Simulation and Optimization of Electric Ship with Low Voltage AC/DC Hybrid Power System

Mohan Kumar Gandiboyana[1], **Venkateswara Rao .K**[2]

[1]M.Tech Student, Electrical and Electronics Engineering, Baba Institute of Technology and Sciences, Visakhapatnam, India

[2]Associate Professor, Baba Institute of Technology and Sciences, Visakhapatnam, India

Abstract: ***DC hybrid power systems are of interest for future low emission, fuel-efficient vessels. In spite of the advantages they offer onboard a ship, they result in a complex, interconnected system, which requires effective analysis tools to enable a full realization of the advantages. Modeling and simulation are essential tools to facilitate design, analysis, and optimization of the system. This paper reviews modeling of hybrid electric ship components including mechanical and electrical elements. Power electronic converters are modeled by nonlinear averaging methods to suit system-level studies. A unified model for bidirectional converters is proposed to avoid transitions between two separate models. A simulation platform using the derived models is developed for the system-level analysis of hybrid electric ships. Simulation results of power sharing among two diesel generators, a fuel cell module, and an energy storage system are presented for three modes of operation.***

Keywords: DC distribution systems, modeling, simulation, transportation.

1. Introduction

The advantages gained from electrification of ship propulsion systems have created an increasing interest in all-electric ships. Future electric ships require reliable power systems with improved fuel economy, and reduced emission, while they are able to meet the ever-increasing power demands. Shipboard hybrid power systems have become appealing options to meet these needs . With penetration of power electronic converters into power systems, shipboard dc distribution systems offer further advantages , such as space and weight savings, and flexible arrangement of equipment . Despite the benefits offered by shipboard dc hybrid power systems, their complexity calls for the development of effective analysis tools to take full advantage of these systems. Modeling and simulation of such power-electronic based systems are essential tools in their design, analysis, power management, and control. As the standard power system analysis packages need excessive computation time to simulate these systems, an appropriate modeling for all modules must be carried out. In terms of computation time, the limiting elements in the modeling of these systems are power electronic converters, as they require extremely small time steps.

This paper is focused on modeling and simulation of hybrid electric ship power and propulsion systems. Models are derived for different electrical and mechanical elements including the synchronous generator–rectifier system, inverter, dc/dc converters, diesel engine, propeller, and ship hydrodynamics. Power electronic converters are modeled through nonlinear averaging techniques to give an effective solution with the accuracy and speed of simulation for large signal analysis. Thereafter, a simulation platform is developed in MATLAB/Simulink for system-level studies of hybrid electric ships. As a case study, a hybrid electric ship is simulated in different modes of operation. The simulation results of a power sharing control among two diesel generators, a fuel cell unit, and an energy storage system show practical utility of such a simulation tool in system studies associated with design, evaluation, power management, etc.

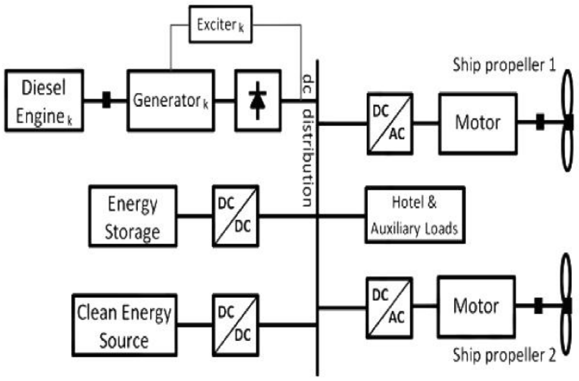


Figure 1: Single-line diagram overview of a typical shipboard dc hybrid electric power system.

2. System Characteristics and Overview

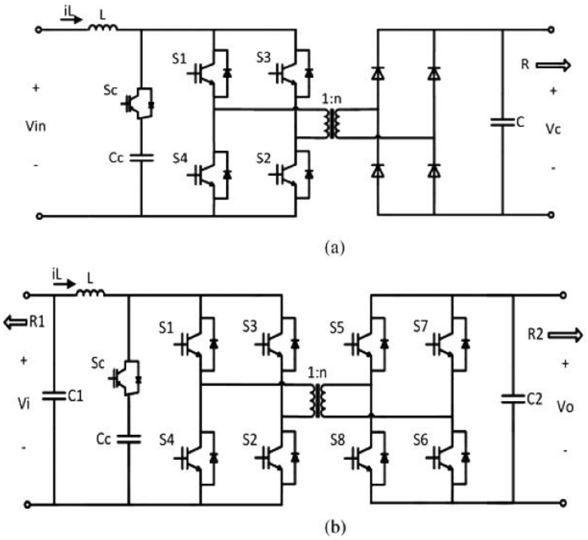
Along with the benefits gained from power electronic converters in hybrid power systems, they add to system complexity due to switching behavior of the semiconductors and the nonlinear properties of the power converters. In order to model the components of such systems, some considerations should be taken into account. Appropriate modeling for system-level analysis of ship dc distribution power systems requires specific features imposed by the system characteristics. First of all, there are mechanical and electrical components in such a system with extremely different dynamics. This difference ranges from a very small time constant of a power electronic switch, which is on the order of nanoseconds to a large time constant of ship hydrodynamics, which is tens of seconds. Thus, detailed switching models of power electronic converters lead to excessive simulation runtime. Reduced-order converter models via averaging techniques make the simulation orders of magnitude faster. Therefore, dynamic averaging is a time-efficient solution when studying the exact switching behavior is not necessary. Second, for system level studies, in which large variations occur in system states, small signal or linearized averaging is invalid, and large signal models must be developed instead. Large signal modeling is carried out by nonlinear averaging methods . Third, the interactions among connected elements should be included in order for the system model to be realistic. In other words, each element should receive the reaction of the connected elements, as soon as it affects them. Therefore, the interfaces among connected models must be bidirectional. Lastly, it is also preferred that the developed models are able to interface with elements in standard software packages, in order to take the advantage of existing valid models. A single-line diagram of a shipboard dc hybrid distribution system is depicted in Fig. 1. This chosen combination includes typical components and modules of such a hybrid system. Fuel cells and solar energy are the proposed clean energy sources for future fuel-efficient vessels. Solar power can be combined with wind power by using fixed sails that are equipped with solar panels. This provides zero-emission operation. Energy storage onboard an all-electric ship can be based on different technologies, such as electrochemical batteries and super capacitors.

Detail dynamic models of the sources and energy storages are important for time -domain analysis in order to implement the constraints associated with them, e.g., their dynamic behavior, power limits, and capacity. Diesel engines have slow dynamics resulted from ignition delay and mechanical time constant, which will be discussed in section IV. Fuel cell voltage drops sharply at high currents due to fuel starvation, which may lead to irreversible damages to the cell. This phenomenon is avoided by restricting its current dynamics, which causes fuel cell to be a slow dynamic source. Batteries or super capacitors that have faster dynamics are used in combination with fuel cells to manage fast transient loads. However, these energy storage devices have also limitations regarding their capacity as well as dynamic behavior. The mentioned restrictions can be implemented in simulation through their detailed dynamic models.

3. Modeling Of Power Electronic Converters

In a shipboard dc distribution system, the majority of the power supplied to the dc grid passes through three-phase rectifiers after originating from synchronous generators. These rectifiers could be uncontrolled three -phase diode rectifiers if the generators are of wound rotor type. In this case, the voltage regulation is performed by the generator excitation system. A thyristor-based rectifier can also be employed . However, since its control functionality is mainly used under fault conditions, it can be considered as an uncontrolled rectifier in normal operation. In case a permanent magnet synchronous generator is used, the rectifier would be of controlled type with three-phase bridge inverter topology. The controlled rectifier is able to perform either voltage regulation or current control depending on the system requirements.

DC/DC converters are prominent for energy management of shipboard hybrid electric systems. They could also be used to shift dc voltage level along the dc distribution system. It is a common practice to use a bidirectional converter to incorporate energy storage in electric power systems. Although most ships do not currently have energy storage except in the fuel, future all-electric ships would need electric energy storage, such as batteries, which can be controlled by bidirectional converters. Since lower number of series battery cells is desirable to have better reliability, a boost-type bidirectional converter is preferable to connect low-voltage energy storage to the high voltage dc bus. In case of employing auxiliary dc energy source,



A considerable amount of the generated power onboard an electric-propelled ship is consumed by its propulsion system, after passing through the variable speed drives. The motor drive primarily uses a three-phase bridge inverter to supply and control the motor. Modeling of the mentioned power electronic converters is discussed in the following.

A. DC/DC Converters

Topological circuits of a full-bridge boost converter and a full-bridge bidirectional converter are shown in Fig. 2(a) and (b), respectively.

Figure 2: Topological circuit of the converters under study: (a) boost and (b) bidirectional.

High-frequency transformer might be necessary in those applications where the voltage ratio between LV and HV is so high that devices are not economical to tolerate both high voltage and high current simultaneously. There is also an additional degree of freedom compared to the basic topology by introducing the transformer turns ratio. The high-frequency transformer, however, leads to additional cost and losses. The advantage of the full-bridge topology is to provide lower voltage and current stresses, resulting in significant decrease in losses compared to half-bridge and push–pull topologies. It, however, needs higher number of switches. To simulate these power converters, a number of software packages are available. Therefore, when exact switching behavior is not required in the study, dynamic averaging methods may be used to make the simulation faster . As large variations may occur in the system, small signal models are not valid for system simulation. Large signal models must be derived for converters, which are nonlinear.

B. Voltage Source Inverter Average Model

The topology of a three-phase voltage source inverter (VSI) is shown in Fig. 3. The average value model for a PWM voltage source inverter is considered here. The PWM VSI can be modeled with an equivalent stationary circuit by d–q transformation.

In order to develop an average model for VSI, it is assumed that all switches operate at continuous conduction mode with a PWM switching pattern provided that the switching harmonics are not dominant. Considering these assumptions, averaging can be done by approximating the sinusoidal PWM with a continuous sinusoidal waveform.

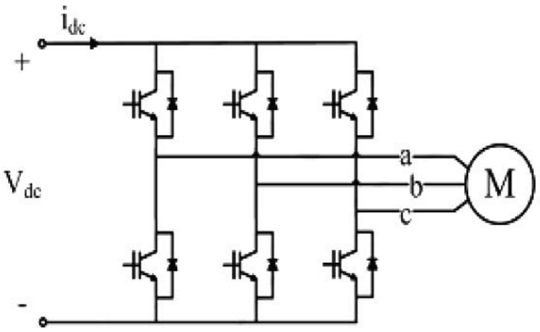


Figure 3: Topology of a three phase voltage source inverter

$$\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = \begin{bmatrix} d_a \\ d_b \\ d_c \end{bmatrix} \cdot v_{dc} \tag{1}$$

where switching functions “$d_{a,b,c}$” can be defined using the modulation index “m” by

$$\begin{bmatrix} d_a \\ d_b \\ d_c \end{bmatrix} = \begin{bmatrix} \sin(\theta(t)+\varphi_2) \\ \sin(\theta(t)+\varphi_2-2\pi/3) \\ \sin(\theta(t)+\varphi_2+2\pi/3) \end{bmatrix} \cdot m \tag{2}$$

Where ϕ_2 is the arbitrary initial phase angle of SPWM. DC current can now be expressed by

$$i_{dc} = d_a i_a + d_b i_b + d_c i_c. \tag{3}$$

Defining a switching vector S for the inverter, the transformation of variables from ac side to the inverter dc side can be simply expressed by

$$\begin{cases} \boldsymbol{v}_{abc} = \boldsymbol{S} \cdot v_{dc} \\ i_{dc} = \boldsymbol{S}^T \cdot \boldsymbol{i}_{abc} \end{cases} \tag{4}$$

where the switching vector **S** is

$$\boldsymbol{S} = m \cdot \begin{bmatrix} \sin(\theta(t)+\varphi_2) \\ \sin(\theta(t)+\varphi_2-2\pi/3) \\ \sin(\theta(t)+\varphi_2+2\pi/3) \end{bmatrix}. \tag{5}$$

In order for the inverter model to interface with electric machine d–q models, the earlier phasor representation is transformed to d–q domain

$$\boldsymbol{X}_{qdo} = \boldsymbol{K} \cdot \boldsymbol{X}_{abc} \tag{6}$$

Where K is the d–q transformation matrix with a transformation angle of ϕ which is defined by

K=2/3

$$\begin{bmatrix} \cos(\theta(t)+\varphi) & \cos(\theta(t)+\varphi-2\pi/3) & \cos(\theta(t)+\varphi+2\pi/3) \\ \sin(\theta(t)+\varphi) & \sin(\theta(t)+\varphi-2\pi/3) & \sin(\theta(t)+\varphi+2\pi/3) \\ 1/2 & 1/2 & 1/2 \end{bmatrix}.$$

Substituting variables of (5) into (6), we will have

$$\begin{cases} \boldsymbol{v}_{qdo} = \boldsymbol{K} \cdot \boldsymbol{S} \cdot v_{dc} \\ i_{dc} = \boldsymbol{S}^T \cdot \boldsymbol{i}_{abc} = \boldsymbol{S}^T \cdot \boldsymbol{K}^{-1} \cdot \boldsymbol{i}_{qdo} \end{cases}. \tag{7}$$

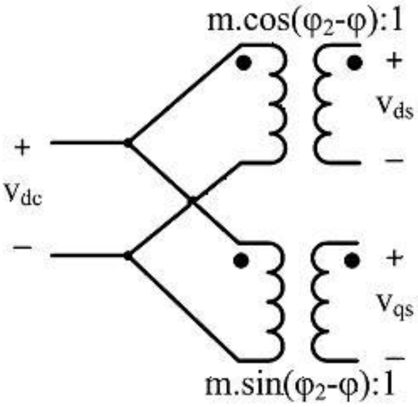


Figure 4: D–Q average model of a three phase PWM voltage source inverter.

Simplifying the equations, we will obtain

$$\begin{cases} \begin{bmatrix} v_q \\ v_d \end{bmatrix} = \begin{bmatrix} \sin(\varphi_2-\varphi) \\ \cos(\varphi_2-\varphi) \end{bmatrix} \cdot m \cdot v_{dc} \\ i_{dc} = m \cdot (i_q \cdot \sin(\varphi_2-\varphi) + i_d \cdot \cos(\varphi_2-\varphi)) \end{cases}. \tag{8}$$

Therefore, the inverter can be represented by time-invariant transformers shown in Fig. 4.

The equivalent circuit can be simplified if a unit power factor strategy is applied, whereinϕ_2 is equal to ϕ . In this case, one of the transformers will be eliminated, and the model will be as simple as (9). In general, however, the equivalent circuit of Fig. 4 is used

$$\text{if } \varphi_2 \overset{\Delta}{=} \varphi \overset{d}{\Rightarrow} \begin{cases} v_d = m \cdot v_{dc} \\ i_{dc} = m \cdot i_d \end{cases}. \tag{10}$$

4. Modeling of Mechanical Subsystems

In this section, dynamic models of mechanical elements in an integrated ship power and propulsion system are presented.

A. Propeller

Modeling of the propeller can be established by relationships among thrust, torque, and speed. For a fixed pitch propeller, these relationships can be expressed by

$$T_p = \rho D_p^4 K_T n_m \ |n_m|$$

$$Q_p = \rho D_p^5 K_Q n_m \ |n_m| \qquad (11)$$

Where Tp is propeller thrust [N], nmis propeller shaft speed [rpm], and Qp is propeller torque [N·m]. The parameters ρ, Dp, KT, and KQ are water density, propeller diameter, thrust coefficient, and torque coefficient, respectively. KT and KQ are functions of the propeller structure, and advance ratio J, which is defined by

$$J = \frac{V_A}{n_m D_p} \qquad (12)$$

Where V_A is the advance velocity of the propeller. V_A is normally less than the ship speed V_S due to wake. Their relationship is expressed by

$$V_A = V_S(1 - w) \qquad (13)$$

Where w is Taylor's wake fraction. In order to calculate the ship speed resulted from the propeller thrust, ship hydrodynamic model is also required.

B. Ship Hydrodynamics

The vessel hydrodynamic model could be complicated when dynamic positioning is purposed. However, for power system analysis in integrated power and propulsion systems, a one dimensional forward-motion model suffices. Therefore, the ship can be treated as an inertial mass with a resistive drag, on which the propeller thrust "Tp" applies. The resistive drag is proportional to the square of ship speed "VS."

In order to take advantage of the established models with identified parameters, Marine system simulator toolbox is employed for the propeller and ship models.

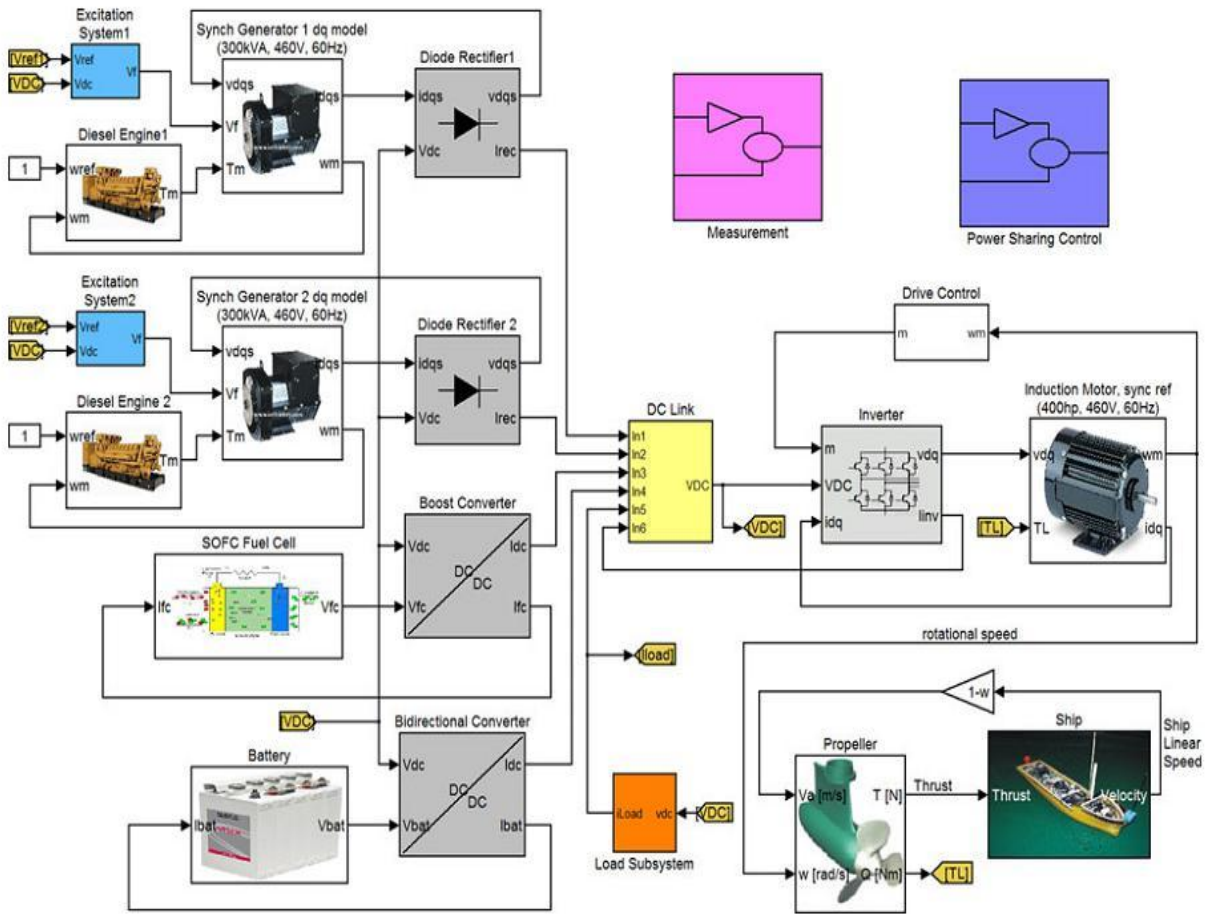


Figure 4: Overview of the ship dc hybrid power system implemented in MATLAB/Simulink

C. Diesel Engine

Diesel engine dynamics can be modeled in different levels of complexity, depending on the application. In this paper, it is approximated by a time delay τ and a time constant τc as represented in (14)

$$T_m(s) = e^{-\tau s} \frac{K_y}{1 + \tau_c s} Y(s) \qquad (14)$$

Where Tm is the generated torque, Ky is the torque constant, and Y is the fuel index (governor setting). The time delay is

$$\tau \approx \frac{1}{2n_m N} \quad (15)$$

Where n_M is the engine rotational speed in [rps], and N is the number of cylinders. The time constant is calculated by

$$\tau_c \approx \frac{0.9}{2\pi n_m}. \quad (16)$$

half the period between consecutive cylinder firings, which can be calculated by

In order to model the interaction between the diesel engine and the synchronous generator, a speed control loop is established by a PI controller, which acts as a governor.

5. System Simulation

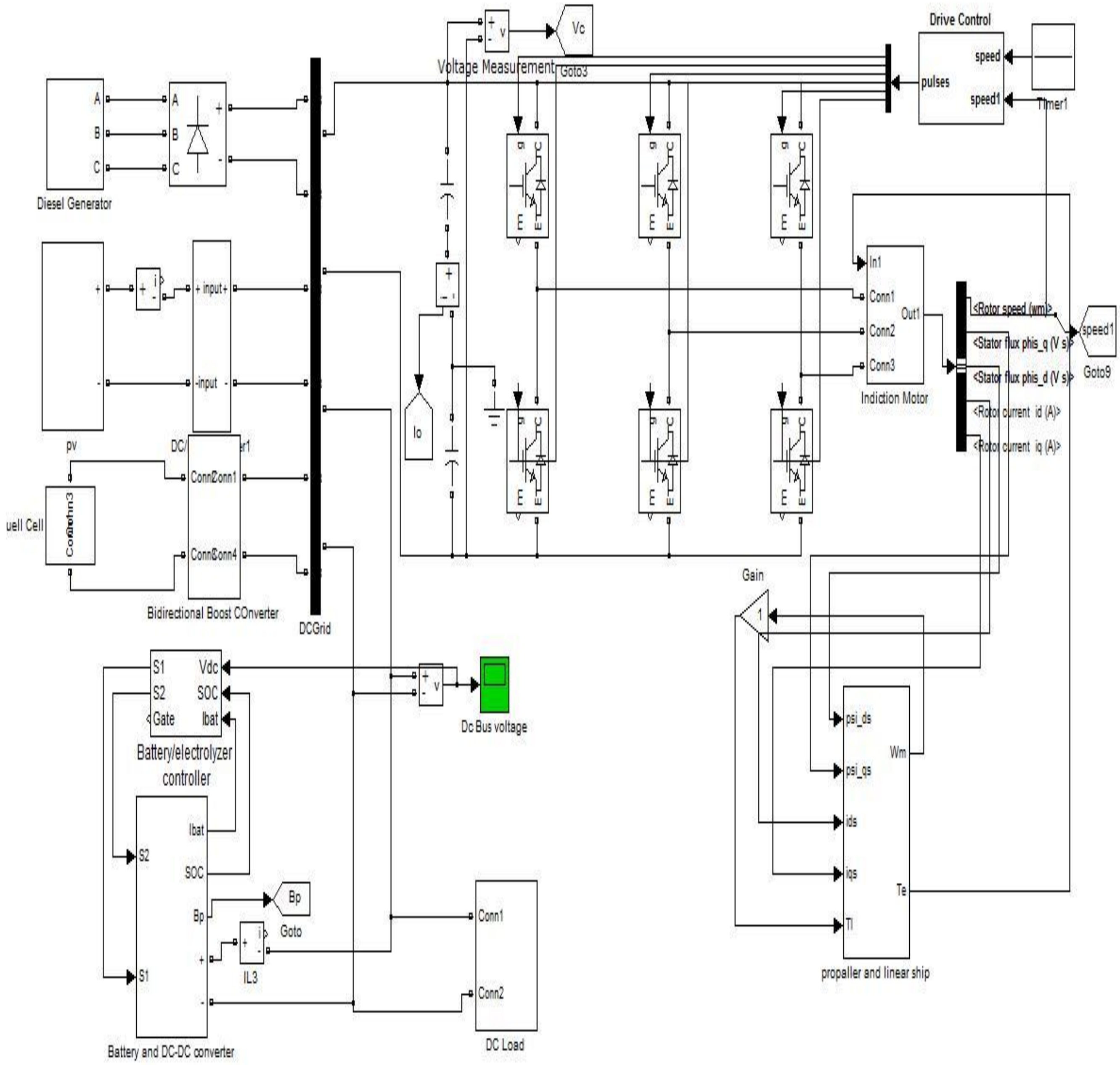


Figure 5: Simulation Model Ship DC Hybrid Power System

Appropriate models according to the system characteristics in Section II are already obtained for each part of the system. The derived models of power electronic converters are validated against detailed simulations. In this section, simulation results of a hybrid electric power and propulsion system are presented. Among various possible combinations, a hybrid power system is chosen that includes two diesel generators rated at 300 kW, a fuel cell system as an auxiliary source, and an energy storage system based on Li-ion battery. Specifications of the fuel cell and the energy storage can be found in the Appendix (see 3 and 4). Integration of super capacitors is also proposed in ship applications where load transients repeatedly occur, e.g., dynamic positioning mode in offshore support vessels. As the major operational mode of the studied ship is cruise mode in that load transients are not so frequent, super capacitors are not used in this case study.

The overview of the system implemented in MATLAB/ Simulink is depicted in the block diagram of Fig. 4. Interfaces among elements are bidirectional to represent interactions among connected elements. The product of two exchanged variables among connected elements gives power. This facilitates the interface among different types of electrical, mechanical, and electromechanical elements. The generators and converters have the same parameters as those studied previously in Section III. The propulsion motor is a three-phase 460Vl−l induction motor rated at 400hp. To represent the simulation results, a sailing profile including high speed (10 kt), moderate speed (5 kt), and low speed (1.5 kt) is studied in this section. Due to slow dynamics of the ship motion, each speed range is simulated for at least 60 s so that the ship can reach its steady-state speed. The simulated ship is a large version of Cybership II weighing 300 tons with a length of 50 m, which shows similar hydrodynamic response.

6. Conclusion

Modeling of an all-electric ship with low-voltage dc power system was carried out. Averaging methods were used to model the power electronic converters by neglecting high-frequency switching behavior in order to reduce the computation burden and time. A simulation platform was developed using the derived models of different components for system-level studies. The simulation results for a sailing profile of an all-electric ship showed how the dynamic behaviors of different mechanical and electrical variables can be observed and studied by using the simulation program. Providing significant savings in terms of time and computational intensity, the presented simulation platform could be useful for long-term or repetitive simulations that are required for research on all-electric ship dc power systems.

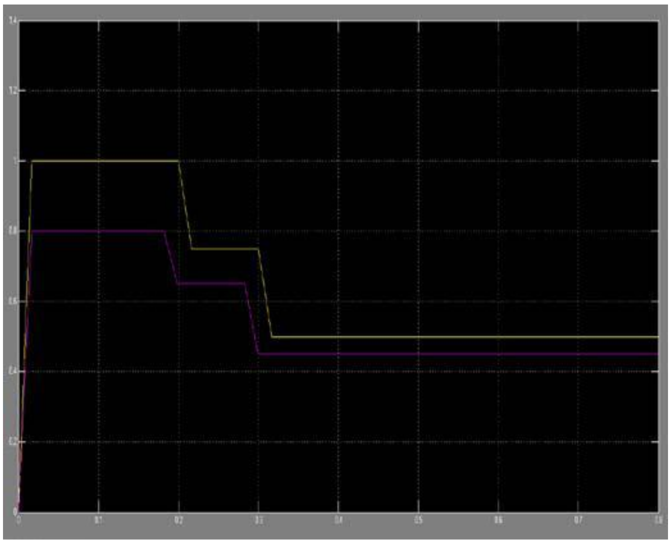


Figure 7: Ship and propeller speeds

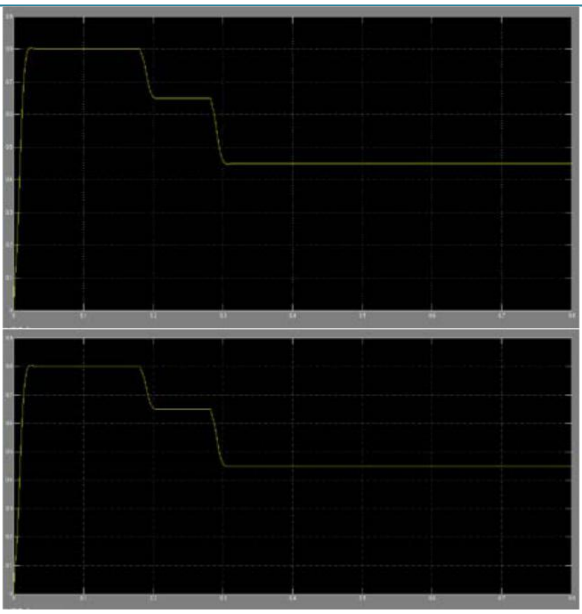
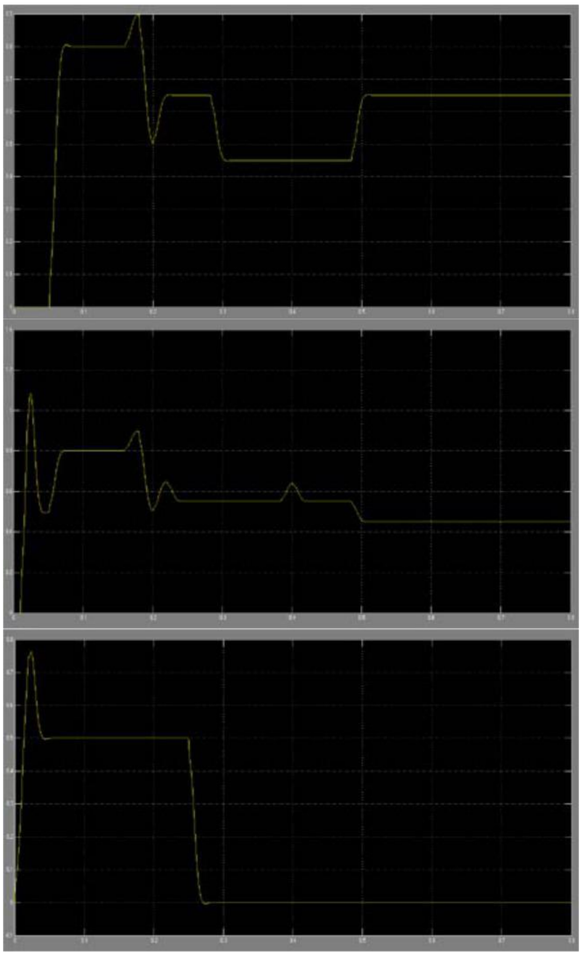


Figure 8: Electromagnetic torque and thrust



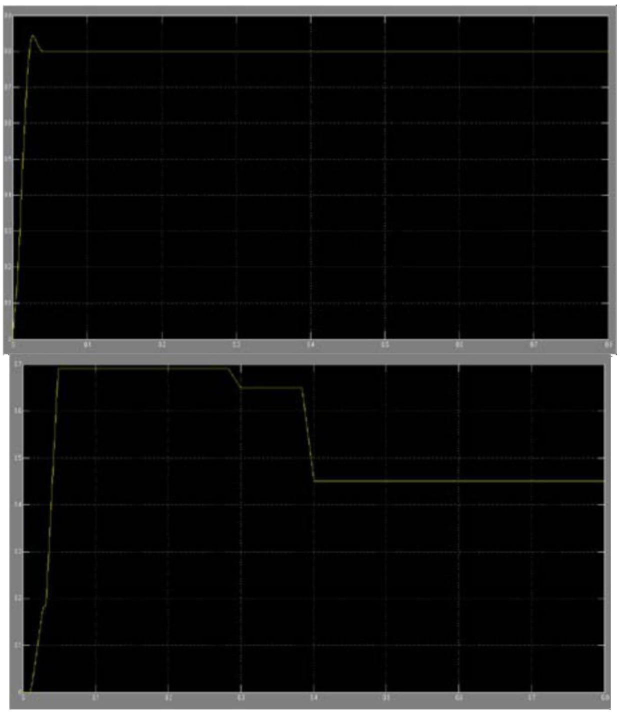


Figure 9: DC currents of the sources, energy storage system (ESS), and load

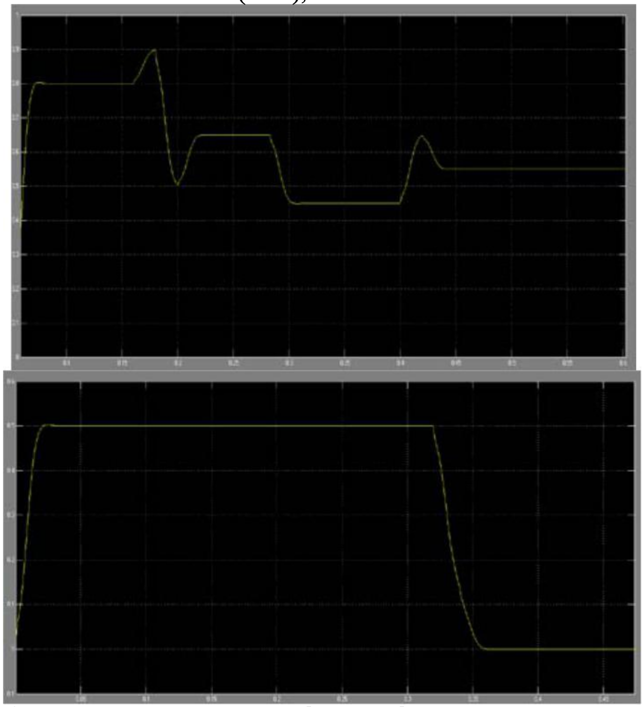


Figure 10: Compensation voltage to the exciters.

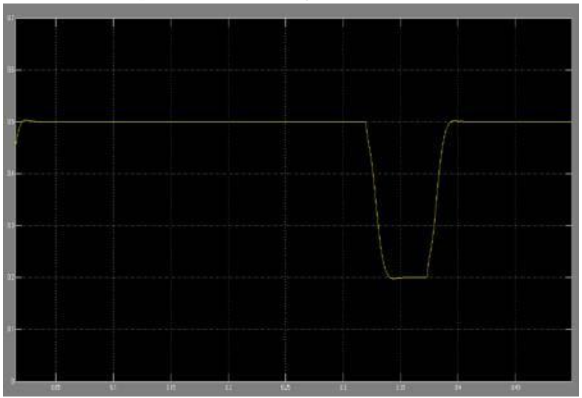


Figure 11: Rotational speeds of the diesel generators.

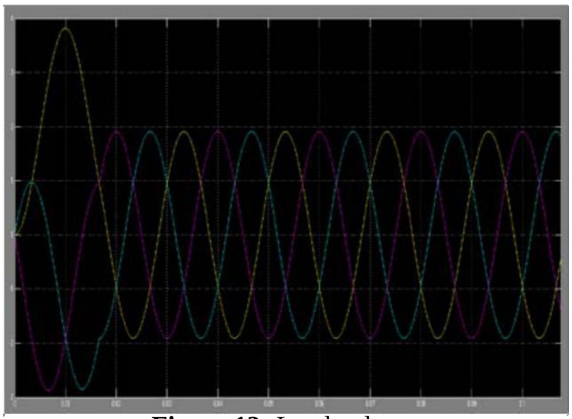


Figure 12: Load voltage

Appendix

1) dc/dc converter models

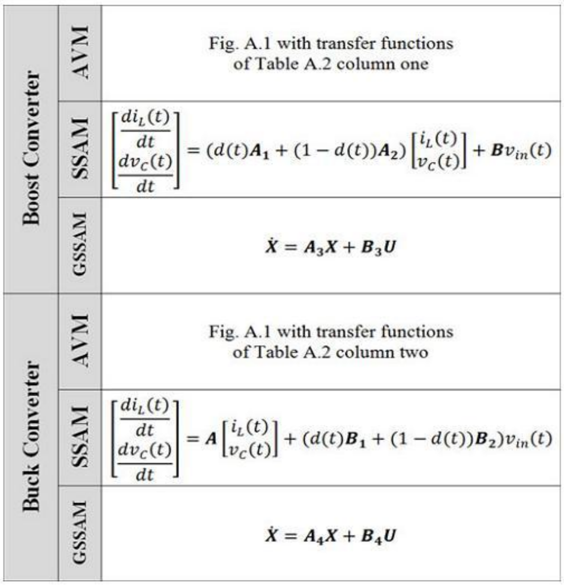
$$\boldsymbol{A} \triangleq \begin{bmatrix} 0 & -\frac{1}{L} \\ \frac{1}{C} & -\frac{1}{RC} \end{bmatrix}, \quad \boldsymbol{A}_1 \triangleq \begin{bmatrix} 0 & -\frac{1}{nL} \\ \frac{1}{nC} & -\frac{1}{RC} \end{bmatrix}$$

$$\boldsymbol{A}_2 \triangleq \begin{bmatrix} 0 & 0 \\ 0 & -\frac{1}{RC} \end{bmatrix}, \quad \boldsymbol{B} \triangleq \begin{bmatrix} \frac{1}{L} \\ 0 \end{bmatrix}$$

$$\boldsymbol{B}_1 \triangleq \begin{bmatrix} \frac{1}{nL} \\ 0 \end{bmatrix}, \quad \boldsymbol{B}_2 \triangleq \begin{bmatrix} 0 \\ 0 \end{bmatrix}.$$

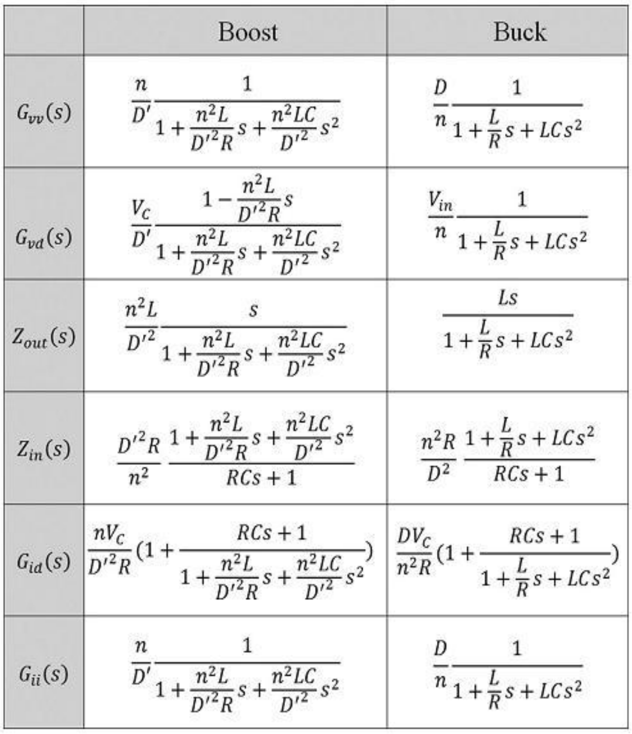
2) Li-ion battery parameters:Vfull =93.1 V, Vnom=80 V,5kAh.

TABLE A.1
DC/DC CONVERTER AVERAGE MODELS



Boost Converter	AVM	Fig. A.1 with transfer functions of Table A.2 column one
	SSAM	$\begin{bmatrix}\frac{di_L(t)}{dt} \\ \frac{dv_C(t)}{dt}\end{bmatrix} = (d(t)\boldsymbol{A}_1 + (1-d(t))\boldsymbol{A}_2)\begin{bmatrix}i_L(t) \\ v_C(t)\end{bmatrix} + \boldsymbol{B}v_{in}(t)$
	GSSAM	$\dot{\boldsymbol{X}} = \boldsymbol{A}_3\boldsymbol{X} + \boldsymbol{B}_3\boldsymbol{U}$
Buck Converter	AVM	Fig. A.1 with transfer functions of Table A.2 column two
	SSAM	$\begin{bmatrix}\frac{di_L(t)}{dt} \\ \frac{dv_C(t)}{dt}\end{bmatrix} = \boldsymbol{A}\begin{bmatrix}i_L(t) \\ v_C(t)\end{bmatrix} + (d(t)\boldsymbol{B}_1 + (1-d(t))\boldsymbol{B}_2)v_{in}(t)$
	GSSAM	$\dot{\boldsymbol{X}} = \boldsymbol{A}_4\boldsymbol{X} + \boldsymbol{B}_4\boldsymbol{U}$

TABLE A.2
TRANSFER FUNCTIONS OF DC/DC CONVERTERS



	Boost	Buck
$G_{vv}(s)$	$\frac{n}{D'}\frac{1}{1+\frac{n^2L}{D'^2R}s+\frac{n^2LC}{D'^2}s^2}$	$\frac{D}{n}\frac{1}{1+\frac{L}{R}s+LCs^2}$
$G_{vd}(s)$	$\frac{V_C}{D'}\frac{1-\frac{n^2L}{D'^2R}s}{1+\frac{n^2L}{D'^2R}s+\frac{n^2LC}{D'^2}s^2}$	$\frac{V_{in}}{n}\frac{1}{1+\frac{L}{R}s+LCs^2}$
$Z_{out}(s)$	$\frac{n^2L}{D'^2}\frac{s}{1+\frac{n^2L}{D'^2R}s+\frac{n^2LC}{D'^2}s^2}$	$\frac{Ls}{1+\frac{L}{R}s+LCs^2}$
$Z_{in}(s)$	$\frac{D'^2R}{n^2}\frac{1+\frac{n^2L}{D'^2R}s+\frac{n^2LC}{D'^2}s^2}{RCs+1}$	$\frac{n^2R}{D^2}\frac{1+\frac{L}{R}s+LCs^2}{RCs+1}$
$G_{id}(s)$	$\frac{nV_C}{D'^2R}(1+\frac{RCs+1}{1+\frac{n^2L}{D'^2R}s+\frac{n^2LC}{D'^2}s^2})$	$\frac{DV_C}{n^2R}(1+\frac{RCs+1}{1+\frac{L}{R}s+LCs^2})$
$G_{ii}(s)$	$\frac{n}{D'}\frac{1}{1+\frac{n^2L}{D'^2R}s+\frac{n^2LC}{D'^2}s^2}$	$\frac{D}{n}\frac{1}{1+\frac{L}{R}s+LCs^2}$

References

[1] A. K. Adnanes, "Maritime electrical installations and diesel electric propulsion," ABB AS Marine, Oslo, Norway, 2003.

[2] J. M. Apsley, A. Gonzalez-Villasenor, M. Barnes, A. C. Smith, S. Williamson, J. D. Schuddebeurs, P. J. Norman, C. D. Booth, G. M. Burt, and J. R. McDonald, "Propulsion drive models for full electric marine propulsion systems,"IEEE Trans. Ind. Appl., vol. 45, no. 2, pp. 676–684, Mar. 2009.

[3] S. De Breucker, E. Peeters, and J. Driesen, "Possible applications of plugin hybrid electric ships," inProc. IEEE Electric Ship Technol. Symp.,Apr. 20–22, 2009, pp. 560–567.

[4] P. Mitra and G. K. Venayagamoorthy, "An adaptive control strategy for DSTATCOM applications in an electric ship power system,"IEEE Trans.Power Electron., vol. 25, no. 1, pp. 95–104, Jan. 2010.

[5] R. R. Chan, Y. Lee, S. D. Sudhoff, and E. L. Zivi, "Evolutionary optimization of powerelectronics based power systems,"IEEE Trans. Power Electron., vol. 23, no. 4, pp. 1907–1917, Jul. 2008.

[6] R. E. Hebner, "Electric ship power system—Research at the University of Texas at Austin," in Proc. IEEE Electric Ship Technol. Symp., Jul. 25–27, 2005, pp. 34–38.

[7] M. Bash, R. R. Chan, J. Crider, C. Harianto, J. Lian, J. Neely, S. D. Pekarek, S. D. Sudhoff, and N. Vaks, "A medium voltage dc testbed for ship power system research," in Proc. IEEE Electric Ship Technol. Symp., Apr. 20–22, 2009, pp. 560–567.

[8] R. Nilsen and I. Sorfonn, "Hybrid power generation systems," in Proc. 13th Eur. Conf. Power Electron. Appl., Sep. 2009.

[9] J. F. Hansen, J. O. Lindtjorn, U. U. Odegaard, and T. A. Myklebust, "Increased operational performance of OSVs by onboard dc Grid," presented at the 4th Int. Conf. Technol. Oper. Offshore Support Vessels, Singapore, Aug. 2011.

[10] G. Seenumani, H. Peng, and Sun, "A reference governor-based hierarchical control for failure mode power management of hybrid power systems for all-electric ships,"J. Power Sources, vol. 196, no. 3, pp. 1599–1607,2011

[11] R. S. Balog and P. T. Krein, "Bus selection in multibus dc microgrids," IEEE Trans. Power Electron., vol. 26, no. 3, pp. 860–867, Mar. 2011.

[12] S. Chiniforoosh, J. Jatskevich, A. Yazdani, V. Sood, V. Dinavahi, J. A. Martinez, and A. Ramirez, "Definitions and applications of dynamic average models for analysis of power systems,"IEEE Trans. Power Del., vol. 25, no. 4, pp. 2655–2669, Oct. 2010.

[13] A. Emadi, "Modeling and analysis of multiconverter dc power electronic systems using the generalized state-space averaging method," IEEE Trans. Ind. Electron., vol. 51, no. 3, pp. 661–668, Jun. 2004.

[14] K. Hochkirch and V. Bertram, "Options for fuel saving for ships," Mare Forum: Maritime Transportation of Energy, Houston, TX, Feb. 19, 2010.

[15] Ph. Thounthong, S. Ra¨ el, and B. Davat, "Energy management of fuel cell/battery/supercapacitor hybrid power source for vehicle applications," J. Power Sources, vol. 193, no. 1, pp. 376–385, Aug. 2009.

[16] J.-S. Lai and D. J. Nelson, "Energy management power converters in hybrid electric and fuel cell vehicles,"Proc. IEEE, vol. 95, no. 4, pp. 766–777, Apr. 2007.

[17] S. R. Sanders, J. M. Noworolski, X. Z. Liu, and G. C. Verghese, "Generalized averaging method for power conversion circuits,"IEEE Trans. Power Electron., vol. 6, no. 2, pp. 251–259, Apr. 1991.

[18] B. Zahedi and L. E. Norum, "Modeling, analysis and control of an isolated boost converter for system level studies," inProc. Aegean Conf. Electric Mach. Power Electron., Sep. 2011.

[19] J. Zhang, J.-S. Lai, and W. Yu, "Bidirectional dc–dc converter modeling and unified controller with digital implementation," inProc. IEEE 23rd Annu. Appl. Power Electron. Conf. Expo., Feb. 2008, pp. 1747–1753.

[20] B. Zahedi, O. C. Nebb, and L. E. Norum, "An isolated bidirectional converter modeling for hybrid electric ship simulations," inProc. IEEE Transp. Electrification Conf. Expo., Jun. 2012.

[21] Robert W. Erickson, Fundamentals of Power Electronics. Norwell,, MA: Kluwer, 1999.

Author Profile

GANDIBOYANA MOHAN KUMAR born on 02nd FEB 1991. He received his B. Tech from Baba Institute of Technology and Sciences, in Electrical Engineering in Visakhapatnam in 2012. He is currently pursuing M. Tech in Baba Institute of Technology and Sciences, Visakhapatnam, Andhra Pradesh state in India.

Mr. K.VENKATESWARA RAO, B.Tech, M.Tech [PID], Assistant Professor, Dept. of EEE at "Baba Institute of Technology & Sciences" is a pillar of hard work, sincerity, planning & creativity. He did his Master of Engineering (PID) from DIET Engineering. College, Bachelor of Technology in Electrical & Electronics Engineering from B.V.C.I.T.S, Amalapuram. He is having a Teaching experience of more than 10 years.