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Mechanical Coupled BLDC Motors for Energy Saving in Submarine Application

***Abstract**. Energy saving is an important issue in mobile applications where portable energy resources are limited. This paper proposed a configuration consists of a coupled set of two brushless permanent magnet motors instead of conventional single motor configuration to increase the efficiency in a wide range of motor operation points. Proposed system includes two brushless DC permanent magnet motors with ratings equal to one third and two third of the original single motor rate. A proper control system is then designed for appropriate usage of these motors in different operation speeds. Simulation results demonstrate an efficiency improvement in a wide range of speed control.*

***Streszczenie.**. W artykule zaproponowano dwa sprzężone bezszczotkowe silniki zamiast konwencjonalnego pojedynczego silnika dla zwiększenia efektywności układu napędowego w zastosowaniu do łodzi podwodnych. (**Mechanicznie sprzężone silniki bezszczotkowe w zastosowaniu do łodzi podwodnych**)*

Keywords: energy saving, submarines, brushless DC motor, mechanical coupling, efficiency.
Słowa kluczowe: łódź podwodna, silniki bezszcvzotkowe.

Introduction

Propulsion systems face energy resource restrictions in many applications such as ships, submarines, electric vehicles and aerospace applications [1, 2]. Therefore, energy saving schemes are vital in the selection and the design of their electric machines and control systems. It is especially tensed when a vehicle works under water such as submarines where energy transferring is too hard.

DC motors have been widely used in submarines propulsion systems due to their high power density, simple control strategies and the availability of DC sources in such applications [3]. Nowadays, with the advent of high energy permanent magnets, the brushless DC permanent (BLDC) motor and the permanent magnet synchronous (PMS) motor become as appropriate alternatives to the DC motor in such applications [4-9]. BLDC motors have a higher efficiency, an improved power density and also a lower efficiency reduction in low load operations, with respect to DC motors.

This paper presents a configuration which consists of a coupled set of two BLDC motors for submarines propulsion systems. Using two coupled BLDC motors instead of a single BLDC motor along with a proper control system, improves the system efficiency especially in fractional load operation points. The system reliability is also increased in the proposed system and the system can continue the operation after one motor has been out of service due to a fault. A proper control scheme is then devised for the coupled operation of two BLDC motors. Finally, the performance of proposed system is evaluated and compared with a conventional single motor configuration in a different operation points. Simulation results confirm the effectiveness of proposed method in the improving the overall system efficiency.

Dynamic model of BLDC motors

The voltage equation set and the mechanical equation of a three-phase BLDC motor is given by [10]:

(1) $$v_{ab} = R\left(i_a - i_b\right) + L\frac{d}{dt}\left(i_a - i_b\right) + e_a - e_b$$

(2) $$v_{bc} = R\left(i_b - i_c\right) + L\frac{d}{dt}\left(i_b - i_c\right) + e_b - e_c$$

(3) $$v_{ca} = R\left(i_c - i_a\right) + L\frac{d}{dt}\left(i_c - i_a\right) + e_c - e_a$$

(4) $$T_e = B\omega_m + J\frac{d\omega_m}{dt} + T_L$$

where R ، L ، J ، B and T_L are the phase resistance, the phase inductance, the rotor moment of inertia, the friction coefficient and the load torque respectively. Also, v ، i ، e ، ω_m and T_e stand for the phase voltage, the phase current, the phase back-emf and the electromagnetic torque of the motor. Equations (1)-(4) are implemented in state-space form as:

(5) $$\begin{pmatrix} i_a' \\ i_b' \\ \omega_m' \\ \theta_m' \end{pmatrix} = \begin{pmatrix} -\frac{R}{L} & 0 & 0 & 0 \\ 0 & -\frac{R}{L} & 0 & 0 \\ 0 & 0 & -\frac{k_f}{J} & 0 \\ 0 & 0 & 1 & 0 \end{pmatrix} \begin{pmatrix} i_a \\ i_b \\ \omega_m \\ \theta_m \end{pmatrix} + \begin{pmatrix} -\frac{2}{3L} & \frac{1}{3L} & 0 \\ -\frac{1}{3L} & \frac{1}{3L} & 0 \\ 0 & 0 & \frac{1}{J} \\ 0 & 0 & 0 \end{pmatrix} \begin{pmatrix} v_{ab} - e_{ab} \\ v_{bc} - e_{bc} \\ T_e - T_L \end{pmatrix}$$

(6) $$\begin{pmatrix} i_a \\ i_b \\ i_c \\ \omega_m \\ \theta_m \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ -1 & -1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} i_a \\ i_b \\ \omega_m \\ \theta_m \end{pmatrix}$$

Coupled motors strategy

In propulsion systems the load torque is a function of propeller speed as:

(7) $$T_L = k\omega^2$$

Therefore, the required power significantly decreases by a reduction in the speed. Conventional propulsion systems utilize only one motor which has proper efficiency and power factor in its nominal speed. However, the propulsion system does not always work in its nominal speed and in many cases it works in a fraction of the nominal speed resulting in a low output power. In these conditions, the efficiency of the motor reduces considerably. Since the energy sources are limited in submarines, the efficiency reduction is a major drawback. In this paper, a configuration including two coupled BLDC motors is proposed to alleviate this drawback. The motors ratings equal to one third and two third of the nominal power of propulsion system. Therefore, the operation region of the propulsion system is divided into three sub-regions.

For a speed range in which the required output power is less than one third of nominal propulsion system power, the larger motor is disconnected from main shaft and the propulsion system works with only the smaller motor. For a speed range with the required output power between one third and two third of nominal propulsion system power, only the larger motor is used and the smaller motor is disconnected from the main shaft. Finally for higher output powers up to nominal power both motors are used in a coupled configuration. Therefore, iron losses and extra losses as well as mechanical losses reduce in low speed operation points resulting in an efficiency improvement in regions.

The configuration of the conventional single motor configuration and also the proposed coupled motors configuration are depicted in figs 1 and 2 respectively. It is seen that in the proposed system, both motors are connected to the main shaft through a mechanical clutch.

Control System Scheme

The control system includes two control loops i.e. a speed control loop and a current control loop. First loop is the speed control loop in which the actual motor speed is passed from a low-pass filter and then is compared with the speed reference. The speed error passes through a PI controller and then a limiter to produce a torque reference as shown in Fig.3. The torque reference is then converted to a current reference by a P controller. The current reference, actual motor current, and Hall sensor signals pass through a hysteresis control block to produce a pulse function which is used to generate gates commands by switching control block as depicted in Fig.4. In the coupled configuration, the torque reference for each motor is determined by a block called torque dedicator illustrated in Fig.5. In low loads, where the smaller motor starts working, a signal is sent to the mechanical clutch to disconnect the larger motor from the shaft and also a signal is sent to an electrical relay to disconnect the larger motor from the inverter. Therefore, the mechanical lasses and extra lasses of the larger motor are vanished. When the required power is larger than the nominal power of smaller motor but smaller than the nominal power of larger motor, the smaller motor is disconnected from the shaft and the inverter as it is mentioned in the previous case.

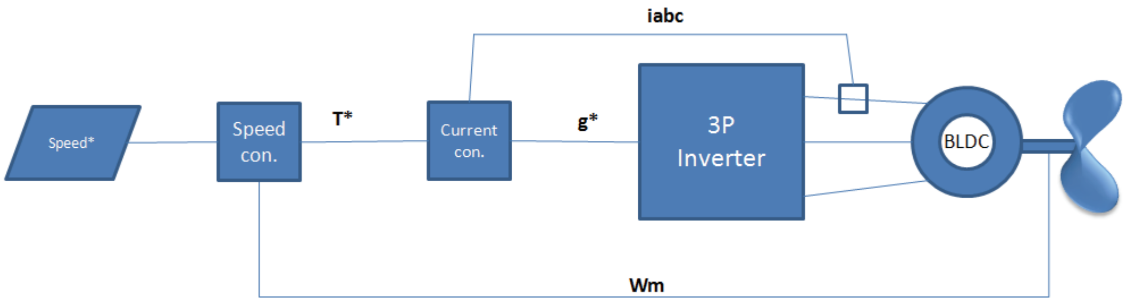

Fig. 1. Conventional single motor configuration

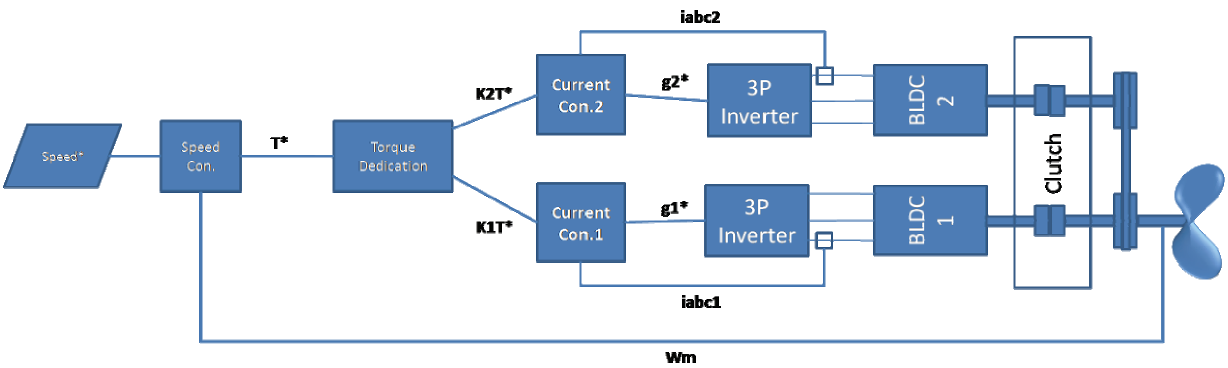

Fig. 2. Coupled motors configuration

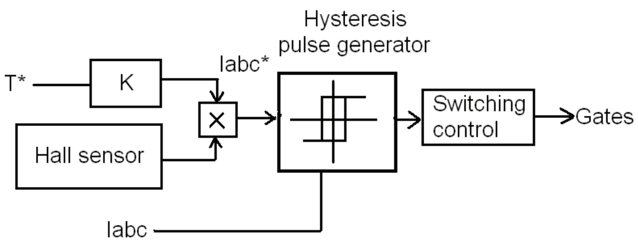

Fig 4. Current control blocks

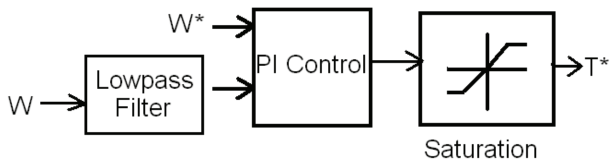

Fig. 3. Speed control blocks

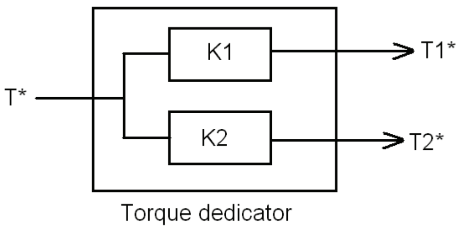

Fig. 5. Torque dedicator

For larger loads where both motors should work simultaneously, the torque coefficient is calculated by the torque dedicator block as:

$$(8)\quad \begin{cases} k_1 = 0, \quad k_2 = 1 & for \quad T < T_{2n} \\ k_1 = 1, \quad k_2 = 0 & for \quad T_{2n} < T < T_{1n} \\ k_1 = \dfrac{T_{1n}}{T_{1n} + T_{2n}}, \quad k_2 = \dfrac{T_{2n}}{T_{1n} + T_{2n}} & for \quad T_{1n} < T \end{cases}$$

Since the power is a function of speed in this application, the clutch and relays commands are produced by comparing shaft speed with specific speed boundaries determined by torque boundaries of (8).

Evaluation of the proposed configuration

In this section, performances of both single motor and two coupled motors configurations are investigated for different operation points. The single motor configuration employs a 7.4 kw motor and the coupled motors configuration uses a 5 kw and a 2.4 kw motors. The motors characteristics are listed in table I. Six operation speeds are selected to compare the performance of both systems. The performance of conventional single motor configuration for a 500 rpm operation speed command is depicted in Fig.6. The motor speed, torque, current and efficiency are shown in the figure. The overall efficiency of the conventional configuration in the full load condition is about 87.9%. It is notable that, the convertor lasses is also considered in calculations.

The performance of the proposed coupled configuration is also depicted in Fig.7. It is seen that, the torque dedicated to each motor is proportional to its nominal power. The overall efficiency is 87.2%, a little lower than the overall efficiency in the conventional configuration which is mainly due to naturally lower efficiency of smaller motors. However, this reduction in the overall efficiency is negligible with respect to its increasing in a wide range of speed control.

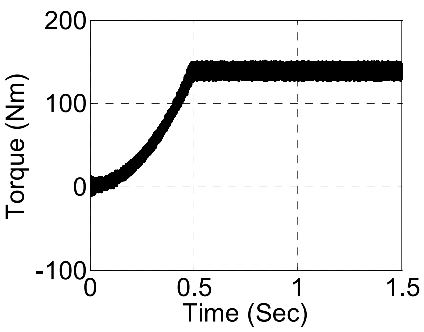

Fig. 6a. The motor torque in the single motor configuration for 500 rpm operation speed.

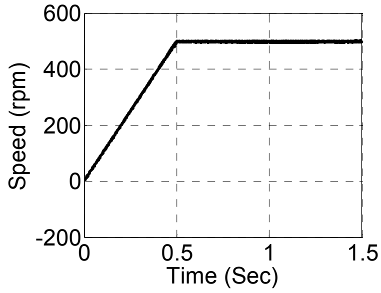

Fig. 6b. The shaft speed in the single motor configuration for 500 rpm operation speed.

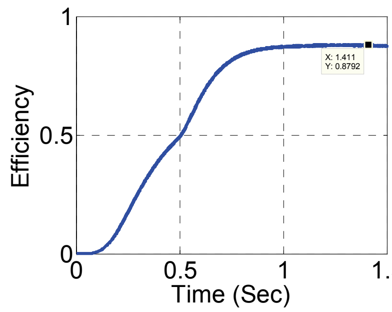

Fig. 6c. The overall efficiency in the single motor configuration for 500 rpm operation speed.

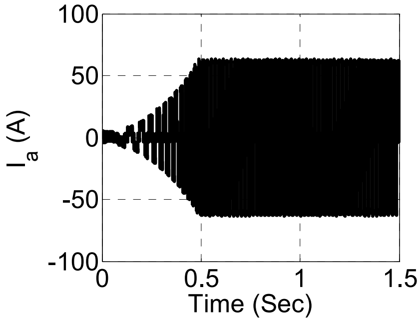

Fig. 6d. The motor current in the single motor configuration for 500 rpm operation speed.

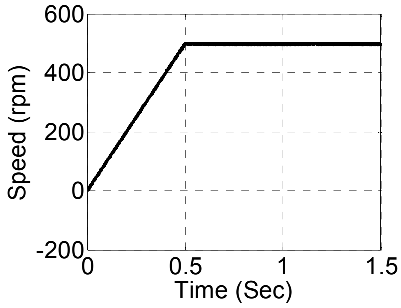

Fig. 7a. The shaft speed in the coupled motors configuration for 500 rpm operation speed.

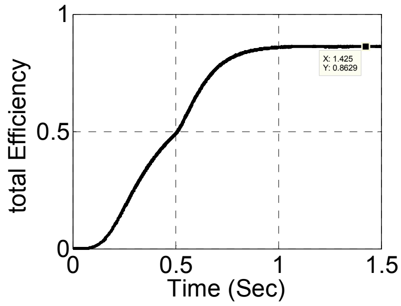

Fig. 7b. The overall efficiency in the coupled motors configuration for 500 rpm operation speed.

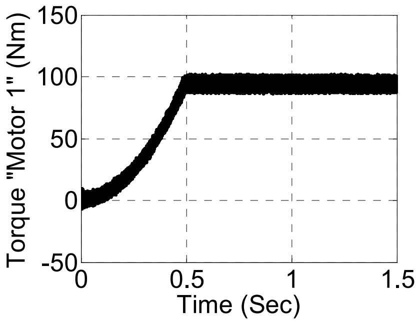

Fig. 7c. The larger motor torque in the coupled motors configuration for 500 rpm operation speed.

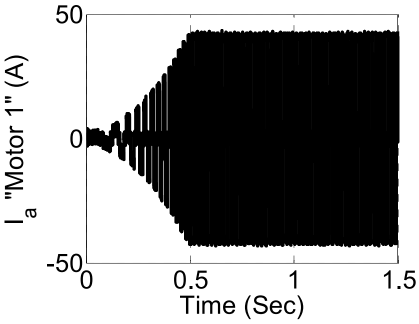

Fig. 7d. The larger motor current in the coupled motors configuration for 500 rpm operation speed.

The torque dedicated to each motor is listed in table I for different operation points. It is seen that, in the most of speeds only one motor is connected to the shaft. The overall efficiency of both configurations for a wide range of working speeds is compared in Fig. 8. It is seen that, the proposed method improves efficiency up to 13% in the fractional output power operation points. This study shows the effectiveness of proposed method in the energy saving in submarines propulsion systems.

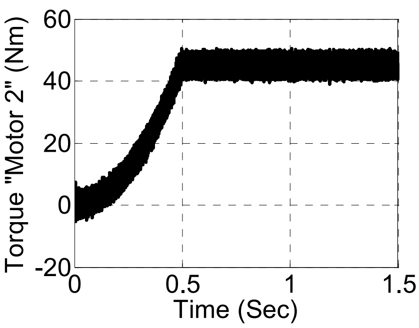

Fig. 7e. The smaller motor torque in the coupled motors configuration for 500 rpm operation speed.

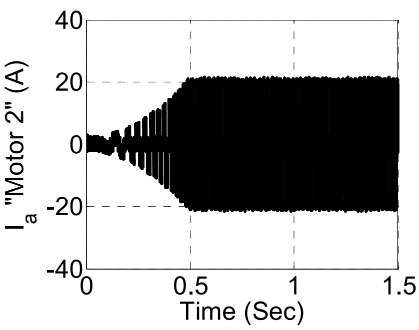

Fig. 7f. The smaller motor current in the coupled motors configuration for 500 rpm operation speed.

Table I. The torque dedicated to each motor

Speed (rpm)	Total torque (Nm)	The larger motor torque (Nm)	The smaller motor torque (Nm)
100	5.8	0	5.8
200	22.9	0	22.9
300	51.3	51.3	0
400	91	91	0
450	114.8	77.9	36.9
500	140.25	95.06	45.19

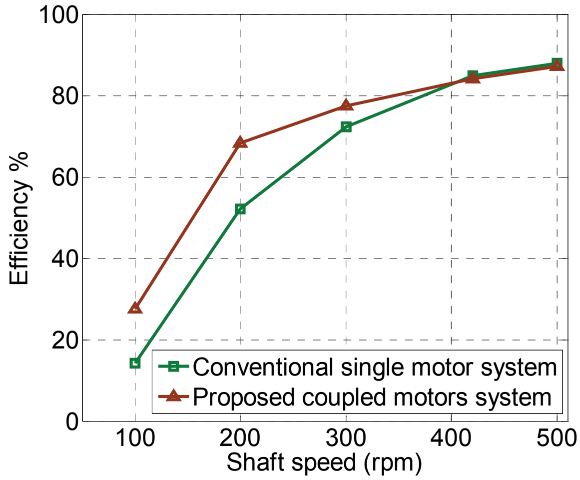

Fig. 8. Comparison of overall efficiency of both configurations in different operation speeds.

Conclusion

This paper is proposed a configuration including two coupled BLDC motors instead of the conventional single motor configuration for the submarine applications. The motor ratings used in the proposed configuration are equal to the one third and two third of the nominal motor power in the conventional single motor configuration. A proper control scheme is then presented in which a torque dedicator block distributes the total torque between two BLDC motors. In the most of operating points only one motor is connected to the main shaft and therefore mechanical and extra losses reduce resulting in an increase in the system overall efficiency. It is shown that this method improves the overall efficiency of the system up to 13% in low speed operation points.

Appendix

Table II. Characteristics of motors

Motor parameters	Single motor	larger coupled motor 1	smaller coupled motor
Rs(Ω)	0.045	0.077	0.17
Ls(mH)	2.1	2.7	3.3
(Wb)λ	0.2	0.2	0.2

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