inverter maintain healthy operating conditions during fluctuations and changes in the load and system. During the quasi steady state simulations in PSCAD, the SSDG, motors, and inverter must demonstrate stability and reliability. If certain undesirable conditions arise solutions for these conditions must be proposed.

The controls systems and inverter protocol must be demonstrated and show to work well on a small ships grid. A quick and appropriate response must be elicited from the SSDG and Inverter during changing grid conditions. Motors must be shown to successfully interact with the grid while the inverter is connected.

Since the inverter controls its power supply off of the SSDG, it is key that the inverter has a robust protection system to prevent a situation where the SSDG and inverter are decoupled yet the inverter is trying to reduce the SSDGs power demand.

3-2 Limitations of the PSCAD Model

PSCAD offers an extremely useful time domain analysis for power systems. Some of the limitations, however, are that PSCADs line models do not work well for short distance lines. PSCAD does not offer a viable alternative to grounding the system. Additionally some of the models in PSCAD (specifically the autotransformer model) operated in unusual ways. Most of these limitations were addressed and the PSCAD model is sufficient for the purposes of this analysis.

3-3 Description of PSCAD Model

The main view of the PSCAD model is shown below. Figures that provide a more in-depth analysis will be provided throughout the rest of this chapter in sections 3-3-1 through 3-3-4.

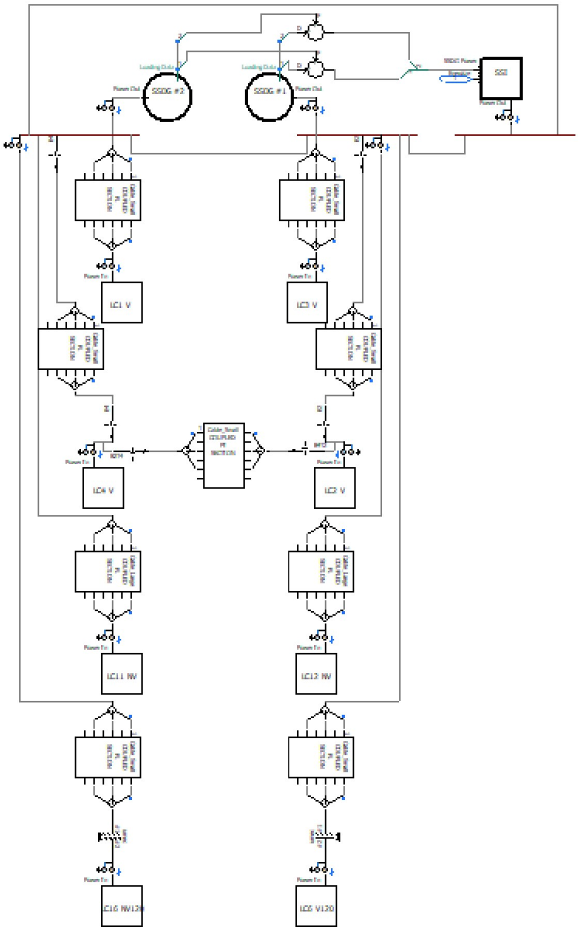


Figure 3.1: Main View of the PSCAD Modeled CONSHT Grid

3-3-1 Ships Service Diesel Generator

PSCAD has an excellent built in library of synchronous machines, exciter models, and continuous system model functions. The Ships Service Diesel Generators (SSDG) in this model represents two 115kW, 130kVA (assuming about a .88 power factor) machines that are the traditional sources of power onboard a conventional ship. These SSDGs are powered by a 118kW internal combustion diesel engine. The SSDG model demonstrates the ability to fully power the grid when the load is within the power capacity for the SSDG (130kVA).

The prime mover is modeled as an internal combustion engine. PSCAD has an in house model for internal combustion engine that has as inputs: ***w*** which represents the input shaft mechanical speed control in per-unit (this is the actual rotational speed of the synchronous machine); ***FL*** the engine fuel intake. This proportionally scales the output shaft torque ***Tm*** (meaning this value is a function of how much fuel is going to the diesel engine); and ***Tm*** or the output shaft torque, per-unitized based on Machine Rating parameter [10]. This internal combustion engine was designed as a four stroke engine with 12 cylinders and 24 pistons (opposing piston). The efficiency is 98%. The diesel engine model is shown with the control system that represents the governor below.

The controls system starts with a difference junction that takes the difference between the reference speed ***WREF*** and the speed which, when the machine is above a speed of .997 pu, is the ***W*** signal from the synchronous machine mentioned above. This is done so that when the machine is coming up to speed the controls system doesn't overcompensate for the difference from the reference speed. The signal then goes through a gain of 60. This gain was determined to be optimal through both trial and error and referencing [11] and [12]. The signal was then processed through a lead/lag pole and a real pole. This was done to improve stability of the controls system and because similar models used this setup when mimicking a diesel governor [11] [12]. The signal is then put through a PI controller with a proportional gain of 1 and an integrator time constant of .1. This proved to give a robust response with good stability. A hard limiter is in place to ensure that no more than 1.2pu fuel (FL) can be supplied to the IC engine. And a time delay is introduced to simulate a delay in the governor response. This system is shown below.

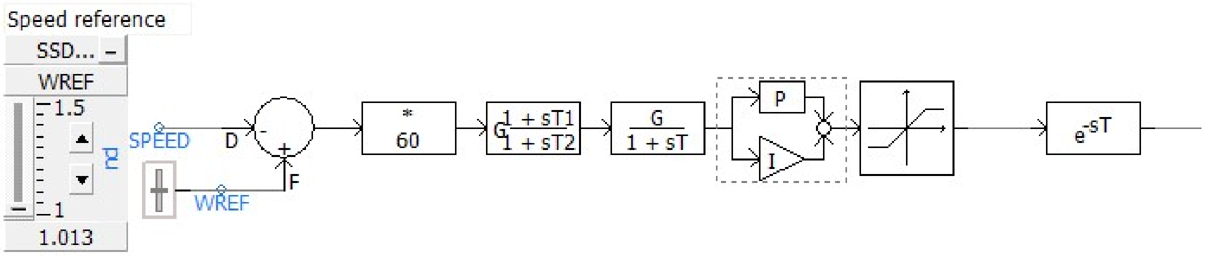


Figure 3.2: View of the Governor Model for SSDG1&2

This controls system determines the ***FL*** input in the IC engine below.

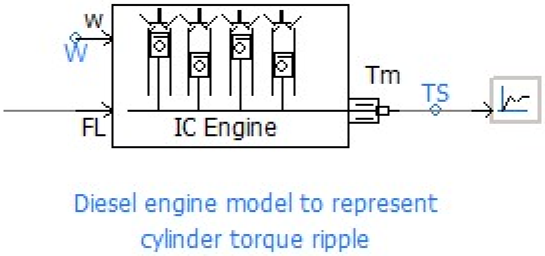


Figure 3.3: View of the Built in Diesel Engine Model on PSCAD

The diesel engine isn’t necessary for the model but it gives the system a more realistic response to changes. This realistic response to system changes is necessary to demonstrate the interaction between loads, motors, inverters, and another generator. The figure below demonstrates what the ***Tm or TS*** signal looks like when changes to the grid occur. The diesel engine model effectively introduces torque ripple that can be observed in real-world situations.

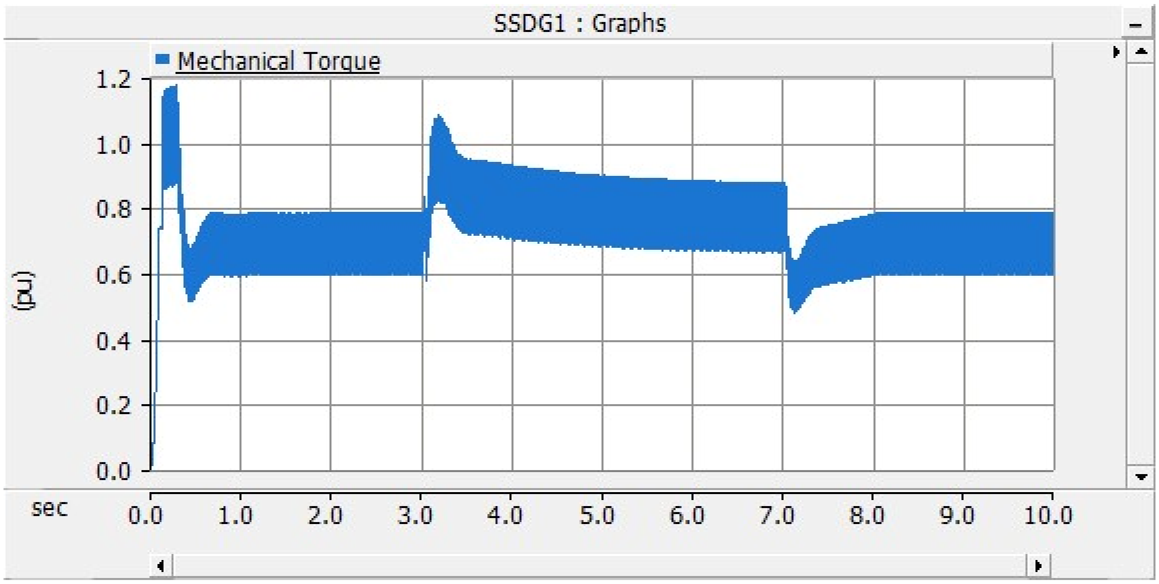


Figure 3.4: Torque Output of 24 Piston Diesel Generator

The torque from this IC Engine is then fed as an input into the generator portion of the model, shown below. The synchronous machine model in PSCAD has many variables that can be manipulated. The base values for this machine are 254Vln or 440Vll, 169A, a rotational frequency base of 376.992 rad/sec (60Hz), and an inertia constant of 1.7 seconds.

The exciter model is set up in standard fashion for a generator model in PSCAD. PSCAD provides several exciter models with slightly different transfer functions. Some are AC exciters and some are static exciter models. The exciter model chosen (AC1A) was chosen because it is both the baseline model and provided sufficient voltage control for the purposes here [10].

The SSDG Loading signal you see above the multi-meter in this diagram represents the data output that is sent to the inverter. This data is then used to determine the ***Iq*** and ***Id*** supplied by the inverter.

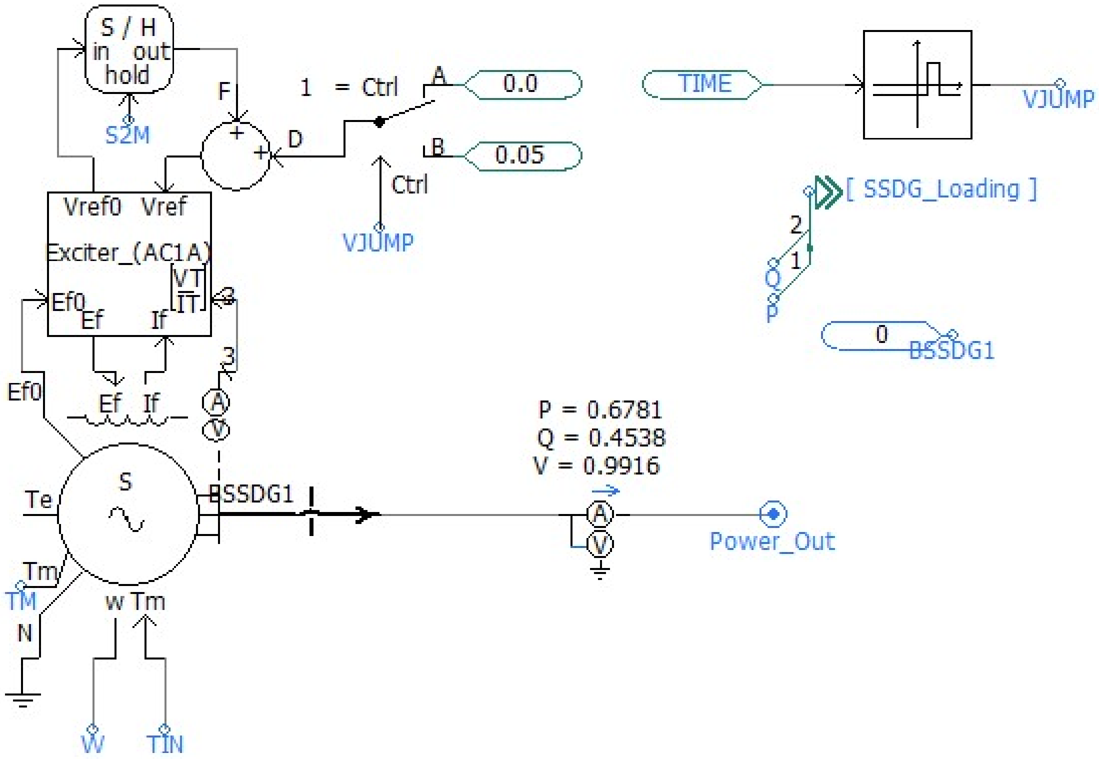


Figure 3.5: SSDG Model with Overexcitation and Breaker Operation

3-3-2 Ships Inverter

The inverter is the most difficult and important model in this system. How the inverter behaves and responds to the changing electrical environment onboard the Construction SHT is the most important data for validation of this model. This model needs to provide an accurate representation of a high power inverter in the quasi steady state domain. Since high frequency distortion is usually filtered out through DG sets before the power is supplied to sensitive electronics, the systems response to frequencies on the order of thousands of hertz is not of critical importance. With this in mind, the inverter is approximated as a current source. This approximation should result in accurate data as long as the system voltage is maintained at the injection point for the inverter, and harmonic distortion is irrelevant to the results [13].

The inverter is modeled as a current source controlled in order to maintain the desired amount of real and reactive power injection into the ships grid. The below figure depicts the inverter. The inverter is a three phase current source with a filtering inductor connected to short, mostly resistive cables, and a y-y transformer (230V_{LL} – 440V_{LL}). The inverter controls are metered at the point where current is injected into the bus.

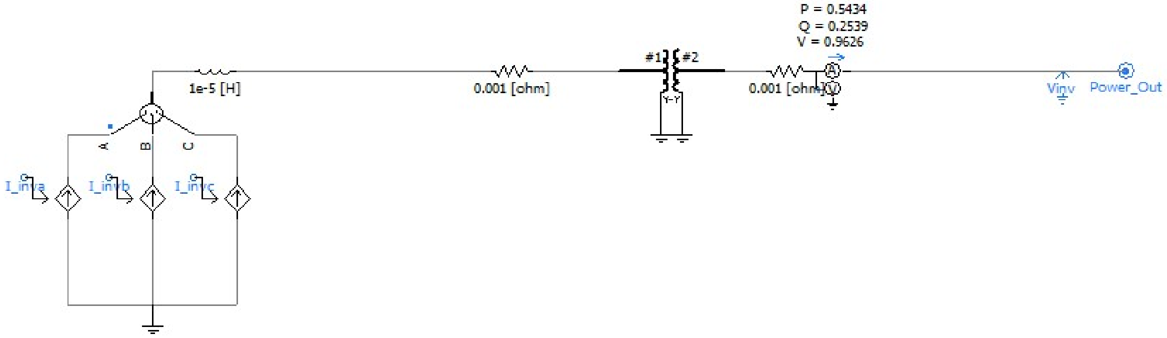


Figure 3.6: Current Source Model of Inverter

The controls system for the inverter, show in **Figures 3.7 and 3.8**, works by taking the error between the desired real and reactive power and processing that error signal through a real pole then a PI controller and adding a delay of .025 sec. This signal is then divided through a voltage correction (for instance lower voltage would imply more current needed to supply the same power) and results in a signal of the desired current *d* (in phase with voltage) and *q* (current that will be 90º out of phase with the voltage) [13].

The reason the controls are set up this way is that the inverter is designed to maintain a rated output from the SSDG. It accomplishes this by supplying real power until the generator is supplying 90% of its rated real power, and increasing/decreasing the supply of reactive power until the SSDG is supplying 90% of it rated reactive power. With this protocol, the inverter rarely supplies much reactive power which is useful because the analysis of the system is mostly done on the real power of the system.

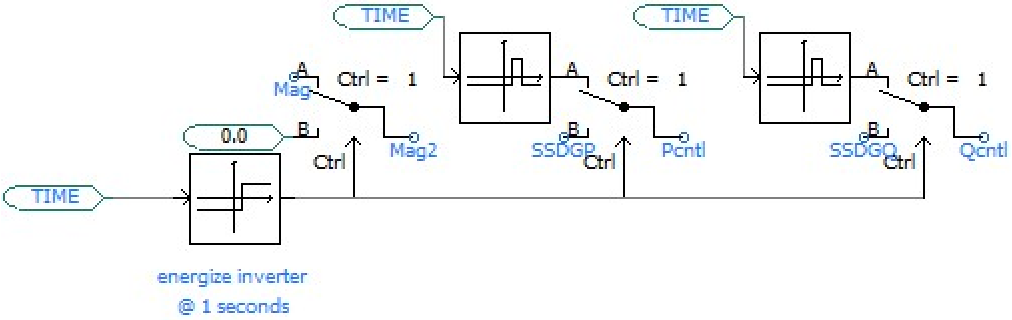


Figure 3.7: Controls System for Inverter (1/2)

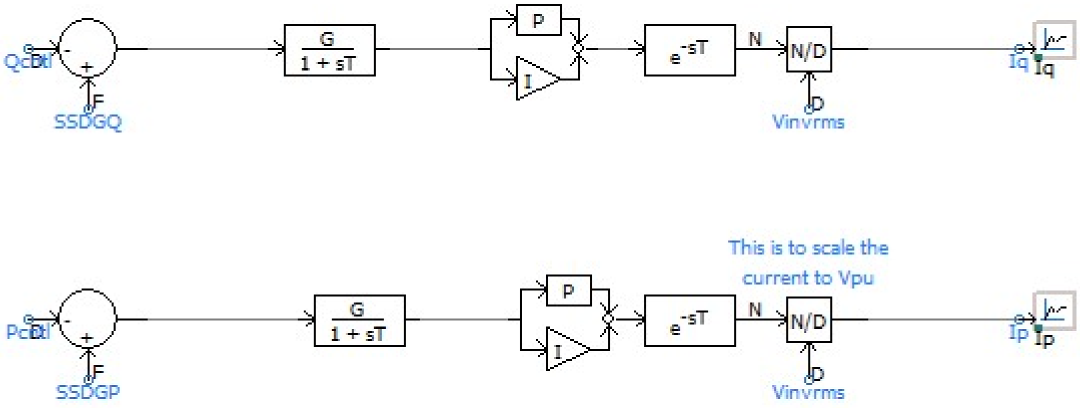


Figure 3.8: Controls System for Inverter (2/2)

The voltage phase is determined through meters and a phase locked loop (PLL) shown in **Figure 3.9**. That phase will be used to produce the desired three phase current waveform. The ***Phi*** value provides the phase of the ***Va*** wave. From this phase the current waveform can be determined by adding the current lead/lag angle. Once that is determined a set of functions will produce the desired current waveform.

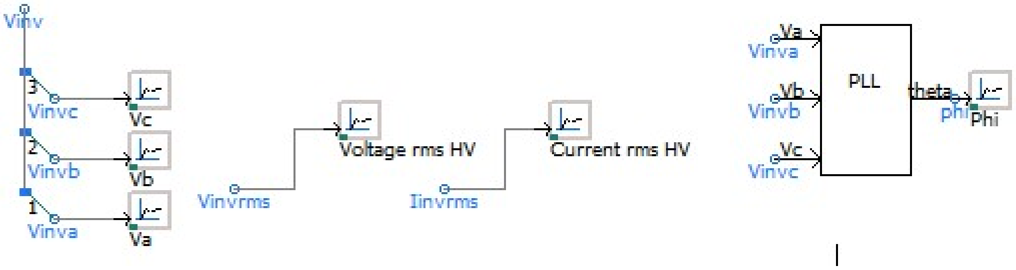


Figure 3.9: Measurements Taken from Inverter

With the control system (that determines ***Id*** and ***Iq***) and the PLL we take the ***Id**, **Iq**, and **Phi*** and convert first to power factor angle, here simply termed ***Ang**,* and the current magnitude ***Mag*** all shown in **Figure 3.10**. With ***Ang*** and ***Mag***, the necessary information on the current waveforms has been determined. The ***Ang*** and ***Mag*** are then used to produce the desired sinusoids shown in **Figure 3.11**.

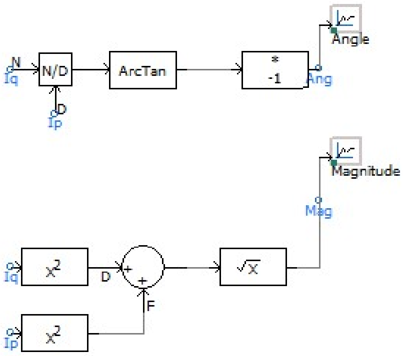


Figure 3.10: Conversion from D – Q domain to Magnitude and Angle

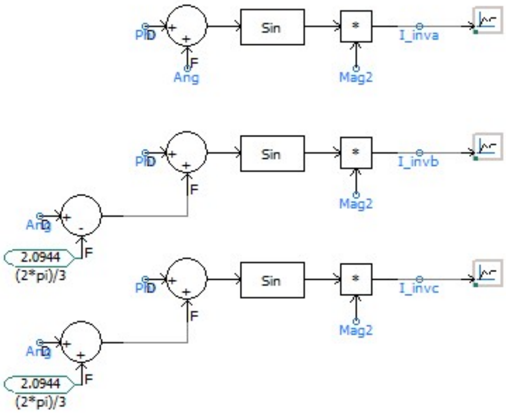


Figure 3.11: Conversion from Magnitude and Angle to Current Waveform

If it were decided that the inverter should be modelled with the 6-pulse bridge and a DC source, the next step would be to compare these three phase current signals to a very high frequency (2500 – 5000 Hz) triangle waveform as shown in **Figure 3.2** [13]. This comparison would then serve as the basis for the opening and closing of the gates on the 6-pulse bridge. If the inverter is modeled as a current source then the signals can directly determine the current supplied from the source on PSCAD.

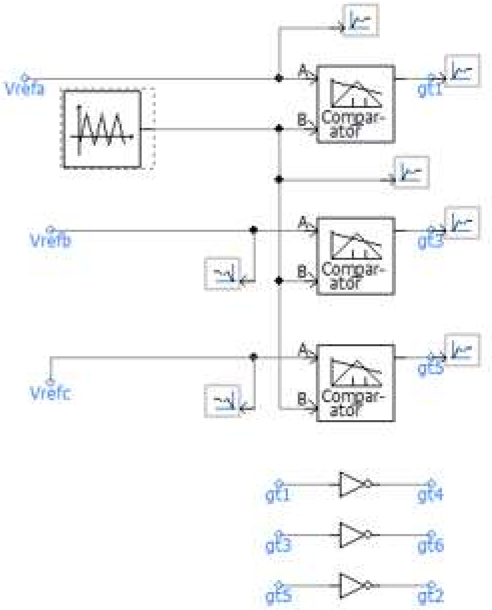


Figure 3.12: Implementation of Gate Switching on Inverter

3-3-3 Load Center Model

These 'Load Centers' represent aggregated loads onboard the ship that are fed by the same cable or the same set of cables. These loads are aggregated for the accurate modeling of line losses, since these loads will be fed by cables rated for the connected load. The load centers also allow for a neat look at the level of the main canvas view on PSCAD.

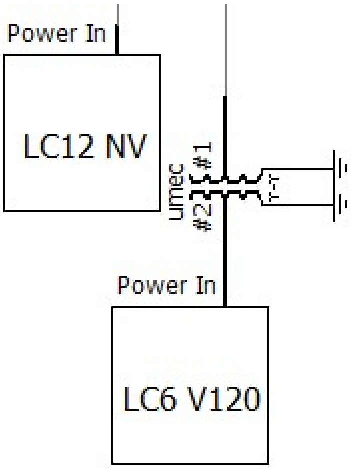


Figure 3.13: Simple view of Two Load Centers

The model for the load center is relatively simple. The model consists of a bus connecting the input (from the power cable) to the load(s). In the simple load centers the load simply consists of a single modeled complex load. This load has constant inputs such as ***P*** and ***Q***. However the load is a function of both the frequency and voltage levels. This dependence on both voltage and frequency is so if the voltage suddenly increases the load will not simply remain constant ***P*** and ***Q*** but will increase as a function of the voltage level squared (this better models a load then a pure fixed ***P*** and ***Q***). The simplest load center is shown below in **Figure 3.14**.

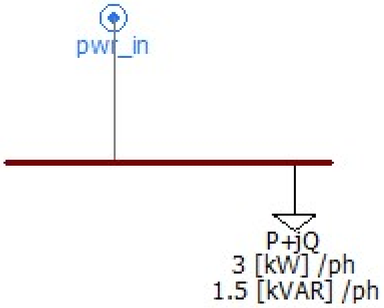


Figure 3.14: Simple Load Center

There are two load centers that have induction motor models attached. It is necessary to model these motors reliably since the motor staring phenomena will be of critical importance to the simulations. Therefor the two largest motors (149kW and 29.8kW) were modeled as induction motors instead of a simple load. Load Center 12 is shown in **Figure 3.15**.

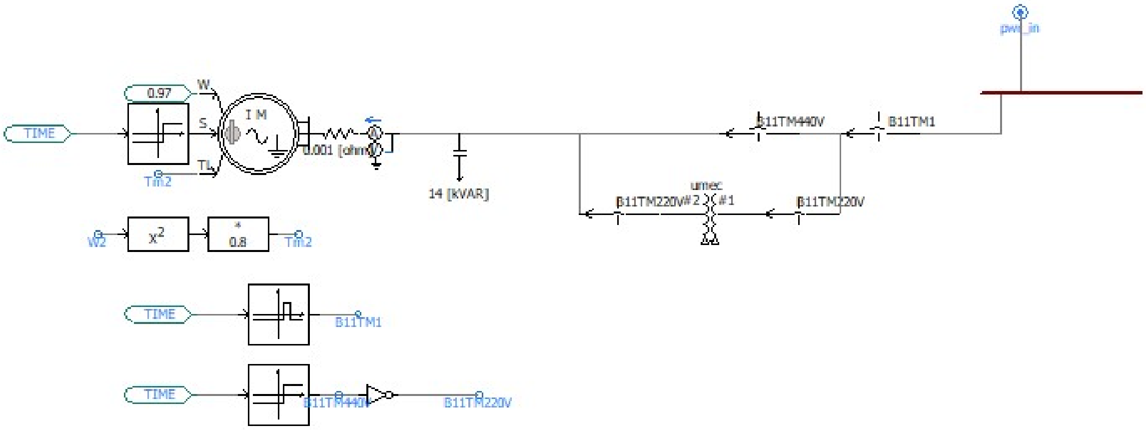


Figure 3.15: View of Load Center 12 with Large Induction Motor

This motor is the most complex motor on the Ship. This is because the voltage dip caused by inrush currents had to be addressed (in Chapter 4). The electric path that has the transformer is a method for reduced voltage starting. The lower path starts the motor at $300V_{LL}$ or about .68 per unit. The 14 KVAR three phase load of a capacitor is attached to the motor to limit the demand on reactive power onboard the ship. Demand for reactive power is usually higher onboard ships than terrestrial applications due to the high prevalence of motors and electric heaters.

3-3-4 Cables Model

There are two main traveling wave models for cables within PSCAD. There is a Frequency Dependent Cable model and the Bergeron Model. It was determined that since extremely small time scale transient phenomena was not the focus, the Bergeron model would be sufficient. The Bergeron model is usually sufficient when line losses are the focus and the power system frequency is assumed to be mostly 60Hz with few harmonics.

Two Bergeron Cable models were developed. The sizing of the 9 cables is shown in the table below. Keep in mind the sizing of these cables was based off of tape shielded underground cables found in Kersting's *Distribution System Modeling and Analysis* [14]. These cable sizes are slightly different then the cable sizes that the line loss calculations were based off of. Since the resistance per mile values were less than the line loss calculation resistance values in all cases, the calculations would be 'safe assumptions' and were kept.

Table 3.1: Amps Rating of LC and Cable Sizing

Cable	Amps Rating	PSCAD Model Conductor UG Tape-Shielded Cable
C1	167.735225	2/0
C4	166.0937894	2/0
C11	255.7389305	350
C16	71.50808935	2/0
C1T3	84.9971153	2/0
C3	167.735225	2/0
C2	166.0937894	2/0
C12	309.4837604	350
C6	56.13385014	2/0

PSCAD has a simple method for building cable models where the spacing, orientation, materials, insulators, sheaths, and armor can be selected. These values were selected based off of the sizes given in [14]. The values of metal were assumed to be aluminum alloy and the values for the insulators were assumed to be the values of polyethylene. However, once the Bergeron model was implemented it became clear that this model would be overkill for the simulations.

Both cable models use traveling wave calculations and since the cables were assumed to be 37m long (the default value for cables is 100km) [10] the traveling wave models required a time step of .3 µs. The default step time is 50 µs (a step time 167 times greater than the one required for the cable models.) additionally the traveling wave models required calculations that further slowed down the simulations. These two complications changed the average simulation time from around 30 seconds to around and hour.

It was determined that since these cables were needed to model line losses over time periods of about 10 seconds, an accurate coupled Pi Model would suffice. PSCAD has an unusual feature where Pi Model code can be autogenerated by the cable model and then imported into the project directory. This was done for both models and then the coupled Pi Models were used instead. An image of a Pi Model (modeling the cable) connected to the load center is shown below.

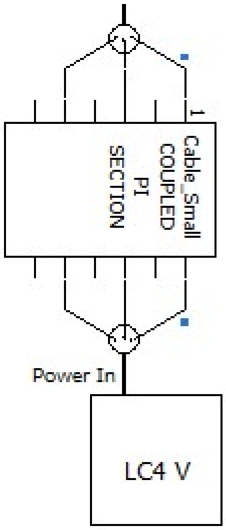


Figure 3.16: Simple View of Coupled Pi-Section Model of Cable

These Pi Models yielded steady state line losses that closely resembled the steady state line losses that were calculated from the simplified I^2 R calculations in excel. The simulations were to ignore much of the transient phenomena in the system and focus more on power flows, power losses, system changes, and voltage drop in the time domain, therefore, coupled Pi Models were deemed sufficient.

3-4 Discussion on Power Protection

Due to both scope of the work and time constraints, no protection systems were modeled on the CONSHT. Protection was seen as beyond the scope of this work for two main reason. The first reason is that for the conventional side of the grid, protection is well defined, understood, and standardized in references [2] [7], and [3]. The conventional side of the grid described here refers to the grid with the exception of the inverter and the LC distribution redundancy discussed in **Section 4-6.** Specifically reference [3] the "ABS Rules for Building and Classing Steel Vessels" section 4-8-2/9 goes into distribution protection, cascading protection, generator protection, load shedding protocol, harmonic distortion protection, and a number of other protection subjects. The conventional side of this grid wouldn't add to the general knowledge of shipboard protection systems in anyway. Additionally the design process covered here does not address protection.

The second reason is that the inverter model included in **Chapter 4** is not specific enough to warrant a modeled protection system. Since the inverter is modeled as a current source, the protection applied to the inverter would have to be implemented differently when applied to an actual inverter. However, the protection of this inverter can be described, and is in the following paragraph, to the same effect.

In addition to the protection usually considered with inverters, there would be a protection against isolation of the inverter from the grid. This protection would be important since the controls system of the inverter is controlled by the power outputs of the generators. If the inverter became decoupled the intended inverter would do all it could to supply the max rated current to the system. Differential protection could be implemented where the current flowing into the inverter transformer (in per unit) would need to be flowing out of the bus or the inverter would shut down and the buss would be isolated through breaker operation. Another protection scheme that could be implemented would be a system response protection. The loads onboard the CONSHT illicit a quick response from the generators as you can see in **Chapter 4**. Therefore if the generating power is above the set point for power output (usually about 103.5 kW per generator) and over a given amount of time such as .2 seconds, the generator loading has not dropped, the inverter could be shut off. This protection would have a slow response time but could be implemented to address problems not covered by other forms of protection.

Another unique aspect of the protection system on the CONSHT could be, if the three largest motors onboard can be safely de-energized at any time, than LCs 11 and 12 can be isolated during any protection operation at the Generator or inverter level. The reasoning behind this is that LCs 11 and 12 account for a combined 209.6 kW of nameplate loading (see **Appendix A**). Due to constraints on the system the max demand from these to LCs will be 179.8 kW. Despite the possibility of these LCs demanding 179.8 kW, they are nonvital systems. Therefor if they can safely be brought offline at any time, then it would make sense to do so when generating capacity is lost for any reason. This would protect the stability of the system. Losing the inverter would drop the generating capacity on the ship by 75 kW but de-energizing LC 11 or LC 12 equipment could drop the load by 29.8 kW (motor #2 on), 150 kW (motor #1 on), or even 179.8 kW (motors #1 and #2 on). This protection could easily be implemented by semiconductor relays and should be a subject of possible future work.

Chapter 4 – PSCAD Simulation Results

4-1 Simulation Information

Below is a quick breakdown of the loading of the CONSHT, organized by operating condition. Only Construction Winter (CON Winter), and Standby Winter are included because they are the most demanding possible loading conditions during daytime (0700-1700) and nighttime (1700-0700) respectively.

It is important to note that in the simulations where the VibraHammer (here referred to as Motor #1) or Crane HPU (here referred to as Motor #2) are ran, they add significant loads to LC12 and LC11 respectively. These different loading conditions will be tested to ensure that the assumptions made in the simple model are met.

Table 4.1: Table of Loading Scenarios by LC

	CON Winter	CON Winter -15%	CON Winter +15%	Standby Winter
LC1	32.34	27.4873	37.1887	25.12
LC11	4.40	3.74	5.06	2.33
LC12	0.00	0	0	0.00
LC16	12.65	10.7559	14.5521	12.58
LC2	11.80	10.0317	13.5723	9.77
LC3	10.82	9.19615	12.44185	10.27
LC4	12.50	10.62415	14.37385	8.02
LC6	11.31	9.609505	13.001095	8.64
	95.82	81.444705	110.189895	76.73

*Additionally Motor #1 adds another 149kW to LC12 and Motor #2 another 29.8kW to LC11

**Assumptions were that all loads were of power factor .85, this assumption ensures that currents are sizable for the given loads

4-2 Power loss verifications

The assumption for power losses is that over the course of any one hour over the ships duration, the total energy (in kWhs) consumed by losses that occur in the distribution of that energy will not exceed 3% of the energy consumed by the load over those same hour. More simply put the assumption is that for any given amount of energy consumed by the load over an hour, the energy lost in the lines and transformers (in distribution) will not exceed 3% of that load energy. Since the load analysis is done at the terminals of the loads, the losses that occur within the loads (for example mechanical losses in a motor) are factored into the load values themselves. It is for this reason that ‘losses’ can be simplified down to distribution losses.

An even more specific case of this 3% loss assumption could be that, ignoring transients or short lived phenomena in the system, the power losses never exceed 3%. In order to disregard short lived phenomena it must be shown that this phenomena is the exception that proves the rule. The way this is shown is by smoothing the signal through a moving average. In all loading cases a graph is provided of the instantaneous power losses (as calculated by the model) and another graph containing a smoothed signal is provided afterwards. This smoothed signal is calculated by smoothing out (taking the mean of) the power lost over the preceding and following 12.5 mSec, and the power consumed by the load over that same time and dividing. This is shown below where k is the sample from the simulation and there are 100 samples per 25ms.

$$LOSS\ SMOOTH_k(\%) = 100 \times \frac{\sum_{k-49}^{k+50} Ploss_k}{\sum_{k-49}^{k+50} Pload_k} \tag{9}$$

This LOSS SMOOTH signal represents the averaged losses of power over any 25ms. If these losses do not exceed 3% for the most demanding scenarios, then more generally the energy losses will not exceed 3% and the assumption is safe.

The advantage to a ships grid is that the worst possible loading scenarios can be know beforehand. On this particular ship there are only 61 loads separated into 8 load centers. There are only 3 loads that exceed 20% of the capacity of an SSDG, and the worst inrush currents are known to come from the energizing of motor #1.

Therefore the worst loading condition isn’t an exercise in abstraction but is instead a knowable determinable value. Below are the results of the simulations in different scenarios. The assumption is that if the average power losses never exceed 3% over a 25ms period, then the energy losses are certainly under 3%.

4-2-1 Construction Winter Scenario with Loading +15%

This first scenario is the Construction Winter scenario with the largest three motors offline. But all other loading is 15% greater than the average loading during this time.

As you can see below, due to the nature of the load models used in PSCAD, at the beginning of every scenario there is a spike of losses that tops 5-7%. However these losses never survive the smoothing.

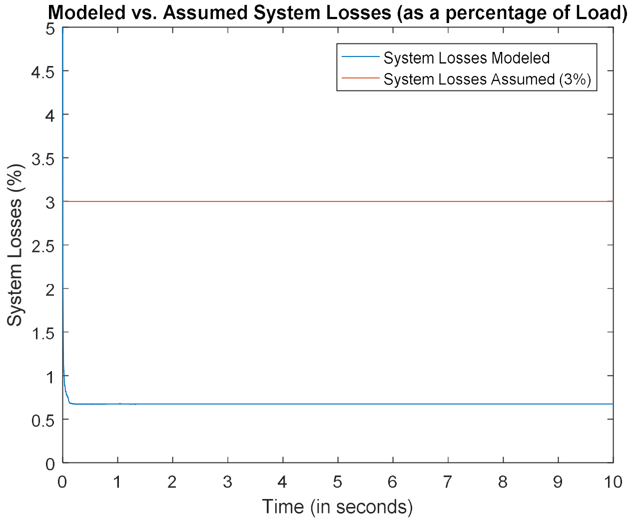


Figure 4.1: System Losses

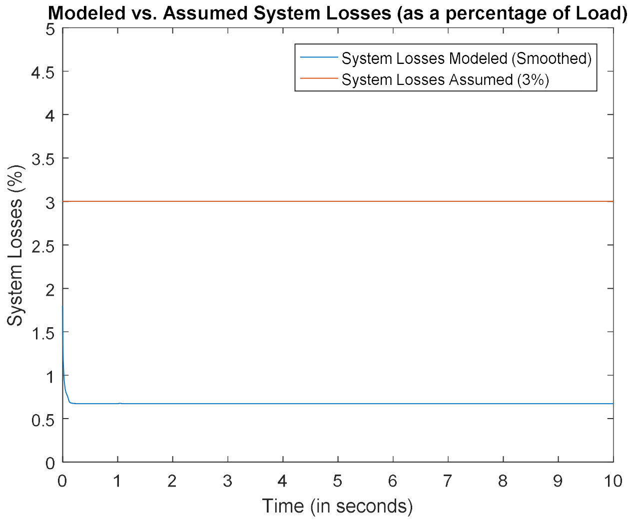


Figure 4.2: System Losses Smoothed

As you can see in the above figure, the initial spike of losses are reduced to 1.75% when smoothed, and at steady state the losses barely exceed .7%.

4-2-2 Standby Winter Scenario

The standby Winter scenario is once again based off of **Table 4.1**. The losses once again exceed 5% but are greatly reduced when averaged over 25ms.

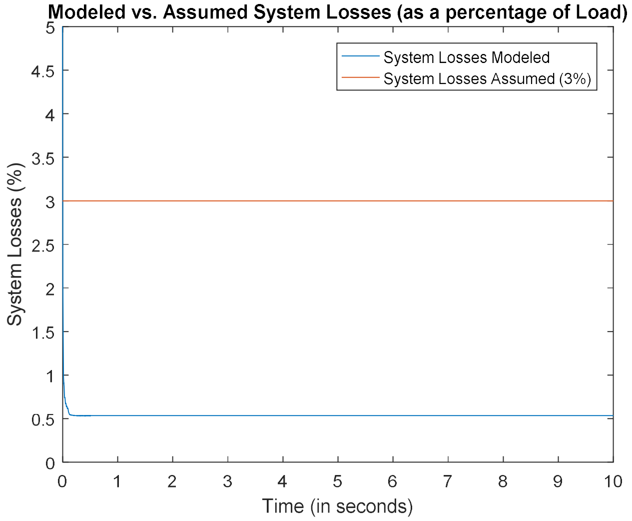


Figure 4.3: System Losses

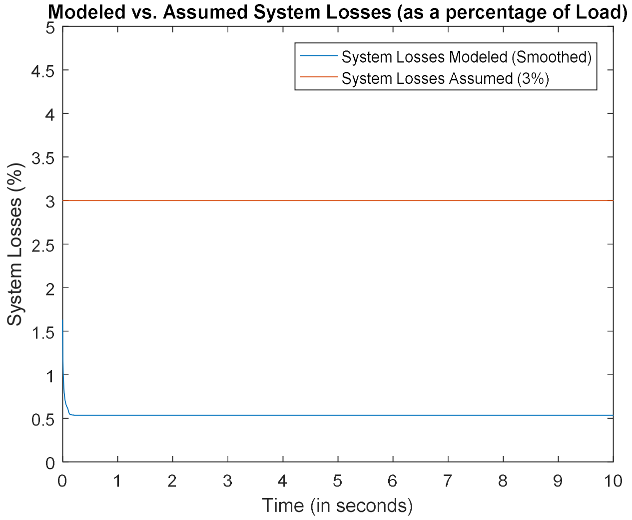


Figure 4.4: System Losses Smoothed

The losses in steady state are just above .5%.

4-2-4 Construction Winter Scenario where Motor #2 is Energized

In this scenario the loading is what is expected during Construction Winter and Motor #2 is brought online at 2 seconds and offline at 8 seconds. Only one SSDG is online in this scenario. With the exception of the initial spike in losses, the unsmoothed losses never exceed three percent.

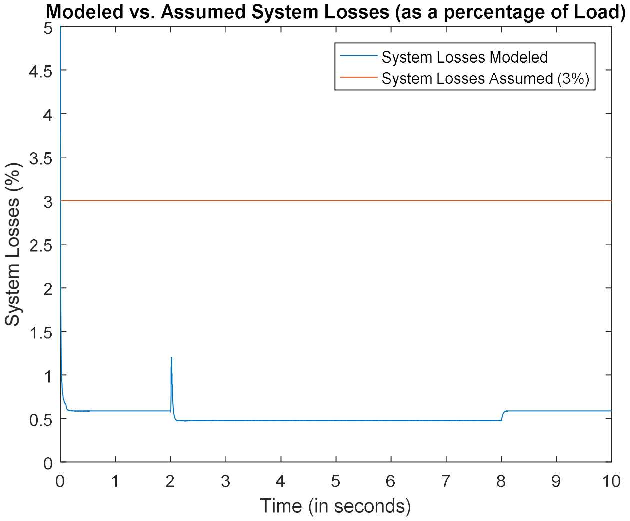


Figure 4.5: System Losses

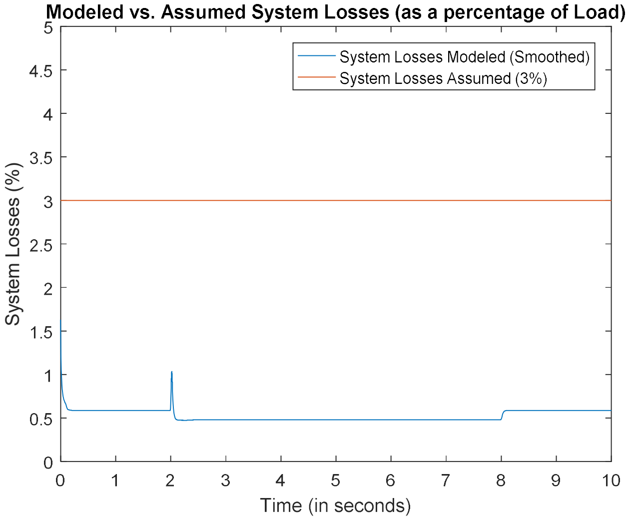


Figure 4.6: System Losses Smoothed

The smoothed signal peaks out at about 1% losses when the motor is brought online, but at all other times the losses are between .4-.6%.

4-2-6 Construction Winter Scenario with Motor #1 Energized

This scenario is the same as above except Motor #1 is being brought online, and both SSDGs are online. As can be observed the instantaneous power losses from the simulation do exceed 3% briefly when the motor is energized.

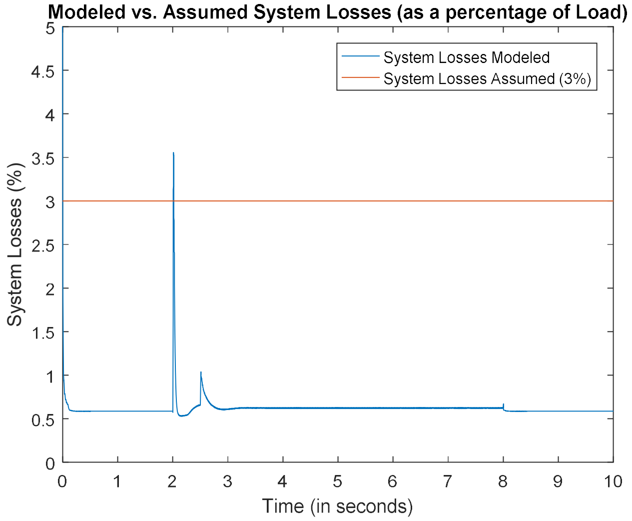


Figure 4.7: System Losses

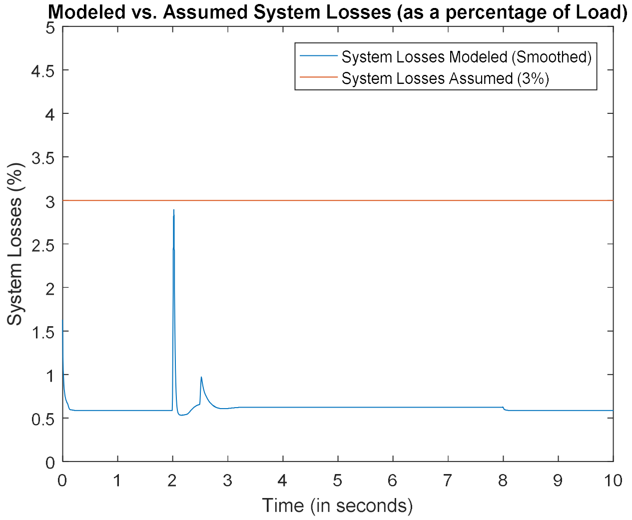


Figure 4.8: System Losses Smoothed

However, when the signal is smoothed the average power losses over any 25ms period are below 3%.

4-2-7 Construction Winter Scenario with Motors #1 & #2 Energized

This scenario is the same as above except motor #2 is brought online at 3 seconds and offline at 7 seconds. Motor #1 is brought online at 2 seconds and offline at 8 seconds. As what occurred above, the observed power losses momentarily exceed 3%, but that exception vanishes when the signal is smoothed.

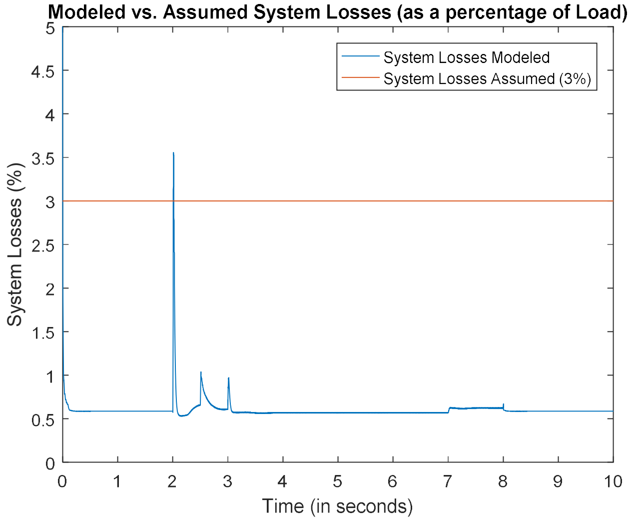


Figure 4.9: System Losses

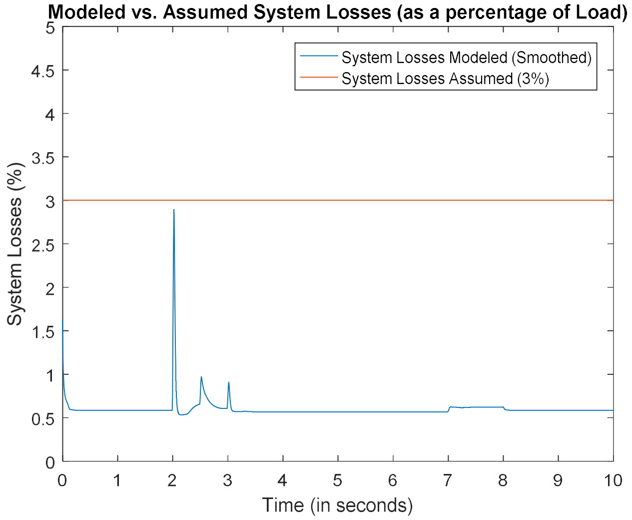


Figure 4.10: System Losses Smoothed

4-3 Inverter and Battery Power Verification

The process for validating the inverter assumptions in the simplified model is a little more cumbersome. The assumption of the simplified model is, simply put, that the energy supplied by the inverter will be less than the energy assumed in the simplified model. The energy that is assumed to be provided by the inverter is the energy of the load, plus the three percent for losses, minus 90% the rated power of the online generators. This 90% is there to increase fuel efficiency and to allow for excess capacity to handle unexpected changes in load. This assumption is shown below.

.

$$Einverter \leq (Eload \ \times 1.03) - \ .9 \times Egencapacity \qquad (10)$$

Since the data that PSCAD provides is an array of values, the energy above can be represented as

$$\sum_{1\ hour} Pinverter_k \leq 1.03 \times \sum_{1\ hour} Pload_k - \sum_{1\ hour} Pgencapacity \qquad (11)$$

Where ***Pgencapacity*** is constant and ***Pload$_k$*** and ***Pinverter$_k$*** represent different samples of these respective values over the course of an hour. Instead of proving that this is the case for every hours' worth of loading possible, samples of the most challenging ten second periods will be shown to exhibit the property below.

$$0 \leq \sum_{10\ seconds} (((1.03 \times Pload_k) - \ Pgencapacity) - Pinverter_k) \qquad (12)$$

If it can be shown that the above property holds true for ten second periods in steady state. And that, additionally, this property holds true in challenging periods of change then the assumptions made in the simplified Matlab model will be validated.

Since a 72 hour simulation on PSCAD is not realistic, challenging loading situations will be simulated over 10 seconds. If the inverter energy assumptions hold true over all the most challenging 10 second simulations, then the more general case assumption over 72 hours should hold true. The analysis done in this section is looking at the predicted inverter power output and comparing it to the modeled inverter power output.

The difference between these two signals is calculated. This difference represents the assumed minus the modeled power output of the inverter. Therefore a positive signal represents less power being consumed then predicted in the simplified model where a negative signal represents just the opposite. Since there are times when the inverter is supplying more power than predicted, particularly when a motor or large load is de-energized, the signal is integrated. The reason for this integration is that the assumptions for the inverter are in the energy output. Therefor the signal is integrated and converted to kWh. This is done by integrating using the trapezoidal method, which of course is an estimate but a good one since there are 4,000 samples per second. This means that the integrated signal represents the amount of energy that the inverter was assumed to provide but did not. Therefore a positive integral would imply that the inverter has provided less energy than assumed and the assumptions made in the design process are safe.

This process is the exact same for the analysis of the battery with one exception. That exception is that the power from the modeled inverter is divided by the efficiency curve below. This efficiency curve is built from data provided by Go Solar California on the Yaskawa Solectria Inverter [9]. This inverter was chosen because it was the right size (75kW) and had a good yet believable weighted efficiency of 97%.

The power output assumed by the simplified model is built from the inverter power output but is divided by 93.5% (the 10% efficiency value on the Yaskawa inverter) when the power output is less than 10% rated, and divided by 96.5% (the 100% efficiency value on the Yaskawa inverter) when the power output is greater than 10% rated. These battery power output signals are then put through the same analysis.

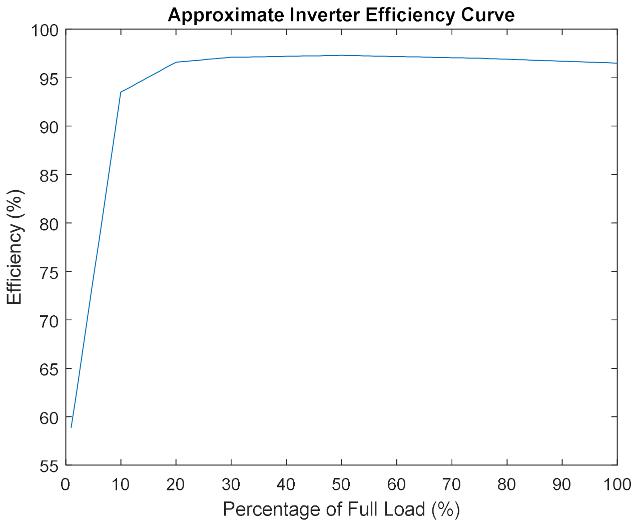


Figure 4.11: Inverter Efficiency Curve for CONSHT Inverter

4-3-1 Construction Winter Scenario with Motor #2 Energized

In this simulation Motor #2 is run for 8 seconds. This is so the inverter output can approach its steady state condition. As is demonstrated in this simulation, the approximated steady state power output of the inverter is greater than the modeled steady state output. Therefore the longer the motor is run, the greater the difference between the assumed and modeled energy outputs.

Figure 4.12 below depicts the assumed inverter power output compared to the modeled inverter power output.

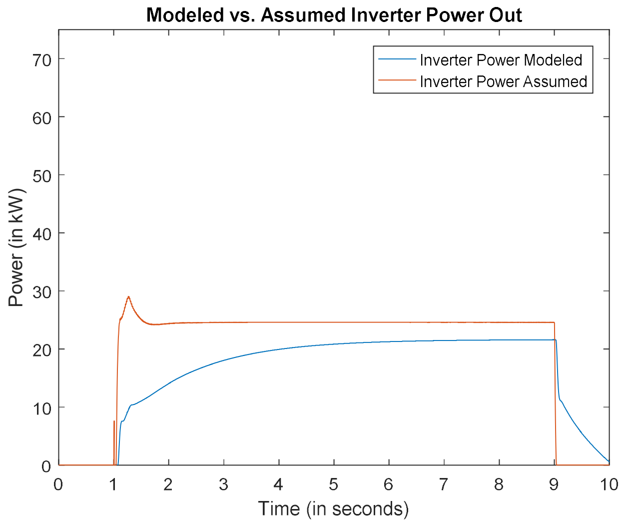


Figure 4.12: Assumed vs. Modeled Inverter Power

Figure 4.13 is just the difference between these two power outputs.

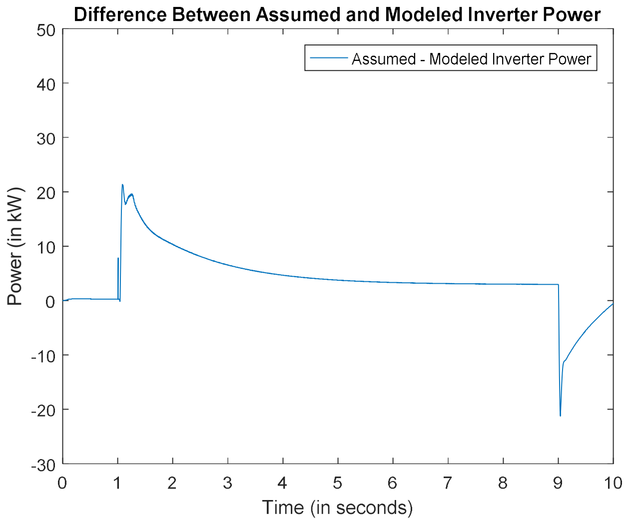


Figure 4.13: Assumed – Modeled Inverter Power

The difference is integrated in the figure below. This therefore represents how much energy was assumed to be used by the inverter but wasn't in the simulation.

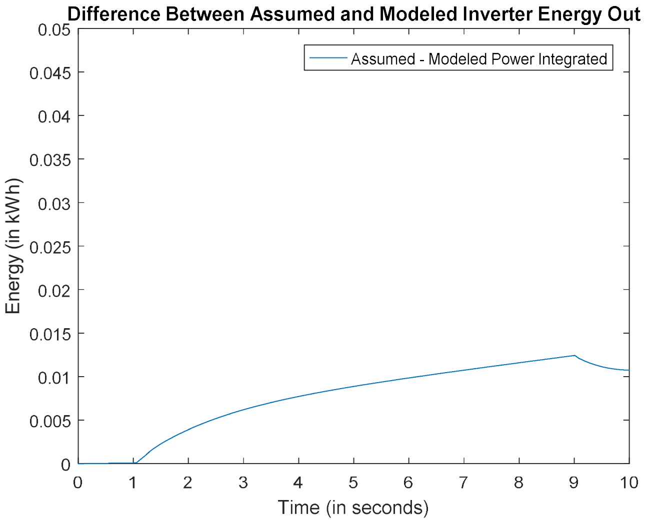


Figure 4.14: Energy Preserved as Compared to Simplified Model

Figures 4.15, 4.16, and 4.17 are the same but looking at the assumed and modeled battery outputs as opposed to the inverter outputs.

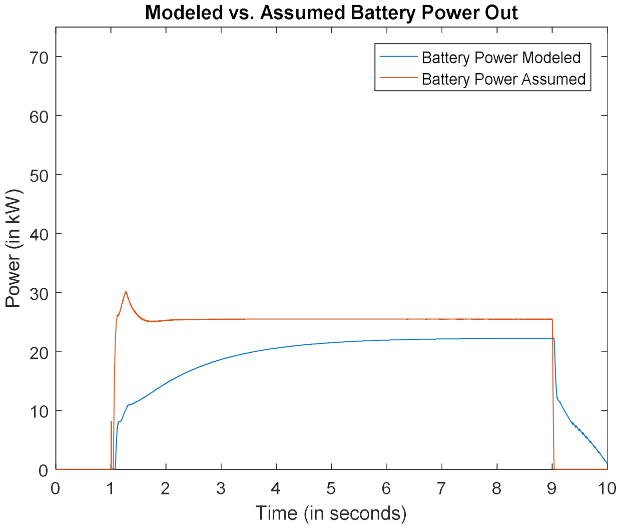


Figure 4.15: Assumed vs. Modeled Battery Power

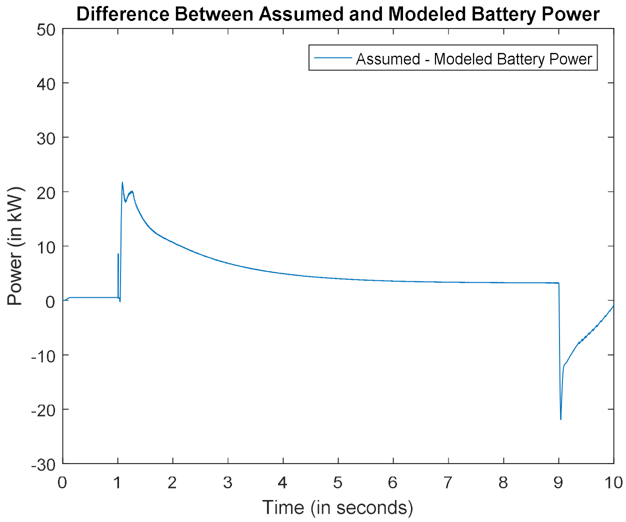


Figure 4.16: Assumed - Modeled Battery Power

Since the whole point of the simplified model assumptions is to properly size the batteries based off of load data and generator data, the **Figure 4.17**, below, is the most important in verifying our assumptions. Fortunately this figure shows that when the motor is brought online, the assumed energy needed for the battery is more than is actually needed. Even after reaching steady state there is consistently less energy drawn from the batteries than assumed. When the motor is brought offline, slightly more energy is needed then assumed but so little that after running the motor for 9 seconds, there is an excess of about 10 watt hours of energy in the batteries.

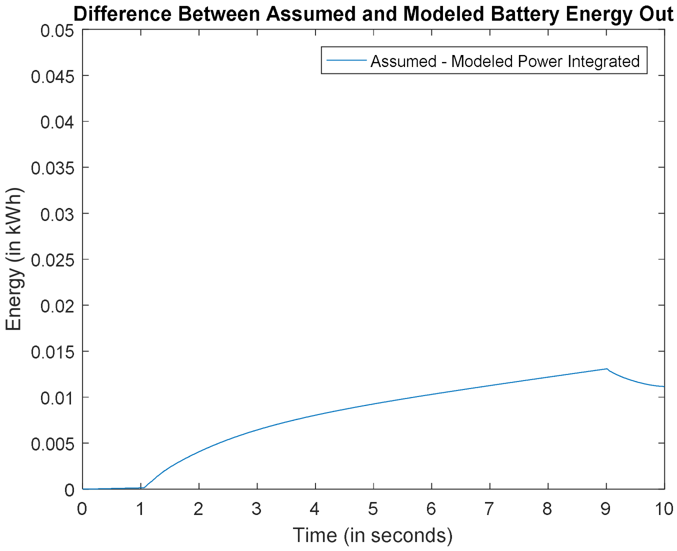


Figure 4.17: Energy Preserved as Compared to Simplified Model

4-3-3 Construction Winter Scenario with Motor #1 Energized

Below is the same analysis as above but with the largest motor, Motor #1, being energized as opposed to motor #2. The figures all represent the same quantities as in 4-4-2.

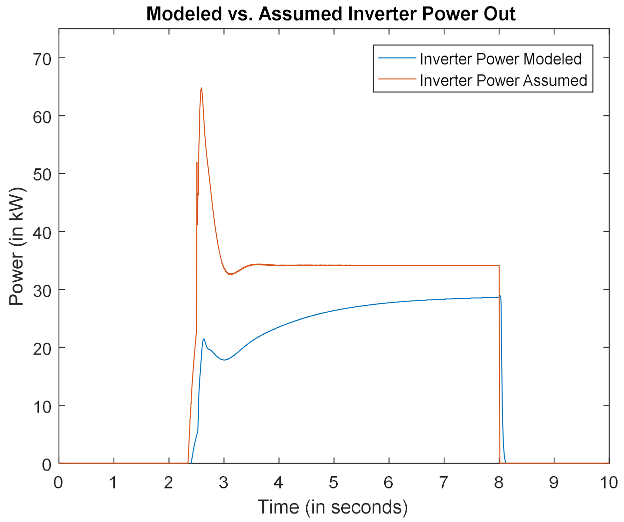


Figure 4.18: Assumed vs. Modeled Inverter Power

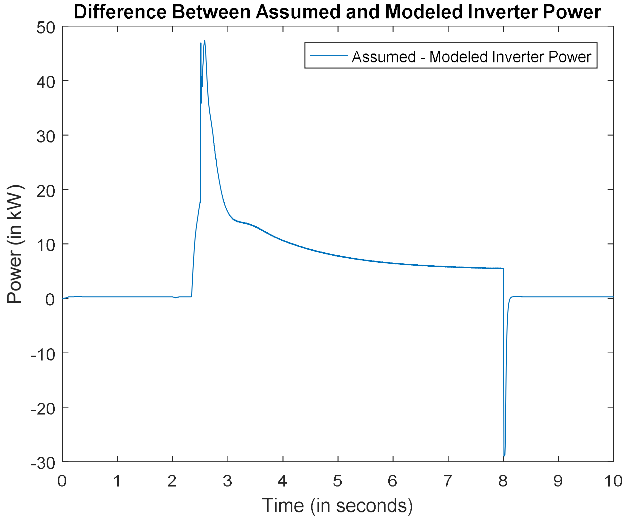


Figure 4.19: Assumed – Modeled Inverter Power

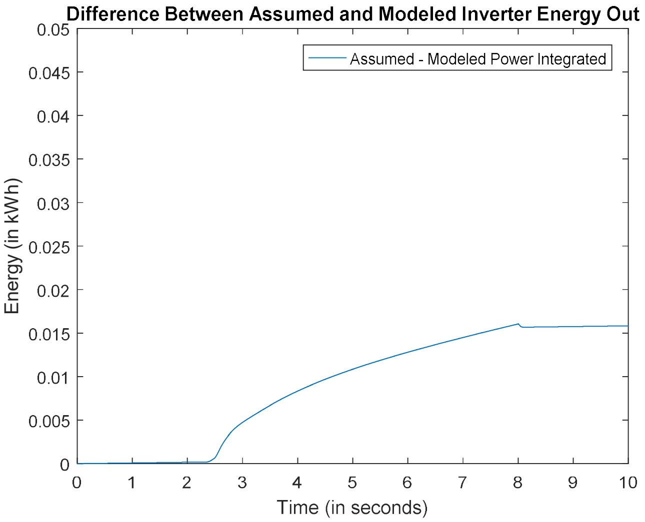


Figure 4.20: Energy Preserved as Compared to Simplified Model

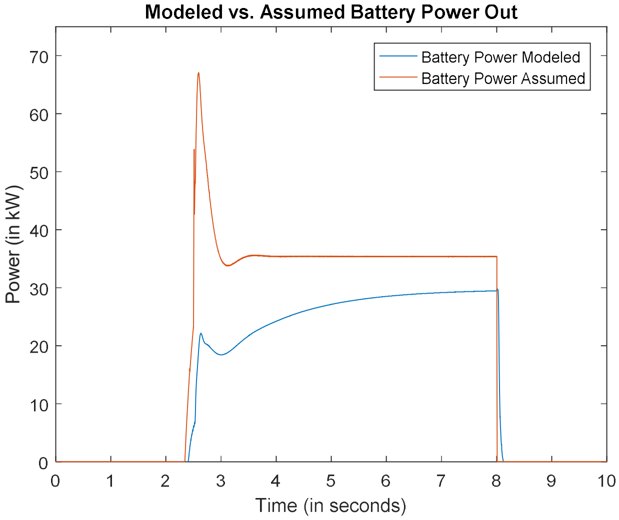


Figure 4.21: Assumed vs. Modeled Battery Power

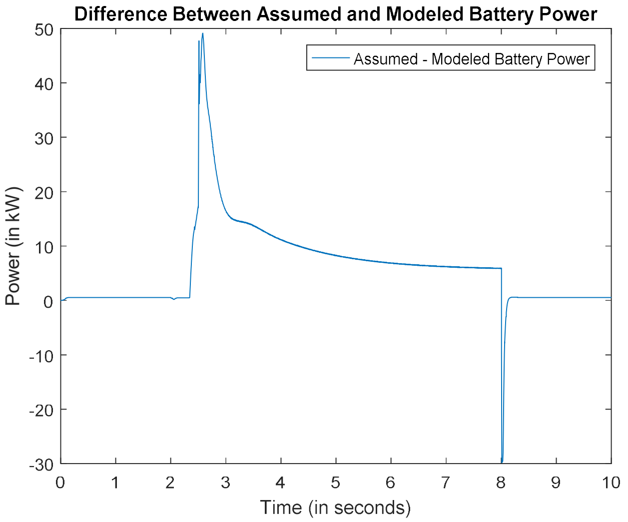


Figure 4.22: Assumed – Modeled Battery Power

As shown in **Figure 4.23** running motor #1 for only six seconds results in 15 watt hours less demand than assumed in the simplified model.

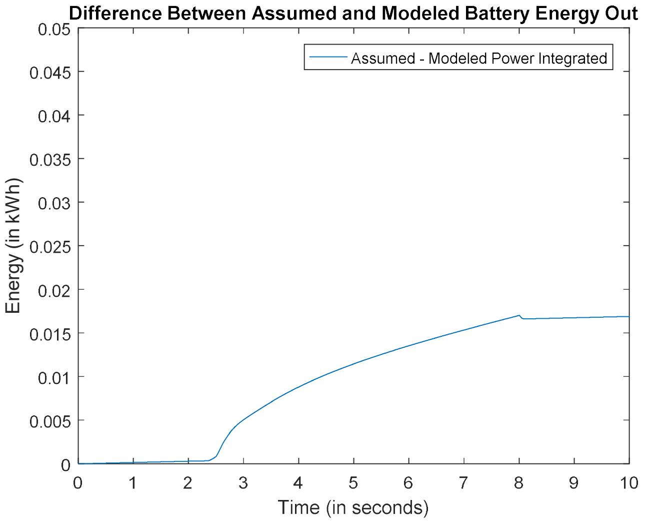


Figure 4.23: Energy Preserved as Compared to Simplified Model

4-3-4 Construction Winter Scenario with Motors #1 and #2 Energized

This analysis is done with both Motor #1 and #2 being energized and de-energized.

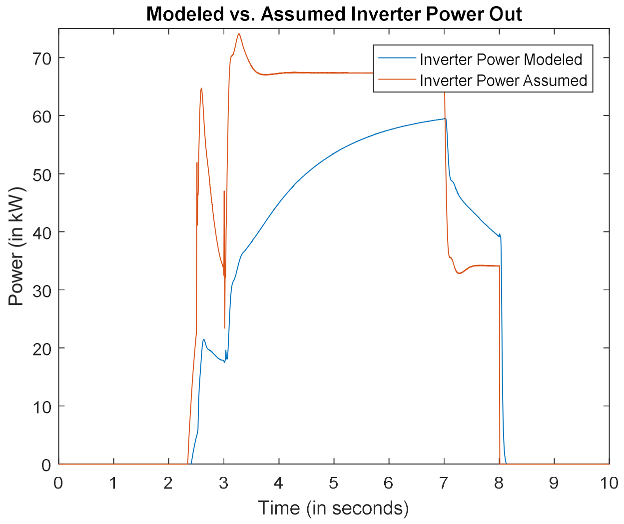


Figure 4.24: Assumed vs. Modeled Inverter Power

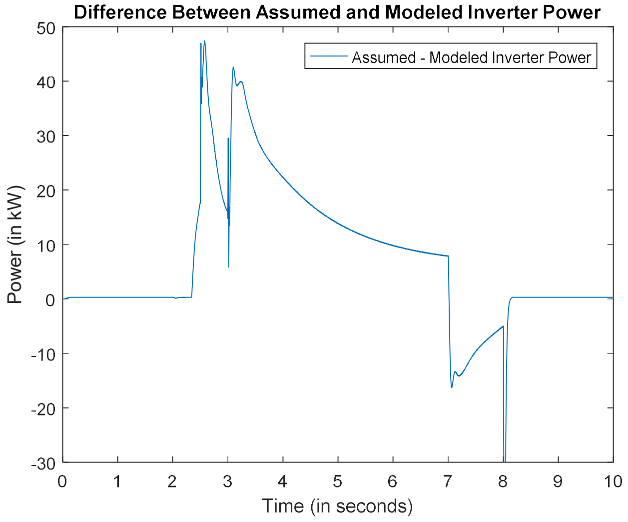


Figure 4.25: Assumed – Modeled Inverter Power

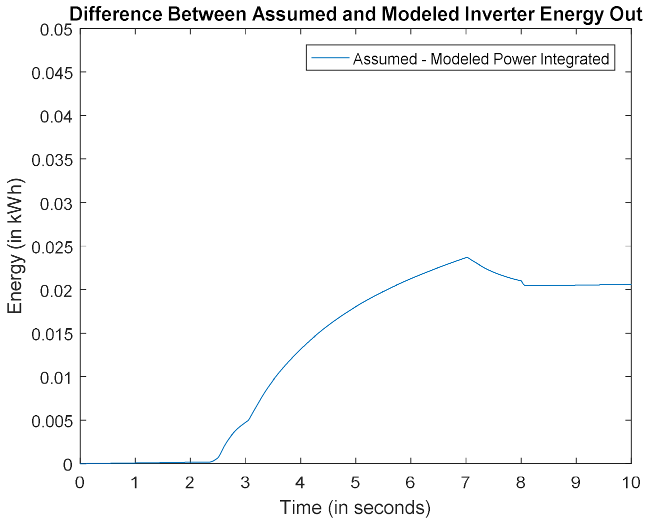


Figure 4.26: Energy Preserved as Compared to Simplified Model

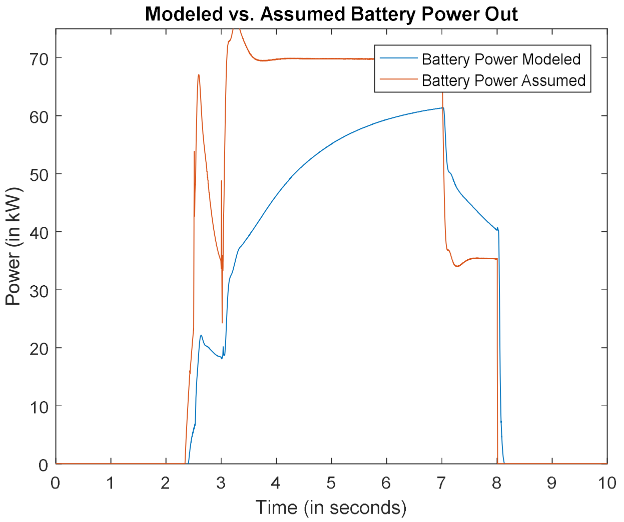


Figure 4.27: Assumed vs. Modeled Battery Power

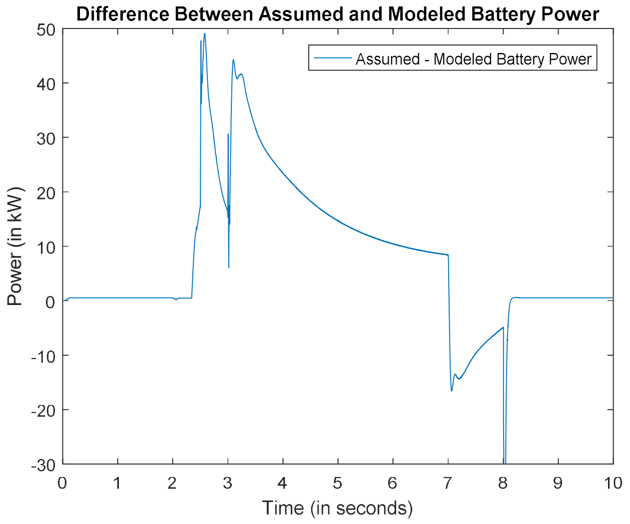


Figure 4.28: Assumed – Modeled Battery Power

Once again, **Figure 4.29** shows that about 20 watt hours less energy is used than was originally assumed. In the steady state less power is demanded from the inverter than assumed. This means that if the motors are run for even longer, there assumptions made in the simplified model will continue to be validated.

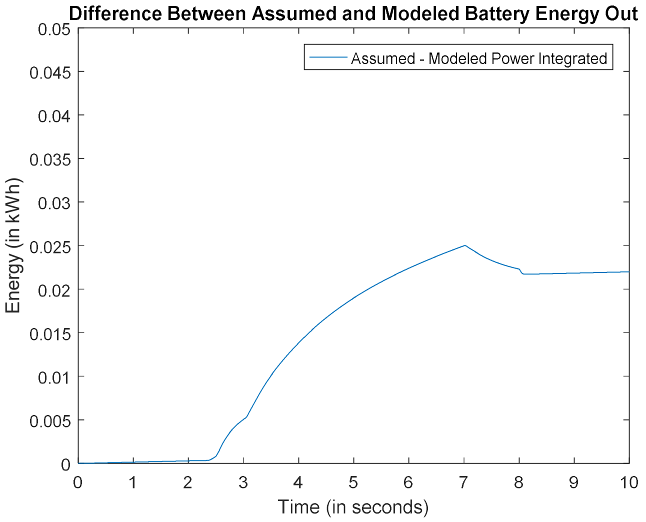


Figure 4.29: Energy Preserved as Compared to Simplified Model

4-4 Verification of system design

For the verification of the systems design two different situations were analyzed. In almost all steady state situations the system remained stable and was capable of sufficiently providing for the load. The situations that provided challenges were, voltage control when energizing Motor #1, and, additionally, meeting the N – 1 criterion.

4-4-1 Discussion on voltage control with 1&2E

When energizing the largest two motors, voltage control became an issue. The ABS Rules for Building and Classing Steel Vessels provide the most explicit requirements on voltage control onboard steel hull vessels. Section 3.13.2(c) states that "Momentary voltage variations are to be within the range of −15% to +20% of the rated voltage, and the voltage is to be restored to within ±3% of the rated voltage in not more than 1.5 seconds [3]."

The figure below shows the voltage measured at the buss when the largest motor is energized at 2 seconds and the second largest motor is energized at 3 seconds.

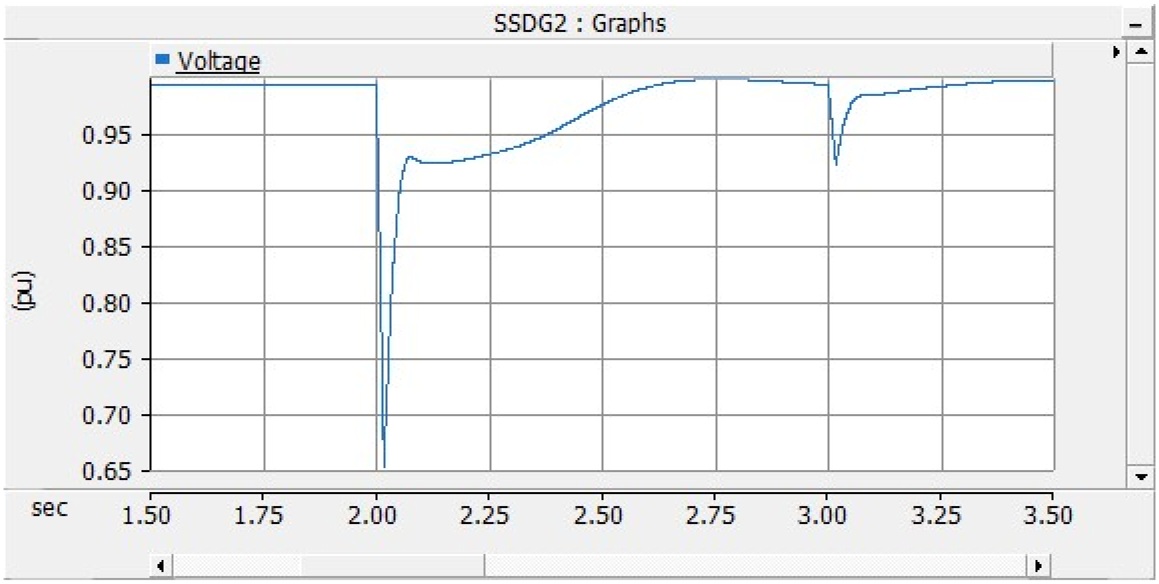


Figure 4.30: Voltage Dip Due to Energizing the Largest Motor

The voltage momentarily dips to around .65 per unit, or about a 35% drop. And the voltage remains below .95 per unit for around .37s.

The figure below shows the same motor starting scenario except the motor is energized with a reduced voltage starter. This would normally be accomplished with a wye delta starter or an autotransformer but the autotransformer models on PSCAD proved troublesome. Instead breaker operation allows the largest motor to be started through a 440-300V_{LL} delta-delta transformer then brought up to normal voltage after .25 seconds. This can be viewed in Chapter 3. The results are shown below.

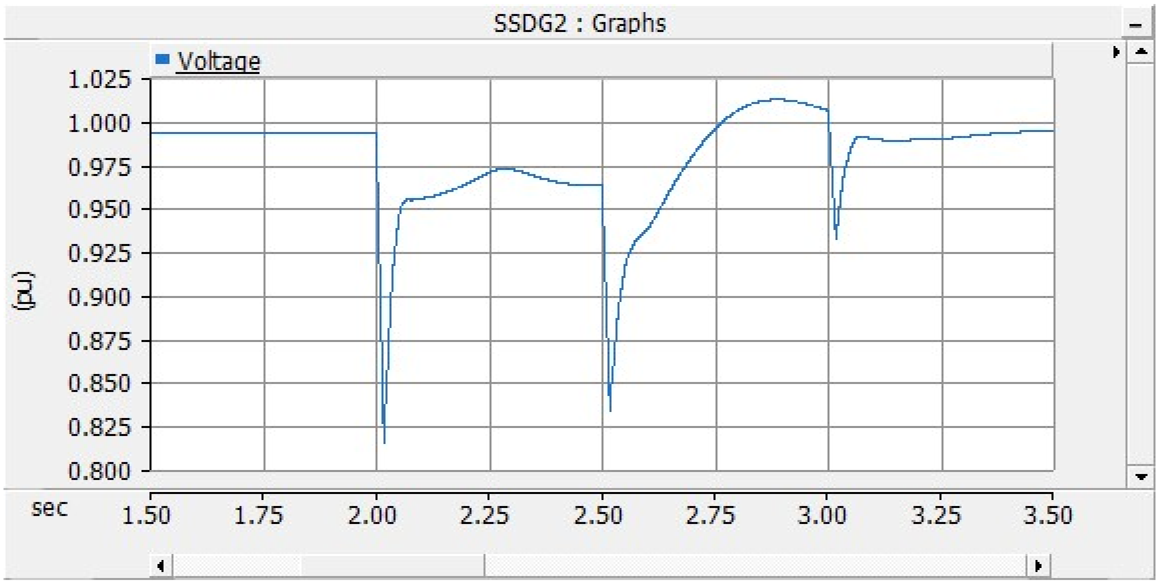


Figure 4.31: Voltage Dip When Reduced Voltage Starting is implemented

As can be observed, the voltage drop is now reduced to a little over 18% and the voltage is only below .95 per unit for around .05 seconds.

In order to further reduce the voltage drop the exciter is momentarily overexcited. Since the exciter models used are built in to PSCAD, the method for overexcitation is shown below.

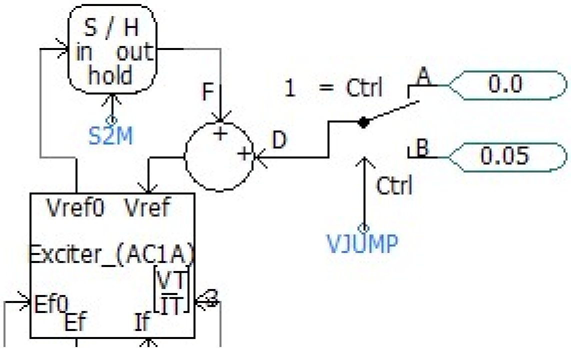


Figure 4.32: Implementation of Overexcitation on the SSDG

This causes the reference voltage to momentarily surge by 5%. However the original reference voltage is quickly restored so that the system can remain as close to the designated nominal voltage as possible. The results of adding this momentary overexcitation are shown below.

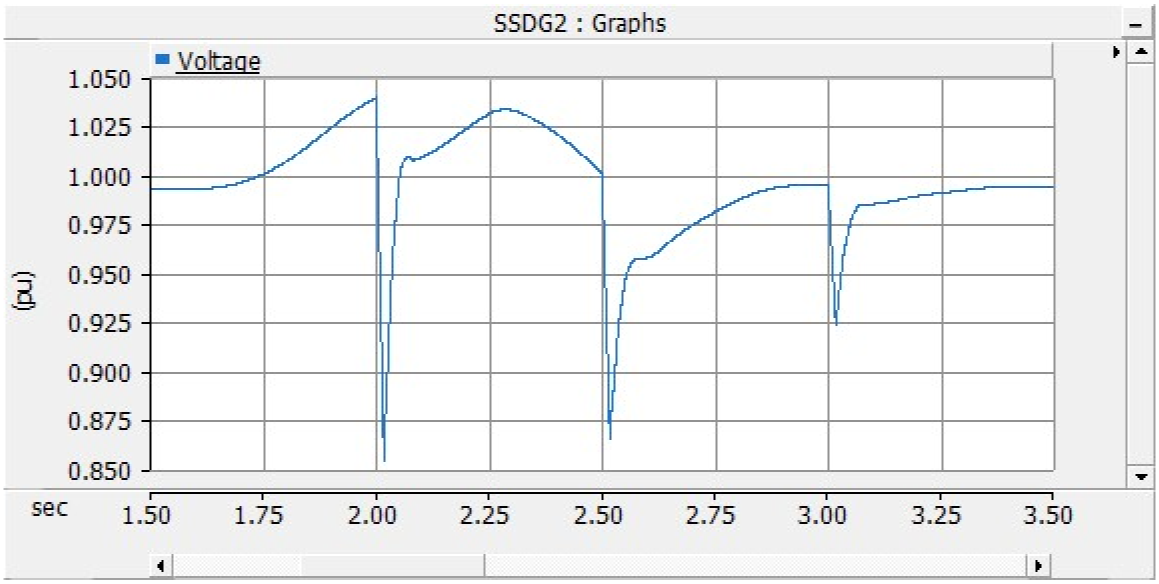


Figure 4.33: Resultant Voltage when Methods are Used for Regulatory Compliance

The voltage now remains within 15% of the rated voltage at all times and remains below .95pu for less than .05 seconds. Therefore with the above two methods employed, the voltage is brought within regulations.

4-4-2 Discussion on N-1 Criterion

The ABS Rules for Building and Classing Steel Vessels state in 4-8-2/3.1.2 that "In selecting the capacity of a generating set, particular attention is to be given to the starting current of motors forming part of the system. With any one generator held in reserve as a standby, the remaining generator sets, operating in parallel and initially carrying the loads in 4-8-2/3.1.1, are to have sufficient capacity with respect to the largest idle essential motor on the vessel so that the motor can be started and the voltage drop occasioned by its starting current will not cause any already running motor to stall or control equipment to drop out. The limits of transient voltage variation under suddenly-applied loads are to be in accordance with 4-8-3/3.13.2(c) [3]."

The loads mentioned in the above paragraph are the same loads to supply essential services and conditions of minimum habitability that were reviewed in Chapter 1. In order to validate the compliance with the N – 1 criterion, the design was shown be hyper-compliant when the inverter was viewed as a source for generation. This was demonstrated by simulating bringing the second largest motor online (over 2x larger than the largest **essential** motor) with the average load during construction winter conditions already online.

Figure 4.34 shows the power output of the inverter as the motor is brought online.

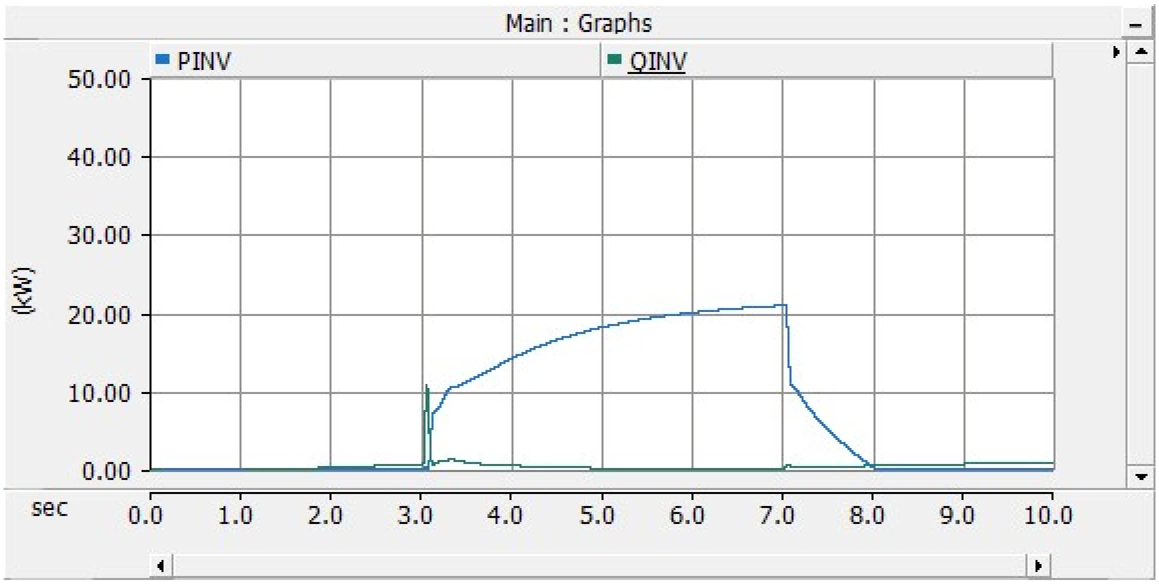


Figure 4.34: Power Output of Inverter during N-1 Situation

Figure 4.35 shows the power output from the remaining SSDG.

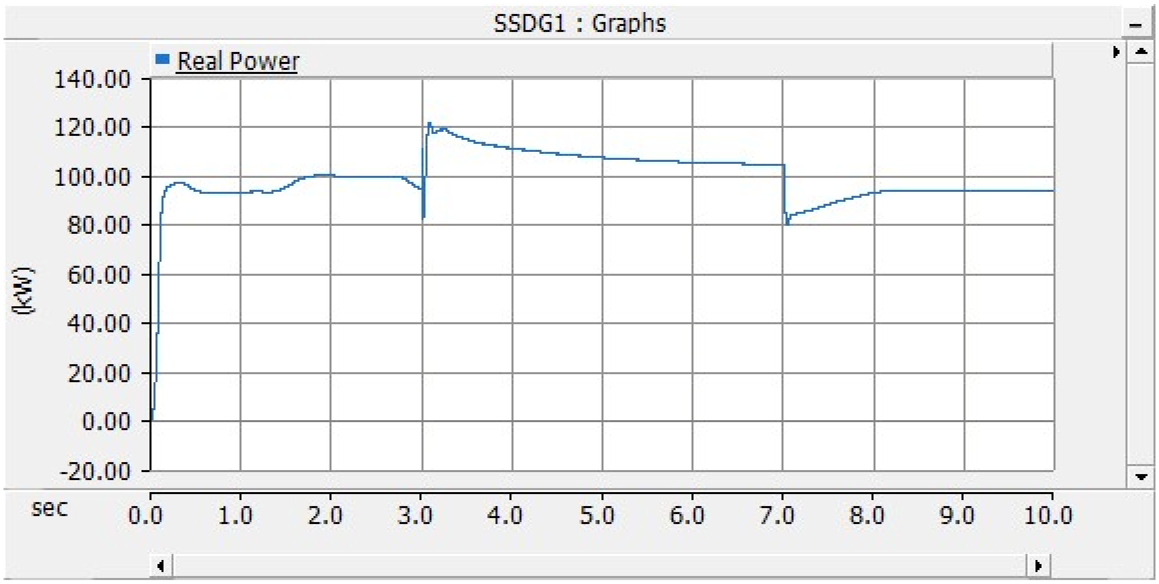


Figure 4.35: Power Output of SSDG1 in N-1 Situation

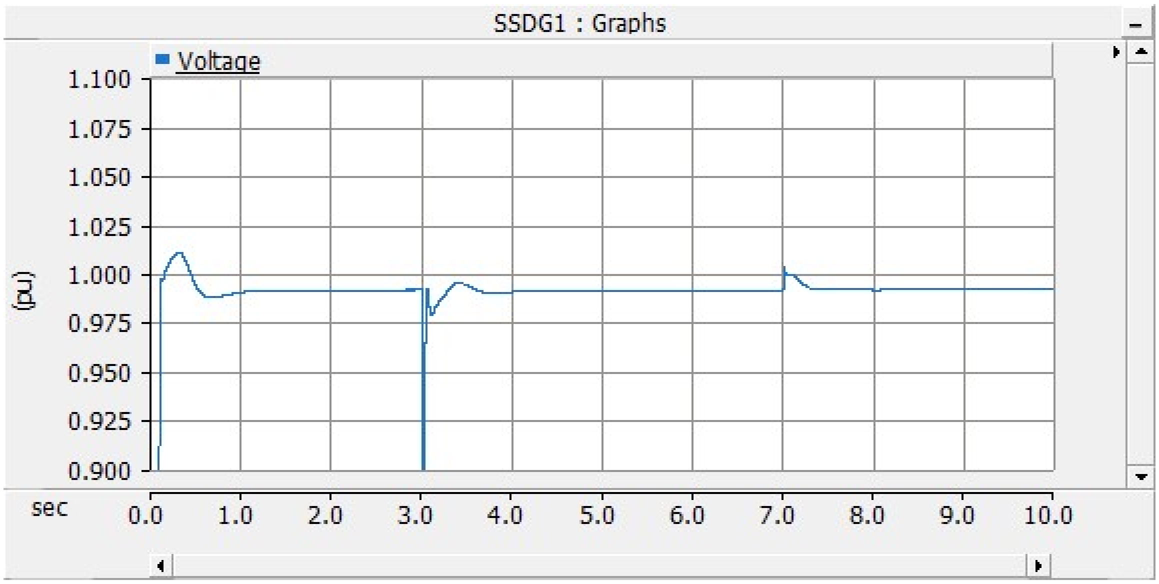


Figure 4.36: Voltage Level at the Buss During N-1 Situation

Figure 4.36 shows the voltage waveform during the whole simulation and **Figure 4.37** focuses on the large voltage dip that occurs when the motor is brought online. The voltage needs to be bumped up 2.5% to be hyper-compliant.

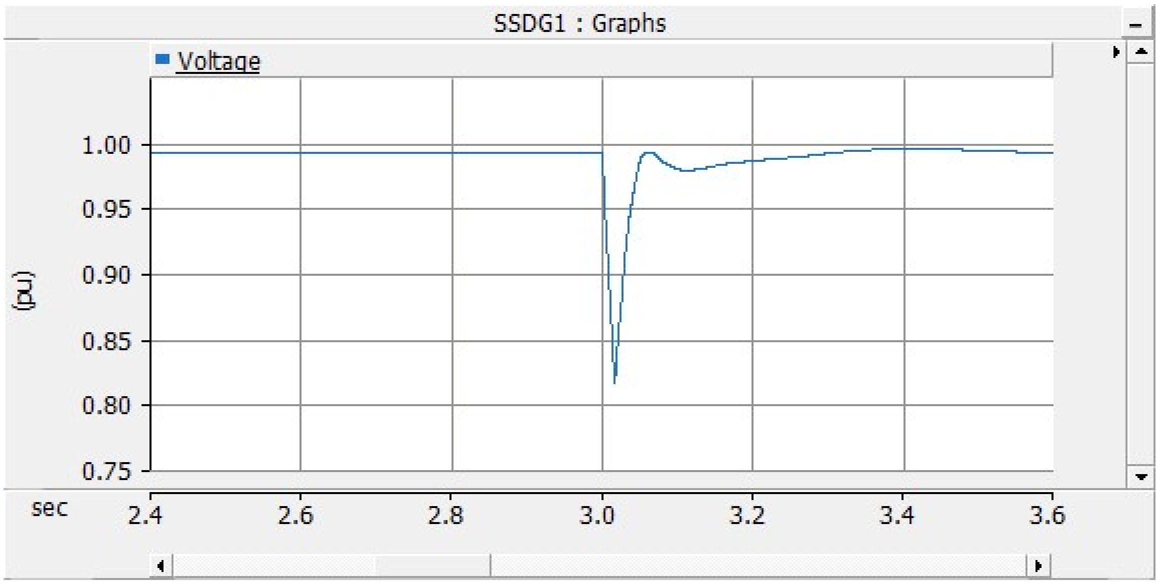


Figure 4.37: View of the Voltage Dip during N-1 Situation

The same overexcitation method that is used to address the problem with energizing Motor #1 is used below and the results are that the CONSHT exceeds the restrictions imposed by the N – 1 criterion when the inverter is viewed as a power source. This demonstrates the reliability that will be desired by the Maritime Community.

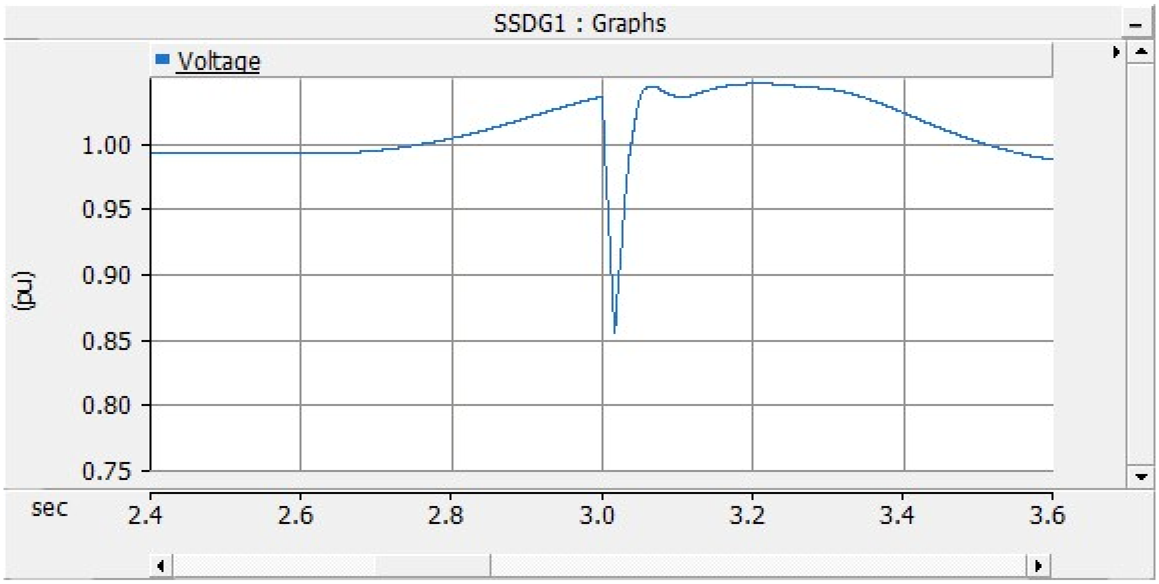


Figure 4.38: Improved Voltage Dip Using Overexcitation

Below is the torque output of the SSDGs diesel engine. The diesel engine can handle over 1 per unit of torque over short period of time. This means that the diesel engine isn't put under undue stress either.

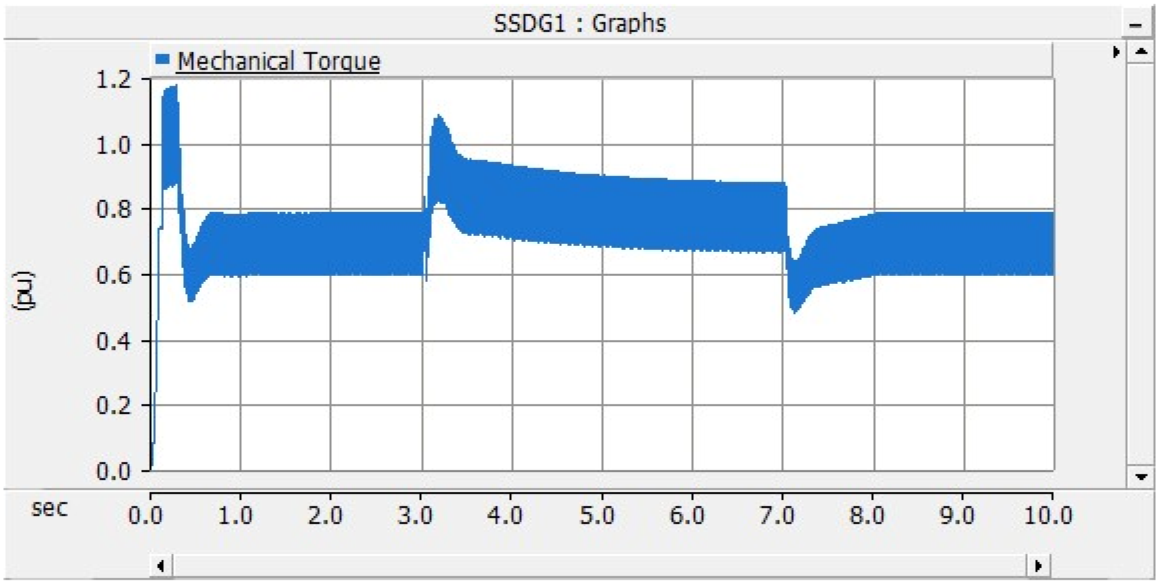


Figure 4.39: Torque Output of Engine During N-1 Situation

4-6 Discussion on System Redundancy

Redundancy is a focus of the maritime industry in general and the armed services sector of the maritime industry specifically. Some loads need at a minimum two pathways to provide power to these loads. In the naming conventions for the load centers, any load center numbered below 10 on the CONSHT is considered to be a vital load center. This means that a steady source of power is considered essential to these loads.

The model I built only shows the distribution system redundancy on two of the five vital load centers. An example of this system redundancy is shown in **Figure 4.40** below.

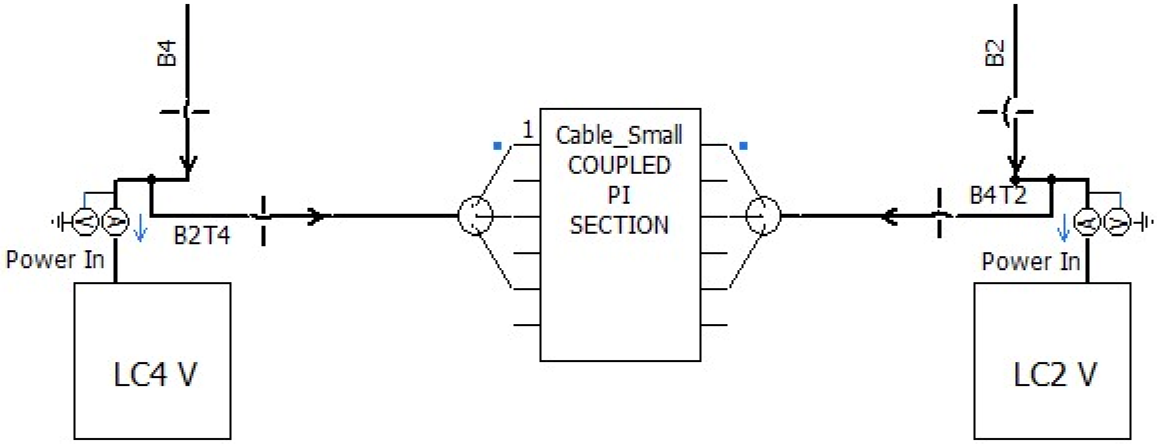


Figure 4.40: Load Centers with Breakers to allow for Power Supply Redundancy

This system works by the operation of an automatic buss transfer (ABT) which is shown below. This ABT will automatically switch the source of power from one of the main laterals to the cables that interconnect load centers 4 and 2. This operation can occur when the breakers supplying power to LCs 2 or 4 are opened or when the load center measures no voltage or current at its terminals.

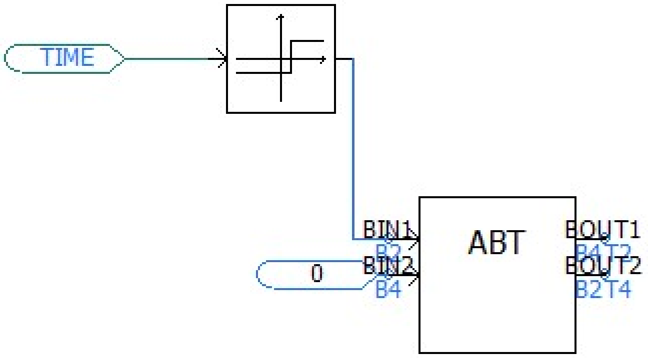


Figure 4.41: Automatic Buss Transfer

The graphs below are meant to simulate the breaker operation, but not a fault on the system. However, a fault or some sort of abnormality on the system would usually precede breaker operation.

The point of this simulation is to simply show system redundancy in operation, and to measure the resulting line losses after the operation. The line losses would be expected to increase after the breaker operation. Since the laterals supplying one of the load centers would now be supplying two of the load centers. It is also for this reason that cables would usually be oversized on a ship like this. The cost added by using 120ft of 350 Kcmil wire instead of 250 Kcmil wire pales in comparison to the cost of a large scale maritime disaster brought about by a complete loss of power to a vital load.

These 'oversized' cables are another reason why the 3% distribution losses assumption provides such a liberal estimate for losses.

Figure 4.42 shows the line losses before and after the breaker operation (starts at 5 seconds). **Figure 4.43** Just below that depicts the power in and out of the distribution grid.

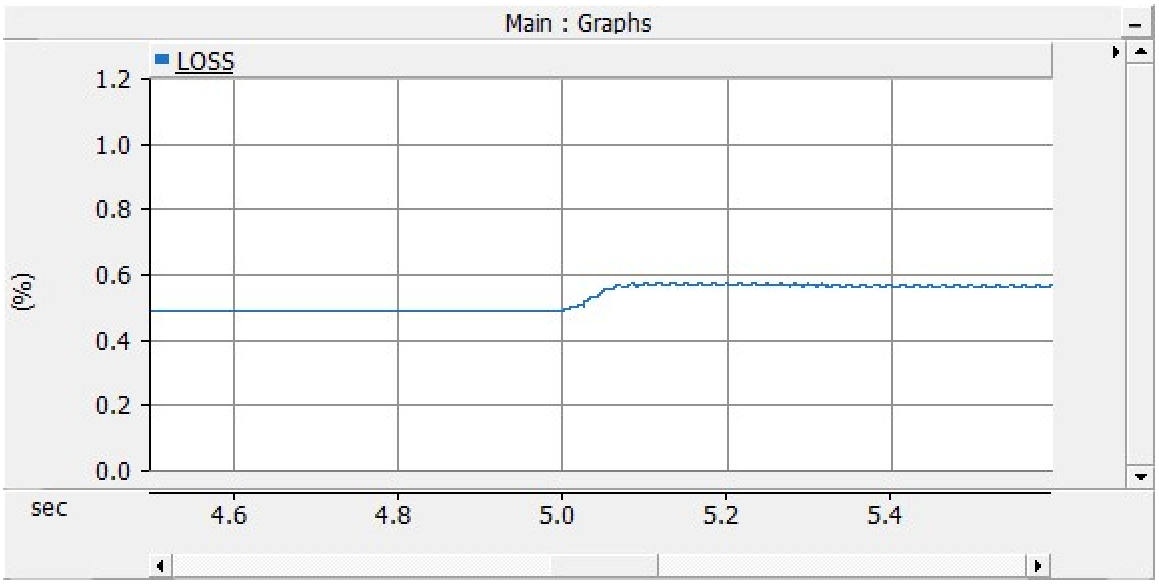


Figure 4.42: Slight Increase in System Losses Due to Raised Current in Cable Section

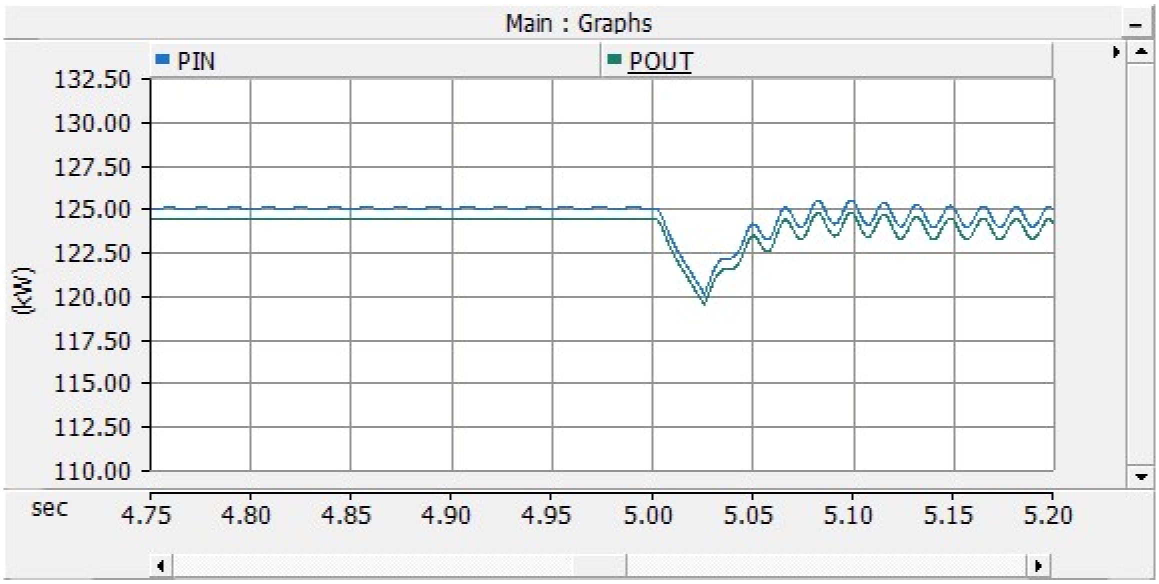


Figure 4.43: Disruption in Power Supply when Breaker Operation Occurs

Chapter 5 – Conclusions, Recommendations, and Future Work

5-1 Future work

A tough learning curve in PSCAD and time constraints resulted in there being numerous aspects of the work contained in this thesis that can be expounded upon.

5-1-1 Realistic Modeling of the Inverter and Charger

The inverter was modeled as a current source. This assumes that the switching frequency on the 6 pulse bridge is infinite and that there is no delay between the opening of one gate and the closing of another [13]. A more realistic model of an inverter could be accomplished by using items from PSCADs built in High Voltage DC (HVDC) library [10]. An inverter could be built that models and inverter with a finite switching frequency and a 6-pulse bridge connected to a battery. This would more accurately model the effects that the inverter would have on the system's stability and voltage level.

Modeling the inverter more accurately would also allow the user to directly measure the power output from the battery in the form of DC Voltage and Current as opposed to inferring the power from the batteries through use of an efficiency curve.

5-1-2 Better Understanding of Shipboard Load Profiles

When designing the shipboard load profiles, the only information that was known was a list of equipment and the corresponding rated loads and demand factors for different loading conditions [5]. The load profiles were assumed to be Gaussian which can be a good assumption if there is not much correlation between the loads minute by minute and you are building a load profile to model hourly loads. By assuming the loading distribution hour-by-hour was Gaussian it became possible to provide energy storage for a 'worst case' scenario instead of basing the battery capacity upon average situations.

A better understanding of how the loading depends on time could be studied. For example the load would likely drop during mealtimes when demanding work was going on, since the large motors would likely be de-energized. However, the opposite would likely hold true in the evening since the galley equipment would increase load without a compensatory phenomenon occurring elsewhere.

5-1-3 Better Modeling of the Grounding

The solution to this problem that was proposed Anna Moorman in her thesis [15] was to ground the equipment through a few mega ohms of resistance. Since there was no fault analysis on this system and the loads and cables were assumed to be balanced there would be no current flowing through the ground.

With all this in mind the decision was made to ground the system like a terrestrial system (with no grounding resistance).

If there were a desire for a more accurate model of this grounding, then there would need to be a neutral cable modeled that would connect to the ground connection on the generator and the loads. Some ships use neutrals and some ships ground those neutrals at certain points. This accurate grounding would allow for a better fault analysis and testing of protection systems.

5-1-4 Modeling the Grid with a Diesel Electric Hybrid Propulsion System

In this context diesel electric hybrid propulsion refers to powering the propulsion motors from the ships electric grid. Meaning there would be no dedicated engines powering the propellers. The propellers would be powered by motors connected to the ships grid through a variable frequency drive. Modeling and designing a ship such as this would be useful since there would be the opportunity to reduce emissions and system losses to an even greater degree.

However, the modeling of the variable frequency drives and the connected motors would make the model even more complex and would introduce more power electronics to the system.

5-1-5 Designing a Protection Scheme for this Hybrid Grid with Energy Storage

Protection was not a focus of this thesis. This is because, with the exception of the introduction of an inverter, the protection of a grid such as this would be rather straightforward. The protection would involve overcurrent protection and time-inverse overcurrent protection at the buss level. At the level of the load center there would likely be more overcurrent protection close to the large motors and fuses for the smaller loads. The implementation of these protection schemes is well understood and had limited applicability to the scope of this thesis.

Future work could, however, focus on protecting the grid while focusing on redundancy and reliability. Protection of the inverter could become a focus. Also if the grid were to be upsized and the voltage level increased, the need for differential protection of the system could arise. Differential protection is starting to be implemented on larger ships with higher voltage levels where faults can have greater consequences on the health of the system and crew.

5-1-6 In-Depth Cost Analysis for the Hybridization of a Ships Grid

While a simple cost analysis alone wouldn’t constitute the work of a thesis, a cost analysis could easily be performed by sizing the energy storage and generators using the heuristic design method proposed in this thesis. Different energy storage could be compared and the resulting reduction in generating capacity and fuel costs could be used to justify the cost of said energy storage. This could be a senior design capstone for an undergrad who is interested in ships or boats. This could also be done in addition to any of the previously mentioned future work.

5-2 Conclusion

This work provides good justification and methodology for designing a small ships grid with energy storage. Issues such as systems redundancy, N – 1 Criterion, and system stability are addressed and solutions geared towards addressing the problem are put forward and implemented within a PSCAD model. The design methodology is appropriate for the needs of the Maritime Community and assumptions have been validated through simulations in the steady-state and quasi-steady-state. The design methodology can be easily implemented with the help of R, Matlab, or Excel and provides an accurate estimate with a built in margin for error for the amount of energy storage required. This method would be improved with a greater understanding of the ships load profile and if necessary could be analyzed with smaller windows of time.

The CONSHT concept proposed in this work has two 115 kW SSDGs. This is compared to three 215 kW SSDGs proposed in [5]. If implemented, the CONSHT with Energy Storage Concept would likely add to the rating of the generators by 15-20% for a safety and grown margin. This would still result in a massive downsizing of the generation plant and would result in better emissions and much lighter weights that could easily balance out the weight increase due to the energy storage.

The CONSHT with Energy Storage Concept proposed here is predicted by the Simplified Model to operate within the 80-90% of continuous rated load window for the majority of the underway duration. The simplified model is not sophisticated enough to accurately predict this but the estimate is likely not far off. As long as the load is greater than 80% of the rated capacity of the online generators or the batteries are not fully charged, the setup of the grid ensures that the online generators will operate between 80-90% of rated continuous load. This will likely result in a drop in emissions due to both the downsizing of the power plant and maintaining efficient operating conditions for the generators that are online.

The CONSHT with Energy Storage Concept was designed with inherent margins of safety and has built in system redundancy from the perspective of the N – 1 criterion, and servicing vital loads. If the concept is implemented successfully than over time the concept can be better understood and the invert may be able to constitute a larger and larger portion of the Generation Capacity. For this reason, the most crucial future work to this thesis will be in implementing a better inverter model and observing the resulting voltage control and harmonic distortion at the buss level when the inverter constitutes a large portion of the Generating capacity.

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Appendix

Appendix A

(1) Conventional Diesel Propulsion						
			Construction		Standby	
	HP or KW	Total	Winter		Winter	
Equipment	Input	KW	D.F.	KW	D.F.	KW
Capstan	15 HP	11.2	0.05	0.56	0.1	1.12
Rotating Jib Crane	1.3 HP	1.26	0	0.00	0.1	0.13
Towing Winches	2 @ 7.5 HP	13.16	0.05	0.66	0	0.00
M.E. Jacket Water Heater	3 @ 1.5 KW	4.5	0	0.00	0.2	0.90
Fuel Oil Transfer Pumps	2 @1.5 HP	2.86	0	0.00	0.05	0.14
Lube Oil Pumps	1 HP	0.98	0.1	0.10	0.1	0.10
Gear Oil Pumps	1 HP	0.98	0.1	0.10	0.1	0.10
Hydraulic Oil Pump	1 HP	0.98	0.1	0.10	0.1	0.10
Waste Oil Pump	1 HP	0.98	0.1	0.10	0.1	0.10
Fire Pump	15 HP	13.01	0	0.00	0	0.00
Bilge Pump	3 HP	2.76	0.1	0.28	0.1	0.28
Ballast Pump	3 HP	2.76	0.1	0.28	0.1	0.28
Automatic Sump Pumps	3 @ 0.175 KW	0.53	0.1	0.05	0.1	0.05
Potable Water Sets	2@ 0.75 HP	1.64	0.3	0.49	0.3	0.49
Sewage Treatment Plant	1.4 HP	1.46	0.3	0.44	0.3	0.44
Tank Stripping Pump	2 HP	1.84	0	0.00	0.1	0.18
Air Compressors	2 @5 HP	9.1	0.3	2.73	0.3	2.73
E.R. Supply Fans	2 @ 3 HP	5.52	0.9	4.97	0.3	1.66
E.R. Stack Exhaust Fans	2 @2 HP	3.68	0.9	3.31	0.3	1.10
Gen. RM. Supply Fans	0.75 HP	0.82	0.9	0.74	0.3	0.25
Gen. RM. Exhaust Fans	0.5 HP	0.54	0.9	0.49	0.3	0.16
Steering RM. Exhaust Fan	0.25 HP	0.3	0.9	0.27	0.3	0.09
Machinery Space Exh. Fan	0.5 HP	0.54	0.9	0.49	0.3	0.16
Engr's. Workshop Exh. Fan	0.05 HP	0.07	0.9	0.06	0.3	0.02
Head Exhaust Fans/Lights	-	0.5	0.2	0.10	0.2	0.10
Unit Heaters	-	49.5	0.2	9.90	0.2	9.90
Outdoor A/C Heat Pumps	-	15	0.4	6.00	0.4	6.00
Strip Heaters	-	37	0.7	25.90	0.5	18.50
Fan Coil Units	-	0.5	0.8	0.40	0.8	0.40
Generator Space Heaters	2 @ 0.15 KW	0.3	0	0.00	0.2	0.06
Water Heaters	2 @ 6 KW	12	0.5	6.00	0.5	6.00
P.H. Refrigerator / Freezer	-	0.6	0.3	0.18	0.3	0.18
P.H. Coffee Maker	-	0.8	0.08	0.06	0.1	0.08
Range / Oven	11.2 KW	11.2	0.3	3.36	0.2	2.24

Range Hood	-	0.3	0.1	0.03	0.1	0.03
Coffee Brewer	-	1.2	0.1	0.12	0.1	0.12
Dishwasher	-	1.3	0.1	0.13	0.1	0.13
Refrigerator	-	0.8	0.3	0.24	0.3	0.24
Refrigerator / Freezer	-	1.1	0.3	0.33	0.3	0.33
Microwave Oven	-	0.8	0.1	0.08	0.1	0.08
Ice Machine	-	1.4	0.2	0.28	0.2	0.28
Food Waste Disposer	-	0.3	0.1	0.03	0.1	0.03
Trash Compactor	0.33 HP	0.4	0.1	0.04	0.1	0.04
Water Cooler	-	0.3	0.2	0.06	0.2	0.06
Radar	3 @ 0.27 KW	0.81	0.33	0.27	0	0.00
Depth Sounder	0.1 KW	0.1	1	0.10	0	0.00
Swing Meter	0.1 KW	0.1	1	0.10	0	0.00
DGPS / Chart Plotter	0.2 KW	0.2	1	0.20	0	0.00
Wind Monitor	0.15 KW	0.15	1	0.15	0	0.00
VHF Radio Power Supply	0.3 KW	0.3	0.5	0.15	0.2	0.06
Battery Chargers	5 @ 0.7 KW	3.5	0.5	1.75	0.3	1.05
General Lighting	-	9.3	0.7	6.51	0.6	5.58
Xenon Search Light	1 KW	1	0.2	0.20	0	0.00
Incandesent Searchlights	2 @ 1 KW	2	0.2	0.40	0	0.00
Floodlights	16 @ 0.5 KW	8	0.25	2.00	0.25	2.00
Navigation Lights	-	0.42	0.9	0.38	0	0.00
Unassigned Receptacles	64 @ 0.18 KW	11.52	1	11.52	1	11.52
Crane HPU	40	29.8	0.2	5.96	0	0.00
Spud Winches	30	22	0.2	4.40	0.1	2.20
Jetting Pump	40	29.8	0.2	5.96	0	0.00
VibraHammer	200 HP	149	0.2	29.80	0	0.00
			Construction		**Standby**	
	HP or KW	**Total**	**Winter**		**Winter**	
Equipment	**Input**	**KW**	**D.F.**	**KW**	**D.F.**	**KW**
Totals		**484.77**		**139.29**		**77.78**