Exergy Analysis of Ship Power Systems

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Synopsis

Ship subsystems and mission modules perform energy conversion during their operation resulting in a combination of electricity consumption, heat generation and mechanical work. These multi-physics subsystems often have opportunities for performing an energy storage role during their operation cycle. The kinetic energy stored in the rotating mass of a generator set or the electrical energy stored in a railgun pulse forming network are but two examples of energy storage aboard warships. Treating each subsystem as a disconnected entity reduces the potential for exploiting their inherent interactions and results in over- designed shipboard systems with excessive weight and volume. Exergy - the amount of energy available for performing useful work - provides a path for exploiting multi-physics energy flows. Utilizing the Second Law of Thermodynamics, by modeling and minimizing exergy destruction, a recent study, showed that exergy control increased the overall efficiency by 18% over traditional optimization techniques when applied to a terrestrial HVAC application. In this paper a notional, multi-physics ship power system is developed that explicitly captures the exergy flows. Particular attention is given to exergy destruction phenomena. Simulation of the system illustrates operational characteristics with greatest impact on exergy destruction highlighting areas for applying optimal, exergy-based control schemes. This approach will allow ship designers to minimize the size and weight of installed power generation, energy storage and thermal management systems, enabling the affordable implementation of advanced weapons and sensors.

Keywords: Exergy; Control; Pulsed Load; Energy Storage

1 Introduction

The US military has been pursuing the development of various electrically powered mission systems for a number of years. These systems include electromagnetic railguns, lasers, radio frequency weapons and solid-state radars (Kuseian, 2015), (Hecht, 2018), (O'Rourke, 2017). All of these new systems require large amounts of electric power compared to existing mission systems and the power is required in pulses of energy as opposed to a steady state draw. Because of the pulse-type nature of these new loads, power system designers are looking to energy storage to augment traditional generator sets for supplying the correct amount of power at the right time. The introduction of electrically powered mission systems also affects the ship's cooling plant. With efficiencies

Authors' Biographies

Eddy H. Trinklein Has both a B.S. and M.S. in Mechanical Engineering (2009 & 2011) and has worked at Michigan Technological University since 2011. Mr. Trinklein has worked on U.S. Navy projects for the past 7 years including control system development, motion sensor design and evaluation, scale model development leading to full-scale control system implementation and testing. His present research interests are ship mounted motion platforms designed to mitigate undesired payload motion. Prior to working for Michigan Tech, he was a fixture and machine designer at Key Design Inc.

Gordon G. Parker is the John & Cathi Drake Chair Professor Mechanical Engineering and co-Director of the center for Agile and Interconnected Microgrids (AIM) at Michigan Technological University. He specializes in control system design and optimization of mixed-physics dynamic systems. A key area of his research is the optimal control of power systems with particular attention given to networked topologies. Dr. Parker and his colleagues recently formed the Agile and Interconnected Micrgorid (AIM) Center to bring together faculty from Computer Science, Mathematics, Cognitive Sciences and Learning, Electrical and Computer Engineering and Mechanical Engineering to focus an interdisciplinary team on this technical area. As co-Director of AIM, Dr. Parker works with its 18 faculty to execute successful S&T projects with customers from DoD, DOE, and NSF. While at Michigan Tech he has mentored 50 graduate students, co-authored over 100 peer-reviewed publications and is a fellow of the Society of Automotive Engineers. Prior to his Michigan Tech appointment he was a senior member of the technical staff at Sandia National Laboratories in Albuquerque, New Mexico and a trajectory and control designer at General Dynamics Space Systems in San Diego, California.

Timothy J. McCoy is a consultant in the naval and marine industry. He was formerly the Director of the Electric Ship's Office (PMS-320) in Washington, DC where he was responsible for developing electric power, propulsion and control systems for the US Navy's fleet. There he initiated multi-million dollar international agreements for joint development of advanced ship power and control systems. Prior to entering government service, he worked in industry as a consultant, R&D Director and President of a defense contractor where he established a large R&D program for the marine, steel, renewables and oil & gas markets. Previously, he served active duty in the US Navy, where he developed integrated electric power and propulsion systems, control systems and designed several classes of ships. Dr. McCoy holds a BS in Mechanical Engineering from the University of Illinois; a Naval Engineer's Degree, SM in Electrical Engineering and PhD from MIT. He taught ship design and systems engineering while on the MIT faculty. A registered Professional Engineer, he is an IEEE Fellow and a member of ASNE. He is widely published and is an Adjunct Professor in the Electrical and Computer Engineering Department at Carnegie Mellon University.

Rush D. Robinett III is the Director of Research and the Richard and Elizabeth Henes Chair Professor of Energy Systems in Mechanical Engineering-Engineering Mechanics at Michigan Technological University. In January 2013, he retired from Sandia National Laboratories after 25 years of service as the Senior Manager of the Grid Modernization and Military Energy Systems Group focusing on the research and development of microgrids and networked microgrids. During his 25 year career, Dr. Robinett worked on ballistic missile defense, spacecraft systems, glide weapons, teams of robots, and renewable energy grid integration. He is an associate fellow of AIAA and has authored more than 180 technical articles, including three books and holds twelve patents. Dr. Robinett has three degrees in Aerospace Engineering: a BS and Ph.D. from Texas A&M University and an MS from the University of Texas at Austin.

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4 Conclusions and Further Research

With the addition of storage, the railgun fire rate was improved from 33 seconds as the baseline case to 6 seconds. For fire rates in the 6 to 21 second period the exergy destruction had an exponential trend. For 21 to 33 second fire periods, exergy destruction was nearly flat.

To achieve a 6 second fire period, a supplementarity energy storage size of roughly 750 MJ with a 6000 volt supply voltage and a current capacity of 2500 amps is required to fire ten sequential shots. The storage system would be fully responsible for supplying the charging current for the railgun capacitor energy storage. After the fire sequence, both the energy storage would need to be brought back to its initial storage state to allow another fire sequence.

A tradeoff between total exergy destruction and installed electrical storage was observed where as storage was increased exergy destruction decreased. This trend is more complicated since it is tied to the cooling system performance and desired operating temperature of the railgun. An investigation is required for non-static cooling size where railgun temperatures are kept constant while comparing exergy destruction.

In future work, an additional gas turbine could be added to improve ramp rate limits and to further explore system optimization under varying loading conditions. The trapezoidal charge profile, with fifth order polynomial transitions, provides a starting place for an optimal railgun charging profile. By optimizing both the bulk energy storage along with the charge profile utilizing an arbitrary curve could provide further performance improvements. Feed forward commands to the cooling system could also be used to reduced exergy destruction and further investigation is required. The coolant system is a significant portion of the total exergy destruction of the ship system and changes to coolant inlet temperature or tank temperature set points require further study.

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