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Specialized Hierarchical Control Strategy for DC Distribution based Shipboard Microgrids

A combination of emerging DC shipboard power systems and microgrid technologies

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Abstract—Recently, DC distribution has been more and more considered in shipbuilding industry as an emerging solution due to its potential to enhance the system performance in terms of fuel economy, reliability, volume and weight. Moreover, there is a growing trend to integrate alternative power sources (APs) and energy storage systems (ESSs) into next-generation ships, and thus reducing cost and emission. In this context, the future shipboard power systems (SPSs) are expected to be compatible with various generation methods and complex onboard power consumers, which can be naturally identified as islanding microgrids (MGs). In this paper, specialized hierarchical control strategy is proposed to coordinate the system operation and meet the requirement of shipboard applications. Several advantageous functions are achieved by proposed control strategy. A study case of DC SPS is modeled and simulations are carried out to verify the proposed control strategy.

Keywords—All-electric ship; hierarchical control; energy storage system; microgrid; shipboard power system.

I. INTRODUCTION

Driven by the ever stricter requirement of emission and increasingly fierce price competition, shipbuilding industry is dedicating to develop greener and more economical solution for future ships. Currently, a number of research and development activities are dedicated to reduce the cost and emission from different perspectives. Electric propulsion [1, 2], onboard ESSs [1-4], low-emission or high-efficiency generators (e.g. fuel cell and gas turbine) [5, 6] and onboard renewable energy harvesters (e.g. PV array) [7-9] are proposed as primary trends. However, it leaves a challenging task to effectively combine these methods, and therefore, provides a comprehensive solution. For this purpose, DC solution is being considered because of its competitive advantages [1, 10]. From economic point of view, the major benefit of DC solution is enabling variable-speed operation of diesel generator sets, which can significantly reduce fuel consumption in light load conditions. There are also research activities dedicated to exploit the enhancement in terms of survivability and support for high-power pulsed loads by using ESSs and specially designed DC power architectures [4, 10-12]. In this context, future shipboard power systems are expected to be not only compatible with various power sources but also able to support onboard loads of different characteristics. Meanwhile, it is foreseeable that DC distribution will take

a great share in the next-generation SPSs. Such a system features in its isolated operation and diversity of power sources, thus reasonable to be defined as a DC shipboard MG (SMG).

It is undeniable that there are several differences between terrestrial and shipboard applications due to their totally different operating conditions and requirements. However, a number of technical problems are essentially the same in these two kinds of systems. Over the past decades, active researches have been made in the field of terrestrial MGs, and thus resulting in advanced coordinated control strategies [13-15] and real-time optimization methods [16-17]. Recently, the concept of DC MGs are drawing more and more attention in several different industrial applications, such as uninterruptible power supplies, energy-efficient buildings, off-grid datacenters and transportation electrification. Such a tendency is also impacting marine applications, where DC solutions are recently recognized to be promising for certain categories of ships (e.g. offshore support vessel and ferries). For comparison, a number of key features of terrestrial and shipboard MGs are listed in Table I.

In terrestrial MGs, hierarchical control strategy is becoming a standardized solution, which is an adoption of ISA-95 framework in MG control. It is preferred because of the independency between control layers [13]. A hierarchical control scheme typically includes the following control layers:

- 1) *Basic Regulation level (Inner-loop control)*: The basic regulation of voltage and current in local controllers.
- 2) *Load sharing level (Primary control)*: The control layer aims at sharing load according to rated power.
- 3) *Power quality level (Secondary control)*: The control layer aims at maintaining or restoring the bus signal to its nominal values.
- 4) *Power management level (Tertiary control)*: The control layer aims at intentional scheduling or intervention without affecting maximization of power supply to the demand side.

Since many of the problems in terrestrial and shipboard MGs are essentially the same, this advanced control architecture is potentially applicable in the field of SMGs. In this paper, a hierarchical control strategy specialized for DC SMG is proposed to coordinate the system operation and overcome several

drawbacks of conventional excitation control. In section 2, the major components of DC SMGs is discussed and modeled. In section 3, the proposed hierarchical control strategy is presented and implemented in the DC SMG discussed in section 2. In section 4, a simulation of proposed control strategy in the notional DC SMG is carried out by using MATLAB/Simulink. The simulation results are also discussed in this section.

TABLE I. COMPARISON OF TERRESTRIAL AND SHIPBOARD MGs

Terms	Terrestrial MGs	Shipboard MGs
Generation	Intermittent renewables and other sources	Diesel generator sets and APSs
Storage	Battery, super capacitor and /or flywheel based ESS	Mainly battery based ESS
Loads	Regularly changed loads	Dynamic propulsion loads and ship-service loads
Control	Three-layer hierarchical control	Excitation control and basic droop control
Optimization	Real-time management and offline methods	Mainly pre-designed load-matching curves

II. MODELING DC SHIPBOARD MICROGRID

A. Systemic architecture of DC shipboard microgrid

Recommended by IEEE Std 1709-2010 [11], a shipboard DC MG is composed by diesel generator sets, onboard ESSs, APS (fuel cells and PV array, etc.), electric propulsion systems and ship-service loads. In SPSs, dual-bus configuration is a preferred choice for not only reliability concerns but also geometric symmetry. Meanwhile, the onboard loads are usually package with backup power sources to found zonal load centers. Fig. 1(a) illustrated a typical arrangement of a DC SMG, the system can be regarded as a cluster of interconnected DC MGs, each of them can be simplified to be a single-line DC MG as shown in Fig. 1(b).

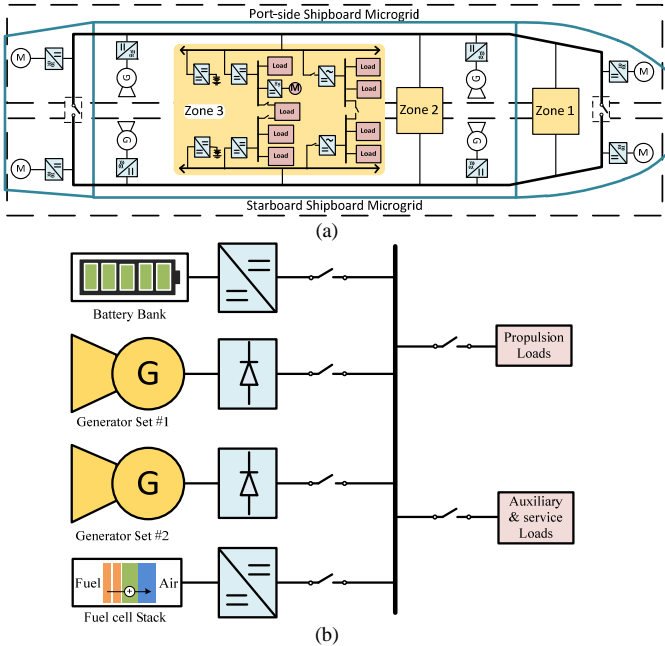


Fig. 1. Typical power architecture of DC SMG: (a) ZEDS based architecture and its sectionalization; (b) simplified architecture of a sectionalized DC SMG.

B. Diesel generator sets

Diesel generator set is still the major power source in the maritime electrical system. A diesel generator set is composed by prime mover and generator. In general cases, marine internal combustion engine is commonly used as prime mover, whereas three-phase synchronous generators (SGs) is used. In such a system, the dynamic response of mechanical part (i.e. diesel engine and its governor) will also directly impact the transient of the electrical system, moreover, the major objectives (e.g. fuel consumption) of optimization function is relying on the mechanical governor. In this context, it is necessary to model the mechanical part.

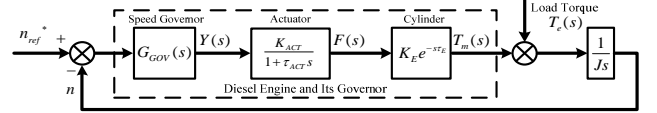


Fig. 2. Block diagram of diesel engine and its governor.

There are several different dynamic models can be derived depending on the application of diesel engine. In this paper, the delay based model is used to model the diesel engine, meanwhile, the actuator is modeled as inertia link. Fig. 2 shows the block diagram of the mechanical part of the diesel generator set, where T_m is the mechanical torque, K_{ACT} is the actuator constant, K_E is the engine torque variable. The time delays are calculated by (1) [18], where n is the rotating speed of the coaxial structure.

$$\tau_{ACT} = \frac{0.9}{2\pi n} \quad \tau_E = \frac{1}{2n} \quad (1)$$

The load torque of the mechanical part is a sum of the input of generator and frictional resistance. For synchronous generators, the electromagnetic torque can be calculated by (2) [19], where n_p is number of pole pairs; ψ_s is the stator flux linkage; ψ_f is the flux linkage established by either exciter or permanent magnets; δ is the power angle; L_{ds} and L_{qs} are the inductances of d-axis and q-axis, respectively.

$$T_e = 3n_p \left(\frac{\psi_s \psi_f}{L_{ds}} \sin \delta - \psi_s^2 \frac{L_{ds} - L_{qs}}{2L_{ds} L_{qs}} \sin 2\delta \right) \quad (2)$$

In case of round rotor (common in permanent magnetic generators), the inductances in d-axis will be equal to the one in q-axis, and thus cancel the second term (which is also referenced as the reluctance torque) in (2). In addition, with the presence of power electronic interfaces and bus voltage support function of ESS, the generator do not have to meet the substantial sudden torque pulsation, which means the damper windings are not necessary for these generators [20]. In this paper, the generators are assumed to be well designed to avoid working in magnetic saturation region and damper windings are not taken into consideration.

C. Alternative power sources

Recently, PV array or fuel cells have been considered in SPSs to reduce the cost and emission [5-9]. It is foreseeable that APSs will take a greater share in marine applications along with the increase of environmental awareness. However, the power density and capacity of APSs is usually not comparable with conventional diesel generator sets, and therefore, they are usually playing a supporting role in current marine applications.

For all kinds of alternative power sources, the common characteristic is that the peak output power can only be achieved at a certain point, which is referred as maximum power point. The average cost and emission of alternative power sources are relatively lower than conventional diesel generation, so that the power generated by alternative power sources have higher priority than diesel generation. In addition, there is a disparity in dynamic response of different kinds of alternative sources. For example, fuel cell can only provide very slow response while PV system can provide a fast response. For all those reasons, they are set to be grid-following components, which work in current source mode at their maximum power points in this paper.

D. Energy storage systems

Currently, the integration of ESSs is an important trend drawing great attention from both industrial and naval applications. Thanks to its unique bidirectional characteristic, ESSs can play an all-rounder in DC SMGs. Reference [1] summarized the potential functions of onboard ESS from the industrial sight, the most representative ones are picked and listed as follows:

- 1) *Zonal Power Backup*: The function that maintain power supply in a zonal sub-system to secure important loads when the systemic failure occurs.
- 2) *Spinning reserve*: The function that provide reserving generation capacity with fast response.
- 3) *Peak shaving*: The function that absorb load variation in the system so that engines can keep working in their most efficient point.
- 4) *Instant power support*: The function that absorb sudden load changes and gradually change the operating point of connecting generators.

It is noteworthy that these functions are arranged according to their requirement in systemic coordination. The former two backup functions can be achieved in existing excitation control. However, the power-supporting functions requires ESS to be in charge of the load variation, which contradicts with the conventional droop-based control scheme, and thus being hard to achieve in conventional control scheme.

Currently, the most frequently used energy storage device in marine applications is battery, especially lithium-ion batteries [3]. There are also some naval applications using super capacitors and flywheels as energy storage device to support high-power pulsed loads [4]. In this paper, battery bank is used as energy storage device, whereas bi-directional Buck-type DC/DC converter is used as its interface.

E. Shipboard electrical loads

The electrical loads aboard a vessel formulate a complex cluster that contains both electric propulsion systems and ship service loads. The propulsion power accounts a large proportion of the total power consumption, and it depends on the speed and sailing resistance. In addition, the unique dynamic positioning (DP) operation of marine vessels can lead to highly dynamic propulsion loads. Moreover, the electric propulsion systems are powered by power electronic converters with instantaneous constant power characteristic.

In this study, a programmable load is used to emulate the characteristic of shipboard electrical loads, in which load variations and sudden load changes can be programmed.

III. PROPOSED HIERARCHICAL CONTROL STRATEGY

A. Problems of the conventional excitation control

The conventional control strategy of a DC SPS is shown in Fig. 3. In each diesel generator set, a prime mover is coupled to a wound-rotor SG. The rotational speed of the generator set is regulated by its mechanical governor and the voltage in common DC bus is maintained by the synergetic effect of all exciter controllers. In this control strategy, ESS is set as a participant of the droop-based power sharing [21].

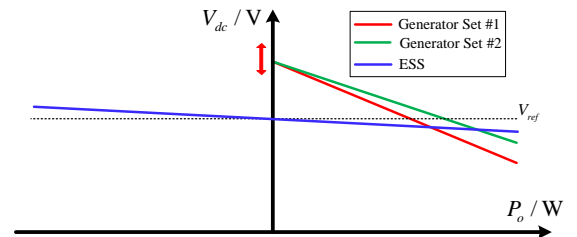


Fig. 3. Illustration of conventional control strategy of DC SPS.

There are several problems associated with this conventional control method, such as:

- The measurement error will directly impact on the load sharing effect, it can easily lead to overload.
- The droop curve is based on steady-state equations, the speed of dynamic response is not taken into account;
- The control strategy is only partially applicable to permanent magnetic synchronous generators (PMSGs);
- Sub-optimal use of ESSs, the “peak shaving” and “instant power support” functions are not included.

B. Primary control level of proposed control strategy

Because of non-linear relationship between fuel efficiency and load conditions (i.e. speed and torque), the optimum fuel economy can be only achieved at a certain area in the full range of operation. In conventional droop-based power sharing methods, not only the loads but also the load variations will be shared. In this context, it is difficult to maintain a stable operation point for diesel generator sets.

In order to overcome such a problem and achieve the optimum fuel efficiency, a master/slave power sharing method is proposed as a specialized primary control level for DC SMGs in this paper. In proposed primary control, the full operation range is divided into two parts according to the limitation in available power. In the normal operation area, the ESS will take the role to directly control the voltage of DC common bus as shown in Fig. 4. In this context, the instant power support function is automatically done, and thus the operation point of diesel generator sets will be constant. In emergency operation area, the ESS will support the system with its maximum output. It is noteworthy that the exciters are working in unified excitation in this level, so that it is compliant with both SGs and PMSGs.

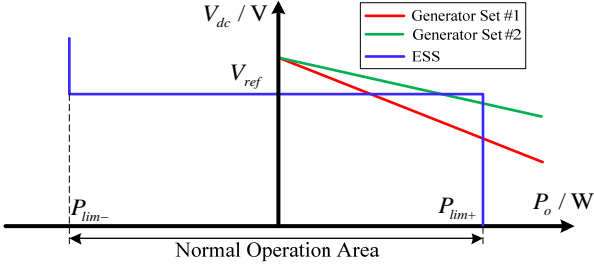


Fig. 4. Illustration of proposed master/slave based primary control.

C. Secondary control level of proposed control strategy

It differs from terrestrial MGs, the voltage in common DC bus do not have to be maintained in its nominal value. In general cases, a floating range of $\pm 10\%$ is acceptable [11]. Although the secondary control level is an optional function of DC SMGs, it can still be achieved by introducing deviations into the reference values of generator sets. The voltage equation of SGs is as shown in (3) [20], for the same mechanism, P - V droop curve of diesel generator sets can be roughly presented as (4).

$$V_s = \omega_e \psi_f - j(I_{ds} X_{ds} + I_{qs} X_{qs}) = \omega_e [\psi_f - j(I_{ds} L_{ds} + I_{qs} L_{qs})] \quad (3)$$

$$V_{dc} = \frac{\omega}{\omega_{base}} (V_{oc} - mP) \quad (4)$$

where ω_e is the angular speed of stator; ω_{base} is the base angular speed; ω is the actual speed of generator; m is the droop coefficient; V_{oc} is the open circuit voltage in base angular speed, which has a proportional relationship with ψ_f .

It can be seen from (4) that the voltage restoration can be achieved by introducing deviation in either speed reference or flux reference. For SG based system, introducing flux deviation is preferred due to the fact that it can avoid changing mechanical operation point of the diesel engine. In this context, the conventional excitation control function is integrated within this hierarchical controller. As for PMSG based system, speed deviation is the only choice, however, it will leave a tradeoff between efficiency and voltage restoration.

D. Tertiary control level of proposed control strategy

The tertiary control level is focusing on optimizing the efficiency and minimizing the cost of MGs [17, 22]. Currently, there have been a number of generation scheduling algorithms proposed for shipboard systems. In this paper, the implementation of control methods in tertiary control level is the major concern, so that the detail optimization algorithm and cost functions are not discussed. In shipboard MGs, the common optimization objective is the fuel economy, which focusing on fulfill the onboard power demand with minimum fuel consumption. From the systemic control perspective, the key to this optimization problem lies on the control method that keep the diesel generators working at its most efficient point (a certain set of engine speed and load condition) without using controllable PWM rectifier.

In this paper, a backward droop control method is proposed to achieve intentional control of power flow among all the power sources. In proposed power flow management function, two kinds of methods are proposed to achieve the same control effect: (1) introducing deviation in the flux deviation to change the endpoint value, and thus moving droop curve; (2) tuning the bus voltage to achieve optimal load matching.

E. Implementation of proposed control strategy

In order to achieve proposed control strategy, controllers for both ESS and exciter need to be reformed. The proposed control methods are presented as shown in Fig. 5.

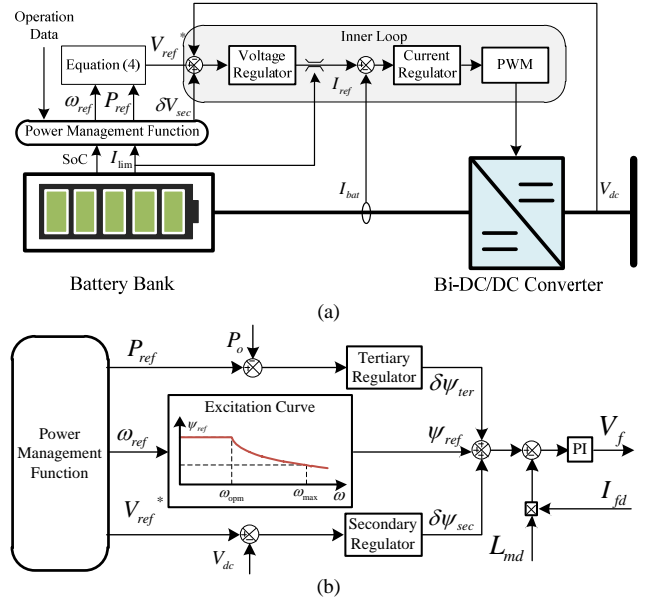


Fig. 5. Implementation of proposed control strategy in ESS and exciter controller: (a) ESS master controller; (b) exciter slave controller.

IV. SIMULATION RESULTS AND DISCUSSION

In order to verify the proposed hierarchical control strategy, a simulation is carried out based on MATLAB/Simulink. In this simulation, the notional DC SMG is composed by two diesel generator sets, an alternative power source modeled by current-mode controlled DC/DC converter with DC source,

and a voltage-mode controlled DC/DC converter with battery bank as ESS. The loads are emulated by programmable loads. In addition, the charging current is defined as positive direction and all switching frequency is set to be 1kHz in this simulation. The parameters are given in Table II.

Two scenarios are set to test and verify proposed hierarchical control strategy: (1) a rapid DP process to verify the power-supporting functions under highly dynamic loads; (2) a normal propulsion process to verify the comprehensive hierarchical control strategy.

A. Simulation scenario 1: dynamic positioning process

In this simulation scenario, the propulsion power is rapidly changing to emulate the load characteristic in DP process. In this context, several advantageous functions of proposed control strategy can be performed as shown in Fig. 6. The scenario is divided into the following three stages:

1) *Stage 1 (0-1s)*: Grid-forming is emulated in this stage, in which there are only auxiliary loads and desired power from generators is set to be zero.

2) *Stage 2 (1-5s)*: In this stage, only generator 1 is connected in order to perform peak shaving and instant power support functions.

3) *Stage 3 (5-10s)*: In this stage, both generator 1 and 2 are connected in order to perform strategic loading function for fuel consumption optimization.

In this simulation scenario, the performance of proposed control strategy is presented. In stage 2, the instant power support function is achieved automatically by proposed master/slave based primary control. In stage 3, the strategic loading function is performed. The output power of diesel generator sets are following the given references very well in this highly dynamic load condition.

TABLE II. TABLE TYPE STYLES

Component	Parameter	Value	Unit
DC Bus	Nominal DC Bus Voltage	1500±10%	V
ESS	Maximum power (dis-/charge)	510/408	kW
	Nominal Capacity	51	Ah
Diesel Genset	Maximum Output Power	300	kW
	Nominal Rotational Speed	1800	rpm
APS	Power output	100	kW
Loads	Nominal Propulsion Power	600	kW
	Auxiliary & Service Loads	85	kW
Droop Control	Droop Coefficient	0.63	V/kW

B. Simulation scenario 2: propulsion process

In this simulation scenario, the normal propulsion is emulated, in which the propulsion power maintains its rated value in steady state. In this context, the proposed hierarchical control strategy is comprehensively presented. The scenario is divided into the following four stages:

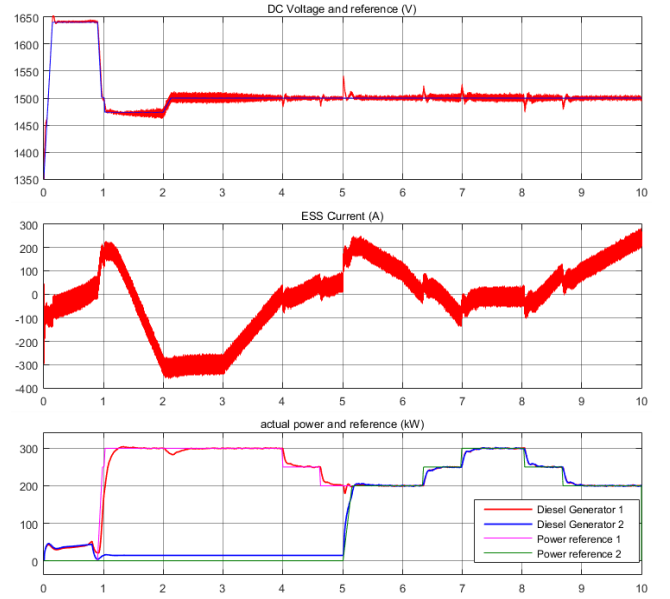


Fig. 6. Simulation result of scenario 1.

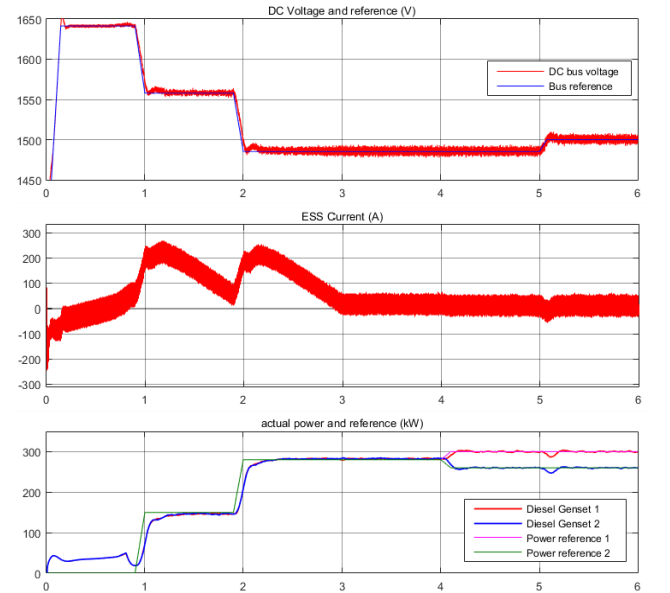


Fig. 7. Simulation result of scenario 2.

1) *Stage 1 (0-1s)*: Grid-forming is emulated in this stage, in which there are only auxiliary loads and desired power from generators is set to be zero.

2) *Stage 2 (1-3s)*: In this stage, propulsion loads increases from 0 to 1 p.u, the output power reference also increases as two steps.

3) *Stage 3 (4-5s)*: In this stage, tertiary control is activated and different references of output power are set to generators.

4) *Stage 3 (5-6s)*: In this stage, secondary control is activated to restore the voltage of common DC bus.

The simulation results are as shown in Fig. 7. It can be seen from the simulation results that the power flow management

and nominal voltage restoration can be done independently. The output power of diesel generator sets can follow their references very well. And the voltage of common DC bus can be restored directly without changing operation points of the diesel generators.

V. CONCLUSION

In this paper, a specialized hierarchical control architecture is proposed for DC SMGs. In order to adapt shipboard applications, especially limitations in controllability, the conventional control layers are redefined and reformed in this paper. In primary control level, a master/slave based control method is employed to overcome the efficiency degradation caused by load variation. In secondary and tertiary control levels, the voltage restoration and power flow management functions are achieved with backward droop control method and flux deviations. In addition, peak shaving and instant power support functions, which are regarded as major advantage of using onboard ESSs, are inherently integrated in the proposed method. It is also noteworthy that proposed control strategy can achieve similar strategic power sharing in PMSG-based DC SMGs. Simulation results under two different operation scenarios are performed to verify the performance of proposed control strategy.

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