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Alternative Maritime Power System Based on Four-Level Hybrid-Clamped Inverter with Seamless Changeover Control Scheme

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ABSTRACT

In this paper, an alternative maritime power system is proposed based on four-level hybrid-clamped inverter to enhance the adaptability and interoperability in shore-to-ship power transfer. The proposed system enables the power delivery at various medium-voltage levels and operating frequencies (50/60 Hz) without step-up or step-down transformers. In addition, a changeover between the onboard generator and shore-side power is proposed based on the hybrid grid-following and grid-forming modes for a seamless transition without having to initially turn off the main and auxiliary engines of the vessel. The effectiveness of the proposed technique has been verified with simulation results.

1. Introduction

During docking periods at the seaports, the auxiliary engines of the vessels emit significant quantities of emissions which degrade air quality and pose health risks to port workers, nearby residents, and visitors. The alternative maritime power (AMP) provides an effective solution to this issue by connecting the vessels to shore-based electricity grids, providing power to the onboard systems without using auxiliary diesel engines [1]. By cutting or eliminating emissions from docked ships, this system significantly improves air quality, reduces greenhouse gas emissions, and promotes environmental sustainability in port areas. However, one of the remaining challenges is ensuring compatibility between the voltage and frequency of the shore-side grid and those of the various vessels. Failure to comply with these parameters can result in connection failures, equipment damage, and safety hazards.

The AMP systems with static frequency converters provide more flexible voltage and frequency control [2]. However, most system using these converters operate at low voltage on both the input side of the AC-DC converter and the output side of the DC-AC converter. Consequently, step-down and step-up transformers are needed to connect to medium-voltage utility grids and ship electrical buses. Operating these converters at low-voltage AC allows for the use of switches with lower voltage ratings. However, this low-voltage operation necessitates larger conductor sizes to handle higher current levels, which can increase material costs and require more installation space, especially for high-power systems. Additionally, using a static frequency converter at lower voltages oftentimes also results in the limited power capacity compared to medium-voltage systems. To address this limitation, some commercial solutions configure multiple static frequency converters in parallel to provide higher power capacity and increase the redundancy.

In this paper, a novel configuration of AMP system is proposed based on four-level hybrid-clamped (4L-HC) inverter to enable operation at medium-voltage levels without requiring step-up or step-down transformers [3]. In addition, a changeover scheme is proposed to provide a seamless transition between the onboard generator and the shore-side power, resulting in a stable power delivery to the ship load throughout all berthed-in and berthed-out stages. The effectiveness of this technique is verified through simulation results for a 1-MVA 6.6-kV system.

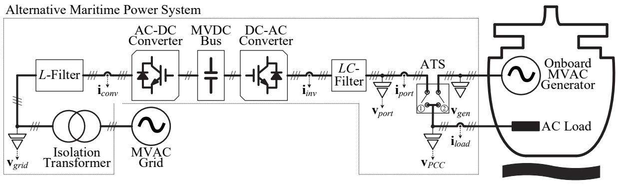

Fig. 1. Configuration of alternative maritime power system.

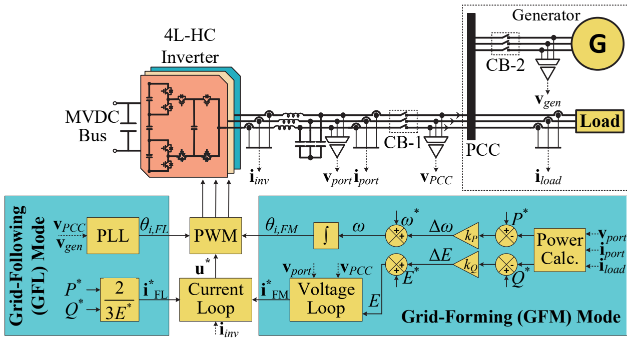

Fig. 2. Hybrid grid-following (GFL) and grid-forming (GFM) modes for four-level hybrid-clamped inverter operation.

TABLE I. OPERATING SCENARIOS FOR SEAMLESS CHANGEOVER

$f(t)$	Scenario	P^*_{port}	Q^*_{port}	Mode
0	Pre-synchronization I	0	0	GFM
1	Parallel I	$(x\%)P_{load}$	$(x\%)Q_{load}$	GFL
2	Parallel II	$(z\%)P_{load}$	$(z\%)Q_{load}$	GFL
3	Parallel III	$(z\%)P_{load}$	$(z\%)Q_{load}$	GFL
4	Standalone	P_{load}	Q_{load}	GFM
5	Pre-synchronization II	P_{load}	Q_{load}	GFM

2. Proposed Alternative Maritime Power System

2.1 Configuration

The proposed configuration of AMP system is illustrated in Fig. 1. The system consists of two conversion stages, i.e., back-to-back AC-DC and DC-AC conversions. Due to the structure of four-level hybrid-clamped topology, where the split DC-link and flying capacitors are uniformly controlled at $E = V_{dc}/3$, the voltage stress is also uniform across all switches (E), as shown in Fig. 2.

2.2 Seamless Synchronization

To provide a seamless changeover between the onboard generator of the ship and the shore-side power without interrupting the load operation, the AMP should be operated with hybrid grid-following and grid-forming modes, as shown in Fig. 2 and Table I. To implement a smooth transition into the parallel operation, the pre-synchronization control should be done to adjust the voltage and frequency of the AMP prior to closing the

TABLE II. PARAMETERS FOR SIMULATION

Parameters	Symbols	Values
Power rating	S_{rated}	1 MVA
DC-bus voltage	V_{dc}	11 kV
Vessel-grid voltage	$v_{LL,ship}$	6.6 kV
Operating frequency	f_{ship}	50/60 Hz
Carrier frequency	f_{sw}	5 kHz
DC-link and flying capacitors	$C_1/C_2/C_3/C_{fx}$	2.5 mF
Inverter *LC*-filter	L_{inv}, C_{inv}	2 mH, 6 µF

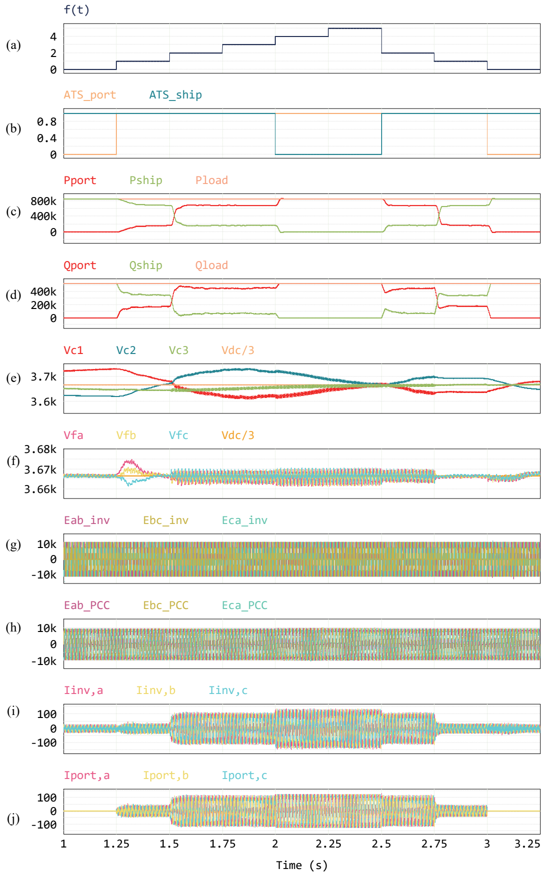

Fig. 3. Performance at PF=0.85 (60 Hz). (a) Scenario. (b) ATS switching. (c) Active power. (d) Reactive power. (e) Split DC-link capacitor voltages. (f) Flying capacitor voltages. (g) Line voltages of inverter before *LC*-filter. (h) Line voltages at PCC. (i) Output currents of AMP before *LC*-filter. (j) Output currents of AMP after *LC*-filter.

automated transfer switch (ATS). The voltage errors between the PCC and either the AMP or generator should be kept within the allowable range (g_{allow}), as follows:

$$\begin{cases} \Delta v_{err,1} = \left| v_{port,ll} - v_{PCC,ll} \right| \le \Delta v_{\max} \\ \Delta v_{err,2} = \left| v_{PCC,ll} - v_{gen,ll} \right| \le \Delta v_{\max} \\ \Delta v_{\max} = g_{allow} V_{PCC,q} \end{cases} . \quad (1)$$

The power sharing from the AMP is gradually increased up to a set value that is close to the sum of power demanded by the load ($P^*_{port} = z\%.P_{load}, Q^*_{port} = z\%.Q_{load}$) while simultaneously reducing the power sharing from the onboard generator down to a minimum set value ($P^*_{port} = x\%.P_{load}, Q^*_{port} = x\%.Q_{load}$) prior to the disconnection of the ship generator from the load.

3. Simulation Results

In order to verify the effectiveness of the proposed technique, a simulation has been conducted with the parameters listed in Table

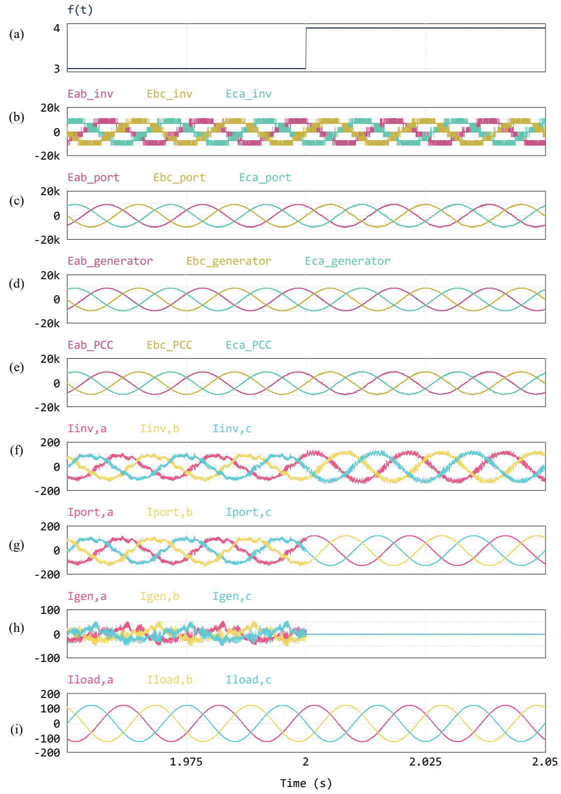

Fig. 4. Transition from GFL to GFM (50 Hz) at t = 2 s. (a) Scenario. (b) Line voltages before *LC*-filter. (c) Line voltages after *LC*-filter. (d) Line voltages of ship generator. (e) Line voltages at PCC. (f) Output currents of AMP before *LC*-filter. (g) Output currents of AMP after *LC*-filter. (h) Output currents of ship generator. (i) Load currents.

II, where g_{allow}=10 %, x=20, and z=80. The performance during all berthed-in and berthed-out stages is shown in Fig. 3, where the load is set at PF=0.85 (60 Hz). The changeover has been done seamlessly, where the power sharing is controlled at the corresponding references.

When the ship load is operated at 50 Hz, a smooth transition is also demonstrated at each stage, as shown in Fig. 4, where the scenario is changed from "Parallel III" (GFL) to "Standalone" (GFM). The PCC voltages are kept intact during this transition and the power sharing of AMP is increased from 80 % to 100 %.

4. Conclusions

In this paper, an alternative maritime power (AMP) configuration has been proposed based on four-level hybrid-clamped inverter for ships with various operating voltages and frequencies (50/60 Hz). A control scheme based on hybrid grid-following and grid-forming modes has been proposed in six key operating scenarios for a seamless changeover between the onboard generator and shore-side power. The effectiveness of the proposed technique has been verified through simulations for a 1-MVA 6.6-kV AMP system.

References

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