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Management of Hybrid Battery Storage System for Naval Applications

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Summary

There has been a recent upsurge in the demand of renewable sources over outdated fossil fuel technologies and these are not only limited to power production but has also shown a great increase in the use of battery powered vehicles. To achieve the energy transformation required for the decarbonization of transport sector, we must rely on and trend towards renewable energy sources such as fuel cells and battery powered vehicles. Increased research and industrialization need to be done for the electrification of transport modes, including using battery electric and plug-in hybrid vehicles, fuel cell, synthetic fuels, and electro-fuels [1]. This trend is not only limited to land operated vehicles but also being followed for marine transport industry and many research project are already in place to meet these demands of future.

One such solution to complex application of marine transport is to use Hybrid Energy Storage System (HESS). It is a system that includes both power and energy dense batteries namely High Power (HP) and High Energy (HE) respectively. It's a system that combines multiple storage systems, multiple power systems or even power and storage systems can be combined such as solar power, grid and battery storage. With HESS system we can better utilize the batteries to their fullest extend and along the way we can reduce the cost and increase the efficiency as well.

In this thesis a control strategy is developed to accommodate a HESS structure that combines both HP and HE batteries in full-active topology system. HE battery will be able to store large amounts of energy and will be able to take care of primary cycles and maintain cruising speed. HP battery can quickly release higher amount of power which will take care of maneuvering by giving higher acceleration time or in braking events. The control strategy for the system uses two bidirectional converters, one with each battery to give a wider range of voltages as well as better switching. Two standard batteries are considered and are

connected to bidirectional converter. These power electronic devices act as switching mechanism between both batteries and distinguish based on frequencies. The switching mechanism is controlled by a control strategy that will act as PWM generator for the converters. There are other HESS strategies also available and in the literature survey part other HESS topologies are also discussed along with their prospects in industry.

Furthermore, we discussed the possibility of different time constant to further explore the involvement of HP battery during maneuvering to better understand the switching mechanism. The plots for various time constants are drawn to show the impact on SOC of both batteries. Quite favorably with bigger time constant the involvement of HP is increased which will in fact increase the use of HP battery which can reflect that with single battery system the lifetime of batteries will be reduced as compared to multiple battery system with smart control strategy in between.

The results show that by combining two batteries we can achieve longer lifespan of batteries, a better utilization of the whole capacity and less wear and tear. The HE will continue to act as consistent source, which is able to store large amounts of energy, whose main purpose will be to take care of maintaining cruise speed, while HP batteries are able to quickly release higher amounts of energy and power which can help to cater for maneuvering by giving high power peaks.

Acknowledgement

It is my pleasure to thank all of those who made this thesis work possible. First, I would like to express my deep and sincere gratitude to Politecnico di Torino, for hosting the topic of my thesis. It has been an immense pleasure for me to work with my supervisor, Prof. Michele Pastorelli, and Dr. Fabio Mandrile from the Department of Energy whom I would like to thank for their cooperation, dynamism, sincerity, and motivation throughout the thesis. I am extremely grateful for what they have offered me, and I would also like to thank them for their friendship, empathy, and compassion. Finally, I would also like to thank my family for their kind encouragements and support.

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Introduction

This chapter addresses the introduction of the thesis, the immediate background and the motivation of the thesis, the research questions that will later be answered along with the problem and objective of this thesis.

Background

The global problem of a rapidly rising CO2-concentration in the atmosphere, the green-house effect and the related severe changes in world surface temperature and world climate must be addressed and solved quickly [2]. There has been a recent upsurge in the demand of electric vehicles because of the much-needed shift from fossil fuel technologies towards renewable sources. This trend is not just limited to cars and other land vehicles but is being followed into marine transport industry as well. The main goal is to reduce greenhouse gas emissions and work in accordance with global climate goals. Most of the European countries have set deadlines towards total and partial shift to renewable energy from fossil fuels and to keep up with these deadlines, further research and drastic changes need to happen in transport industry as it is one of the major contributors towards GHG emissions standing at almost 21% [3].

Electrification has been much lauded as one of the most effective solutions to reducing marine industry emissions, especially in the context of the IMO's directive to cut 50 percent of emissions by 2050 [4]. While the momentum for electrification is growing, the transition is still relatively modest as most marine vessels continue to be powered by diesel or other fossil fuels. If we are to see a more rapid transition to electric propulsion, substantial financial investment is needed. Most importantly, we also need to see authorities taking a stand and setting regulations to limit emissions[5].

Motivation

However beneficial the technology might be there are some barriers that prove as hindrances towards commercialization. Adding to these aspects there is also not much industrial capability, research, or infrastructure in place for marine transport industry. An important aspect to adopt this technology is one's environmental self-identity, the promotion and research of such technology will enhance the sustainable energy behavior [7]. Self-identity and sustainability have become an important part in modern world and more companies want to be affiliated with such technology. The motivation for electrification is not only strictly environmental but also economical. There has been many subsidies and tax reliefs for organizations that have made early shift toward renewable energy.

The electrification of transport got into the political agenda of Governments around the world for two main reasons [6]:

1. The much higher efficiency of electric motors, when compared to internal combustion engines, especially as it relates to energy security; and
2. The zero emissions property of electric motor.

Problem

One major challenge is the various energy and power requirements in marine transport. Marine transport is not a smooth means of travel compared to transport on the roads, the varying conditions of the sea and factors such as maintaining cruising speed requires high energy emissions, while high power peaks are required for maneuvering. These energy and power requirements need to be provided by the traction batteries [8]. Using one specific type of battery system can result in oversizing of the battery system to fulfil both the energy and the power requirements as most batteries are either energy dense or power dense. Another factor in this equation is the number of cycles which will be performed by the batteries that will in turn affect the lifetime of the battery system.

The current Li-ion battery technologies are either distinctively high-energy (HE) or high-power (HP). In this regard, a single technology is unable to cover all these requirements and will either have low energy or power. This will lead to incomplete utilization of the battery, lower efficiency or fast wear and tear which can be costly and inefficient.

Thesis objective

Now that we have defined the problem one effective solution for better fulfillment of full-electric ship requirements is to use a hybrid energy storage system (HESS) which combines HE and HP battery cell technologies. In recent years the electrification in the waterborne transport application is in noticeable development. To face the high battery cost, a proper design of the energy storage system is required. For battery sources, the solution worthy of investigation is the use of a hybrid energy storage system (HESS) [9]. A customized mechanism will utilize both batteries to their fullest potential and will be able to eliminate any limitations of single battery. One battery will be responsible for overall operation that will be to provide constant energy for cruising. An energy dense battery will be able to perform this part. On the other end we will have a power dense battery whose main goal will be to act as a change compensator and provide higher acceleration or during braking events when required. HESS downsizes the required energy storage system whilst providing enough energy and power to the ship to meet the demands. HE batteries can store larger amounts of energy, which can take care of maintaining cruising speed, while HP batteries are able to quickly release higher amounts of energy which can help to cater for maneuvering by giving high power peaks.

The main advantages of a HESS can be summarized as follows [2]:

- Reduction of the total investment cost compared to a mono-type battery system due to limited inherent oversizing.
- Increase of the energy storage lifetime, which also results in cost reduction.
- Increase of the total system efficiency.

In this thesis we will try to answer below a few research questions by implementing real load cycles in MATLAB/Simulink and through simulation we will have a better understanding of our HESS system and its application. he research questions that will be studied and answered in this thesis will include the following questions,

1. Can multiple storage systems that consist of multiple battery system be able to replace monotype battery system?
2. If we implement a hybrid energy storage system, will it impact the lifetime of storage system?
3. Which power electronics components are most optimum to use for the conversion and control?
4. What HESS topology will be most efficient to use for the overall system?

Thesis Scope

In a HESS, the power sharing between HE and HP batteries is also an influencing factor for defining the required capacity and size of each battery type, affecting the system performance and battery life expansion. A smart mechanism is required for optimal power flow distribution which will help use both batteries to their fullest capacity. This thesis works with one such technique which includes using bidirectional converters with PI controlled switching mechanism to distribute the flow accordingly. HP batteries such as LTO and HE batteries such as NMC and LFP can be implemented under this mechanism. Further research can be done to find the best HP and HE battery but by industry standard LTO and NMC are the most suitable, respectively.

This thesis will discuss in detail the mechanism along with the components of bidirectional converter and PWM generator required. Literature review will show some other mechanisms along with the advantages and disadvantages, Next section will show the HESS topology in detail including the PWM generator and bidirectional converter. Results and discussion will show the simulation results from MATLAB/Simulink.

Literature Survey

Type of batteries

Electromobility is a future market, and the use of batteries has been increased in the past decade or so. In this thesis we are using two distinct batteries with their own capabilities. Lead acid batteries can be used but they have their own shortcomings such as low energy density and presence of lead that has difficult decommissioning process [9]. Lithium-ion batteries act as the most optimal option because of their easy maintenance, durability, and prolonged service. They have been used in transport industry for quite a while and their industry application and usage has surpassed all others.

The current Li-ion battery technologies are either distinctively high-energy (HE) or high-power (HP). The terms “Energy Battery” and “Power Battery” relate to battery design and material choices with the aim of maximizing and optimizing energy content or maximizing and optimizing power delivery capability of the stored energy [10]. Energy batteries are typically found in consumer devices and EV's. Power batteries are found in automotive, industrial, and rapid charge applications [10]. Batteries, particularly lithium-ion batteries, play a key role in many HESS-applications. They can be utilized both as the “high energy” or the “high power” storage.

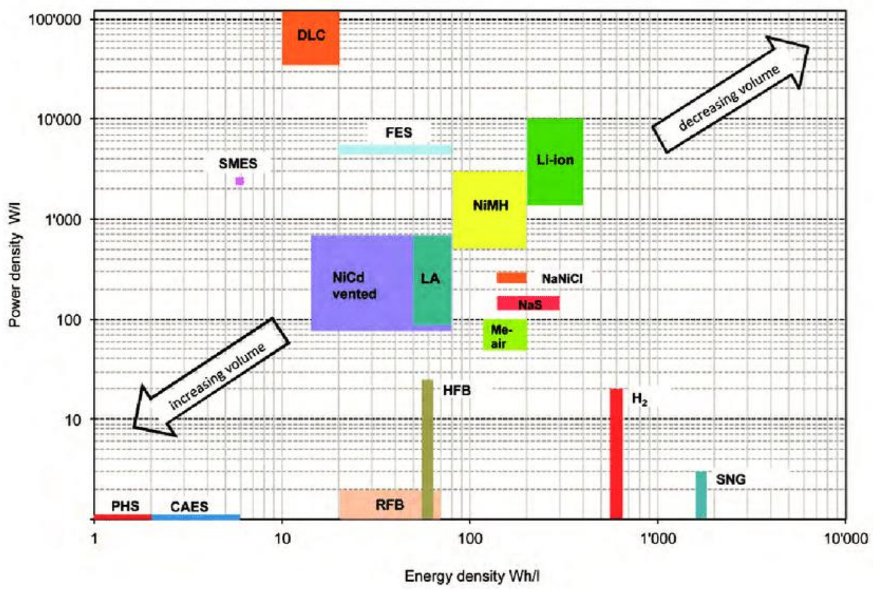

Figure 1: Energy and Power density foe ESS [15].

High Energy Batteries

Energy density of any battery describes the amount of energy it can store per unit mass or volume. Therefore, a battery with higher energy density can supply an electric load for longer than a battery having low energy density but same mass or volume. Lithium-ion batteries used in portable applications are mostly cobalt-based. These batteries consist of lithium cobalt oxide (LiCoO2) as cathode material and a graphite carbon as anode material. The cobalt oxide offers high energy density in lithium-ion batteries.

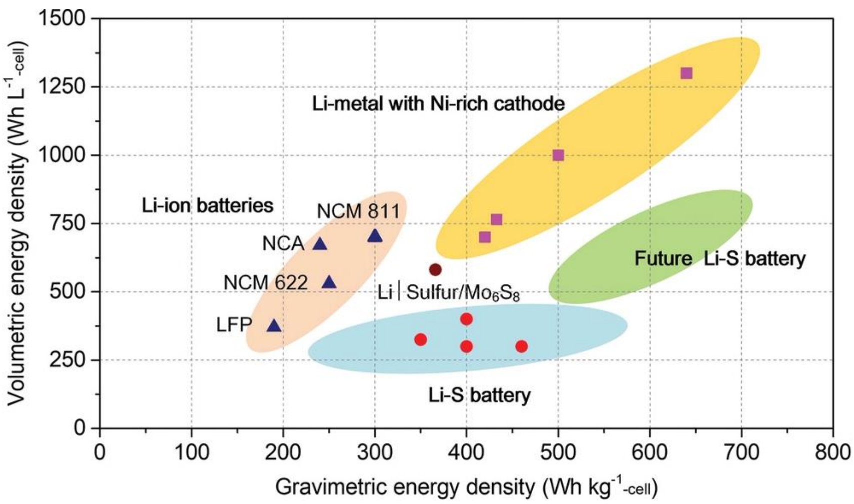

Figure 2: Energy denndity for Li-batteries [16].

High Power batteries

If a system has a high-power density, then it can output substantial amounts of energy based on its mass. The lithium titanate oxide (LTO) battery is a relatively new battery type that possesses high power capability for both charge and discharge and is opening-up and penetrating markets such as city busses where rapid recharge can be used to minimize battery size as the battery can be quickly charged frequently throughout the day. LTO is also an ideal battery for the rapid charge and discharge needed in electrical grid applications such as frequency regulation. Many other industrial applications are enabled by using LTO. Supercapacitors can also replace the HP battery as it also has the same characteristics and even higher power density [2].

HESS topologies

There is more than one possibility to combine two battery system to optimize their output. Several HESS topologies are possible and are operational in today's world such as single converter, voltage-controlled converter, and current controlled converter. Among these combinations most discussed and studied are semi-Active and full active structures as they are more efficient.

Semi-Active HESS

With semi-active there is a lack of possibilities for power flow control and energy management which will result in incomplete utilization of the battery, there is also a drawback which is the fluctuation of a DC-Bus voltage [2].

Fig 3 shows one of the many semi-active strategies which is employing only one converter which is limiting the power flow control to a certain standard. The HESS was controlled in current mode such that the HE battery delivers a constant current by the DC/DC converter, while the free-wheeling HP delivers the peak currents. Liu et al. [14] performed a steady-state analysis for the optimization of the system power and system efficiency. Furthermore, they used a small-signal analysis to improve the transient characteristics and eliminate potential system instabilities. The available battery capacity can be fully used within the permissible operating voltage range, which helps to maximize the range of the BEV.

Song et al. [6] did comprehensive study which featured four semi active HESS systems, various aspects such as cost, efficiency and DC bus voltage variation are studied. Each system had their own drawbacks and merits but nonetheless showed dominance over single battery system. In addition, about 50% of the operation cost of the energy storage system is reduced by the semi-active HESSs when compared to the battery-only topology [12].

The semi-active HESS, which only employs one DC/DC converter, is a good tradeoff between performance and cost. In addition, most control strategies can be implemented in this topology but it cannot overcome the disadvantage of having storage dedvices directly connected to the power port. This leads to an external behavior as the basic single battery system with a largely variable output voltage, depending on the battery SOC [9] .

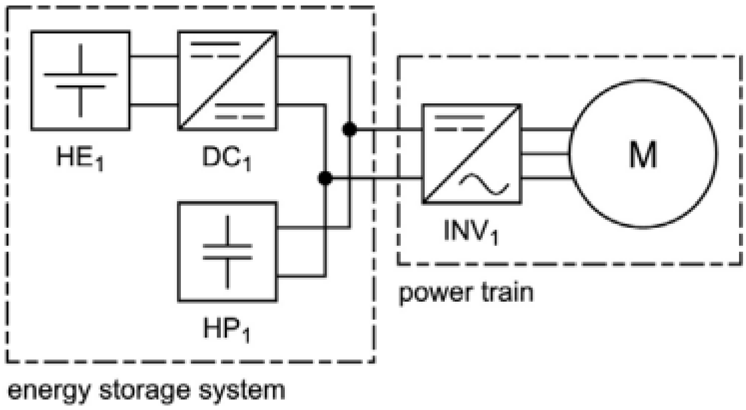

Figure 3: Battery semi-active hybrid energy storage topology [17].

Full-Active HESS

Fig 4 is another variation on the HESS, comprising two or more different energy storage devices, which are connected in parallel and are decoupled from each other and from the load. This configuration allows the both batteries to utilize their full range of operating regions by decoupling them individually [13]. It shows the connection topology of an energy storage system which combines HP and HE storage, each connected to the load via its own DC/DC converter. Each storage device can then be operated independently, based on its voltage characteristics. the fully active HESS achieves the best effect, as it employs two DC/DC converters and an additional control circuit.

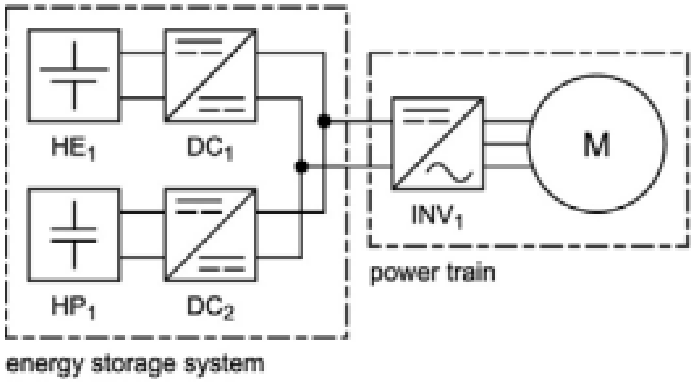

Figure 4: Parallel full-active hybrid energy storage topology [17].

The full active configuration allows an optimal exploitation of all the storage technologies, stress reduction and consequent lifetime extension. Besides being the storage block interfaced with a converter, the output voltages oof the HESS unit can be controlled to the rated value, mitigating the effect of SOC variation [9]. However, the full active system has the disadvantage of lower efficiency, larger volume, weight, and complexity with respect to the semi active solution [9].

In this thesis we will only discuss the full-active structure as it is the most advantageous and give more independence towards control of both batteries and voltage levels. Converter with HP battery will help it to operate in broader voltage band so two converters can bring out more properties of both batteries. This topology is very much like the one in Fig. 3 and will be discussed in detail below.

Hybrid Energy Storage System

Hybrid energy storage systems are beginning to gain traction in the energy storage industry. It is expected that technology will continue to evolve in the future, so that it will have wider applicability and lower costs. There will be increased communication between components that are involved in HESS. This will facilitate control, monitoring, and diagnosis. Finally, there will be increased use of power electronic converters. Power electronic devices are already used in many hybrid systems, and as costs go down and reliability improves, they are expected to be used increasingly [11]. In this thesis we also employ bidirectional converters to facilitate both HE and HP battery and optimization of power switching.

In a HESS typically one storage is dedicated to cover “high power” demand, transients and fast load fluctuations and therefore is characterized by a fast response time, high efficiency, and high cycle lifetime. The other storage is typically the “high energy” storage with a low self-discharge rate and lower energy specific installation costs. As mentioned in the literature survey part there is degree of freedom that is offered by the electronic converters.

These systems offer many benefits, including increased efficiency, improved performance, and reduced costs. The control systems within a hybrid energy storage system are responsible for optimizing and monitoring the energy storage systems. These systems use a variety of methods to optimize the system, including data analysis, demand response, and frequency regulation [11]. The control systems also work to ensure that the energy storage system is running as efficiently as possible and providing the greatest benefit to the customer.

Topology

In this topology we use two bidirectional converters connected to both HP and HE battery to better utilize the available capacity. The main flow strategy for the overall system is shown below in Fig. 4. The bidirectional converter works in a way to utilize HE batter under normal circumstances and to indulge HP battery only in case to work during high cycles such as maneuvering and operate as a change compensator.

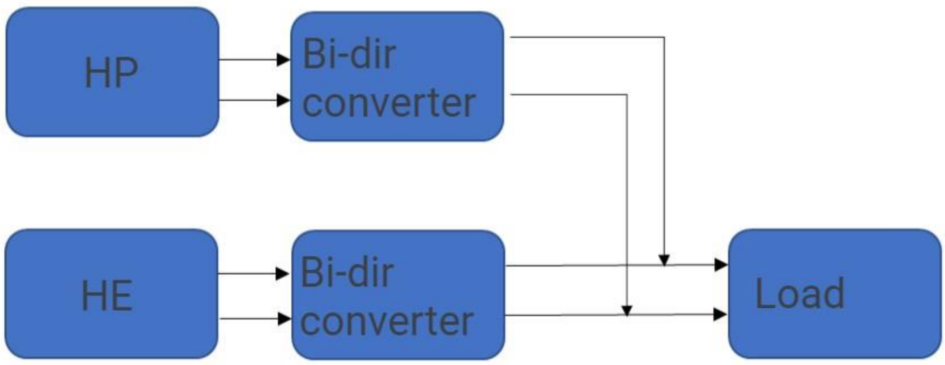

Figure 5: HESS structure.

System Operation

In this hybrid system the load power is provided by the HE battery for any normal duration of time. HE batteries can store larger amounts of energy and HP can produce rapid charge to fill out any higher requirement during change.

A smart mechanism is used for optimal power flow distribution which will help use both batteries to their fullest capacity. This thesis works with one such technique which includes using bidirectional converters with PI controlled switching mechanism to distribute the flow accordingly. HP batteries such as LTO and HE batteries such as NMC and LFP can be implemented under this mechanism.

During maneuvering or such secondary operations where the amount of energy exceeds the normal operation the HP will act as to compensate for the change of operation and cover the additional higher peaks. When the power produced by HE is equal to the load power (Pload), the HP battery will not produce power. When the power produced by HE is less than the load power (Pload), then the lack of energy will be compensated by the HP battery by producing electricity.

High Energy battery

As mentioned earlier, HE battery will act as the main source of the energy to provide required load and will opertae continiously during normal cruise and even during higher peak, The battery paramenter are given below in Fig. 5.

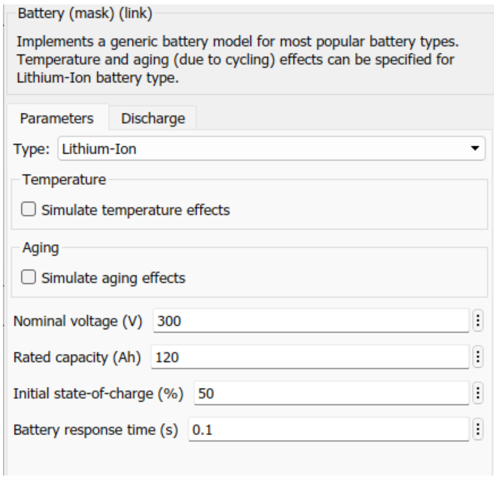

Figure 6: HE Battery parameters.

High Power battery

HP battery which is acting as change compensator and provides power during high cycles. The parameter for this battery is given below in Fig. 6. A small battery can be used here as the main operation of this battery is to provide support during higher peaks. This can help in reducing the cost of the system.

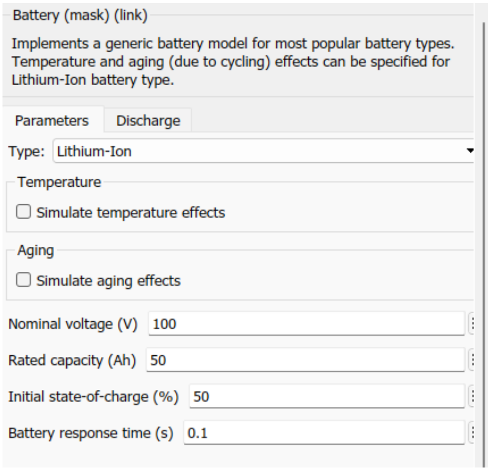

Figure 7: HP Battery parameters.

Bidirectional converter

The bidirectional converter is shown in Fig 8, the gated input is given and produced through a combined controlled system using PI controller and PWM generator which will be explained in next section. The battery is connected to the left side which is low input side and on the other end we have higher output because of the converter which is then connected to load.

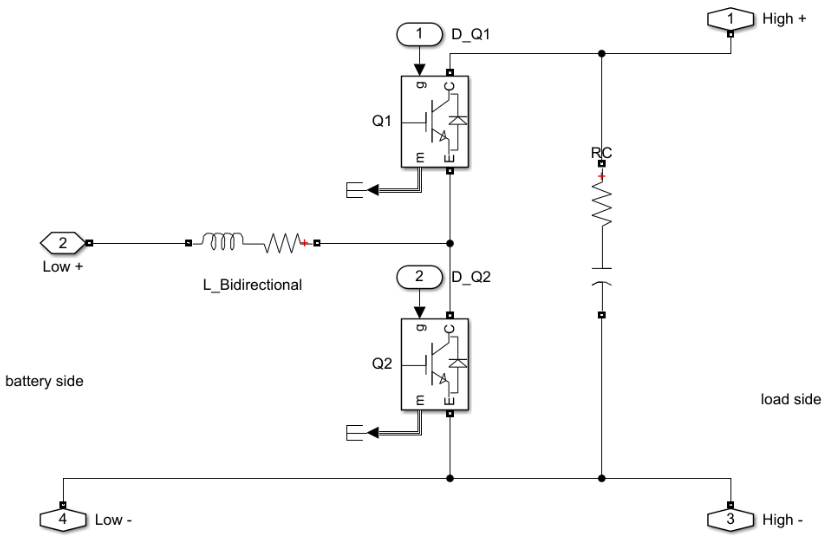

Figure 8: Bidirectional Converter.

The bidirectional nature of this converter is also useful in the case of recharging through either grid or braking mechanism. This feature can further be exploited under additional research. The same converter with different mechanism of operation is connected to both HP and HE battery.

Control Strategy

The combined control strategy to control HP and HE battery and to optimize their activation and switching is shown below in Fig. 9. The reference voltage is provided, and the difference is fed to PI controller and low pass filter. Further down the line we take out the reference current and use that to generate PWM. PI-controlled system will be able to give better result due to compensation of the load power surplus.

The upper part is providing gate PWM for the HE battery and the lower part of the block is giving PWM for the HP battery, The low pass filter is giving the output for the HE battery and the remaining high frequency value is fed to the PI controlled for HP battery.

Further in the thesis we explored the option to vary the size of low pass filter by changing the time constant value. The results are concluded in next section, and this has major implications that show dominance of HESS over single battery system.

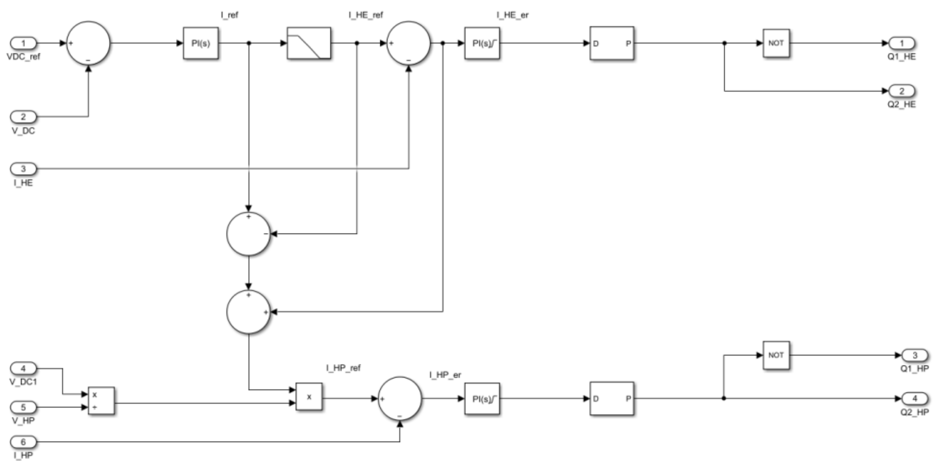

Figure 9: Combined control strategy for HE and HP battery.

MATLAB/Simulink Model

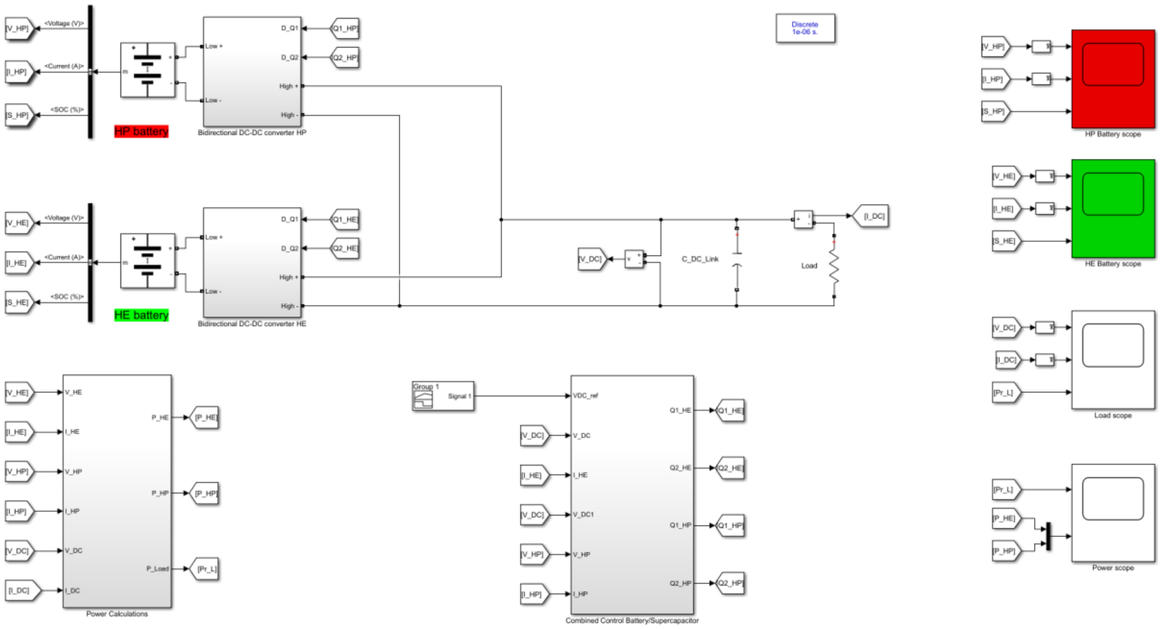

Figure 10: MATLAB/Simulink model.

Fig 10 shows the complete Simulink model, At the top we have our HP and HE batteries, both are connected to their relevant bidirectional converter. The bidirectional converters are getting two kinds of input, one directly from the battery and the other is coming from the control strategy black which is described in previous section.

The Power calculation block is taking voltage and current as input from both batteries as well as the load. It will then calculate the power and the output will be used for visualization.

The control block is taking various inputs, firstly we have the input signal which is being used as reference voltage, then we have output voltage and HE battery current for reference. Same inputs are taken from other battery system as well. The control block is discussed in previous section and the output from this block act as the input for both bidirectional converters. These outputs act as the input for the IGBT diode. Lastly, we have scopes for visualization.

Results and Discussion

The main element of the whole control strategy is the low pass filter embedded in the control strategy block in Simulink. The time constant for the LP filter decided the involvement of HP battery as it will control the fluctuation and hence the PWM for the bidirectional converter. In this simulation we tested our system for multiple values of time constant for the same input signal and evaluated the SOC of HP battery.

Input signal

Fig. 11 shows the input signal used as a reference voltage for the control strategy. This signal will act as load output and will be referenced to check multiple time constants of LP filter. The output for each battery, load and power will be drafted from this signal and will be used for comparison.

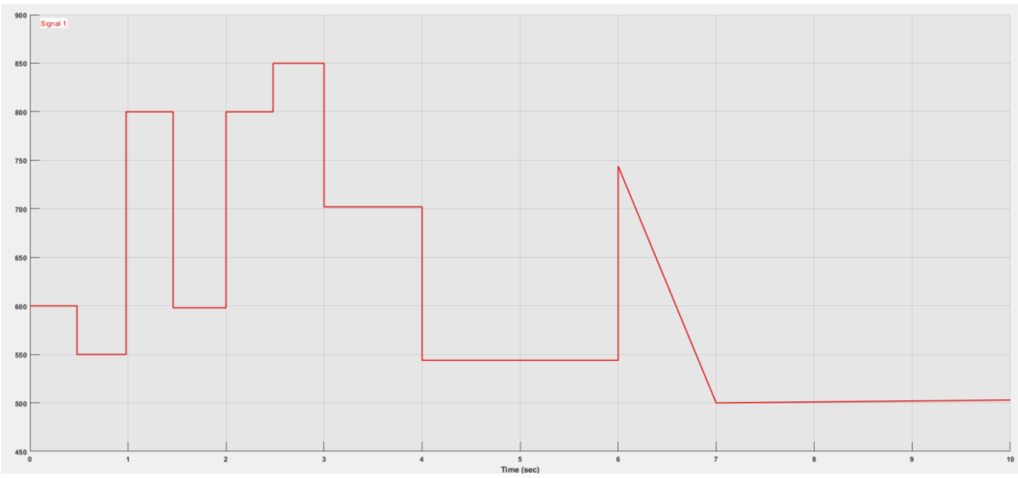

Figure 11: Input signal for Ref. Voltage.

Power Curves

MATLAB/Simulink simulation results are given below, Fig. 12 show the power curve for a versatile load made from the input signal and Fig. 13 shows how that load is divided between the HE and HP battery for different values of time constant.

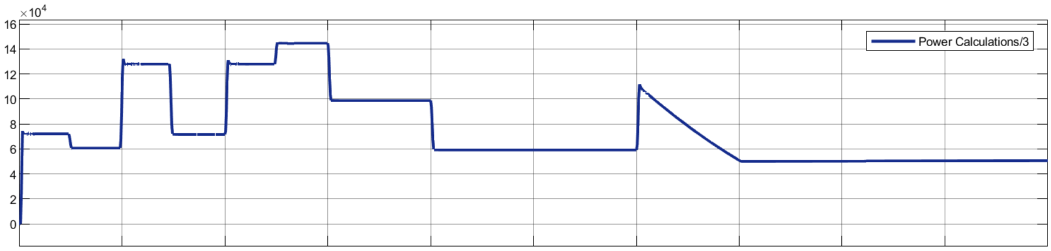

Figure 12: Power curve for the load.

In Fig. 11 the green line represents the power curve for HE battery and red are for HP battery. As its mentioned above and visible below the HP battery is mostly operation only during the change or sudden upsurge of load otherwise it mostly stays at zero. Whereas the HE battery is supplying all the load power. This system provides a stability of supply as well as extends the lifetime of both battery since they are only operation in their own capacity.

From the simulation the HP battery act as change compensator during the high-power cycles such as maneuvering and other such instances where higher peaks are required. It can supply a sudden surge of power at a higher speed and intensity than the HE battery. The HP battery is given in Fig. 11 with red line for various LP filters. As expected, the fluctuations increase with time constant and the HP battery will be utilized more if the time constant is increased, it will be further discussed in SOC section to see the usage of battery. During the normal load operation, the HE battery provides the full limit of the load power as it is expected from such battery.

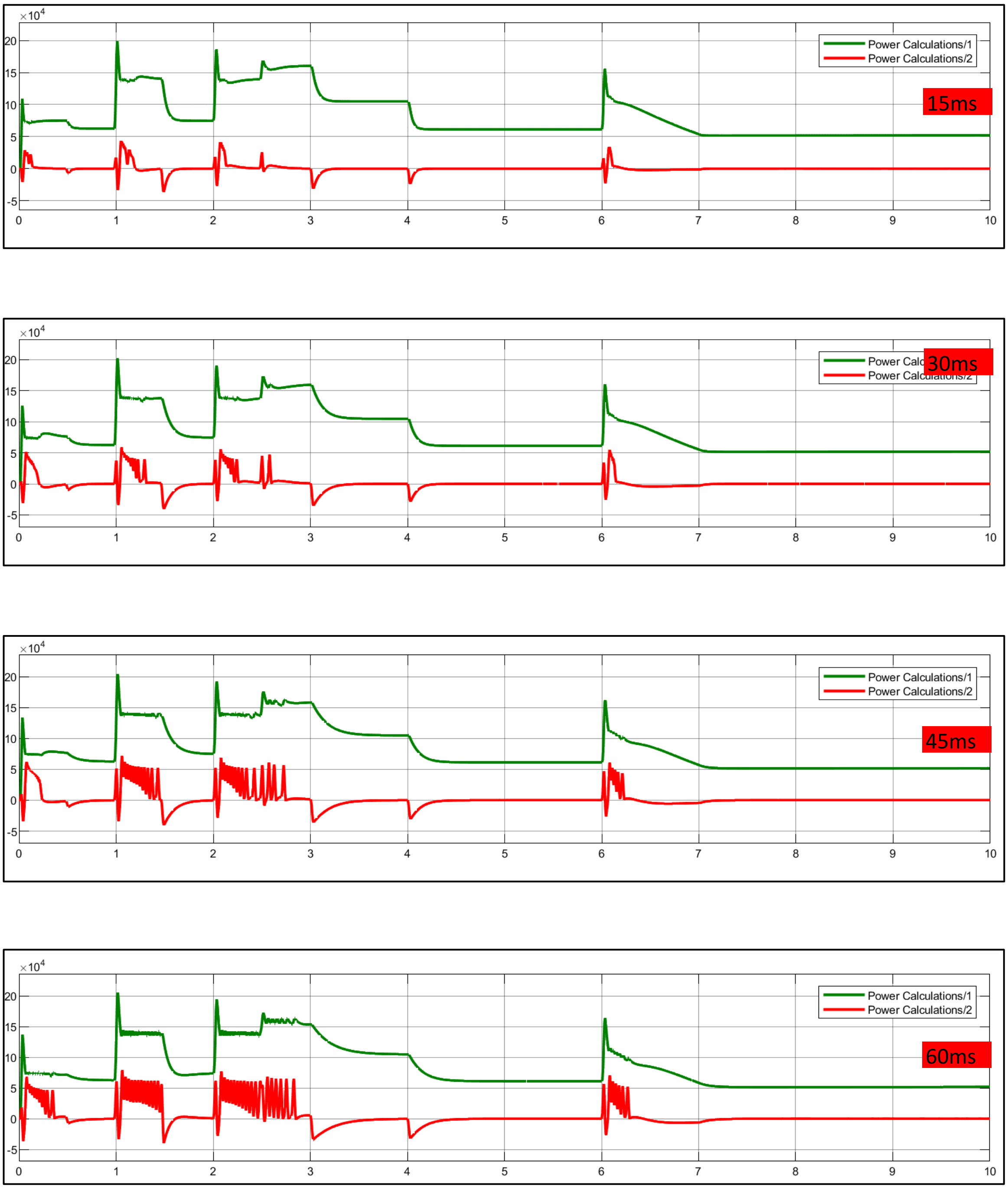

Figure 13: Power curve for HE and HP battery.

This HESS structure will last longer as compared to mono battery system since both batteries are only being used when needed and whole operation is not expected from a single battery and during negative power, because of the bidirectional converter the battery gets charged.

From these profiles we can see that the impact of HESS structure, both batteries are utilized as per their own capacity and much less load is put on a single battery. Without the HP battery all loads will be shifted towards the HE battery and this can result in rapid degradation and losses. But with HESS the higher peaks and changes are compensated by the HP battery while the HE battery performs its normal operation with much load or losses.

Voltage and Current Profile

Fig. 14 shows the load voltage and current profile. From the profile the change in load voltage can be seen. The input signal is acting as the load voltage and same trend can be seen here.

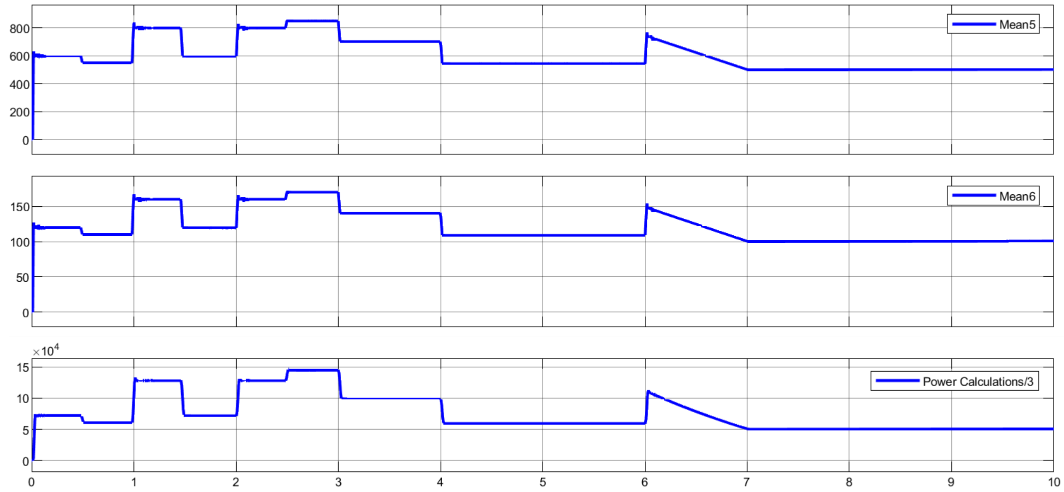

Figure 14: Voltage and Current profile of Load.

Voltage and current profile for both HE and HP batteries are given below in Fig. 15 and 16, respectively. These curves are provided by the battery. The system overall acknowledges the impact of HESS structure as in this system both batteries are utilized when needed and there is no wastage of capacity.

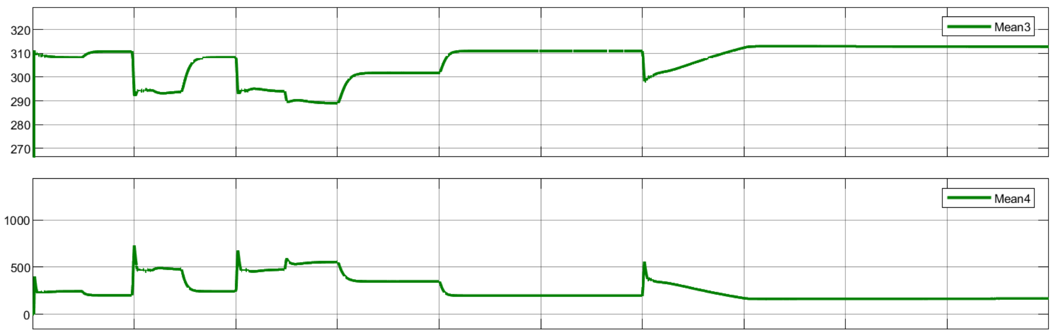

Figure 15: Voltage and Current for HE battery.

From Fig. 15 we can see the HE voltage is in accordance with the load voltage and mostly stable around changes, it will stay same for different values of time constant.

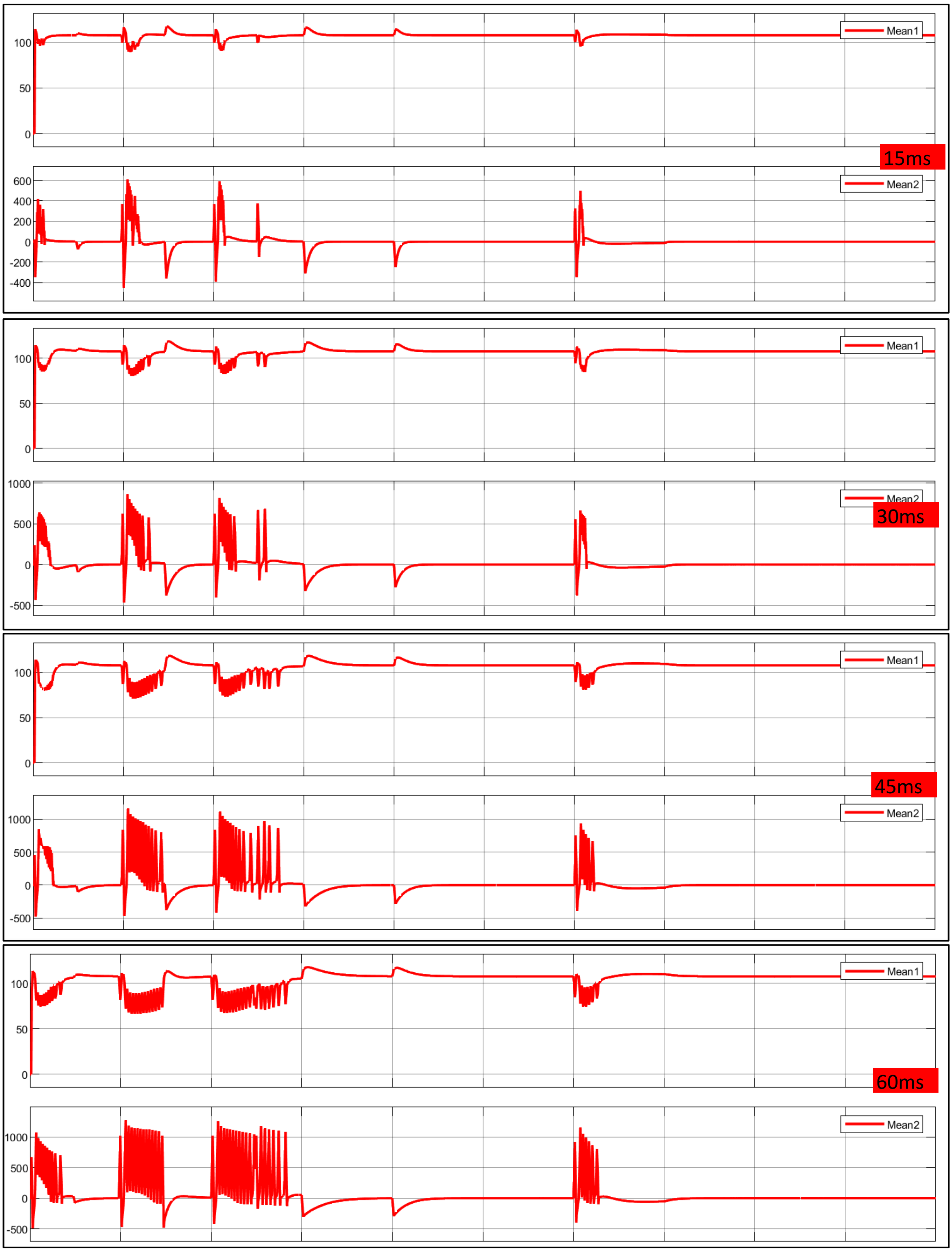

Figure 16: Voltage and Current for HP battery.

Fig. 14 shows the voltage and current profile for various time constants. As its visible the voltage and current are much more varied during the higher values of time constant as the HP battery will be more utilized. For lower value, the fluctuations are low, and the SOC will be high in those case. HP battery is only acting as change compensator, so the time constant defines the involvement of HP battery during such changes.

SOC

Now that we have acquired the voltage, current and power profiles of both batteries and load we can now further discuss the impact of this system on the lifetime and usage of batteries and overall power system.

HE battery

The SOC for HE battery will remain same in all cases. It will be constant drop but not linear. The HE battery is feeding the main output power and so its constantly in operation. The SOC is shown in Fig. 15.

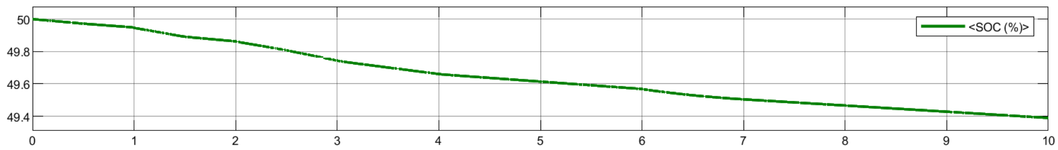

Figure 17: SOC of HE battery.

HP battery

The HP battery SOC varies with time constant as the frequency increases and decreases and that will eventually affect the PWM generator for bidirectional converter that is connected with HP battery. The varying values are shown below in Table. 1. When time constant is increased the SOC for the HP battery will decrease, this is because of the reason mentioned above in which case the HP battery will give out more power during changes in the load.

Table 1: HP battery SOC for different time constants.

Time constant (s)	**HP battery SOC (%)**
15ms	49.98
30ms	49.92
45ms	49.80
60ms	49.61

The same pattern is shown below in Fig 16, the SOC is decreasing with increasing time constants. The SOC is drawn against all time constants below and the impact of time constant is visible from the fig. there is more utilization during higher time constants as the involvement of HP will be increased. For 15ms the HP SOC only decreased 0.02 which is marginally extremely low but for 60ms the drop is 0.39. the simulation is done for small time, but the impact is consistent during longer operation.

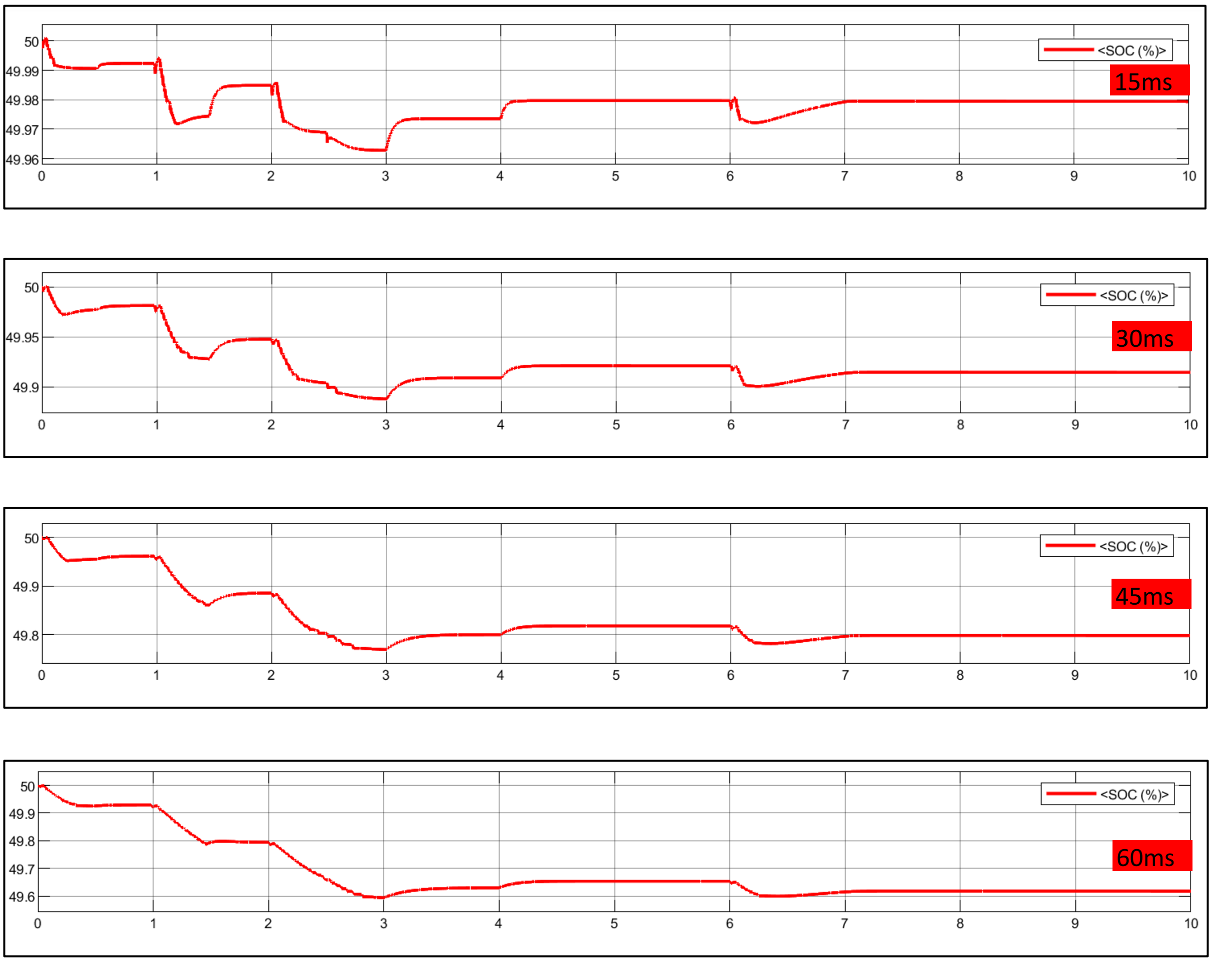

Figure 18: SOC of HP battery.

Conclusion

Electrification of transport sector is a much-needed aspect in reducing GHG emissions and marine transport, however important it is to world economy has a massive impact towards these emissions.

In this thesis we have shown a method to improve the electrification of marine transport in an efficient way. With a monotype battery the whole load will be accumulated on a single type of battery which will result in early degradation as well as power loses. To avoid such cases, we use two type of storage technologies and share the load among them so that no single system is utilized more than its original capacity and, in this way, both systems will be able to perform for extended period and with more efficiency.

Moreover, we showed the literature on HE and HP type of batteries and built an understanding to make use of baoth to their best potentail. We also showed multiple type of HESS structures that can be used depending upon the demand of the system.

From the simulation results we can conclude the impact the HESS structure has on overall system. The HE battery can perform its normal operation while HP battery can take care of the higher peaks and change demands. In this way the operations are divided evenly between both storage systems. The HE battery will be able to perform during simple load cycles and HP battery will function as a change compensator. This division is managed well by the control strategy in place which is using PI controller and Low-pass filter to generate PWM for our bidirectional converters.

Further research can be done into multiple HESS topology and with different kind of storage technologies such as supercapacitors.

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