TASK 4.2.2
CONTROL OF DISTRIBUTED ENERGY STORAGE

Year One – Deliverable(s)

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Submitted by:
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1 TASK DESCRIPTION

While extensive research in the area of energy storage has been conducted with the focus on a) the storage media and b) the power system interface of individual storage devices the focus of this task is optimal and rapid utilization of energy storage distributed throughout the ship power system.

In order to quantify the availability of distributed energy storage embedded in the ship power systems to the mission loads this task will develop a probabilistic approach to allow objective comparisons between centralized energy storage allocations and mission load centric energy storage to support dynamic mission load profiles. An analysis framework will be developed along with supporting software tools which takes into account the controllability of localized energy storage via the supervisory control approach and interface characteristics.

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2 YEAR ONE DELIVERABLES

- Report detailing the framework for probabilistic analysis of energy storage allocation.

3 APPENDIX OF REPORTS SUBMITTED

A. Overview: Framework for Analysis of Distributed Energy Storage
B. Distributed Control for Power and Energy Management
C. Fuzzy-logic Based Optimal Control of Distributed Energy Storage for MVDC Systems
D. Technical Report: Framework for Analysis of Distributed Energy Storage
E. Modular Multilevel DAB Converter with Energy Storage and DC Active Filter function for Shipboard MVDC System Applications

4 REFERENCES

[1] Z. Ding, D. Cartes, and S. Srivastava, “New load shedding scheme for islanded power systems,” Proc. 2006 IEEE/SMC International Conference on System of Systems Engineering, 2006.

[2] A. Shrestha, E. L. Foulks, and R. W. Cox, “Dynamic load shedding for shipboard power systems using the non-intrusive load monitor,” Proc. 2009 IEEE Electric Ship Technologies Symposium, pp. 412-419, 2009.

[3] A. Cramer, “Metric based design of integrated engineering plants for robust performance during hostile disruptions,” Ph.D. Dissertation, Purdue University, 2008.

[4] M. Bruns, “Propagation of imprecise probabilities through black box models,” Master Thesis, Georgia Institute of Technology, 2006.

[5] G. Klir, *Uncertainty and information: foundations of generalized information theory*. Wiley, 2005.

[6] K. Sentz and S. Ferson, “Combination of evidence in Dempster-Shafer theory,” SAND 2002-0835, April 2002.

[7] H. Zhou, T. Bhattacharya, and A. M. Khambadkone, “Composite energy storage system using dynamic energy management in microgrid applications,” in Proc. 2010 Int. Power Electron. Conf., Jun., pp. 1163–1168

APPENDIX A

OVERVIEW: FRAMEWORK FOR ANALYSIS OF DISTRIBUTED ENERGY STORAGE

1. Technical Objectives

The sizing and placement of energy storage systems in future naval warships may be key considerations as high power loads become more prevalent and become more critical to the operation and fulfillment of missions for these ships. Motivated by a challenge problem presented in "Machinery System Alternatives Based on Mission Load Elasticity" by J. Borraccini, this effort focuses on the development of a more comprehensive analytical framework and supporting software tools to better assess the appropriate magnitude, distribution, and capabilities of energy storage systems for meeting desired mission requirements. The general framework described by Borraccini includes assessment of performance of a system using the probability of success of mission systems as a function of available energy, treating the availability of centrally stored energy as a random variable, and incorporating the size and weight of energy storage systems as functions of capability into the analysis. This work seeks to extend this framework to include additional considerations driving the optimal solution, including system topology, load buffering, leveling, and shedding as sources of energy storage, and power limitations for components, and to heavily incorporate uncertainty into the analysis.

2. Technical Approach

Efforts within the first year of work focused development of the general framework for analysis, with the second year of work intended to focus on implementation of software tools to support the analysis. The planned approach was to largely focus on a quasi-static analysis, in order to minimize the amount of information required and the number of parameters needed to specify a system in order to better support propagation of uncertainty. The framework is intended to be modular, allowing modules to be independently refined and/or replaced over time.

3. Progress Statement Summary

Initial efforts have focused on the development of an initial framework for quasi-static time-domain simulation of networks including energy storage and review of some of the existing work on analysis of energy storage systems and related topics such as load shedding [1], [2], [3], as well as on methods for uncertainty modeling and propagation [4], [5], [6]. A report on an initial formulation of the framework has been developed. The framework is intended to be implemented as a set of software tools in the next year, and the approach is anticipated to be refined during the process of implementation.

4. Progress

Based on the objectives, a framework was developed for analysis of systems employing distributed energy storage based on quasi-static analysis of power flow, as illustrated by Figure 1. At the lowest levels of the analysis, a graph-based power flow is intended to be used to assess the ability of the sources in the system to deliver power to the loads at a single point in time, based on the system topology and component power capacities. This module will then be interfaced to and used by a time-domain module, in order to account for power flow over time. By treating the power flow as a directed graph problem, considerations for dynamic behavior are not included, but the amount of information and the number of parameters needed to specify the system are dramatically reduced. This minimization of the number of parameters needed to specify the system is important to keeping the uncertainty at a manageable level for propagation. The graph-based power flow can also be solved using linear programming techniques, allowing a relatively computationally inexpensive solution. The low computational cost facilitates propagation of uncertainty using black-box propagation techniques. The approach of using a deterministic power flow analysis in conjunction with black-box uncertainty propagation would allow the representation and propagation of uncertainty to be decoupled from the power flow analysis, allow existing software to be employed in these modules, and allow each of these modules to be independently enhanced and/or replaced over time as needed.

Accounting for load buffering, leveling, and shedding, which is one of the goals of the framework, can also be directly addressed through the graph-based power flow. As the power flow solution optimizes the power delivered to the loads, by using load priority values as weighting factors in the optimization, lower priority loading is automatically shed when power constraints of the sources limit the power that can be delivered to the loads. Priority is provided to the power flow module from each of the component models, which are implemented as MATLAB classes. Simple classes for loads, generation units, energy storage units, and power transfer units (such as cables, converters, transformers, etc.) are intended to be implemented as part of the initial tool set, but additional component models may be added over time. Other modules of the framework include modules for load profile generation, uncertainty propagation, optimization, and size, weight, and cost estimation. It is anticipated that existing tools and techniques will be employed for the optimization and uncertainty propagation modules, but these could also be further developed over time. The module for size, weight, and cost is somewhat independent of the other modules, but serves as a counterbalance in optimization activities. The framework is intended to be implemented as a set of software tools, and the approach is anticipated to be refined during the process of implementation. The framework is intended to be modular, allowing modules to be independently refined and/or replaced over time. The tools may also be integrated into some larger framework for analysis and design, such as S3D.

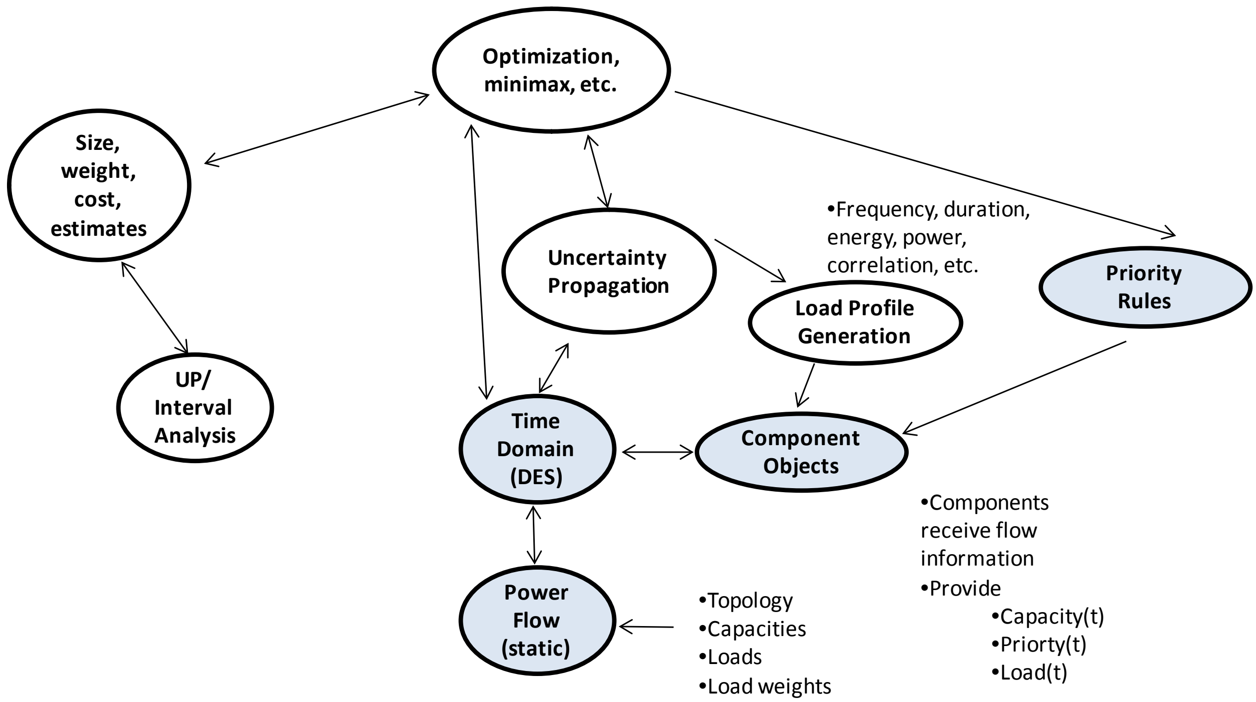

Figure 1: Framework

APPENDIX B

DISTRIBUTED CONTROL FOR POWER AND ENERGY MANAGEMENT

1. Technical Objectives

This research deals specifically with the development of intelligent hierarchical distributed control scheme with a focus especially on the ship power and energy management (Figure 2). In the proposed distributed control scheme, distributed controllers will be deployed using the multi-agent technology. Each agent responds to changes, which may be triggered through failures, priority changes (other loads become more important to the current mission and require load shedding), and constraint resources. In order to maintain the global objectives, agents should interact and communicate between each other in efficient way. The objective of this research is to (i) develop the control algorithm for the agent, and (ii) design the agents communication interfaces so that their interaction and social behavior should result in achieving the global objective of keeping vital load operational. This will be achieved by proper routing of power through the electrical distribution system.
Another objective of our research is to drive the research from the development of fundamental control tools for SPS to the testing and validation in the CHIL. The hardware demonstration and validation of the approaches applied in this project will be tested on the hardware test-bed facility in the Energy Conversion and Integration Thrust.

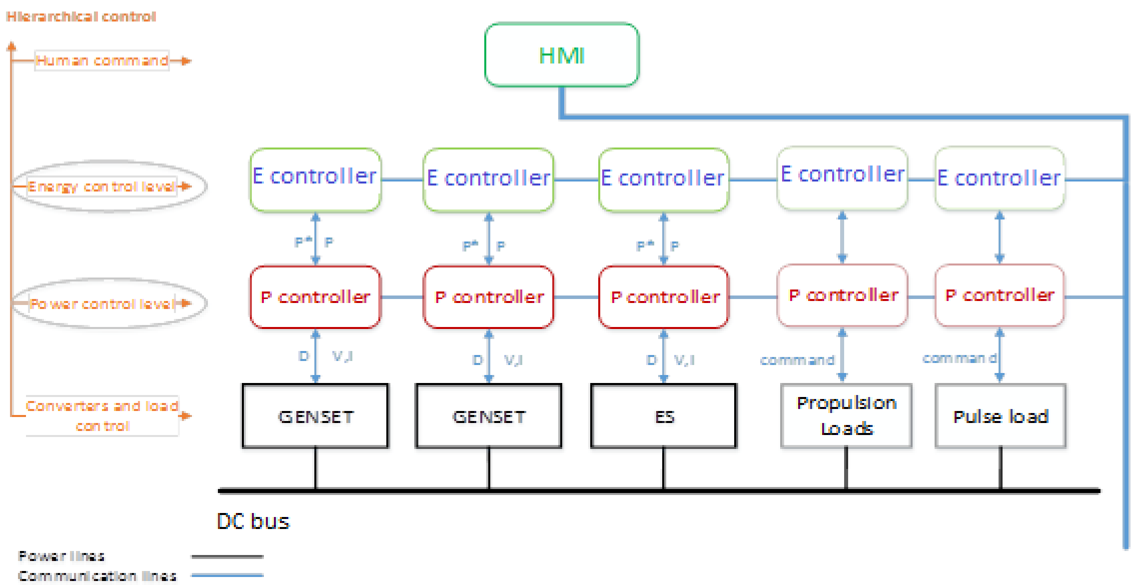

Figure 2: Hierarchical Control

2. Technical Approach

In a Ship Power System (SPS), the control approach should ensure load sharing among converters while maintaining the DC bus voltage stable. The droop control has been widely utilized to regulate the output voltage of individual converters. In a DC MG controlled by droop method, the power sharing method is recognized by linearly reducing the voltage reference as the output current. Even though the droop controller improves the system efficiency, it has some limitations. Since the voltage drop has effect across the line impedance, the output current sharing accuracy is reduced. In order to effectively manage the power flow from distributed power resources in DC MGs, the droop method needs to be further studied. In this research, we investigated the adaptive droop control methodology based on Particle Swarm Optimization (PSO). This control approach will be deployed for the power management of SPS.

An intelligent control performs the control actions based on some sort of system model of the system it controls, a set of constraints under which it has to perform the control, and an objective function describing the goals of the control. Using the objective function, the agent can determine those actions that are optimal with respect to its predictions. When such control actions are developed over horizons, it is called Model Predictive Control (MPC). In this work, we develop a control technique for energy management of SPS based on the MPC approach. The major advantage of MPC is its straightforward design procedure. In addition, additional constraints can be accounted for in the objective by using penalties for violations, which is very practical in the design of distributed controls.

3. Progress Statement Summary

The focus of our research in Y14 was the development of tools for an intelligent control system using a distributed approach, and based on multi-agent technology. Literature review for different types of distributed controllers has been done along with their pros and cons. In this work, we developed intelligent control strategies for energy and power management in SPS.

4. Progress

Two types of agent based solutions are developed for the proposed distributed control: energy control agent and power control agents.

Energy Control Agent (ECA):
The control algorithm in the ECA is developed based on a Model Predictive Control (MPC) technique. Each ECA receives the information from the energy sources and exchange information with others, in order to forecast the capacity of sources and loads demand, thereby, decides the amount of energy needed. To determine which action to take, an ECA typically has some sort of model of the system it controls, a set of constraints under which it has to perform the control, and an objective function describing the goals of the control. The output of the ECA is the input of the lower level controllers (i.e. power and device controllers) that regulate the power and voltage (Figure 2). Therefore, the control input u for the MPC is the energy demand E and the control output y is the power command P^*. To achieve the optimal power command P^* over a predicted Horizon, the optimization problem is formulated by a cost function J.
In order to demonstrate the MPC capability, a specific device control level has been taken, in which the MPC is applied to the voltage control loop of two neutral point-clamped converters (NPCs) supplying power to a resistive load . Figure 3 shows that the model's predictive control

scheme minimizes the cost function J *by* generating the control signal u, to achieve the optimal output voltage value V_{dc}.

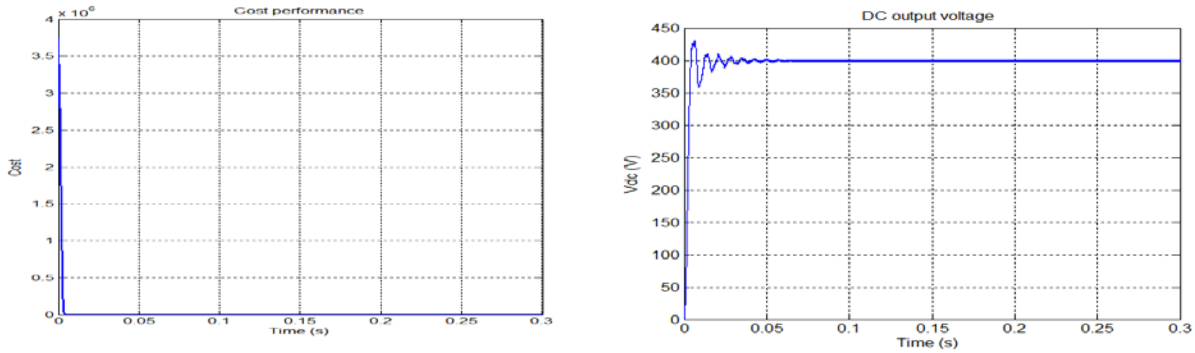

Figure 3: Voltage control loop performance.

Power Control Agents (PCAs):

A PCA receives the command from EMA and current and voltage feedbacks from the devices level. The PMA control algorithm is developed using the adaptive droop control techniques. Since the droop resistance is a variable that can be controlled, the proposed control diagram is developed to adaptively change the droop resistance under different power and load conditions. An algorithm based on PSO is developed to define the optimal value for the droop resistance.

Therefore the adaptive droop control performs the droop control task for balancing the power between resources by generating the droop commands for the device controllers. This achieves the power requirement and stabilizes the grid voltage operation. The simulation results for two neutral point-clamped converters (NPCs) supplying power to a resistive load is shown in Figure 4. Figure 4 shows that the cost function is minimized and the accurate current share (power share) is obtained.

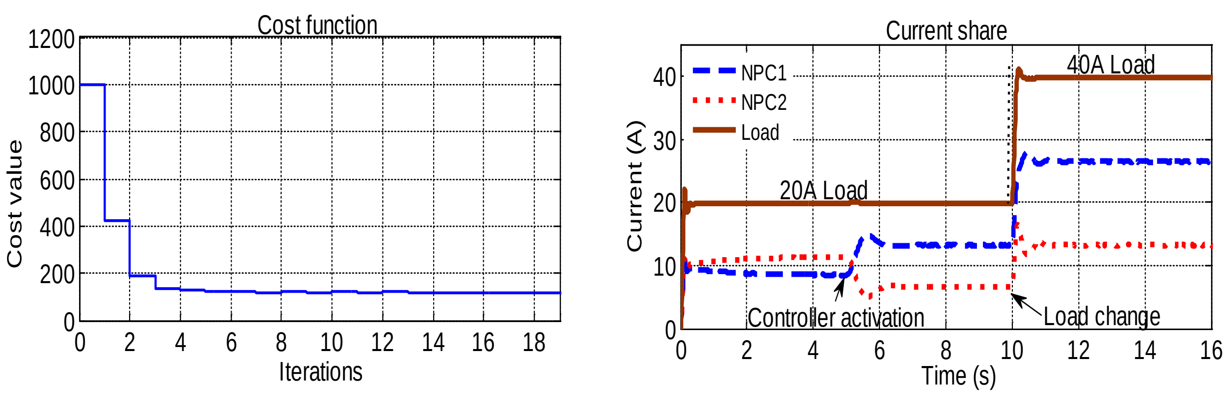

Figure 4: Control loop performance

APPENDIX C

FUZZY-LOGIC BASED OPTIMAL CONTROL OF DISTRIBUTED ENERGY STORAGE FOR MVDC SYSTEMS

1. Technical Objectives

This sub-task (under Task 4.2.2) focused on developing an intelligent control methodology for efficient energy storage management of a MVDC based all-electric ship. The main objective function of this storage management system is to properly maintain the balance of energy between sources and loads, control the timing of energy storage charging and discharging and optimal utilization of the energy storage.

2. Technical Approach

It is already established that the elegant solution related to the integration of energy storage management in an All-Electric Ship (AES) is the integrated fight-through power (IFTP) system where energy storage are distributed into different areas. With zonal energy storage (ZES), each zone will contain an Energy Storage Module (ESM) that is customized to the needs of the zone in terms of voltage, peak power, capacity, signal quality, etc. Because of its distributed nature, ZES requires that the technology chosen to power the ESM have a simple and reliable method for determining the amount of energy stored, be relatively insensitive to undisciplined charging and discharging, and have limited maintenance requirements. The most common energy storage technologies that were considered in this work are: batteries, super-capacitor or ultra-capacitors, and superconducting magnetic energy storage (SMES). To develop a centralized energy storage control methodology utilizing these energy storage technologies, following steps are planned:

1. Develop the time domain behavior model of the selected energy storage technologies.
2. Compare their characteristic with respect to energy density, power density, energy and power range, charging and discharging time at rated power, efficiency, suitability etc.
3. Identify the best location for energy storage based on previously published research.
4. Develop an average model of an MVDC ship system including state of the art converter technologies and their controls. The model will be a representative notional bench mark system including zonal service loads and pulsed loads. The initial system is considered with two generators, single propulsion and other zonal loads interfaced through state-of-the-art converters.
5. Integrate a fuzzy-logic based intelligent hierarchical control system to the model to manage energy storage modules to provide reliable support to the ship power system. The entire system with the energy storage models and their controls is being simulated using MATLAB/Simulink toolboxes.
6. Once the off-line simulation based model performs satisfactorily, a controller hardware-in-the-loop (CHIL) based validation would be performed using a digital real-time simulator.

3. Control Methodology

Storage location identification:

Although, knowledge from other research would be used to identify the location of the energy storage module, a best option would be to locate the converters that have very low utilization factors (weapons systems, emergency systems, etc. are used very rarely during the life of a ship). Energy storage connected to the dc bus can thus be widely distributed, and the converters not in use for idle equipment can be controlled to manage the flow of energy back and forth to the DC rails. This will reduce the requirement of interface converters for the ESM.

Type of Energy Storage:

Since the ESM is required to support primary generators and emergency power back up, a storage system with high energy density is essential. On the other hand, during transient and pulse load operation, storage with high power density is required. Considering the need for both high energy and high power storage, a composite or hybrid energy storage system (CESS) is used in the study which is a combination of batteries and ultra-capacitors. These two types of storages are selected for applications in the ship so that batteries can be used when high energy density is required and ultra-capacitor can be used when high power density is required.

Topology of CESS:

Following are the features/topology of the CESS as shown in Figure 5

- ✓ Modular bidirectional dual active bridge (DAB) converter is being considered to be used.
- ✓ Each storage module will have separate converter.
- ✓ If any storage module malfunctions, others will keep operational.
- ✓ Due to modular architecture, easy to replace without hampering system operation.
- ✓ Dynamic allocation of power demand to the batteries and transient power demand to ultra-capacitors.
- ✓ Flexible to upgrade power rating.

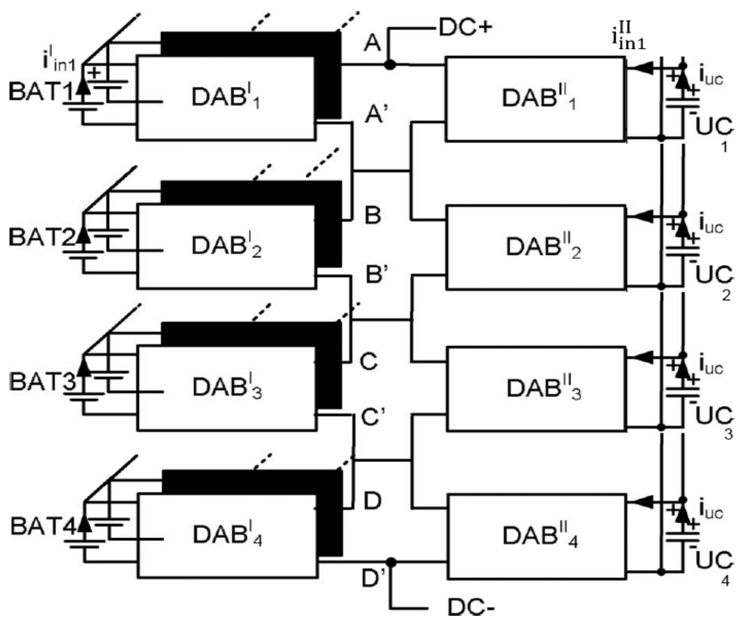

Figure 5: Topology of dual-active bridge based CESS [7]

Control Principle:

The control system will work mainly by monitoring the DC bus voltage and other currents. Once the DC voltage is lower than a set reference value, the ESMs start supplying power to recover the bus voltage and vice versa. In case of excessive DC bus voltage, the ESM will be used in charging mode. However, some dissipation of energy may also be needed, especially in the cases of charging the ESM fails to reduce the DC voltage to the desired level. The three main functions of the energy storage management controller are:

1. To balance power supply and demand (during normal mode, storage will perform energy balance and during transient or pulsed load operation, storage will compensate for sudden power changes)
2. To coordinate charging and discharging of storage based on state of charge (this will be done by estimating State of Charge (SOC) of all distributed storages, then allocating power demand accordingly and by ensuring the availability of energy storage devices based on state of charge)
3. Efficient and optimum utilization of storage (power split among generators, batteries and ultra-capacitors considering cost-effective estimation and maintaining DC bus voltage in the range of acceptable tolerance)

Control architecture:

The proposed Fuzzy-logic based energy storage controller will have two levels of controls. The schematic diagram (in Figure 6) describes the two-level supervisory control concept. Level 1 will determine the total reference power at every instant or time step. Based on the measurements obtained, the calculated reference power could either be positive or negative indicating power either to be stored or dissipated. This will be done using both PI control and Minimum Power (MP) based fuzzy logic controller. Level II controller will optimize energy efficiency and distribute power into either storage or dissipation circuit.

4. Progress summary and Future work:

Until today, the work is being concentrated in Step 1, 2 and 3 (listed above) which mainly dealt with component level modeling. Performance comparison (especially time-domain response) of various energy storage technologies are being done at this stage in Matlab/Simulink environment. Average value models are being developed for various converters including AC-DC and DC-DC converters. In the next step, system level modeling with supervisory control will be implemented in Matlab/Simulink.

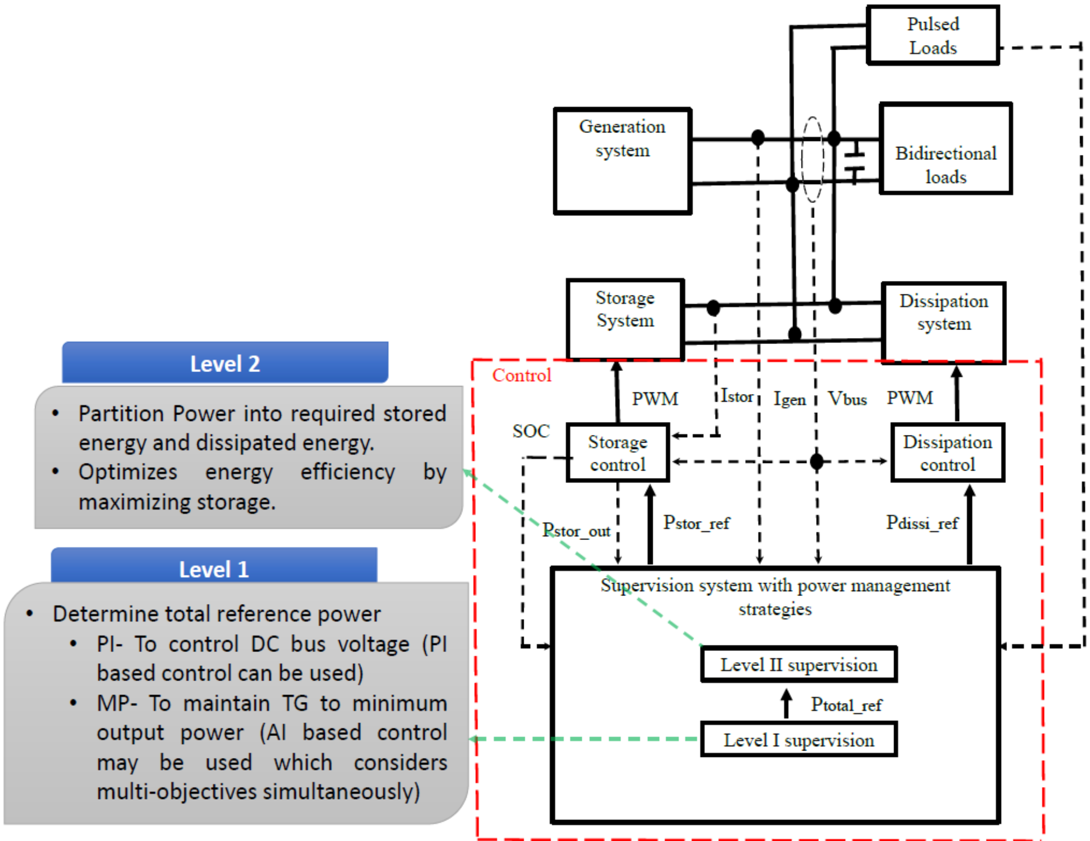

Figure 6: Control architecture for distributed energy storage

APPENDIX D

Framework for Analysis of Distributed Energy Storage, Version 1.0

Technical Report

Submitted to:
The Office of Naval Research

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Submitted by:
James Langston, Karl Schoder, Michael Andrus, and Mischa Steurer

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1 Executive Summary

In the white paper "Machinery System Alternatives Based on Mission Load Elasticity", the question of distribution of energy storage within a shipboard power system employing high power mission loads is discussed. In the paper, the analysis focuses on the probability of these loads to meet specified objectives as a function of the amount of energy that can be delivered over an interval of interest, along with the probability of the power system being able to deliver given amounts of energy to these loads. Certainly, there are other considerations in the design and placement of energy storage systems, including fault current contributions, dynamic power transfer capabilities of the system, power quality, system stability, etc. However, simultaneously addressing all of these considerations in a design optimization can be challenging due to the large number of parameters to be considered, the need to propagate substantial uncertainty, and the computational burden associated with the dynamic simulations needed to evaluate designs. Considering these challenges, a formulation similar to that described in the white paper may be useful in the early stages of design to allow consideration of a wider space of possibilities for assessing the appropriate magnitude, distribution, and capabilities of energy storage units in the context of uncertainty than may be feasible for more comprehensive design analyses in later stages.

Motivated by the approach presented in the white paper, this report proposes a framework for analysis of systems employing distributed energy storage systems, using a quasi-static analysis of power transfer through the system. While limiting the scope of analysis, and not considering many of the aspects noted above, the proposed framework was intended to extend the scope of considerations from those described in the white paper, including the following aspects.

- The framework was intended to explicitly consider the topology of the power system, including power limitations of generation units and power delivery equipment. This would facilitate analysis of the impacts of the loss of equipment on power delivery to loads, more easily supporting computation of the probability a given amount of energy can be delivered to a load.

- The effects of load buffering, leveling, and shedding were to be included, as these approaches can play a major role in the capacity of the system to deliver energy to mission critical loads.

- The framework was intended to heavily support the incorporation of uncertainty into the analyses. As substantial uncertainty may be present, particularly in the early design stages, it is important to account for this uncertainty in order to avoid drawing incorrect conclusions based on assumptions. The presence of the uncertainty may render it impossible to decisively determine the optimal design of a system, but the analysis may allow the elimination of a large space of designs which are clearly inferior. In any case, it is important to place any results in the context of the existing uncertainty in order to draw appropriate conclusions from the results.

- The size, weight, and cost of a system were intended to be incorporated into the analysis in order to serve as a counterbalance in optimization activities. It is intuitive that the performance of a system could be increased by incorporating more capacity for power generation and transfer and more energy storage. However, the enhancements of these characteristics typically have implications in terms of the cost, size, and weight of the equipment, which ultimately are driving factors in ship design. Although substantial uncertainty may be present in projections of the size, weight, and cost of equipment which may not yet be available, it is important that these considerations somehow be included in the analysis. Again, a method for propagating this uncertainty was intended to be incorporated into the framework.

Thus, the proposed framework was intended to address the types of analyses put forth in the white paper, but was intended to include these considerations.

Based on these objectives, a framework was developed for analysis of systems employing distributed energy storage based on quasi-static analysis of power flow. At the lowest levels of the analysis, a graph-based power flow is intended to be used to assess the ability of the sources in the system to deliver power to the loads at a single point in time, based on the system topology and component power capacities. This module will then be interfaced to and used by a time-domain module, in order to account for power flow over time. By treating the power flow as a directed graph problem, considerations for dynamic behavior are not included, but the amount of information and the number of parameters needed to specify the system are dramatically reduced. This minimization of the number of parameters needed to specify the system is important to keeping the uncertainty at a manageable level for propagation. The graph-based power flow can also be solved using linear programming techniques, allowing a relatively computationally inexpensive solution. The low computational cost facilitates propagation of uncertainty using black-box propagation techniques. The use of a deterministic power flow analysis in conjunction with black-box uncertainty propagation would allow the representation and propagation of uncertainty to be decoupled from the power flow analysis, allow existing software to be employed in these modules, and allow each of these modules to be independently enhanced and/or replaced over time as needed.

Accounting for load buffering, leveling, and shedding, which is one of the goals of the framework, can also be directly addressed through the graph-based power flow. As the power flow solution optimizes the power delivered to the loads, by using load priority values as weighting factors in the optimization, lower priority loading is automatically shed when power constraints of the sources limit the power that can be delivered to the loads. Priority is provided to the power flow module from each of the component models, which are implemented as MATLAB classes. Simple classes for loads, generation units, energy storage units, and power transfer units (such as cables, converters, transformers, etc.) are intended to be implemented as part of the initial tool set, but additional component models may be added over time. Other modules of the framework include modules for load profile generation, uncertainty propagation, optimization, and size, weight, and cost estimation. It is anticipated that existing tools and techniques will be employed for the optimization and uncertainty propagation modules, but these could also be further developed over time. The module for size, weight, and cost is somewhat independent of the other modules, but serves as a counterbalance in optimization activities. The framework is intended to be implemented as a set of software tools, and the approach is anticipated to be refined during the process of implementation. The framework is intended to be modular, allowing modules to be independently refined and/or replaced over time. The tools may also be integrated into some larger framework for analysis and design, such as S3D.

2 NOMENCLATURE

The following nomenclature conventions are used in the description of the proposed framework.

E Energy.

- E_d Integrated power demand deficit for a load (Section 4.3.1).
- ΔE The difference between the storage capacity and the actual stored energy of an energy storage module (Section 4.3.3).

I Priority.

- I_{max} Maximum priority to be assumed by a component (Section 4.3.1, Section 4.3.3).

k Used as a constant (includes subscript versions, e.g. $k_0, k_1, \ldots, k_i$).

P Power.

- $P_{capacity}$ The power capacity of a component (Section 4.3.2).
- $P_{capacity-1}$ The power transfer capacity of a component in the forward direction (Section 4.3.4).
- $P_{capacity-2}$ The power transfer capacity of a component in the reverse direction (Section 4.3.4).
- P_{charge} The charging capacity of an energy storage module (Section 4.3.3).
- P_{del} Power delivered to a load (Section 4.3.1).
- P_{dem} Power demand for a load (Section 4.3.1).
- $P_{discharge}$ The discharging capacity of an energy storage module (Section 4.3.3).

$p_n(x)$ An n$^{\text{th}}$ order polynomial of x of the form $p_n(x) = k_0 + k_1 x + k_2 x^2 + \ldots + k_n x^n$ (Section 4.3.1, Section 4.3.2.

t Time.

- t_d Time at which the delivered power to a load falls below the power demand for the load (Section 4.3.1).
- t_r Time at which the delivered power to a load is restored to the power demand for the load (Section 4.3.1).

τ Used as a variable of integration, but also used as a time-constant in cases used with a subscript.

- τ_r Time constant for exponential decay of priority upon restoration of power to the level of demand for a load (Section 4.3.1).

3 INTRODUCTION

The sizing and placement of energy storage systems in future naval warships may be key considerations as high power loads become more prevalent and become more critical to the operation and fulfillment of missions for these ships. In the white paper "Machinery System Alternatives Based on Mission Load Elasticity" [1], the question of distribution of energy storage within a shipboard power system employing high power mission loads is discussed. In [1], the analysis focuses on the probability of these loads to meet specified objectives as a function of the amount of energy that can be delivered over an interval of interest, along with the probability of the power system being able to deliver given amounts of energy to these loads. Certainly, there are other considerations in the design and placement of energy storage systems, including fault current contributions, dynamic power transfer capabilities of the system, power quality, system stability, etc. [2]. However, simultaneously addressing all of these considerations in a design optimization can be challenging due to the large number of parameters to be considered, the need to propagate substantial uncertainty, and the computational burden associated with the dynamic simulations needed to evaluate designs. Considering these challenges, a formulation similar to that described in [1] may be useful in the early stages of design to allow consideration of a wider space of possibilities for assessing the appropriate magnitude, distribution, and capabilities of energy storage units in the context of uncertainty than may be feasible for more comprehensive design analyses in later stages.

Motivated by the approach presented in [1], this report proposes a framework for analysis of systems employing distributed energy storage systems, using a quasi-static analysis of power transfer through the system. While limiting the scope of analysis, and not considering many of the aspects noted above, the proposed framework was intended to extend the scope of considerations from those described in [1], including the following aspects.

- The framework was intended to explicitly consider the topology of the power system, including power limitations of generation units and power delivery equipment. This would facilitate analysis of the impacts of the loss of equipment on power delivery to loads, more easily supporting computation of the probability a given amount of energy can be delivered to a load.

- The effects of load buffering, leveling, and shedding were to be included, as these approaches can play a major role in the capacity of the system to deliver energy to mission critical loads.

- The framework was intended to heavily support the incorporation of uncertainty into the analyses. As substantial uncertainty may be present, particularly in the early design stages, it is important to account for this uncertainty in order to avoid drawing incorrect conclusions based on assumptions. The presence of the uncertainty may render it impossible to decisively determine the optimal design of a system, but the analysis may allow the elimination of a large space of designs which are clearly inferior. In any case, it is important to place any results in the context of the existing uncertainty in order to draw appropriate conclusions from the results.

- The size, weight, and cost of a system were intended to be incorporated into the analysis in order to serve as a counterbalance in optimization activities. It is intuitive that the performance of a system could be increased by incorporating more capacity for power generation and transfer and more energy storage. However, the enhancements of these characteristics typically have implications in terms of the cost, size, and weight of the equipment, which ultimately are driving factors in ship design. Although substantial uncertainty may be present in projections of the size, weight, and cost of equipment which may not yet be available, it is important that these considerations somehow be included in the analysis. Again, a method for propagating this uncertainty was intended to be incorporated into the framework.

Thus, the proposed framework was intended to address the types of analyses put forth in [1], but was intended to include these considerations.

4 Framework Description

4.1 Overview

Based on the objectives described in Section 3, a framework was developed for analysis of systems employing distributed energy storage based on quasi-static analysis of power flow. The proposed framework is generally illustrated by Fig. 1, with the modules of particular focus for development shaded. At the lowest levels of the analysis, a graph-based power flow is intended to be used to assess the ability of the sources in the system to deliver power to the loads at a single point in time, based on the system topology and component power capacities. This module will then be interfaced to and used by a time-domain module, in order to account for power flow over time. The power flow module is described in further detail in Section 4.2. By treating the power flow as a directed graph problem, considerations for dynamic behavior are not included, but the amount of information and the number of parameters needed to specify the system are dramatically reduced. This minimization of the number of parameters needed to specify the system is important to keeping the uncertainty at a manageable level for propagation. The graph-based power flow can also be solved using linear programming techniques, allowing a relatively computationally inexpensive solution. The low computational cost facilitates propagation of uncertainty using black-box propagation techniques. The approach of using a deterministic power flow analysis in conjunction with black-box uncertainty propagation would allow the representation and propagation of uncertainty to be decoupled from the power flow analysis, allow existing software to be employed in these modules, and allow each of these modules to be independently enhanced and/or replaced over time as needed.

Accounting for load buffering, leveling, and shedding, which is one of the goals of the framework, can also be directly addressed through the graph-based power flow. As the power flow solution optimizes the power delivered to the loads, by using load priority values as weighting factors in the optimization, lower priority loading is automatically shed when power constraints of the sources limit the power that can be delivered to the loads. This approach, however, allows fractions of the power demand for loads to be met, which is not necessarily consistent with the behavior of many loads that are either on or off. However, for the analyses for which the framework was envisioned to be used, large numbers of ship service loads would likely be aggregated,

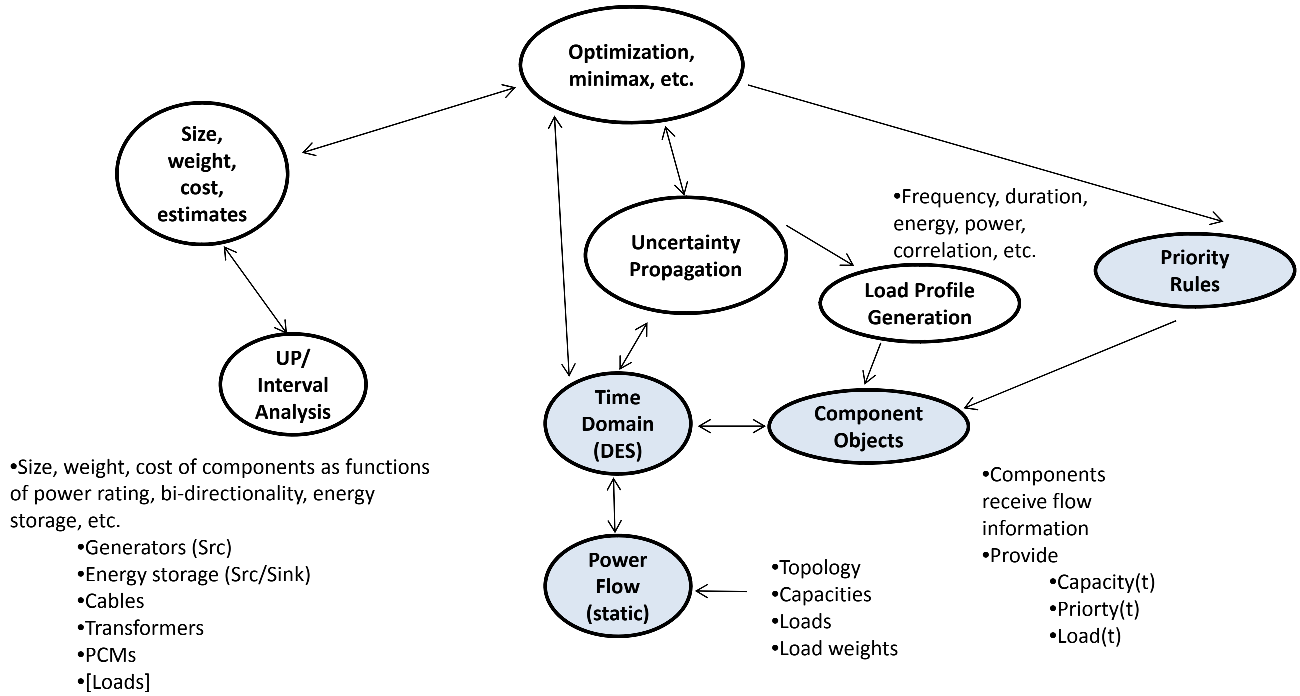

Fig. 1: Overview of Proposed Framework

in which case, delivery of a fraction of the demanded power would be representative of a portion of the aggregate loads being served, which may be a reasonable approximation of behavior. The analysis assumes that all systems and controls needed to facilitate such load shedding and routing of power are in place (this is not to suggest that all of these issues are resolved issues, but, rather, that these aspects are not part of this analysis). However, this analysis also assumes that a load prioritization system is in place, which specifies the priority of each load represented in the system. This also requires that, at each point in time, each energy storage module be represented either as a source (discharging) or as a load (charging) with a specified charging priority. The approach taken for the framework was to allow an object-oriented implementation of components (in MATLAB), such that the individual component objects interface to the power flow module, specifying information such as capacity (source, transfer, or load) and priority to the power flow module. Different prioritization approaches and algorithms could be interfaced to the component objects or implemented within the component objects. The topic of load shedding and prioritization has been addressed in works such as [3] and [4], for example, and these types of approaches could potentially be implemented within the framework in the future. However, as the development of load prioritization schemes was not one of the core objectives of this work, the planned initial solution is to implement a simple, local priority scheme for each type of component, as described in Section 4.3. The planned approach characterizes priority through a small set of parameters, with the intent to allow optimization of the parameters to attempt to represent the best system behavior for a given scenario.

Other modules of the framework illustrated by Fig. 1 include modules for load profile generation, uncertainty propagation, optimization, and size, weight, and cost estimation. Although power demand is specified by each load at each point in time, the framework was intended to support a load profile generation module, which could be used to generate a profile for each load at initialization of the components. Thus, rather than focus the analysis on a set of pre-defined profiles, analyses could be carried out on a range of profiles generated according to specified characteristics of these time series. As noted above, the uncertainty propagation module is also anticipated to make use of existing algorithms and software for black-box uncertainty propagation. This module will facilitate simulation of loss or degradation of components based on probabilities of failures, as well as variations in system parameters based on uncertainty. The module will generally be used to generate and evaluate multiple system models based on descriptions of the model uncertainty and other sources of uncertainty. As described in Section 4.5, the module is generally representative of a suite of tools that may be employed, ranging from simple Monte Carlo simulation techniques to more targeted techniques from the fields of design and analysis of computer experiments (DACE) or machine learning. The optimization module is also expected to make use of existing tools and techniques, and is generally representative of a suite of tools. These may be used in system optimization, optimization of priority rules, and/or in conjunction with the uncertainty propagation module for uncertainty propagation (e.g. as outer loop in probabilistic bounds analysis). The module for size, weight, and cost is somewhat independent of the other modules, but serves as a counterbalance in optimization activities. All of the modules are described in further detail in the subsequent sections. The metrics for evaluation of performance of a system are expected to be based on probability of mission success, similar to the approach used in [1]. This would require specification of the probability of success of each key load as a function of the energy delivered over the interval of interest. However, alternative approaches for evaluation of performance may also be considered, and this analysis could also be considered to be independent of the other modules.

4.2 Power Flow Solution

The role of the static power flow solution module is to determine the power that will be delivered to each of the loads at a fixed point in time, given load power demands and priorities, source power capacities and priorities, and the power capacity constraints for the components of the power system linking the sources and loads. In order to minimize both the required information and computational expense of the power flow solution, it is proposed to make use of a graph-based power flow solution, similar to that employed in [5]. With this approach, the system is represented by a directed graph, as illustrated by Fig. 2, for example. In this formulation, generators are represented as sources (G1 and G2), loads are represented as sinks (L11, L12, L21, and L22), buses are represented as nodes (SB11, SB12, SB21, and SB22), and power transfer equipment (cables, transformers, converters, etc.) are represented as edges. In this formulation, an energy storage component could be represented as either a source or a sink, depending on the situation. The status of each energy storage module as a source or sink, along with corresponding power charge or discharge capacity, would be determined by another layer of the framework. The flows in the graph represent power, with no consideration given for voltage or current, eliminating the need to specify impedance information or system frequency, as would be required in a traditional load flow solution. The graph-based power flow problem can be solved using linear programming techniques, as employed in [6]. If load demand cannot be met, the solution reflects the system constraints by curtailing the power delivered to the loads, as if the minimal amount of load shedding has occurred. By including priority values for the sources and sinks as weights, the problem can be framed such that the solution represents the optimal power delivery for the given constraints. This allows the solution to inherently reflect load shedding that would occur based on the specified priority levels. Thus, this module is simply required to determine the steady state power that would be delivered to the loads for the given constraints of the topology and components.

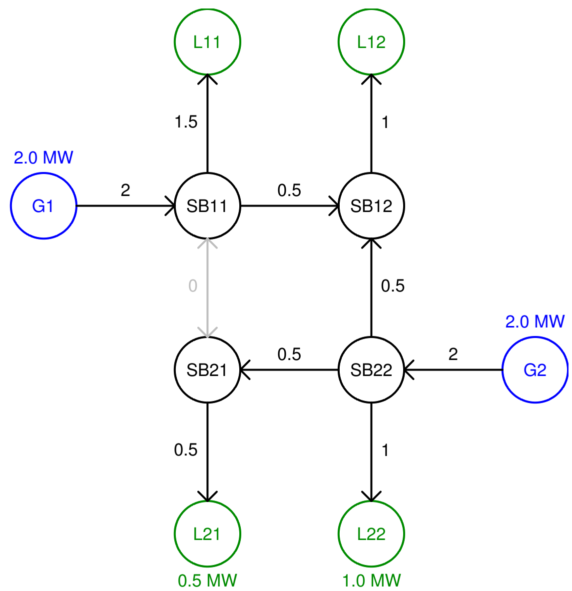

Fig. 2: Graph-Based Power Flow Solution [5]

In order to incorporate time into the analysis, a quasi-steady state approach is intended to be employed, making use of multiple calls to the static power flow module. With this approach, it is assumed that the for the time duration between static solutions, the system remains in the state for the previous static solution. The time domain power flow module is therefore required to initiate a new static solution at any time in which the system conditions require change. A change in the system conditions may be triggered by changing loading conditions or priorities, by a change in the topology or component capacity due to a fault or failure, or by the full charge or discharge of an energy storage unit, for example. The initial inclination in the formulation of the framework was to employ a discrete event simulation (DES) approach, and require the time-domain power flow module to project forward in time to the next change in the system conditions. However, this module may additionally (or instead), make use of a fixed time-step approach. This point has yet to be determined and will be further considered as the framework is implemented. In either case, the intent of the approach is to employ reasonably large time durations between calls to the static solution, in order to result in significantly fewer solutions than would be required for dynamic simulations of equivalent time scales.

4.3 Component Models for Power Flow Solution

As the power flow solution module deals simply with sources, sinks, and edges, the functionality of the system components will be implemented through MATLAB classes. This will allow new types of components, priority rules, etc. to be developed as needed and incorporated into the framework. The component models will ultimately specify the capacities and priorities for the sources, sinks, and edges in the power flow solution, making use of the power flows provided at each point in time from the power flow module. Each component will be responsible for keeping track of needed state variables and implementing appropriate logic. A small set of flexible, parameterized component models is proposed to be initially developed, with more specific models to be developed, as needed. Descriptions of some of the initial component classes to be developed are given in the following subsections. In order to simplify the issue of energy management and load prioritization (for which a wide range of solutions may be developed/proposed, but are generally not within the planned scope of work for this effort), these initial base components make use of simple, local-based approaches for determining priority. This will allow the user to generally have flexibility in configuring the prioritization rules for the components through a small number of parameters. This will also allow a small set of parameters to be exposed to an optimization engine in order to attempt to identify the best behavior for a system in the absence of a known, optimal approach for energy management. In later stages of the development of the tools, however, prioritization functions (based on centralized management of the system) could be employed for setting component priority.

4.3.1 Load Component

A basic load component is proposed to be developed, which supports specification of a time-based loading profile and priority based on integrated power demand deficit. This basic approach is illustrated by Fig. 3. Referring to the power demand and the power delivered to the load in Fig. 3, power demand is met except for the period of time between $t = t_d$ (the time at which the power demand deficit begins), and $t = t_r$ (the time at which the power demand is again met). In general, it is expected that the power demand will be specified through a piecewise defined time-based profile. It is intended that these load profiles may be generated from the load profile generation module, as well as being specified directly. The integrated power demand deficit over this time, $E_d(t)$, is given by (1), where P_{dem} is the power demand and P_{del} is the power delivered to the load.

$$E_d(t) = \int_{t_d}^{t} \left[P_{dem}(\tau) - P_{del}(\tau)\right] d\tau \tag{1}$$

The load priority, $I(t)$, is to be determined as a polynomial function of the integrated power demand deficit, and an exponential decay in priority following restoration of power to the level of demand, as given in (2).

$$I(t) = \begin{cases} p_n\left[E_d(t)\right] + I(t_d), & \text{for} P_{del}(t) < P_{dem}(t) \\ k_0 + \left[I(t_r) - k_0\right] e^{\dfrac{t - t_r}{\tau_r}}, & \text{otherwise} \end{cases} \tag{2}$$

Here, $p_n[E_d(t)]$ is an n^{th} order polynomial function of $E_d(t)$, where $p_n(x) = k_0 + k_1 x + k_2 x^2 + \ldots + k_n x^n$. However, it is proposed to limit this to a first order polynomial in most cases, in order to minimize the number of parameters governing the priority of the load. It is also proposed to apply limits to the resulting priority. Thus, for a first order polynomial function, the priority function for the load would be determined by the following parameters:

k_0 Minimum priority for the load.

k_1 Coefficient affecting the rate of rise of priority during a power demand deficit.

τ_r Time constant for exponential decay of priority upon restoration of power to the level of demand.

I_{max} Maximum priority to be assumed by the load.

Other inputs for configuration of a load component include:

$P_{dem}(t)$ Power demand profile. This may be explicitly provided, or may be generated by a separate module.

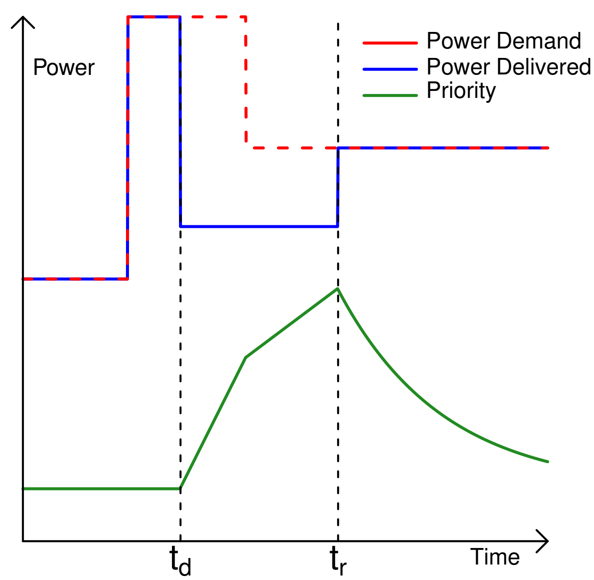

Fig. 3: Example Illustration of Load Priority

It should be noted that the traditional use of constant (although mission dependent) priority levels, such as the use of vital, semi-vital, and non-vital designations, is a special case of this approach, in which only the constant polynomial term, k_0, is used (i.e. $k_i = 0$, for $i > 0$). However, this approach may be well suited to describing the priority of many loads, lending itself to a flexible formulation of the priority for a variety of loads. For example, freezers may be considered as semi-vital loads which can be readily shed in emergency situations for limited time durations. However, once power is restored, the priority of these loads may need to remain high for some time, depending on the duration for which power was not available. These characteristics could be captured by a relatively low base priority (k_0), an appropriate linear ramp in priority (k_1), and a long time constant (τ_r) for decay of priority following restoration of power. Thus, a small set of parameters can provide a reasonable degree of flexibility for configuring priority rules for loads. Further, while the best settings for loads may not be known at the outset of a study, the small set of parameters for loads may be exposed, along with appropriate ranges for consideration, to an optimization algorithm in order to select the optimum rules for a given scenario or study. In this way, the effect of user choice in these parameters may be minimized. While this load component is intended for general use, component models with more specific priority characteristics may be developed as needed.

4.3.2 Generator Component

The generator component is represented by a source in the power flow, providing to the power flow module a power capacity which can be supplied and a source priority. The basic generator component is envisioned to be simply configured through a time-based capacity profile and a static priority. The time-based capacity could be used to simulate a loss or degradation of the generator during the scenario. This time-based capacity profile could be directly specified, but may also be generated through an uncertainty propagation module to represent random failures. This model could also be easily extended to include short term overload capabilities and/or fuel consumption computation, if necessary. The behavior of the generator component is therefore specified through the following inputs.

$P_{capacity}(t)$ The power capacity of the generation unit. This may be a constant or a time-based profile, in order to represent failures or degradation of the unit during the simulation. This may be directly specified or may be generated through a separate module based on failure characteristics.

I Priority for supplying power. This may be set to give loading precedence to one source over another.

4.3.3 Energy Storage Module Component

An energy storage module can absorb or supply power, and, therefore, may be represented as either a source or a sink in the power flow solution. The energy storage module presents an additional challenge in that the component must determine it's status as a source or a sink on each step of the simulation. The envisioned approach for this is to formulate the charging priority for the component as a polynomial function of the charge deficit, $\Delta E(t)$, as given by (3).

$$I(t) = p_n\left[\Delta E(t)\right] \tag{3}$$

Here, $\Delta E(t)$ is the difference between the storage capacity of the component and the actual stored energy at time t. In order to determine the source/sink status of the component, its charge priority level would be compared to the priority levels of all loads to which it can potentially supply power (obtained through the incidence matrix of the power flow solution module) for which the power demand is not currently met. If there is a connected load with a power deficit having a higher priority than the charging priority of the energy storage component, the component should act as a source. As a source, the energy storage unit will have a constant discharge priority (probably lower than all generation units). If the charging priority of the energy storage component is higher than all connected loads with a power deficit, the component will act as a sink, with priority equal to its charging priority value. With this approach, it may be necessary to implement multiple charging capacities with different priority characteristics to allow the the energy storage components to charge at different rates with different priority (e.g. high charge rates at lower priority). Using a single, linear priority characteristic, the energy storage component would be characterized by the following parameters.

$E_{capacity}$ Energy storage capacity.

k_0 Minimum charging priority.

k_1 Coefficient affecting the charging priority as a function of the charge deficit, ΔE.

I_{max} Maximum charging priority to be assumed by the load.

$P_{charge}(t)$ Maximum charging rate. This may be a constant or a time-based profile.

$P_{discharge}(t)$ Maximum discharge rate. Again, this may be a constant or a time-based profile.

4.3.4 Power Transfer Component

A basic power transfer component is planned to be developed to model equipment used to deliver power from the sources to the loads such as cables, power converters, and transformers. These components are represented by edges in the power flow solution, and, thus, provide a power capacity (possibly different in the two directions) to the power flow module. The basic power transfer component is envisioned to be simply configured through a time-based capacity profile. The time-based capacity could be used to simulate a loss or degradation of the component during the scenario. This time-based capacity profile could be directly specified, but may also be generated through an uncertainty propagation module to represent random component failures. The power transfer component is characterized through the following inputs.

$P_{capacity-1}(t)$ The power transfer capacity in the forward direction. This may be a constant or a time-based profile, in order to represent failure or degradation. This may be specified directly or through a separate module based on failure characteristics.

$P_{capacity-2}(t)$ The power transfer capacity in the reverse direction.

4.4 Load Profile Generation

Rather than focusing on a small set of pre-defined load profiles, it is desired to evaluate the performance of a system for a large set of load profiles based on specified characteristics, including both deterministic and random aspects. This module is intended to support this approach through generation of load demand profiles for components. At this time, the specifications and approach for development of this module have not been fully developed, but it is envisioned that this module will make use of information needed for characterization of time-series models in order to generate the profiles.

4.5 Uncertainty Propagation

While it may be possible to directly integrate uncertainty computations into the power flow solution, the initially envisioned approach is to use a deterministic power flow solution coupled with a module for black box uncertainty propagation. In this way, the uncertainty propagation module will iteratively generate and execute models based on descriptions of uncertain parameters of the system. This module is separated from the other analyses so that different uncertainty propagation techniques can be incorporated or substituted over time. In its simplest form, this module may simply employ Monte Carlo simulation techniques to execute numerous simulations using parameter sets randomly drawn from specified probability distributions, developing corresponding distributions for the simulation results. Other options which could be added to the module include metamodeling techniques from the design and analysis of computer experiments (DACE) and machine learning literature, as discussed in [7], [8], [9], and [10], for example. Further, options for this module are not limited to probability theory, but could include use of other representations of uncertainty [11], [12], [13]. As the representation and propagation of uncertainty are large topics in and of themselves, it is difficult to predict which approach(es) will be the most appropriate. The initial version of the module is intended to support functions for propagation of parametric uncertainty based on probability distributions describing uncertain parameters within the model. The initial implementation may also support propagation of p-boxes [14], to allow for consideration of epistemic uncertainty separately from aleatory uncertainty. This may be important in the analyses, as epistemic uncertainty (lack of information) may be one of the dominant sources of uncertainty in early stage design analyses. This will focus on a minimal set of functionality, with the major focus on exposing interfaces whereby uncertainty in model parameters can be propagated using black-box approaches. This should allow extensions to the module to be easily incorporated.

4.6 Optimization

The optimization module may be used for a number of purposes, including system optimization (optimization of design parameters), optimization of priority rules for components, and in uncertainty propagation. As optimization is also a large topic with large numbers of available approaches, the initial implementation of this module is envisioned to largely make use of existing optimization functions (e.g. functions supported by the MATLAB optimization toolbox), with the major focus on establishing interfaces between this module and the other modules of the framework.

4.7 Size, Weight, and Cost Calculations

The primary purpose of this module is to provide a counterbalance for design optimization activities. It is intuitive that the performance of a system could be increased by incorporating more capacity for power generation and transfer and more energy storage. However, the enhancements of these characteristics often have implications in terms of the cost, size, and weight of the equipment, which ultimately are driving factors in ship design. While a thorough treatment of these considerations (e.g. accounting for available space and geometry) is generally beyond the envisioned scope of this framework, it is necessary to include some means to account for these factors. Furthermore, as substantial uncertainty may be present in the analysis, it is important that the employed approach for accounting for these considerations effectively propagate this uncertainty. Thus, the intended approach for this module is to associate a size, weight, and cost for each component, but allow uncertainty to be specified in these estimates, even if only through simple intervals. Functions could also be included for estimation of these quantities for components (with uncertainty bounds) as functions of power rating, energy storage rating, voltage level, etc. The total size, weight, and cost of the design will be a simple sum of the values for each of the included components, but would appropriately propagate the uncertainty to obtain bounds on the resulting totals. This may be implemented using interval arithmetic [15], but may alternatively be based on some other form of uncertainty expression and propagation.

5 Conclusion and Recommendations

Herein, a proposed framework has been presented for analysis of distributed energy storage in shipboard power systems. The framework is intended to be implemented as a set of software tools, and the approach is anticipated to be refined during the process of implementation. The framework is intended to be modular, allowing modules to be independently refined and/or replaced over time.

6 Acknowledgements

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References

[1] Joseph Borraccini. White paper: Machinery system alternatives based on mission load elasticity. Technical report, Office of Naval Research, 2013.

[2] R. Hebner. Energy storage on future electric ships. Technical report, Electric Ships Research and Development Consortium, April 2014.

[3] Zhiping Ding, David A Cartes, and Sanjeev Srivastava. New load shedding scheme for islanded power systems. In *System of Systems Engineering, 2006 IEEE/SMC International Conference on*, pages 6–pp. IEEE, 2006.

[4] A. Shrestha, E.L. Foulks, and R.W. Cox. Dynamic load shedding for shipboard power systems using the non-intrusive load monitor. In *Electric Ship Technologies Symposium, 2009. ESTS 2009. IEEE*, pages 412–419, April 2009.

[5] James Langston, Michael Andrus, Michael Steurer, D Alexander, J Buck, G Robinson, and Don Wieczenski. System studies for a bi-directional advanced hybrid drive system (AHDS) for application on a future surface combatant. In *Electric Ship Technologies Symposium (ESTS), 2013 IEEE*, pages 509–513. IEEE, 2013.

[6] S. Iglin. grtheory – graph theory toolbox. URL http://www.mathworks.com/matlabcentral/fileexchange/4266, 2009.

[7] K.T. Fang, R. Li, and A. Sudjianto. *Design and modeling for computer experiments*, volume 6. Chapman & Hall/CRC, 2005.

[8] T.J. Santner, B.J. Williams, and W.I. Notz. *The design and analysis of computer experiments*. Springer, 2003.

[9] Trevor Hastie, Robert Tibshirani, and Jerome Friedman. *The elements of statistical learning, 2nd Ed.* Springer, 2009.

[10] Christopher M Bishop et al. *Pattern recognition and machine learning*, volume 1. Springer New York, 2006.

[11] George J Klir. *Uncertainty and information: foundations of generalized information theory*. John Wiley & Sons, 2005.

[12] Jürg Kohlas and Paul-André Monney. Theory of evidence survey of its mathematical foundations, applications and computational aspects. *Zeitschrift für Operations Research*, 39(1):35–68, 1994.

[13] Glenn Shafer. *A mathematical theory of evidence*, volume 1. Princeton university press Princeton, 1976.

[14] Scott Ferson, Vladik Kreinovich, Lev Ginzburg, Davis S Myers, and Kari Sentz. *Constructing probability boxes and Dempster-Shafer structures*, volume 835. Sandia National Laboratories, 2002.

[15] Ramon E Moore. *Interval analysis*, volume 2. Prentice-Hall Englewood Cliffs, 1966.

APPENDIX E

MODULAR MULTILEVEL DAB CONVERTER WITH ENERGY STORAGE AND DC ACTIVE FILTER FUNCTION FOR SHIPBOARD MVDC SYSTEM APPLICATIONS

1. Summary

Nowadays more and more pulsed loads and non-linear loads are carried on the MVDC shipboard power system, whose pulse and non-linear current in different frequency ranges might induce voltage oscillations on the MVDC bus. We proposed a novel galvanic isolated bidirectional dc/dc converter based on modular multilevel converter with energy storage which can implement dc active power filter function that can smooth load current on the MVDC bus. Detail hardware design and control strategy for the system are developed. Simulation study has been conducted.

2. Progress

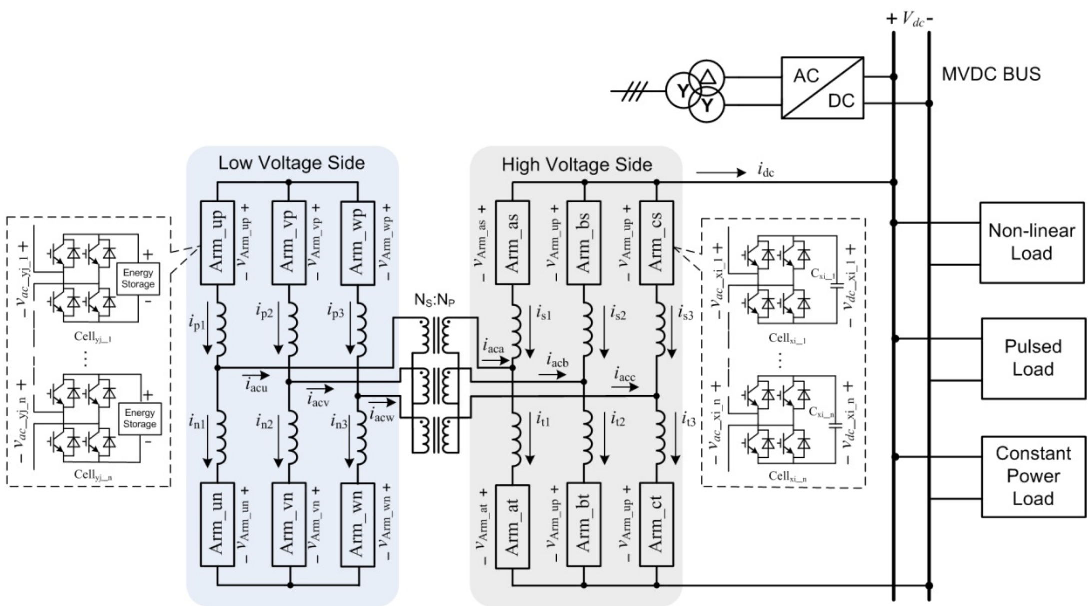

Figure 7 Structure of shipboard MVDC system with proposed MMDAB

The proposed MMDAB converter is in parallel with the MVDC bus to compensate the dc load current ripple and pulse, which is shown in Figure 1. A wide variety of loads which include high power propulsion loads and pulsed loads are connected to the MVDC bus through power converters. In the MMDAB converter, two three-phase MMCs are connected through an ac transformer, both MMCs employ full-bridge cells. Energy storage battery units are connected to the dc side of each of the sub-modules separately in the primary MMC, the dc terminal of secondary MMC is connected to the MVDC bus. The voltage is elevated and inverted by the primary MMC then elevated and rectified by the secondary MMC. Active filter functionality is accomplished by the secondary MCC while the primary MMC is responsible for providing energy to the active power control function. Careful assignment of sub-module cascade number and sub-module voltage rating are important in this system design.

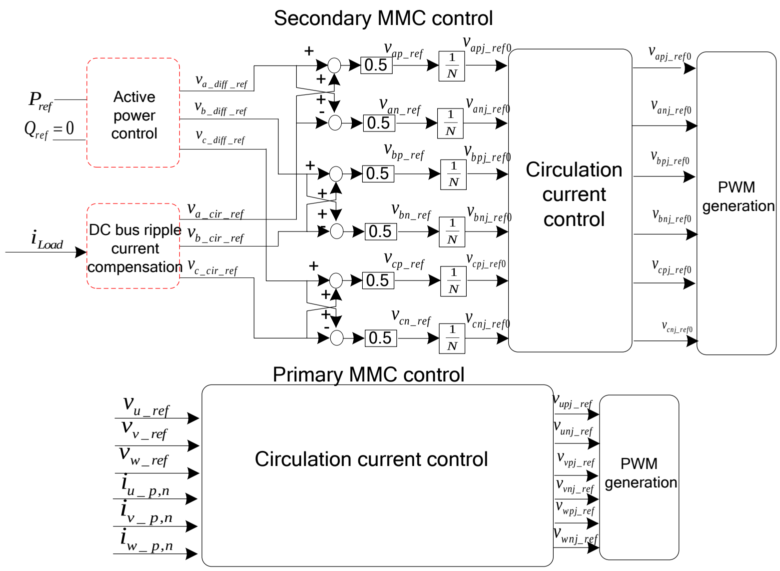

Fig.2. Control block diagram

Fig. 2 shows the control block diagram of the MMDAB. The control is divided into primary MMC control and secondary MMC control. Primary MMC control is only responsible for the transformer side sinusoid voltage generation while the primary MMC sub-module circulation current suppression is finished by the primary MMC control block. The secondary MMC control is divided into the following three sub-controls: active power control, dc bus ripple current compensation control and circulation current control.

The MMDAB with energy storage and dc active filter functions of Figure 1 has been simulated using PSCAD. Fig. 3(a) shows the simulation waveforms of MVDC bus current and load current before and after MMDAB energy storage and active filter function realization. When MMDAB is controlled, the output current can compensate the ripple current of load, while producing part of the active power.

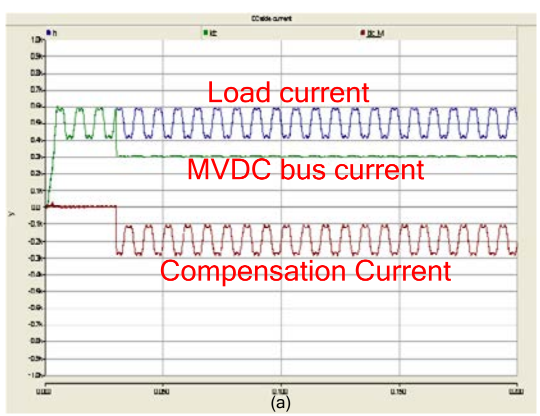

Fig.3. Simulation waveforms: compensation current of MMDAB

3. Publications

A paper based on above research has been submitted to ESTS 2015.