Comparison of Different Topologies of Shaft Generation System in Marine Applications

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***Abstract*—Shaft Generation in vessels has significant benefits in reduction of fuel consumption and energy saving, leading to both environmental and economical advantages. A typical shaft generation system equipped with a fixed pitched propeller (FPP) is composed of a generator and a frequency converter. Several different types of generators are currently being considered, including brushless synchronous machine, induction machine, and brushless doubly-fed machine. This paper tends to provide the introduction and comparison of these three machines with their control systems concentrating on the application of shaft generation.**

Keywords—Shaft Generation, Brushless Synchronous Machine, Brushless Doubly-Fed Machine, Power Take-Off.

I. Introduction

GENERALLY speaking, in a conventional vessel, there are two types of diesel engines. The first one is mechanically connected to the propeller or thruster with or without a gearbox to provide the propulsion force of the ship, normally called as the 'main engine'. The main engine may work at variable speeds if the propeller has a fixed pitch. As a result, the propulsion force and the cruising speed of the vessel are controlled by the rotational velocity of the main engine. Apart from the main engine, another kind of diesel engine is connected to a generator as a generator-set (normally abbreviated as 'gen-set') generating the grid onboard. This diesel engine is referred to as the 'auxiliary engine' and is operated at a fixed speed producing 50 Hz or 60 Hz voltage.

Recently, a novel concept of the so-called 'shaft generation' has appeared [1, 2, 3], where the auxiliary gent-set is replaced by a generator that is mechanically coupled to the screw shaft of the propeller via a gear box, seen in Fig. 1. In such configuration, the generator is named as the 'shaft generator' and the system is called shaft generation, sometimes also referred to as 'Power Take-Off' (PTO) [1]. The main challenge is that the shaft generation system has to supply constant voltage and frequency to the load onboard even at changing speeds of the main engine when the vessel travels at different speeds or if the propeller's speed strongly varies in heavy seas. This characteristic is normally achieved by a frequency converter [2].

When the shaft generation system is in operation, it is possible that the auxiliary gen-set can be totally shut down at the cost of the main engine running at slightly heavier load, therefore leading to decreased maintenance effort, increased engine efficiency, fewer emissions, and better compliance with environmental legislations [3]. All these characteristics result in economical payback and commercial success. More and more vessels equipped with shaft generation have been reported, and it is believed that 2% fuel saving is arrived with shaft generation [2].

It is noted that if the fixed pitched propeller (FPP) is employed, the shaft speed of the generator varies at all times due to variable-speed operation of the main engine. Consequently, the output frequency of the shaft generator also changes accordingly and cannot supply to the grid onboard directly. The frequency converter in Fig. 1 is employed between the generator and the grid to transfer from a variable frequency to constant. It is always a challenge to supply the grid onboard via a converter, since the grid on vessels is normally weak and can be regarded as a mircogrid [4].

The converter normally applies an 'AC-DC-AC' structure composed of a machine-side converter with a variable frequency input and a load-side converter with constant frequency output [5, 8]. From control point of view, control of the machine-side converter is dependent on the type of the generator, which will be discussed in detail in this paper. On the other hand, the load-side converter is always controlled as three-phase power supply [17].

The shaft generator is the core device in the shaft generation system, responsible for converting mechanical energy from the main engine to electrical energy for the load [6, 7]. Many AC machines are used in industry, among which three kinds of machines have been intensively considered in shaft generation, i.e. synchronous machines (SM) [3], induction machines (IM) [8], and brushless doubly-fed machines (BDFM) [10, 11].

This paper will introduce the system structures and control schemes of the shaft generation systems based on the three types of machines. Moreover, their merits and drawbacks will be compared and commented. Finally, a machine test-rig has been built to test the performance and validate the proposed control schemes. Experimental results will be demonstrated and analyzed.

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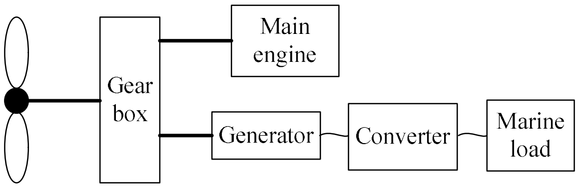


Fig. 1. Configuration of a typical shaft generation system

II. Comparison of Different Shaft Generation Topologies

A. Synchronous machine

In marine applications, the synchronous machine with an electrically-excited rotor is the most widely used generator topology [12], which normally employs a small generator as the exciter mounted on the same shaft of the rotor of the main generator. This exciter is rectified to DC voltage to feed the main rotor winding to achieve brushless operation. This synchronous machine without brushes and slip-rings is the so-called 'brushless synchronous machine'.

In the synchronous machine, the voltage frequency of the stator winding is synchronized with the rotational speed of the rotor, and hence proportional with the velocity of the main engine. The voltage amplitude of the stator winding is regulated by a self-excitation control circuit board, called Active Voltage Regulator (AVR). The AVR compares the stator terminal voltage with the set-point and runs on a feedback control scheme to adjust the excitation to maintain a constant output. The SM-based shaft generation system is illustrated in Fig. 2.

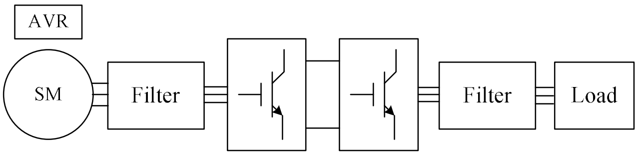


Fig. 2. The SM-based shaft generation system

As a conclusion, the synchronous machine is originally aimed to be connected to a fixed-speed prime move without the need of a converter supplying the load directly. However, in the ships with an FPP where a frequency converter is required to achieve variable speed operation, the SM-based shaft generation system requires a converter. However, the system suffers from the following drawbacks:

1) The synchronous machine has to come with an AVR that is able to maintain the voltage at the full speed range. The synchronous machine should be designed with a larger size to avoid saturation at low speed range.

2) There appear some high redundant systems that require the shaft generator working at the motoring mode to drive the propeller in case the main engine breaks down. Such function is called Power Take-Home (PTH). Apparently, a self-excited synchronous machine does not build the rotor flux during stationary and therefore does not have self-starting capability.

The control of the synchronous machine is similar with a grid-connected function, and tends to synchronize the stator voltage of the SM. The control equation is very simple and can be written as:

$$v = -L\frac{di}{dt} + v_s + j\omega_s i \tag{1}$$

v_s is the stator voltage of the SM, L is the inductance of the input reactor, ω_s is the synchronous electric angular frequency of the SM, i is the stator current and v is the converter output voltage.

The synchronous angle θ_s is selected that the synchronous reference frame is aligned with the stator voltage vector, so that $v_{sq} = 0$. θ_s can be detected with a Phase Locked Loop (PLL).

The real power of the SM can be expressed as in the d-q (direct-quadrature) system as:

$$P = \frac{3}{2}(v_{sd}i_d + v_{sq}i_q) = \frac{3}{2}v_{sd}i_d \tag{2}$$

Therefore, considering a constant v_{sd}, i_d can be used to control the real power, and therefore the DC-link voltage. The diagram of the control system is drawn in Fig. 3.

Generally speaking, the control system can achieve stable operation. However, it should be still noted that the time constant of the vector controller must be much larger than that of the AVR system, so that the assumption of constant v_{sd} and $v_{sq} = 0$ holds.

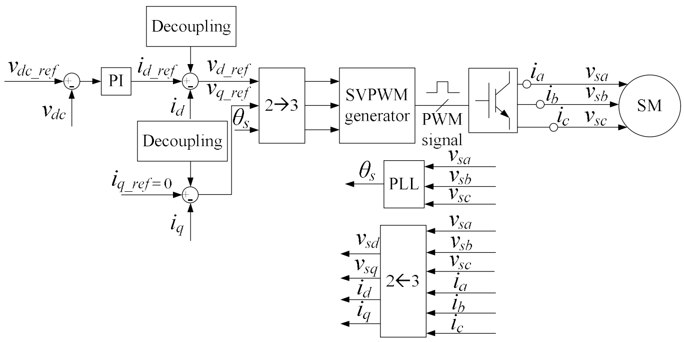


Fig. 3. The control diagram of the synchronous machine

B. Induction Machine

The induction machine has been widely used in adjustable speed drives (ASD) for decades thanks to the rapid development of power electronics [12], especially the IGBTs. The induction machine used in shaft generation has the topology shown in Fig. 4, which can be regarded as the reverse version of ASD since only the direction of power flow changes. Consequently, the shaft generation system based on induction machines does not have any obvious technical obstacle.

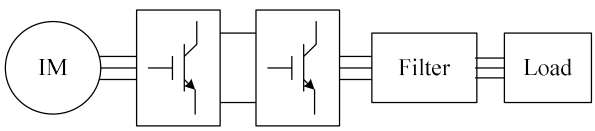


Fig. 4. The IM-based shaft generation system

Compared with the synchronous machine, the induction machine has a more robust mechanical structure, since the rotor is built with copper bars that are qualified to bear harsh environment and high temperature. Moreover, when the induction machine operates, the rotor flux is induced via the excitation of the stator, so that no AVR is required. When the main engine fails, the induction machine can easily work as a motor in the PTH mode.

It should be noted that the IM-based shaft generation system cannot charge the DC-link of the converter during start-up of the generation system. The vessel must have an auxiliary power supply to start the converter. The standard IM-based generation system does not support the recovery from 'black-out'. A speed sensor is believed to be needed for control purposes to achieve high dynamic performance, although control schemes without sensor has already been reported [13, 14].

The control system of an IM-based shaft generation system is very similar to that of an IM-based drive system. The most widely used control philosophy is the widely-known rotor-flux-linkage oriented control. The control equations can be expressed as:

$$v_s = R_s i_s + \frac{d\psi_s}{dt} + j\omega_s \psi_s \tag{3}$$

$$v_r = R_r i_r + \frac{d\psi_r}{dt} + j\omega_{sl} \psi_r \tag{4}$$

$$\psi_s = L_s i_s + L_m i_r \tag{5}$$

$$\psi_r = L_r i_r + L_m i_s \tag{6}$$

W

Where ω_{sl} is the slip frequency of the induction motor and can be defined as:

$$\omega_{sl} = \omega_s - p\omega_\theta \tag{7}$$

An encoder must be mounted on the induction machine to measure the rotor speed ω_θ. If all the equations above are decomposed in d and q axis and aligned with the rotor flux linkage, the torque of the induction machine can be obtained:

$$T = \frac{3}{2} P \frac{L_m^{\ 2}}{L_r} i_{sd} i_{sq} \tag{8}$$

The control diagram is illustrated in Fig. 5. The flux linkage of the induction machine is controlled via the flux-producing current i_{sd}, normally maintained constant, while i_{sq} is regarded as the torque-producing current which is controlled to regulate the DC-link voltage of the converter.

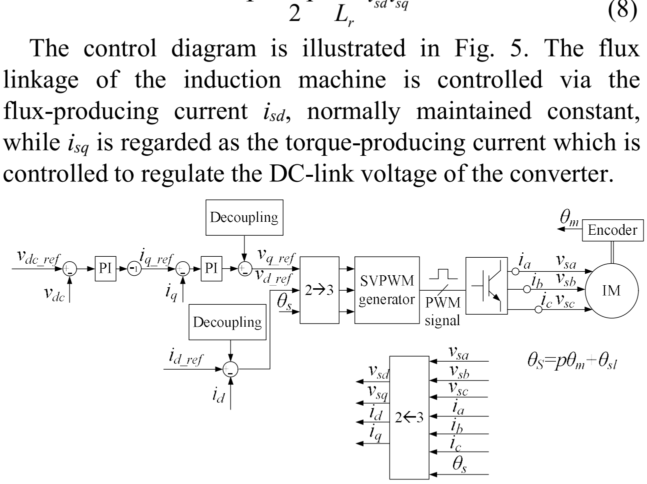


Fig. 5. The control diagram of the induction machine

C. *Brushless doubly fed machine*

The brushless doubly fed machine (BDFM) is a relatively new type machine shown in Fig. 6 [15]. The BDFM has two stator windings, each producing an air-gap field of a different pole number, chosen to avoid transformer coupling between the stator windings [16, 17].

In this arrangement, one winding, the power winding (PW), is connected directly to the grid. The other winding, the control winding (CW), is supplied with variable voltage and variable frequency from a converter also connected to the grid.

The shaft speed of the BDFM is given by (9):

$$\omega_\theta = \frac{\omega_1 + \omega_2}{p_1 + p_2} \tag{9}$$

The subscripts 1 and 2 denote the PW and CW, respectively. The main interest of employing the BDFM in the shaft generation system has been given to the cost reduction from the converter, since it only processes slip power and is rated fractionally when the operating speed range of the BDFM is limited [16].

A potential application of the BDFM is wind power generation. Shaft generation is another likely area, since the BDFM only runs in a relatively narrow speed range, from the idling speed (or higher) to the nominal speed of the main engine.

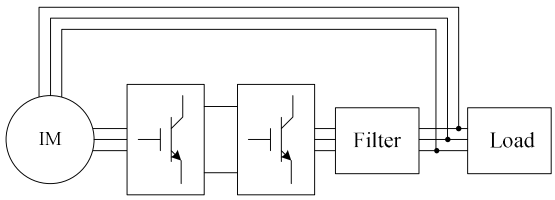


Fig. 6. The BDFM-based shaft generation system

However, no one can deny that the BDFM has some disadvantages:

1) The control scheme of the BDFM is still complicated compared to that of other machine topologies. Moreover, the BDFM shows sluggish dynamic performance that will be explained in detail later on.

2) In order to avoid direct transformer coupling between the two stator windings, the selection of their pole pair numbers has to observe certain rules [18]. Considering that the grid frequency is constant, the selection of the synchronous speed (also referred to as natural speed) of the BDFM is far from flexible, according to (9).

3) The BDFM is normally 25% larger than the induction machine of the same operating speed and power rating [16].

4) The BDFM operates based on induction. Therefore, similar to the induction machine, the BDFM does not have the capability of recovering from black-out of the vessel.

5) In order to save the converter rating, the speed range of the BDFM is limited and zero speed is not the operating speed of the BDFM. Consequently, it is not possible to start the BDFM from standstill in the PTH mode in case the main engine malfunctions.

The complicated structure of the BDFM leads to the complication of the controller design, which considers 6 equations as follows:

$$v_1 = R_1 i_1 + \frac{d\varphi_1}{dt} + j\omega_1\varphi_1 \tag{10}$$

$$\psi_1 = L_1 i_1 + L_{1r} i_r \tag{11}$$

$$v_2 = R_2 i_2 + \frac{d\psi_2}{dt} + j(\omega_1 - (p_1 + p_2)\omega_r)\psi_2 \tag{12}$$

$$\psi_2 = L_2 i_2 + L_{2r} i_r \tag{13}$$

$$v_r = R_r i_r + \frac{d\psi_r}{dt} + j(\omega_1 - p_1\omega_r)\psi_r \tag{14}$$

$$\psi_r = L_r i_r + L_{1r} i_1 + L_{2r} i_2 \tag{15}$$

The torque of the BDFM can be expressed as:

$$T_e = \frac{3}{2} P_1 I_m[\overset{*}{\psi_1} i_1] + \frac{3}{2} p_2 \operatorname{Im}[\psi_2 \overset{*}{i_2}] \tag{16}$$

[18] analyzes the vector control principle of the BDFM in the shaft generation system, concluding that slow dynamic performance is achieved, since the current of both the PW and CW must be controlled simultaneously. Their indirect coupling via the rotor winding results in a strong control disturbance and needs to be compensated by PI controllers. Its control response will be validated in the experimental results that will be given later.

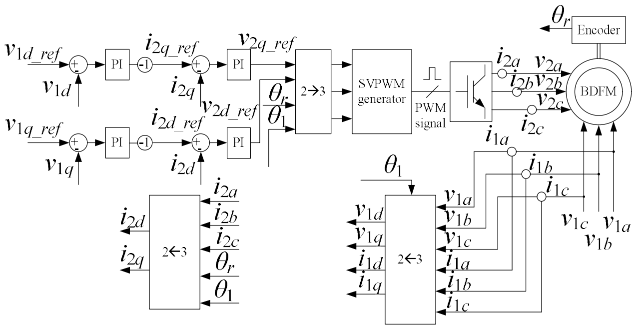


Fig. 7. The control diagram of the brushless doubly fed machine

III. Experimental Verification

A. Test rig setup

In order to compare the control performance of the SM-based, IM-based and BDFM-based shaft generation system, a test rig was established, given in Fig. 8.

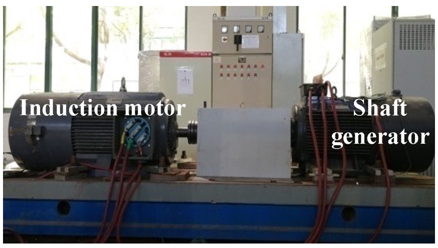


Fig. 8. The test rig

The schematic drawing is provided in Fig. 9. The prime move is a 250 kW induction motor drive system to emulate the behavior of the main engine. Three prototype machines coupled to the driving motor are considered in the experiment, tabled in TABLE 1.

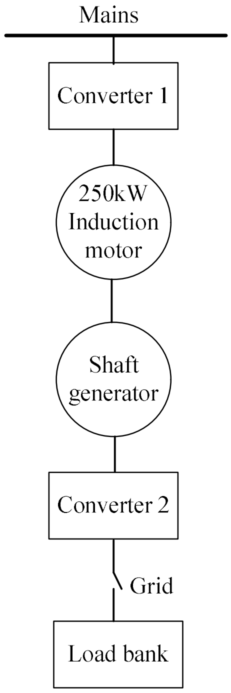


Fig. 9. The schematic of the test rig system

TABLE 1. Machine parameters

Parameters	SM	IM	BDFM
Rated voltage (V)	400	400	400
Rated power (kW)	120	150	90
Minimum speed (rpm)	1200	750	350
Maximum speed (rpm)	1500	1500	650
Rated frequency (Hz)	50	50	50/15
Number of pole pair	2	2	2/4

It is noted that the BDFM has to be operated at lower speed since the BDFM as two stator windings and can be regarded as an equivalent 12-pole machine, seen in (8). The prime move, when testing the BDFM, needs to run slowly with the help of the driving converter (converter 1 in Fig. 9).

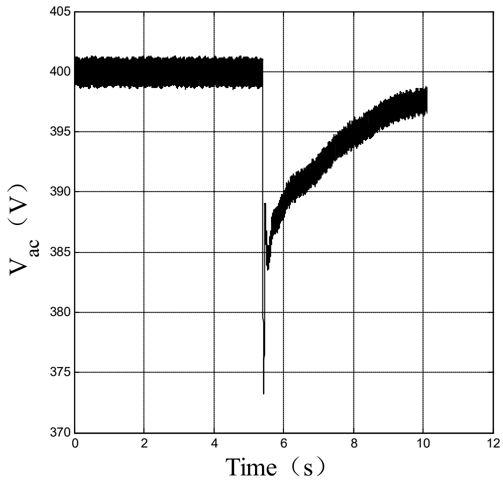
The three types of prototype shaft generators are connected to a frequency converter (converter 2 in Fig. 9) customized with three different control programs for the algorithms introduced in Fig.3, Fig. 5 and Fig. 7, respectively.

The output of the converter is a three-phase resistor bank to provide the load for the shaft generation system. This paper especially investigates the dynamic performance of the system under step load change cutting in and off a set of load bank dramatically.

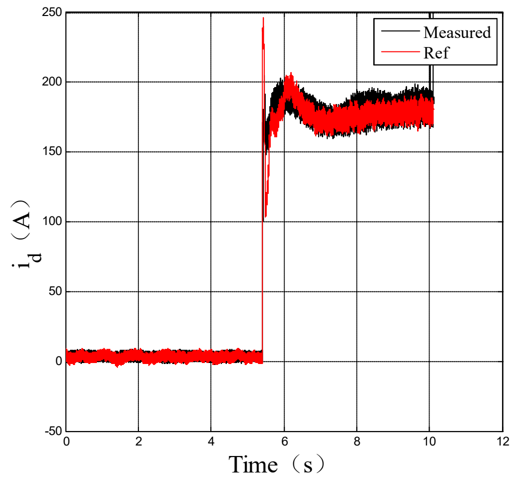
The converter employs an x86 Celeron 650 MHz CPU with a control loop of 0.4 ms generating 2.5 kHz PWM driving signals. The controller parameters including the proportional and integral gains of the PI controllers have been refined through experimental tests.

B. Experimental results

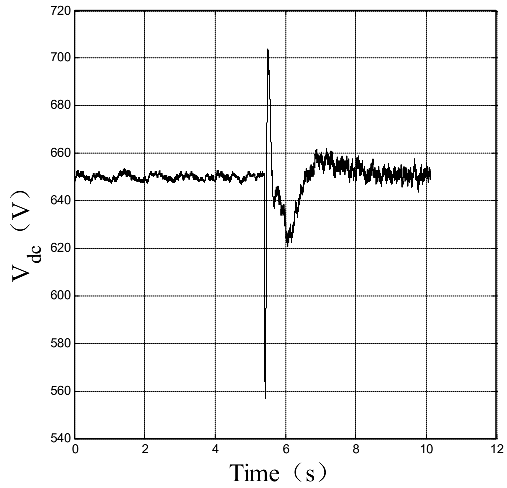
Fig. 10 depicts the experiment when the synchronous machine is operated at the rated speed 1500 rpm and is exerted by a 90 kW load inrush, i.e. 75% of the rated power. It can be seen that the grid voltage has a 20V (5%) dip and returns to the nominal voltage quickly. The active current i_d traces the set-point closely, demonstrating high dynamic performance. During the whole period, the DC-link voltage remains almost constant.



(a) The grid voltage



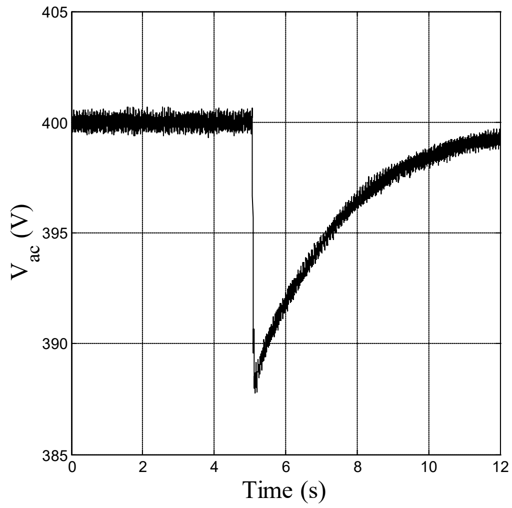
(b) The active current id



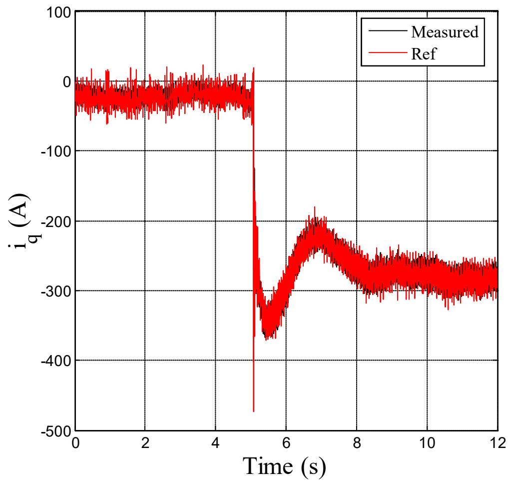
(c) DC-link voltage

Fig. 10. Dynamic performance of the synchronous machine when it was running at 1500 rpm, and the load was increased by 90 kW dramatically.

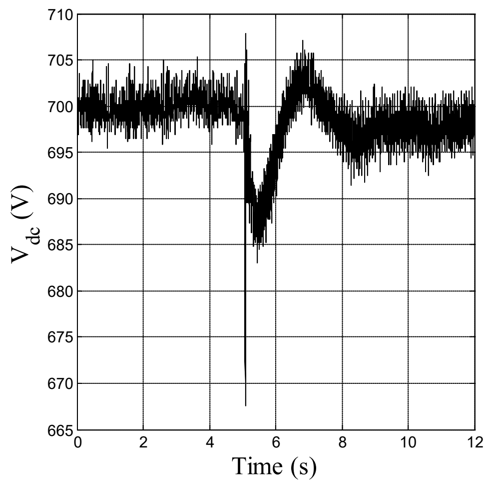
The performance of the IM-based shaft generation system is evaluated in Fig.11, when the induction machine is operated in 1500 rpm and experienced a step load change of 100 kW (0.67 p. u.). Similar to the synchronous machine, the induction machine performs very well in response to a large change. The voltage displays a 12 V (3%) drop and the active current i_{sq} can follow the set-point dynamically with DC-link voltage nearly unchanged.



(a) The grid voltage



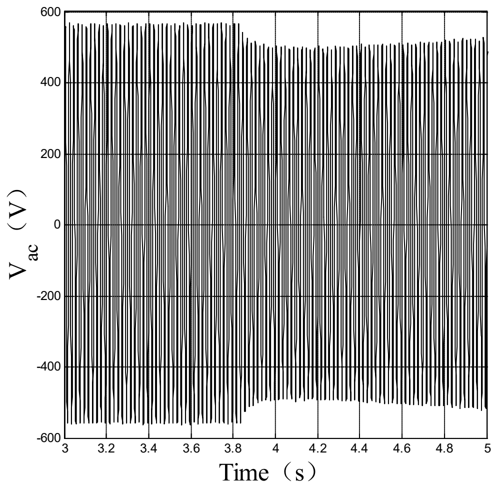
（b） The active current i_q



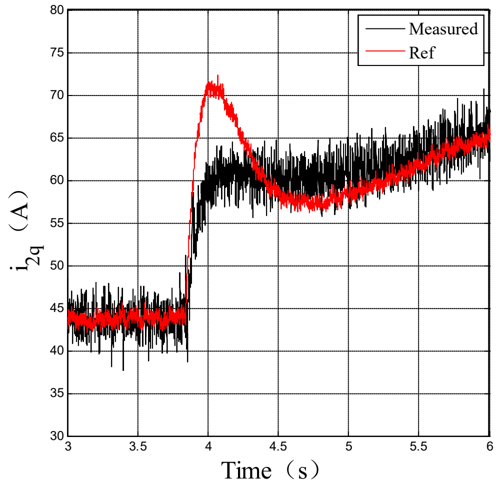
（c） DC-link voltage

Fig. 11. Dynamic performance of the induction machine when it was running at 1500 rpm, and the load was increased by 100 kW dramatically.

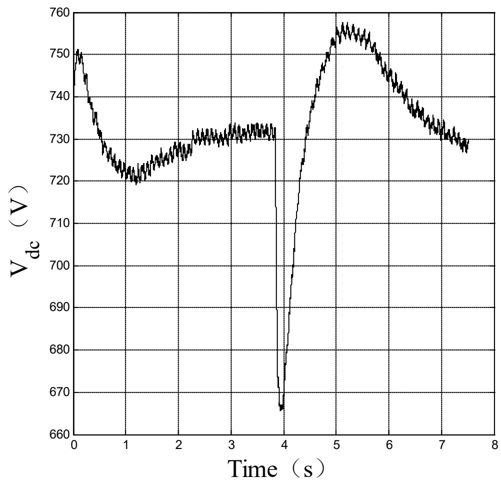
As a fare comparison, the BDFM is operated at 600 rpm (1.2 p. u) and the load varies from 45 kW to 60 kW (50% to 75%) suddenly. This speed is selected to be over-synchronous with which the BDFM can work more efficiently [16]. The grid voltage decreases by 17% and recovers slowly. The active current of the CW i_{2q} successfully traces the reference value, but obvious transient discrepancy of 0.5 s can be witnessed, showing worse performance compared to its counterparts. As a result, larger dips and overshoots of the DC-link voltage are seen. It can be concluded that the BDFM is more unstable facing control disturbance.



（a） PW voltage



（b） CW current i_{2q}



（c） DC-link voltage

Fig. 12. Dynamic performance of the BDFM when it was running at 600 rpm, and the load was changed from 30 kW to 45 kW dramatically.

IV. Conclusion

Shaft generation systems are more and more investigated and installed on vessels. This paper compares the principle and control schemes of the SM-based, IM-based and BDFM-based shaft generation systems with their advantages and disadvantages summarized in TABLE 2. Stable operation during load change can be achieved on the three shaft generators when equipped with proper controllers. However, the synchronous machine and induction machine display better performance in terms of dynamic response.

TABLE 2 The comparison of the SM-based, IM-based and BDFM-based shaft generation systems

	SM	IM	BDFM
Range of speed	Narrow	Wide	Normal
Self-excitation capacity	√	×	×
PTH	×	√	×
Generator cost	Medium	Low	High
Converter cost	High	High	Low
Volume and weight	Small	Small	Large
Technical compatibility	High	Normal	Low

References

[1] ABB Shaft Generators And Turbochargers To Raise Energy Efficiency In Cargo Vessels. MI News. Network Shipping News. [Online]. Available: https://www.marineinsight.com/shipping-news/abb-shaft-generators-turbochargers-raise-energy-efficiency-cargo-vessels/

[2] Shaft Generators for Low Speed Main Engines. [Online]. Available: http://marine.mandieselturbo.com/docs/librariesprovider6/technical-papers/shaft-generators-for-mc-and-me-engines.pdf?sfvrsn=38

[3] Wärtsilä SAM Electronics. [Online]. Available: https://www.wartsila.com/products/marine-oil-gas/electrical-automation/electrical-automation/wartsila-sam-electronics

[4] Kasal, G. K., & Singh, B. Voltage source converter with a transformer as an electronic load controller for a stand-alone power generation. International Journal of Energy Technology and Policy, Vol. 7 (3), pp. 275-287, 2010.

[5] Y. Liu, S. Xue, "Control strategy of the shaft-driven generator based on the PWM converters" .Methods and Models in Automation and Robotics, 2011, pp. 178-181.

[6] Xia, K., Zhang, Z., Wang, N., & Zhang, P. Operation control and simulation research of the variable-speed constant-frequency system of the ship shaft generator. Region 10 Conference IEEE. pp. 301-304. 2017.

[7] Prousalidis, J., Patsios, C., Kanellos, F., Sarigiannidis, A., Tsekouras, N., & Antonopoulos, G. Exploiting shaft generators to improve ship efficiency. *Electrical Systems for Aircraft, Railway and Ship Propulsion. IEEE.* pp. 1-6. 2012.

[8] Liu, Y. J., & Xue, S. L. Control strategy of the shaft-driven generator based on the PWM converters. *Methods and Models in Automation and Robotics (MMAR), 2011 16th International Conference on IEEE*. pp. 178-181.

[9] Kozak, M., & Zawirski, K. Application of induction squirrel cage machine as a generator in ship electric network. *Power Electronics and Motion Control Conference* IEEE. pp. T11-75-T11-79. 2010.

[10] Liu, Y., Ai, W., Chen, B., Chen, K., Luo, G., & Xu, S. Operation control of the brushless doubly-fed machine for stand-alone ship shaft generator systems. *IEEE International Conference on Industrial Technology. IEEE.* Vol.59, pp. 400-413. 2015.

[11] Bruzzese, C., Santini, E., Benucci, V., & Millerani, A. Model-based eccentricity diagnosis for a ship brushless-generator exploiting the Machine Voltage Signature Analysis (MVSA). *IEEE International Symposium on Diagnostics for Electric Machines, Power Electronics and Drives.* pp. 1-7.2009.

[12] Al' Akaya shee, Q. H., Hill-Cottingham, R. J., & Eastham, J. F. 170 kW induction motor for an electric truck and bus drive. *Power Electronics, Machines and Drives, 2002. International Conference on IEEE.* pp. 149-152.

[13] Mossa, M., & Bolognani, S. Effective model predictive instantaneous power control for a sensorless induction motor drive. International Journal of Industrial Electronics and Drives. Vol. 4 (1), pp. 44-55, 2018.

[14] Boufadene, M., Belkheiri, M., & Rabhi, A. Adaptive nonlinear observer augmented by radial basis neural network for a nonlinear sensorless control of an induction machine. International Journal of Automation and Control, Vol. 12 (1), pp. 23-43, 2018.

[15] Wang, X., Mcmahon, R. A., & Tavner, P. J. Design of the Brushless Doubly-Fed (Induction) Machine. Electric Machines & Drives Conference, 2007. IEMDC '07. IEEE International. Vol.2, pp. 1508-1513.

[16] McMahon, R.A, Roberts, P., et al, "Performance of BDFM as generator and motor", Electric Power Applications, IEE Proceedings, 2006, 153(2), pp. 289-299.

[17] Boger, M. S., Wallace, A. K., Spee, R., & Li, R. General Pole number model of the brushless doubly-fed machine. Industry Applications Society Meeting, 1994. Conference Record of the IEEE Xplore. Vol.31, pp. 67-73 vol.1.

[18] Lan, J., Shi, Y., Wu, Y., Liu, Y., Chang, G., & Jin, Y., et al. A new vector control scheme for the Brushless Doubly Fed Induction machine in shaft generation. Energy Conversion. pp. 149-154. 2016.

[19] Prabhakar, P., & Vennila, H. Power quality improvement in microgrid using custom power devices. International Journal of Enterprise Network Management. Vol. 8 (4), pp. 327-339. 2017.