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Multi-layered interactive energy space modeling for near-optimal electrification of terrestrial, shipboard and aircraft systems

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ABSTRACT

In this paper, we introduce a basic multi-layered modeling framework for posing the problem of safe, robust and efficient design and control that may lend itself to ripping potential benefits from electrification. The proposed framework establishes dynamic relations between physical concepts such as stored energy, useful work, and wasted energy, on one hand; and modeling, simulation, and control of interactive modular complex dynamical systems, on the other. In particular, our recently introduced energy state-space modeling approach for electric energy systems is further interpreted using fundamental laws of physics in multi-physical systems, such as terrestrial energy-systems, aircrafts and ships. The interconnected systems are modeled as dynamically interacting modules. This approach is shown to be particularly well-suited for scalable optimization of large-scale complex systems. Instead of having to use simpler models, the proposed multi-layered modeling of system dynamics in energy space offers a promising basic method for modeling and controlling inter-dependencies across multi-physics subsystems for both ensuring feasible and near-optimal operation. It is illustrated how this approach can be used for understanding fundamental physical causes of inefficiencies created either at the component level or are a result of poor matching of their interactions.

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Contents

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1. Background and paper organization

Electric power provision to terrestrial energy users (both stationary and mobile); aircrafts; ships; and far-flung military bases has been undergoing a tremendous transformation. Aircrafts, ships and terrestrial systems are required to meet increasingly complex, often conflicting, objectives. All of these systems critically depend on how is power provided to enable their objectives. For example, future aircrafts need to enhance efficiency, and at the same time ensure minimal environmental impacts, while ensuring safety. Depending on the specific purpose, their missions can be more or less dynamic and uncertain. Future ships and terrestrial electric energy systems are facing similar requirements. Future design and operation of these complex man-made systems will greatly depend on energy conversion processes, power delivery and energy consumption, and their inter-dependencies.

Microgrids have emerged as electric power distribution networks which connect small energy resources to small energy users so that, with help of storage, energy consumption is reduced in previously unseen ways. The energy consumers are beginning to play a proactive role in balancing supply and demand. In terrestrial electric power systems, the role of end users is becoming critical for increasing energy efficiency and, at the same time, for enabling utilization of clean, yet intermittent, energy resources (Ilic, 2016; Jaddivada & Ili, 2017). Military bases are exploring potential benefits of replacing fossil power generation by the smaller distributed energy resources (DERs) (Salcedo et al., 2016). These DERs are often a combination of consumers and small solar photovoltaic (PV) installations. Future aircrafts are considering the use of distributed turbo-electric propulsion instead of having single wing-tube power provision (Felder, Kim, & Brown, 2009; Jankovsky, Bowman, & Jansen, 2016). A similar transformation is taking place in electric power for ships (Doerry, 2009; McCoy & Amy, 2009). As these energy systems are being designed, it is becoming clear that a more distributed grid is needed to enable the best placement of loads and DERs, as well as of their utilization over a wide range of conditions. In future aircrafts, loads are propulsors whose placement is subject to active research. It is becoming possible to place thrust where the drag is, and enhance overall aircrafts efficiency (Moore, 2014). Distributed microgrid makes it possible to do this for the first time. The nature of loads is fundamentally changing in all these systems. Electric vehicles in terrestrial systems both consume and store power. Notably, viewed from the generation side complex energy conversion process can be helped by the controllable load itself. Large industrial consumers in terrestrial power systems are beginning to play a major role in helping power delivery and balancing by the utility. All these changes pose major questions regarding the very design of future electric power systems so that the advanced systems can perform their objectives at as low energy consumption and with as little as possible environmental impacts.

In this paper, we introduce novel modular modeling and multi-layered control needed to enable the above functionalities in the emerging electric energy systems. We start in Section 2 by describing emerging future terrestrial microgrids, electric aircrafts systems, and ships. We suggest that these systems need to be thought of in terms of their energy sources, delivery system components, energy consumption components, and their interactions. For purposes of describing and illustrating concepts for these systems we resort in Section 3 w.l.g. to the simplest architecture comprising a single energy source, one delivery component, and one load; this system is often referred in terrestrial power systems as a two-bus electric power system. In Section 4, this example is used to show how one can have a common unifying framework across seemingly different systems, such as ships, aircrafts, and households. In Section 5 we introduce energy space-based multi-layered modeling. The proposed modeling establishes relations between physical concepts such as stored energy, useful work, and wasted energy, on one hand; and modeling for analysis and control of interactive modular complex physical systems, on the other. The stand-alone modules are modeled in terms of their own internal component-specific physical states and their own energy states. The higher-level interconnected system is modeled by expressing interaction dynamics using energy states only. We stress and illustrate how is this fundamental to being able to both optimize design/operation of subsystems by domain experts and achieve a near-optimal performance of the system as a whole without excessive complexity. In Section 6, we illustrate using the small energy system, energy sub-processes and their interactions. The same modeling approach is used in Section 7 to establish feasibility and stability conditions for these complex physical systems. A brief summary of state-of-the-art modeling for these systems, such as the port-Hamiltonian modeling, Euler–Lagrangian modeling of multi-physics systems in context of the proposed energy space-based multi-layered modeling is given in Section 8. Notably, in Section 9 it is proposed and illustrated that maximization of power contributing to real work done can be achieved by minimizing the reactive power. Ideally, this quantity needs to be equal to zero for maximum efficiency. Once the efficiency of components is understood in terms of reactive power management, in Section 10 we pose a centralized control problem formulation which allows for near-optimally efficient control design and stable feasible operation. The measure of inefficiency is expressed using reactive power and a novel optimal control formulation is introduced which utilizes multi-layered model

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