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2016

Satpathi, K., Ukil, A., Thukral, N., & Zagrodnik, M. A. (2016). Modelling of DC shipboard power system. 2016 IEEE International Conference on Power Electronics, Drives and Energy Systems (PEDES), 1-6. doi: 10.1109/PEDES.2016.7914385

<https://hdl.handle.net/10356/100174>

<https://doi.org/10.1109/PEDES.2016.7914385>

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Modelling of DC Shipboard Power System

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Abstract—Modelling and simulation of emerging DC shipboard power system (SPS) is required to validate the hardware design, converter control and protection algorithms. As DC SPSs may be large and complicated, the simulation of such systems using high fidelity models generally consumes much time and the validation of performance using multiple test scenarios becomes impractical. An alternative method is to conduct such simulations in real-time using a multi-core simulation platform. Real-time simulation also allows protection relays (running embedded protection algorithms) to be verified through ‘hardware in the loop’ techniques. In this paper we discuss the simulation of DC SPSs in real-time using Opal-RT simulation platform. Firstly the system is modelled for non-real-time simulation. Subsequently these models are converted for real-time simulation and executed using RT-Lab on the Opal-RT target. Modelling and control approaches of DC SPS and some of the attributes of Opal-RT are also discussed.

Index Terms—DC Bus Voltage Control, DC Shipboard Power System, Marine application, OPAL-RT, Real-Time Simulation.

I. INTRODUCTION

Electrical power generation and distribution in marine vessels has generally mirrored that of land-based systems having both fixed voltage and fixed AC frequency (50/60Hz). In recent years, the DC shipboard power system (SPS) has become of interest primarily on account of fuel economy that is enabled through variable speed diesel prime movers [1]. Fuel saving as high as 20% is reported [1] with the integration of variable speed diesel generator operating at optimal speed [1]–[2]. Furthermore there is no need of phase and frequency synchronisation when multiple generators are operated in parallel. DC SPS also simplifies the integration of alternative power generation sources (such as fuel cells) and energy storage technologies [3]–[4]. Energy storage allows for peak shaving in generators when load demand undergoes wide variation which in turn helps to reduce the mechanical and thermal stress on the system. One of the main impediments to wide scale adoption of DC SPS is the lack of comprehensive protection algorithms [5]–[6]. The validity of the protection algorithms should be verified with the help of fault studies done on the accurate simulation models. Due to complexity of the DC SPS, offline simulations are quite time consuming. Furthermore, offline simulations are not suitable to verify the performance of actual protection relays with current/voltage measurement sensor performance [7] which operate in real-time. In contrast, real-time simulation of DC SPS enables rapid execution of fault studies (suitable for the validation of

protection algorithms under multiple test cases) and allows the hardware realization of such protection algorithms to be verified through HIL techniques.

In this paper we first model a representative DC SPS comprising generation sources and loads and introduce converter controls that are required for stable system operation. The offline models are subsequently converted to forms suitable for real-time simulation and then simulated using Opal-RT [8]. The various steady-state and transient results are then validated against the high fidelity offline Matlab/Simulink simulation results.

In addition to the modelling of the DC SPS and the preparation of such models for real-time simulation environment, various challenges that are encountered during real-time simulation are highlighted. Solutions to these challenges are discussed. The remainder of the paper is organised as follows. Section II covers the state of the art of the DC SPS. A representative DC SPS is introduced in Section III. The modelling and control of the proposed DC SPS is introduced in Section IV. Section V describes the real-time simulation and control in Opal-RT. Detailed results and discussions are presented in Section VI which is followed by conclusions in Section VII.

II. DC SHIPBOARD POWER SYSTEMS: STATE OF THE ART

The first commercial on-board DC ship can be traced back to *SS Columbia* which was developed in 1880s [9]. This architecture failed to gain support due to lack of power electronic devices and the competition presented by AC systems emerging at the time. In particular, the new AC systems offered voltage transformation and rugged induction machines. Only recently with the development of power electronic devices, emerging storage technologies and rising fuel costs, the DC SPSs have garnered the attention of the research community. Although the main motivations for the development of DC SPS are fuel economy and easier integration of variable frequency generators, other notable advantages include:

- *Regeneration*: Unlike VFD drives with diode front ends in AC SPS, in DC SPS regenerative energy may be easily absorbed to other loads across the DC bus.
- *Distribution loss and power factor*: Due to absence of power factor in DC distribution, resistive loss in cables is reduced.
- *Quick synchronization*: There is no need of phase and voltage synchronization in DC SPS. As a result the reserve generators can be quickly brought on line and connected to DC system.

This work was conducted within the Rolls-Royce@NTU Corporate Lab, supported by the National Research Foundation (NRF) Singapore, under the Corp Lab@University Scheme.

The DC shipboard system can be compared with the land based DC microgrids. Both are isolated finite inertia power systems having high penetration of power electronic interfaced generation systems and loads. One of the major differences between them is the loading conditions. Aggregate load in land based DC microgrids is relatively predictable through the course of the day. In contrast, the loads in DC SPS are dominated by propulsion loads which respond rapidly to mission requirements and sea conditions. Some emerging loads, such as pulsed loads used for naval weapons, present extremely challenging and unpredictable load profiles.

Commercial interest in DC ships is relatively new and few standards are available for reference during the design and analysis of DC SPS. The IEEE Standard 1709-2010 [10] deals with the design steps indicating the technical problem assessment. The IEEE Std 1662-2008 [11] covers the guidelines and specifications of the power converters which are to be used in the DC shipboard systems. If zonal distribution system is used in the system then IEEE Std 1826-2012 [12] may be referred to. IEC/ISO/IEEE Std 80005-1 [13]–[14] deals with the high voltage shore connections when the ship is at the dockyard. The relevant standards have been used in devising the proposed model of the DC SPS in the subsequent sections.

III. TARGET DC SHIPBOARD POWER SYSTEM

The schematic of the target DC SPS is shown in Figure 1. The generation system comprise of two synchronous generators which are directly interfaced to two-level voltage source converters (2L-VSC). The load side consist of four propulsion loads, one pulsed load and one hotel load. The bus voltage is rated at 1500 VDC which according to IEEE Std 1709-2010 is medium voltage DC (MVDC) system [10]. The rating of the components with proper modelling and control approaches are described in subsequent sections.

Figure 1. Representative SLD of DC SPS.

IV. DC SHIP MODELING AND CONTROL

A. Generation Side Modeling and Control

1) *Synchronous Generator*: Synchronous generator (SG) used for the modelling and control purpose [15] includes full d - q model of the generator including the damper windings. The rating and specifications of the generators Gen-1,2 is shown in Table I.

TABLE I
GENERATOR PARAMETERS

Generators	Parameters	Values
Gen-1,2	Nominal Power	2048 kVA
	Nominal rms voltage	690 V
	Nominal frequency	60 Hz
	Number of Poles	8
	Stator resistance (R_s)	0.002581 pu
	Direct axis reactance (X_d)	1.87 pu
	Direct axis transient reactance (X_d')	0.219 pu
	Direct axis transient reactance (X_d'')	0.116 pu
	Quadrature axis reactance (X_q)	1.05 pu
	Quadrature sub-transient axis reactance (X_q'')	0.121 pu

The torque equation is given by Eq. 1.

$$T = 3p \frac{i_{qs}^r \lambda_{ds}^r - i_{ds}^r \lambda_{qs}^r}{4}. \quad (1)$$

The proposed method of output torque control of the generator is achieved by independently controlling the stator q -axis current (i_{qs}^r) and d -axis flux (λ_{ds}^r). This control is achieved by setting $i_{ds}^r = 0$. λ_{ds}^r is the field flux which is an important aspect for maintaining the generator terminal voltage. In AC SPS, the terminal voltage control and subsequently the bus voltage control is typically performed by the automatic voltage regulator (AVR). AVR uses the generator terminal voltage as an input parameter to maintain the d -axis flux. This technique cannot be used in converter interfaced generator system as employed in DC SPS due to presence of switching voltages across generator terminals. To mitigate this problem, flux estimation based DC bus voltage control has been employed [16]. In this method, d -axis generator flux (field flux) is estimated and maintained at desired value by controlling the field current by varying field voltage. The phase voltages are estimated with the help of terminal DC voltage and semiconductor switching combinations. The d -axis flux (λ_{ds}) and q -axis flux (λ_{qs}) is estimated in stationary reference frame according to Eq. 2(a,b,c).

$$\lambda_{ds}^s = \int (v_{ds}^s + i_{ds}^s r_s) dt, \quad (2a)$$

$$\lambda_{qs}^s = \int (v_{qs}^s + i_{qs}^s r_s) dt, \quad (2b)$$

where, v_{ds} and v_{qs} are d -axis and q -axis voltages. The machine flux, λ_s is given by:

$$|\lambda_s|^2 = \lambda_{ds}^{s^2} + \lambda_{qs}^{s^2}. \quad (2c)$$

Since total flux remains same, the d -axis flux in rotor reference frame (λ_{ds}^r) can be estimated by the Eq. 3.

$$(\lambda_{ds}^r)_{est} = \sqrt{|\lambda_s|^2 - ((L_{ls} + L_{mq}) \cdot i_{qs}^r)^2}. \quad (3)$$

This estimated λ_{ds}^r can be maintained at desired value by controlling the field current i_{fd}^r which is given by λ_{ds}^r / L_{md} . The field circuit equations in rotor reference frame is given

by Eq. 4(a,b).

$$v'_{fd} = r'_{fd} i'_{fd} + \frac{d}{dt} \lambda'_{fd}, \quad (4a)$$

$$\lambda'_{fd} = L'_{lfd} + L_{md}(-i'_{ds} + i'_{fd} + i'_{kd}). \quad (4b)$$

According to proposed control system $i'_{ds} = 0$ and at steady-state $i'_{kd} = 0$. Hence Eq. 4(a) and Eq. 4(b) can be arranged as:

$$v'_{fd} = r'_{fd} i'_{fd} + (L'_{lfd} + L_{md}) \frac{d}{dt} i'_{fd}, \quad (4c)$$

which can further be written as

$$I'_{fd}(s) = \frac{V'_{fd}(s)}{r'_{fd} + s(L'_{lfd} + L_{md})}. \quad (4d)$$

Hence, i'_{fd} can be maintained using suitable controller.

The flux estimation based voltage control is also suitable for the generators running at variable speeds. However, this technique requires operation with higher bus-bar voltage [16]. Hence bus voltage of 1500 V is chosen in this paper. This paper aims to develop the DC SPS for fault studies and development of protection algorithms in future. Thus constant speed operation of the generators might suffice our requirements. The justification for this assumption is given below:

- The time frame of the DC-fault transient is short (< 60 ms) and the protection system is expected to operate within this time frame. Owing to large mass and moment of inertia of the generators, it is assumed that the change in speed of the generator prime-mover would be minimum.
- Loss of synchronism does not occur in DC systems as compared to the AC systems. So the change in generator speed will have minimal effect.

2) *Two level Voltage Source Converter (2L-VSC)*: According to the Figure 2(a) and Eq. 1, power equation can be written as:

$$\frac{3.p.\lambda_d.i_q.\omega_m}{4} = C \frac{dv_c}{dt} . v_c + v_c . i_L, \quad (5)$$

Since the output DC voltage v_c is controlled by i_q , the plant transfer function is obtained by small signal analysis of Eq. 5 and is expressed as follows:

$$G_{plant} = \frac{\hat{v}_c}{\hat{i}_q} = \frac{3}{4} \frac{p\lambda_d\omega_m}{sCV_c + I_L}. \quad (6)$$

Figure 2. (a) System comprising of generator interfaced with 2L-VSC; (b) typical time-current characteristic of pulsed load.

Apart from DC bus voltage control, droop control is required for power sharing between the generators. In this paper, the P-V droop (Figure 3(a)) control is employed in which

power sharing between the generators is done on the basis of their rated power capacity. The droop co-efficient (R) is defined as:

$$R = -\frac{\Delta V}{V_{nom}} \bigg/ \frac{\Delta P}{P_{rated}} \quad (7)$$

As analogous to conventional AC systems, in the DC system a falling DC-link voltage indicates an increase in power demand [17]. When the voltage drops by ΔV , the power generation is allowed to increase by ΔP which is governed by droop-coefficient ' R '. Droop-coefficient of 4% is chosen which means that for every 1% decrease of DC voltage, the power output is allowed to increase by 25%. Hence, at rated power the voltage drops by 4%. The modified reference voltage for the output DC-link capacitor V_c using Eq. (8(a)) is given by:

$$\begin{aligned} V_c &= V_{nom} - \Delta V, \\ &= V_{nom} + \frac{R.\Delta P}{P_{rated}} V_{nom}. \end{aligned} \quad (8a)$$

From the Figure 3(a), ΔP is the output power of the generator and is given by:

$$\Delta P = P_{out} - 0 = P_{out}, \quad (8b)$$

$$\Delta P = i_L . V_c. \quad (8c)$$

Hence, the Eq. (8(a)) becomes:

$$V_c = V_c(1 + k_d i_L) \quad (8d)$$

where $k_d = R.V_c/P_{rated}$. The modified reference voltage can also be written as:

$$V_c = V_{nom} \left(1 + \frac{R.P_{out}}{P_{rated}}\right). \quad (8e)$$

The modified voltage reference for the voltage control loop is given in Figure 3(b).

Figure 3. (a) P-V droop control for DC SPS and (b) modified voltage reference as a result of droop control.

3) *DC-link Capacitor Selection*: The selection of DC-link capacitor of the converters is the ultimate trade-off between cost and stability. A DC-link of very large capacitance is highly uneconomical and unrealistic. In this paper the DC-link capacitor is selected by using the converter hold-up time. In this method the capacitor bank is sized to sustain rated load for a given period of time. The converter hold-up time ($t_{hold up time}$) is taken as 5 ms and the tolerable voltage drop (ΔV) during this period is 20%. For $P = 1800$ kW ($S = 2048$ kVA), $t_{hold up time} = 5$ ms and $\Delta V = 20\%$. The sizing of DC-link capacitor is given by [18].

$$\frac{C(V_1^2 - V_2^2)}{2} = P * t_{\text{hold up time}} \quad (9)$$

which gives, $C = 22 \text{ mF}$.

B. Load Side Modeling and Control

1) *Propulsion Load*: The squirrel cage induction motor with a single cage rotor is used for the simulation purpose. Generic motor parameters are defined with base values of P_{rated} (nominal power) and V_n (nominal line to line voltage RMS). It is recognized that the single cage models tend to under-predict the torque at high slip (such as starting torque) and that double cage models would better represent the performance under such conditions. However, these motors are to be connected only to variable frequency drives and will therefore be expected to operate under low slip. The generic motor parameters are shown in Table II. Indirect Field oriented control (FOC) with reference frame aligned with the rotor d-axis flux linkage is used to simulate the induction motor drive [19]. FOC allows for flux linkage to reach the reference levels before applying torque in a gradual manner. Current hysteresis control is implemented because of its easier implementation and substantial reduction in simulation time. Since the equivalent bandwidth under hysteresis current regulation is quite large, it is possible to assume that $i_d = i_d^*$ and $i_q = i_q^*$.

TABLE II
MOTOR PARAMETERS

Motors	Parameters	Values
MP1, MP2	Nominal Power	883 kW
	Number of Poles	6
	Nominal rms voltage	690 V
	Nominal frequency	60 Hz
	Stator Leakage inductance (Ls)	8%
	Rotor Leakage inductance (Lr)	8%
	Magnetizing Inductance (Lm)	250%
	Stator Leakage Resistance (Rs)	4%
	Rotor Leakage Resistance (Rr)	4%
	Rated Slip	2.34%
	Maximum torque (Tmax)	2.625%
	Slip at Tmax	12.83%

2) *Pulsed Load*: The pulsed load is emerging type of load which is mainly used for the electromagnetic guns in naval systems. This load comprises of a low resistance load in parallel with a high resistance load [20]. The low resistance is turned ON after certain time intervals with the help of switching devices. The operation of pulsed load may vary from several microseconds to milliseconds. In this paper, the ON period of the pulsed load is taken as 20 ms. The time-current characteristic of the pulsed load is shown in Figure 2(b).

3) *Hotel Loads*: Hotel loads in SPS represent lighting, ventilation, accommodation loads and auxiliary systems such as small pumps, winches etc. Their contribution to the total load is dependent on the shipboard missions. Passenger cruise carriers and survey vessels may have significant sensor and operational loads during missions thus larger contribution of the hotel loads. To model the hotel loads, a closed loop control to maintain the terminal voltage is implemented. The resonant frequency of the output LC filter is set at three times the fundamental frequency (60 Hz).

V. REAL-TIME SIMULATION OF DC SPS

A discrete real-time simulator OP-5600 with four 3.3 GHz processor cores is used as real-time target system. It uses RedHat Linux real-time operating system. The target system is connected to the host PC using TCP/IP cable. The experimental setup is shown in Figure 4. To execute the model in real-time, Opal-RT uses Artemis solver which is a high-order fixed-time-step integration algorithm and is not prone to numerical oscillations. Hence it provides real-time performance and accelerates system computation [8].

Figure 4. Representative SLD of DC SPS.

A. Simulation in Opal-RT Platform

To ensure parallel computation, the system modelled in MATLAB with proper control algorithm is segregated into master, slave and console subsystems. Master and slave subsystem consists of computation elements which are executed in real-time on separate cores of Opal-RT. The console subsystem forms the input-output GUI interface and is displayed on the host PC. The proposed DC SPS model which has been developed in previous section is simulated in real-time simulation platform Opal-RT. The model is divided into master and slave subsystems which is indicated in Figure 5(a, b).

B. Partitioning Techniques

For successful parallel computation, the model should be properly partitioned into master and slave subsystems. The *OpComm* blocks are inserted in each of the subsystem to enable communication between two computation subsystems as well as between computation and GUI console subsystem. All the inputs of a subsystem go through *OpComm* block before any operation is performed on them. The DC SPS is partitioned into subsystems using gyrators as shown in Figure 5(c). The gyrators comprise of controlled current and voltage sources with suitable time delay.

C. Key Features of Opal-RT Set-up

Apart from the partitioning into subsystems, there are several other features of Opal-RT which can be used for improved real-time simulation. Some of the features are cited below:

- The system can be simulated in XHP (eXtreme High Performance) mode with the time step of $10 \mu\text{s}$. This mode shuts down the avoidable background processes, thereby ensuring reliable system operation. It maximizes the computation that can be done within a time step.
- Improper partitioning of the subsystem results in burdening of a subsystem thus resulting in increased overruns.

Overrun occurs when the Artemis solver of the Opal-RT is not able to solve a particular subsystems in given time step. This can be checked using the monitoring table as shown in Figure 6. The monitoring table shows the computation time, number of overruns and percentage loading of each core. The overruns might be decreased by properly partitioning the system or by increasing the time step.

Model abc Ts:1.0E-5(s) Ts:0.04279(s)		Number of overruns=0			
Probe:		4K Info			
		Usage[%]	Min	Max	Mean
cd	abc Ts:1.0E-5(s)	37.45%			
=	[S]M_main Ts:9.9999999747E-6(s)	37.39%	dir: 3.40 [us]	dir: 4.08 [us]	dir: 3.73 [us]
=	[S]S_gen Ts:9.9999999747E-6(s)	33.32%	dir: 3.30 [us]	dir: 3.59 [us]	dir: 3.27 [us]
=	[S]S_load Ts:9.9999999747E-6(s)	42.83%	dir: 4.00 [us]	dir: 4.56 [us]	dir: 4.26 [us]

Figure 7. (a) Gen-1 output AC current and (b) output DC current when MP-2 and MP-4 are started at 3s.

2) The MP-2 when started at 3 s will take starting current. This input DC current to the VSI and motor input AC current is shown in Figure 8. The Opal-RT and MATLAB results are compared. It can be seen that the results are comparable.

Figure 8. (a) Input AC current and (b) input DC current when MP-2 is started.

3) The DC bus voltage drops momentarily when 50% of the loads are switched ON. The trend of the DC bus voltage is shown in Figure 9(a). The houseload load (Figure 9(b)) is one of the critical load in marine power system. The Opal-RT and MATLAB results are compared in Figure 9.

B. Transient Operation

The transient operation in DC SPS can be accounted by the operation of pulsed loads and short circuit faults. The devised fault management strategies must be able to segregate the difference between pulsed loads and the short circuit faults.

Figure 9. (a) Change on DC bus-voltage when loads turned ON at 3s and (b) houseload voltage trend at steady state.

- 1) The prime objective of real-time simulation in Opal-RT is the validation of control and protection algorithms. When the fault is incepted at the bus-bar, the generators contribute towards the fault current. In converter interfaced generation systems, the DC-link capacitor discharge is dominant followed by steady state fault current supplied by the generator. Accurate trends of these currents are required to device suitable protection algorithm. Figure 10 shows the Opal-RT and MATLAB results for Gen-1 AC current and rectifier output DC current. It can be seen that there is good agreement in results between Opal-RT and MATLAB.

Figure 10. (a) Gen-1 output AC current and (b) rectifier output DC current during fault at bus-bar.

- 2) Apart from fault currents, another feature is the collapsing of the DC bus voltage. The DC bus voltage reduces during the fault which can be seen from Figure 11(a). As explained in Section IV, the emerging DC ships comprise of pulsed loads and the protection algorithms must be able to distinguish between faults and the transients. The Opal-RT and MATLAB results for pulsed load is shown in Figure 11(b) when the load is switched ON for 20 ms at 2 s. It can be seen that the Opal-RT results closely follow the MATLAB results.

Figure 11. (a) DC-bus voltage during fault at DC-bus and (b) pulsed load current.

VII. CONCLUSION

This paper deals with various aspects of DC SPS, briefly covering the historical background, technical advantages, comparison with the land based DC power systems with related standards and practices. A representative system is modelled with suitable control algorithms. The system is then simulated in real-time using Opal-RT as real-time simulator. The results are then compared with the offline accurate simulation results. It can be seen that the real-time simulation results are in close agreement with the offline simulation results for steady-state and fault conditions. The prime aim to develop real-time simulation platform is to develop and validate protection and fault management strategies in future.

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