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A real-time simulator framework for marine power plants with weak power grids☆

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ABSTRACT

This work takes aim at presenting a generic real-time simulation framework for marine power plants with weak power grids, containing transient functionalities such as starting and stopping of arbitrary generators, and phase synchronization. The generator models used in the power plant are hybrid causality models, meaning that they have the ability to switch between causality orientations, between voltage and current. These models facilitate real-time simulations as long as they are solved properly, as will be discussed in this article. Much is devoted to numerical stability, model robustness and power plant control, e.g. rms voltage control, engine speed control, active- and reactive power sharing control and phase synchronization control. Some focus is also given to overall power plant control structure. A case study of a marine power plant including two generators and a fluctuating- and noisy power consumption is presented and analysed, and illustrates the advantages of the proposed framework as well as giving a good foundation for future works.

1. Introduction

To date, diesel electric propulsion is the most preferred solution for propulsion generation for marine vessels with a relatively large change in load conditions on a daily basis [1]. This is mostly due to its flexibility and, in general, low emissions [2], even though conversion losses may become quite significant. For a marine vessel all systems that produce electrical power constitute the power plant. Different diesel engine and generator configurations, here referred to as *gensets*, can be used in a marine power plant, depending on the criteria set by the ship-owner and the classification authorities. One such configuration is shown in Fig. 1 where two gensets constitute the marine power plant for a vessel equipped with two azimuth thrusters placed at the stern and one tunnel thruster in the bow. For reference, this thruster configuration was studied in [3] with respect to optimal thrust allocation control. Such a marine power plant is often tailored for each marine vessel and a mathematical model of the power plant is a good tool in the design process, enabling simulations of various load conditions, due to different vessel operations. One challenge when it comes to marine power plant modeling is proper control, at least if transient power plant operations are considered, e.g. a constantly changing power demand causing starting and stopping of gensets, and synchronization of gensets when being activated. A marine power plant model that facilitate such studies is the main topic presented in this article.

A diesel-electric marine power plant consists in general of diesel engines and electrical machineries [4], such as generators and electrical motors, which on a component basis have been studied thoroughly in the literature. In [5,6], a two-axis bond graph model representing synchronous electrical machines is presented and studied. This model, given in the $(d, q, 0)$-reference frame, is also thoroughly analysed in [7], where equivalent circuit diagrams are also given, along with different model fidelities and model reduction techniques. Such model reductions are also studied in [8,9]. In [7], stability and control of such systems are treated as well, and in [10] the sensitivity of eigenvalues is studied and in [11] the Nyquist stability criterion is used to assure stability in DC power systems. When it comes to overall power plant control, functionalities for synchronizing gensets and for load sharing are important. In [12], active synchronizing control of a microgrid is proposed and studied, while in [13], load sharing control is developed based on droop control and average power control.

Power grids in marine power plants are often characterized as weak, as opposed to onshore ones, which means that in practice, a large power peak in the power grid may change the rms voltage. This is because capacitive effects in the power grid itself are small and often negligible. However, often when modeling such weak power grids, a small capacitive effect is added in order to set the

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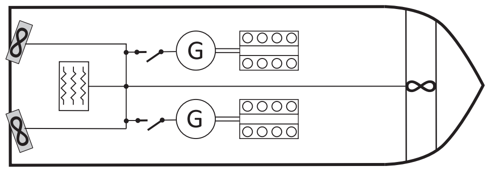

Fig. 1. Marine vessel equipped with two gensets, two azimuths and one tunnel thruster, in addition to auxiliary loads such as hotel loads.

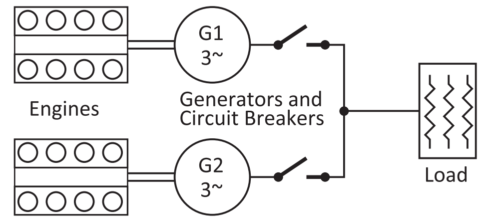

Fig. 2. Marine power plant model.

power grid voltage, mathematically speaking. This means that all power grid consumers and producers can be modeled with electrical current as the model output and the power grid voltage as model input. Nevertheless, such a small capacitive effect would introduce a small time constant which often stiffens the system and increases the time to solve the total system in a simulation, and is hardly wanted when trying to achieve real-time simulations.

By neglecting the capacitive effect in the power grid model itself the small time constant disappears. However, then the power grid voltage must be set by one of the power grid components. Consequently, in a generic marine power plant model where arbitrary power producers can be active, all power producers should have the possibility to set the power grid voltage, though only one at a time, if no loading model in parallel is implemented for providing the voltage. A model that has the ability to change input and output variable(s) online during a simulation is hereafter referred to as a *hybrid causality model*. Such a model switches between having *integral causality* and *differential causality*. The concept of causality is thoroughly elaborated in [14] and will not be given any particular attention here. The reason for using hybrid causality generator models in this context is because we then always have one component in the marine power plant that can provide the voltage, and hence, no small capacitive effect introducing a small time constant is needed. However, other problems are introduced, such as solving the differential causality part of the model in a stable and fast manner without algebraic loops. This will be given more attention in Section 2.4.2.

In the literature, hybrid causality models are also referred to as switched models [15] and hybrid models, in general. In [16], a theory for modeling discontinuities in models is presented, and in general, treats most kinds of hybrid dynamical models, and in [17] it is shown how simulations can be efficiently built from hybrid bond graph models. Generic synchronous generator models, having hybrid causality properties, are presented in [18] but lacks an overall numerical stability discussion, as well as a presentation of a suited power plant control structure and does not have a focus on real-time solvability.

In this work, a hybrid formulation of the well-known synchronous generator model in the (d, q, 0)-reference frame, as first presented in [18] in bond graphs, is further studied with respect to numerical stability, power management and control. This, in order to establish a generic model framework for simulating marine power plants with weak power grids suited for transient operations, while maintaining computational efficiency for real-time applications. This is significant because this topic is not overrepresented in the literature and such a generic framework gives great advantages when e.g. studying marine offshore vessels in demanding operations, as in [19], where interactions between the equipment and the power plant is important. If hardware in the simulation loop are included, such as in [20], it is also important that the models can be simulated in real-time. The proposed marine power plant framework also provides generic connections in both the (d, q, 0)- and the (a, b, c)-reference frame such that electrical equipment, e.g. azimuth thrusters, can be connected directly. Hence, the proposed power plant framework is a stepping stone for fast solvable total marine vessel simulators, as will be a topic in future works. A marine power plant consisting of two generic three-phased synchronous generator models, stiffly connected through a weak power grid, as shown in Fig. 2, will be used as a case study in this work, and will be modeled using bond graph theory [14].

1.1. Outline

In the next section the hybrid causality generator model is presented in detail and analysed with respect to numerical stability when using the Euler integration method. Also, additional models such as auxiliary diesel engines and circuit breakers are presented. In Section 3 simple control systems and strategies needed for running a marine power plant is presented. A case study of a marine power plant including two gensets are studied and simulated in Section 4. Lastly, a conclusion is made in Section 5.

2. Hybrid generator modeling

The hybrid generator models to be used are given in the (d, q, 0)-reference frame as in [18]. To keep it generic, as well as the ability to display simulation results in the (a, b, c)-reference frame, these models should have the ability to connect to the (a, b, c)-reference frame, which means that a power conservative transformation between the two reference frames is of interest.

2.1. Reference frame transformation

According to [5,21], the (d, q, 0)-reference frame is related to the (a, b, c)-reference frame through the phase angle θ such that

$$\boldsymbol{u}_{d,q,0} = A(\theta)\boldsymbol{u}_{a,b,c}$$
$$\boldsymbol{i}_{d,q,0} = A^{-1}(\theta)\boldsymbol{i}_{a,b,c} \quad (1)$$
$$(1)$$

where $\boldsymbol{u}_{i,j,k} = [u_i, u_j, u_k]^T$, $\boldsymbol{i}_{i,j,k} = [i_i, i_j, i_k]^T$, and

$$A(\theta) = \sqrt{\frac{2}{3}} \begin{bmatrix} \cos(\theta) & \cos\left(\theta - \frac{2}{3}\pi\right) & \cos\left(\theta - \frac{4}{3}\pi\right) \\ -\sin(\theta) & -\sin\left(\theta - \frac{2}{3}\pi\right) & -\sin\left(\theta - \frac{4}{3}\pi\right) \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix} \quad (2)$$

is a power-conserving transformation matrix. The phase angle θ is defined as

$$\theta = \int_0^t f_{PG} 2\pi \, dt \quad (3)$$

Here, f_{PG} is the power grid frequency. In order for this transformation to be power conservative, it follows directly that $A(\theta)^{-1} = A(\theta)^T$ [7]. Here, it is assumed that $u_0 = 0$. In other words, u_d, u_q and f_{PG} is a representative set of variables for u_a, u_b and u_c.

2.2. Generator model with current as output

The dynamics of a generator with current as output can be expressed according to [18] as

$$\dot{\boldsymbol{\psi}} = -\omega_m \boldsymbol{D}\boldsymbol{\psi} - \boldsymbol{R}\boldsymbol{i} + \boldsymbol{E}\boldsymbol{u}_{\boldsymbol{d},\boldsymbol{q}} + \boldsymbol{b}u_f \quad (4a)$$