Analysis of Circuit Design of a Rowing Electric Installation with a Distributed DC Bus of a Port Icebreaker

V V Romanovskiy¹, A S Bezhik¹

¹Admiral Makarov State University of Maritime and Inland Shipping, 5/7 Dvinskaya Str., Saint-Petersburg, 198035, Russia

Abstract. Currently, there is a steady trend in increasing the volume of electrical equipment used in shipboard needs. At the same time, the primary electric power system of ships has long been based on an alternating current system. However, due to the changing and increasing requirements for the quality of the generated electric energy, the marine industry is developing more and more promising directions for the development of electrical systems. Thus, the most efficient and environmentally friendly shipboard power distribution system is the direct current (DC) system, which was adopted for a single power plant installation in combination with an alternating current network. This article discusses the current topic of electric propulsion on ships. The circuit design of a rowing electric installation with a distributed DC bus of a port icebreaker is considered. The expressions used to calculate the static load and build an electromagnetic model of a permanent magnet synchronous motor are given. Computer models for calculating the load in static and dynamic modes are shown.

1. Introduction
Recently, there has been a steady trend in increasing the volume of electrical equipment used on board the vessel. As a result, there are growing demands on the quality of the generated electric energy [1]. Shipbuilding companies are faced with urgent tasks, the electric power systems installed by them must ensure the necessary quality of the generated electric energy [2], be reliable, including have an acceptable combination of the cost of its installation and operation with acceptable weight and size parameters [3]. In this case, the technical and economic indicators are determined mainly by a rational choice of the voltage value and the nature of the current [4].

Thus, the most efficient and environmentally friendly shipboard power distribution system is the direct current (DC) system, which was adopted for a single power plant installation in combination with an alternating current network. When it was created, more attention was paid to variable speed generators, the use of special energy storage devices, space saving, and increasing the plant's performance in static and dynamic modes [5].

2. Methods and Materials
In the system under consideration, almost all energy is generated by generators with diesel primary engines. The use of an electric power plant, where the power transmission, as well as the drive and traction motors are variable speed electric drives, can reduce fuel consumption on some types of ships [6]. But in some special operating conditions, such as dynamic positioning, the load changes significantly [7], for example, with the influence of sea waves on the hull of the vessel and the influence of weather. A sudden change in load represents continuous distortion in the electrical system and in prime movers. In addition, in order to maintain safe operation limits of power plants, it is necessary to keep the average load of working drives low, which increases fuel consumption and emissions of
harmful substances into the environment. High-speed energy storage systems can solve these problems by effectively reducing fluctuations in the load power in the power system [8], smoothing out sudden changes in energy consumption, improving system stability and increasing the average power of energy produced with fewer running generators [9], and therefore, reducing fuel consumption and maintenance.

The concept of using a rowing electric installation (REI) with a distributed DC bus (DDCB) has found application in the port icebreaker, which is designed to provide navigation of vessels on approach channels and in port water areas with an ice cover of up to 1.5 meters and has the parameters shown in the table 1.

| Name of the parameter       | Value                                |
|-----------------------------|--------------------------------------|
| Full length                 | 89.2 m                               |
| Waterline length            | 77.6 m                               |
| Waterline width             | 19.9 m                               |
| Maximum draft               | 7.5 m                                |
| Deadweight at max. draft    | 2000 t                               |
| Main DG                     | 3 * 4880 kW                          |
| Harbor DG                   | 800 kW                               |
| REI                         | 4 × 3000 kW electric motor           |
| Ice penetration             | 2 knots at 1.5 m in flat ice         |
| Mooring emphasis            | 115 t                                |
| Speed in clear water        | 15 узлов                             |
| Ice class                   | PMPC- Icebreaker 7, or MAKO- PC3     |

A distinctive feature of the vessel is a propulsion system consisting of four independent azimuthal propulsion systems with an electric drive Azipod ABB Ice-1400 traction type with a capacity of about 3 MW each. The helical-steering columns (HSC) are located in pairs in the bow and stern of the vessel, which makes it possible to work as efficiently as possible in the ice with both stern and bow, maneuvering and performing special tasks in the waters of any port [10].

The main current circuit shown in figure 1 includes:
- three main synchronous generators with a capacity of 4730 kW, adjustable 750 rpm, adjustable output voltage of synchronous generators 810 V;
- three controlled rectifiers, converting 810 V AC to adjustable 890 V DC;
- four frequency inverters based on ACS800 (ABB company) convert a constant voltage into an adjustable voltage within 0 ÷ 660 V of an alternating voltage for controlling Azipod’s systems;
- four HSC of the Azipod ICE 1400 3000 kW type incorporate permanent magnet motors, which greatly simplify the maintenance of the HSC;
- two transformers with a power of 1500 kVA 610V / 400V are used for power supply of a ship power station, after which, after filtration, from the higher harmonics receive 400 V 50 Hz.
The main objective of frequency converters operating at a power plant is to maintain the constancy of standard voltage and frequency parameters. The quality of electricity must be ensured by a filter system. At the same time, on ships with a REI with a DDCB, the block diagram of which is shown in figure 2, special energy storage devices are installed to save fuel.

The main load of the REI with a DDCB, the computer model of which was created and modeled in Matlab / Simulink using the SimPowerSystem tool kit, is shown in figure 3, is connected to the electric propulsion system, including DC / AC converters and electric motors. Such systems demonstrate a constant nature of the load as they are able to consume the same total power at different voltage levels [11]. This phenomenon is caused by an electromechanical modulator, which adjusts the switching time depending on the load.
Figure 3. Computer model of the REI with a DDCB based on the Matlab/Simulink program.

In order to simulate a constant load (CL), a controlled voltage source can be used where the required current is obtained by dividing the set power by the real DC voltage, as shown in equation (1):

\[ I_{\text{load}} = \frac{P_{\text{ref}}}{U} \]  

(1)

The linearized expression of the constant load is found from equation (2), where \( v \) is a small voltage wave:

\[ i = -\frac{P_{\text{ref}}}{U^2} + 2 \frac{P}{U} v \]  

(2)

At this operating point, the constant load can be represented by a negative resistance parallel with constant power, given in equations (3) and (4). A negative increment of resistance has a destabilizing effect on the automatic system and is known as negative unstable impedance:

\[ R_{\text{CPL}} = -\frac{U^2}{P} \]  

(3)

\[ I_{\text{CPL}} = 2 \frac{P}{U} \]  

(4)

In reality, with a dynamic load, the use of a permanent magnet synchronous motor (PMSM) is necessary.

The vector diagram shown in figure 4 describes the processes that occur in the engine, which are considered in a rotating coordinate system \( d \) and \( q \), where the \( d \) axis is oriented relative to the rotor flow.

The motor rotor, which is a permanent magnet, forms a flux linkage \( \psi_f \), equal to the product of the rotor flux by the number of turns of the stator winding. The vector of this flux linkage has a direction along the rotor axis \( (d) \) from the positive to the negative pole and lags behind the stator current vector \( I_s \) by some angle \( \varphi \).

When the rotor rotates, a constant flux creates an EMF vector \( E \) in the stator windings, directed at right angles to the flux and 90º behind it (derivative of flux linkage) [12].

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The EMF value is determined by equation (5):

$$E = \psi_f \omega_e$$

where:

- $\psi_f$ – flux linkage;
- $\omega_e = Z_p \omega_R$ – field rotation speed;
- $\omega_R$ – rotor speed;
- $Z_p$ – the number of pairs of motor poles.

Based on figure 3, the following vector relation (6) can be formed:

$$\mathbf{U}_s = -\mathbf{E} + \mathbf{I}_s R_s + j \omega_e \left( \mathbf{I}_{sd} L_{sd} + \mathbf{I}_{sq} L_{sq} \right)$$

where:

- $\mathbf{U}_s$ – stator voltage vector;
- $\mathbf{I}_s$ – the stator current vector, while $I_{sd}$ and $I_{sq}$ are its component;
- $L_{sd}$ and $L_{sq}$ – stator inductance along the $d$ and $q$ axes;
- $R_s$ – stator resistance.

In accordance with figure 4, the stator voltage vector is balanced by the EMF vector and the voltage drop across the active ($R_s$) and reactive ($L_{sd} I_{sd}^2$, $L_{sq} I_{sq}^2$) resistances of the stator winding.

Considering that flux linkage is a product of current and inductance, and the motor stator is a three-phase inductance coil [13], in this case, excluding magnetic losses, expression (7) can be composed:

$$\begin{aligned}
U_{sd} &= L_{sd} \frac{dI_{sd}}{dt} + R_s I_{sd} - \omega_e L_{sq} I_{sq} \\
U_{sq} &= L_{sq} \frac{dI_{sq}}{dt} + E + R_s I_{sq} + \omega_e L_{sd} I_{sd}
\end{aligned}$$

Figure 4 shows the formation of the components of the stator current differential with respect to a rotating coordinate system.
Taking into account figure 5, that flux linkage is the current multiplied by inductance, confirming expression 7, we can compose the following:

\[
\begin{align*}
    f_d(\omega_e) &= -\omega_e L_{sq} I_{sq} \\
    f_q(\omega_e) &= \omega_e L_{sd} I_{sd}
\end{align*}
\]  

(8)

Given that \( E = \psi_f \omega_e \), we compose expressions (7) with respect to differentials. Also, introducing the moment equation, we obtain equations (9), with which it is possible to build an electromagnetic model of the engine:

\[
\begin{align*}
    p I_{sd} &= \frac{1}{L_{sd}} \left( U_{sd} - R_s I_{sd} + \omega L_{sq} I_{sq} \right) \\
    p I_{sq} &= \frac{1}{L_{sq}} \left( U_{sq} - R_s I_{sq} - \omega L_{sd} I_{sd} - \psi_f \omega_e \right) \\
    M_{em} &= \frac{3Z}{2} \left( I_{sq} \psi_f + I_{sd} I_{sq} (L_{sd} - L_{sq}) \right)
\end{align*}
\]  

(9)

The model of a permanent magnet synchronous motor created in the Matlab/Simulink program is shown in figure 6.

**Figure 5.** Vector diagram.

3. Conclusion

Based on the analysis of the circuit design for a RE with DDCB, we can conclude that this concept improves the efficiency of using a single electric power system, combining the advantages of using
AC and DC. Moreover, the system complies with the rules of selectivity and protection of equipment, can be used for any marine application with a capacity of 20 MW and operates at a rated voltage of 1000 V DC and higher.

The use of the above expressions allows one to mathematically determine the static load of a rowing electric installation and construct an electromagnetic model of a PMSM.

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