Energy Saving Strategy on Electric Propulsion System Integrated with Doubly Fed Asynchronous Motors

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***Abstract*— Electric propulsion system integrated with doubly-fed asynchronous motor contributes efficient characteristics and flexibility in operation. However, in perception of energy saving and full-scale speed variation, the conventional doubly fed asynchronous motor is limited by the ratings of power converters. Generally, the electrical machines are designed to attain maximum efficiency around the full load. To increase energy saving and operating speed range under lightly loaded condition, the proposed strategy injects a low voltage DC supply to the stator winding instead of full rated AC supply. Wherein the DC supply is obtained from the converter's DC-link instead of external source. The proposed system is mathematically modelled using Matlab/Simulink tool and implemented experimentally with a 2.2 kW doubly fed asynchronous motor. In addition to this, the comparative energy conservation analysis of an electric propulsion system (2 MW) with the proposed strategy is carried out as a case study.**

Keywords—doubly fed asynchronous machine; DC insertion strategy; electric propulsion system; energy saving; tugboat; variable speed drives.

I. Introduction

Electric propulsion (EP) technology encompasses an electric drive and propulsion system to produce required propellant thrust with reduced fuel consumption. Particularly, EP system is functioned for transmitting the power from the main generator (coupled with diesel engine, gas turbine, steam turbine, etc.,) to propulsion drive and service loads. Similarly, the detailed classification of the EP system used in marine vessels such as podded, integrated and other common types is discussed in [1]. The EP technologies are mainly adopted in the marine vessels for varying the speed and position dynamically as per navigator's command. Most of the heavy thrust marine vessels like navy ships, cable laying ships, research ships, icebreakers, tugboats, etc., uses EP system for precise navigation. Electrifying the propulsion system offers various benefits like, greater flexibility in operation, redundant operation, higher reliability, higher automation, easy reconfigurable, reduced maintenance, more fuel savings, etc. Generally, the EP systems are engaged with various classes of motors [2], among them DC motors are commonly used due to their easy regulation, wide speed range, heavy starting torque, dynamic braking and throwback capability. However, currently the DC motors have become obsolete due to the limitation of receiving rotor power through brushes and commutators. As well presently, range of power levels extended from kW to MW [3]. Therefore, different types of motors are seemed to be dominating in the electric propulsion system. The most dominating motors are the wound rotor synchronous motor, the permanent magnet synchronous motor (PMSM), and the squirrel cage induction motor. Among these, wound rotor synchronous motor supplied by current source inverters (synchro converter) is very commonly used in ship propulsion, which is limited for higher rating, because it has more weight and volume due to the involved inductors. Even though the PMSM has various benefits like, less rotor loss, larger power density, high efficiency, etc., it has some drawbacks. They are, demagnetization due to the lack of excitation control, higher cost, operating restrictions with operating temperature and mechanical stresses [4].

Ultimately, the recent developments of power electronics and the advancement of the control systems with asynchronous motor improves the overall efficiency of the EP system with smaller displacement [5]. Among the existing AC drives, the doubly fed asynchronous machine based propulsion drive was found to be a promising alternative due to its dynamic stability, faster response, cost effectiveness, flexibility in operation and control. Therefore, the Doubly Fed Asynchronous Motor (DFAM) prevails in the EP system for their enhanced performance [6]. Since the main characteristics of DFAM are variable speed operation (sub synchronous to super synchronous mode) which could help to drive the propeller as per the demand with more energy efficiency. Moreover, control and flexibility in variable speed operation of DFAM are highly credible by energy efficient operation through the slip recovery scheme, which is not possible in squirrel cage induction motor. As well, rating of power converters can be reduced as per the speed variation of the propeller in the tugboat propulsion system [7]. In spite of DFAM based system has more benefits, the speed variation range is limited by the rating of power converters. DFAM is predominantly used for reduced speed-range applications that handle only the slip power. Practically, the rating of the converters is opted less than 30 percent of machine capacity for reducing the overall system cost, hence, the speed variations are limited due to it. However, in a propulsion system a wide range of operating speed including zero speed operation is required. In this case, the rating of power converter must be equal to that of the DFAM, so advancement of conventional DFAM is lost. In order to take over this issue, another approach like controlled double inverters fed DFAM on both stator and rotor winding increases the speed with rated torque capability at all speeds [8]. Despite, following the aforementioned approach the rated mechanical shaft power matches with the total rating of power electronic converter with the advantage of having complete control on rotor and stator excitation. To operate the machine in a wider speed range without increasing the rating of

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the power converter, an external DC supply is applied to the stator winding through a switch in [9]. However, variable-speed drives with DC bus will be a costly proposition, which requires the conversion of ship's generated power into DC and then an inverter to rebuild the variable AC supply. Hence it is inevitable, worthy investment in power electronics is essential for the power-factor corrected rectifier and inverter bus to intrude with the AC generator [10].

In the exiting aforementioned literature as far as nowhere discussed about the energy conservation with the DC injection strategy. Generally, the electrical machines are designed to attain maximum efficiency around the full load, however, in various applications, the motors rarely operated at full load [5]. Therefore, the energy savings strategies are usually applied to the machines running with partial loads. Therefore, in this paper the excitation for stator from the DC link through a unidirectional chopper is proposed to achieve a wide speed range with energy conservation. Hence, to mitigate these losses and to increase the speed variation range under lightly loaded condition, the DC supply from the DC link of the rotor converter is injected in the stator windings instead of AC supply or external DC supply. This action makes the system to operate the full speed range with the substantial amount of energy saving without external DC supply.

The proposed system is mathematically modelled and stimulated using Matlab/ Simulink software, and experimented in the laboratory. In addition to this, an energy conservation analysis with a presumed tugboat load profile (2 MW- DFAM) is performed in this paper. Overall the paper contains, mathematical modelling of doubly fed asynchronous machine in section-II, experimentation in section-III, implementation of energy saving control strategy in section-IV, energy conservation analysis with a case study in section-V and concluded in section-VI.

II. MATHEMATICAL MODELLING OF DFAM

To realize the behavior of the doubly fed asynchronous machine, the steady state model and the dynamic model with the mathematical equations are produced in this paper.

A. Steady State Model

To understand and to analyze the performance of the machine under steady state, the mathematical expressions are developed with the per-phase equivalent circuit (Fig. 1). The equivalent circuit of DFAM is similar to the two-winding

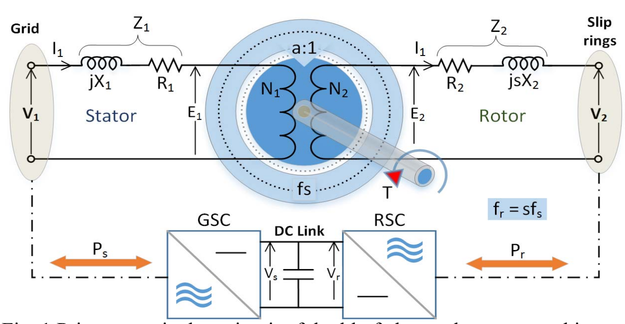


Fig. 1 Primary equivalent circuit of doubly fed asynchronous machine

transformer, excluding the slip. The slip depends upon the rotor parameters and the mechanical load, which cause the variation in the voltage and frequency in the secondary circuit [11].

Applying the Kirchhoff's voltage law to the primary equivalent circuit, the induced emf of the stator (E1) and rotor (E2) are obtained.

$$E_1 = \frac{2\pi}{\sqrt{2}} \varphi f_s N_1 K_{w1} \tag{1}$$

$$E_2 = \frac{2\pi}{\sqrt{2}} \varphi f_s N_2 K_{w2} \tag{1}$$

$$E_2 = \frac{sE_1}{a} \tag{1}$$

$$a = \frac{N_1 K_{W1}}{N_2 K_{W2}} \tag{1 a}$$

Where, V is the phase voltage, E is the induced emf, I is the current, R is the resistance, X is the reactance, Z is the impedance, N is the number of winding turns, Kw is the winding factor, a is the turns ratio between stator and rotor windings, s is the slip; subscript $_1$ and $_2$ represents the stator side and rotor side parameters respectively.

The DFAM consists of the stator and the rotor ports, the air gap is replaced by the magnetizing inductance and incorporated in the stator side. Similarly, the slip is considered on the rotor side. The rotor current referred to the stator side (I_2') is given as

$$I_2' = \frac{E_1 - \frac{a}{s} V_2}{\frac{R_2'}{s} + X_2'} \tag{2}$$

Where, R_2' and X_2' is the resistance and reactance of the rotor referred to the stator side.

Replacing the air-gap induction voltage with the rotor input voltage and rotor impedance drop, the voltage equation can be written as,

$$V_1 = \frac{aV_2}{s} + I_1(R_1 + jX_1) + I_2'\left(\frac{R_2'}{s} + jX_2'\right) \tag{3}$$

Power balance equation: The power (P_g) transmitted across the air gap, equals to the difference between the active power input of the primary winding (P_1) and the copper loss in the windings ($3I^2R$). Neglecting the core losses, the air gap power is given as,

$$P_g = P_1 - 3I_1^2 R \tag{4}$$

Similarly, the active power of the secondary winding (P_2) is given as

$$P_2 = -3aV_2 I_2' \tag{5}$$

The DFAM can operate at sub-synchronous, super-synchronous and synchronous speed through controlling the rotor frequency. During sub-synchronous operating mode, the direction of the phasor is inverse, thus the power is delivered to the converter from the rotor. Similarly, during synchronous and super synchronous mode of operation, the rotor absorbs the power from the converter. The total power (P_T) developed in the rotor is given as,

$$P_T = P_g \pm P_2 \tag{6}$$

Where, "+" sign indicates super-synchronous (or) synchronous motoring mode and "-" sign indicates the sub synchronous motoring mode.

The total rotor power with respect to the rotor parameters can be written as,

$$P_T = 3(I_2')^2 \frac{R_2'}{s} + 3aV_2 I_2' \left(\frac{1-s}{s}\right) \tag{7}$$

The mechanical power (P_M) producing the electromagnetic torque is given as,

$$P_M = P_1 + P_2 - \text{cu. losses} \tag{7}$$

$$P_M = P_1 + P_2 - 3(I_1)^2 R_1 - 3(I_2')^2 R_2' \tag{8}$$

The relationship between the mechanical output power and the total rotor input power through the air gap is obtained by substituting (7) in (8), we get

$$P_M = (1-s)\, P_g \tag{9}$$

The electromagnetic torque of DFAM in terms of mechanical power and rotor speed is given by

$$T_e = \frac{P_M}{\omega_M} \tag{10}$$

$$T_e = \frac{(1-s)\, P_g}{(1-s)\, \omega_m} \times \frac{P}{2} \tag{10}$$

$$T_e = \frac{(I_2')^2 R_2' + a\, V_2 I_2'}{s\, \omega_s} \times \frac{3P}{2} \tag{10}$$

B. Dynamic Modelling of DFAM

The voltages, currents and flux linkages are varied during the transformation of three phases to two phase d-q model, but the winding parameters resistances and inductances remains unchanged. Note that there are zero-sequence variables in d-q model, but the zero-sequence variables are zero in the balanced operation. So, according to [11], the dynamic torque equation of doubly fed asynchronous machine is written as,

$$T_e = \frac{3}{2} \times \frac{P}{2} (M_{sr})\left(i_{ds} i_{qr} - i_{dr} i_{qr}\right) \tag{11}$$

Similarly, the flux linkages are still continuous even if the currents and voltages are discontinuous. According to [12], the voltage equations with respect to the flux linkage (ψ) is written as,

$$V_{qs} = R_s i_{qs} + p\psi_{qs} + \omega_c \psi_{ds} \tag{11}$$

$$V_{ds} = R_s i_{ds} + p\psi_{ds} + \omega_c \psi_{qs} \tag{11}$$

$$V_{qr} = R_r i_{qr} + p\psi_{qr} + (\omega_c - \omega_r)\psi_{dr} \tag{11}$$

$$V_{dr} = R_r i_{dr} + p\psi_{dr} + (\omega_c - \omega_r)\psi_{dr} \tag{11}$$

Where, M_{sr} is the mutual inductance, i_{ds} and i_{dr} is the direct axis stator and rotor current, i_{qs} and i_{qr} is the quadrature axis stator and rotor current, v_{ds} and v_{dr} is the direct axis stator and rotor voltage, v_{qs} and v_{qr} is the quadrature axis stator and rotor voltage, ω_c is the angular speed of the arbitrary d-q coordinate and ω_r is the rotor electrical angle speed.

C. Dynamic Modelling of DC-Link

Modelling of the converter is based on dq-reference frame. The DC link act as a storage element in the DFAM system, is mainly used for decoupling the grid side power and the rotor side power. The DC link provides the reactive power to the rotor circuit for maintaining the unity power factor on the stator side. A good selection of DC link increases the overall system performance [11]. From the Fig.1, the stator voltage (V_s) and the rotor voltage (V_r) were synthesized and the phase voltages are written as,

$$V_r = \frac{1}{\sqrt{2}}\left(V_{qr} - jV_{dr}\right) \tag{11}$$

$$V_s = \frac{1}{\sqrt{2}}\left(V_{qs} - jV_{ds}\right) \tag{11}$$

The DC link voltage can be written as,

$$CV_{dc} = \frac{d}{dt}(V_{dc}) = P_r - P_R \tag{12}$$

$$P_r = \frac{3}{2}\left(V_{qr} I_{qr} - V_{dr} I_{dr}\right) \tag{21}$$

$$P_R = \frac{3}{2}\left(V_{qs} I_{qs} - V_{ds} I_{ds}\right) \tag{21}$$

Where, V_{qr} and V_{dr} are the quadrature axis and the direct axis of the RSC voltage, V_{qs} and V_{ds} are the quadrature axis and the direct axis of the GSC voltage, P_r and P_R are the active power of RSC and GSC respectively. From (12), it is understandable that the variation of the DC link voltage can be controlled by adjusting the quadrature axis current.

III. EXPERIMENTAL ARRANGEMENT

The implementation of proposed energy saving strategy is carried out through the hardware arrangement shown in Fig. 4. The hardware setup consists of a 2.2 kW doubly fed asynchronous machine coupled with the dynamometer loading arrangement (DC machine, lamp load, exciter and load cell). An IGBT based 2-level back to back voltage source converters (grid side converter and rotor side converter) with DC link, filters and chopper circuits is connected between the grid and the rotor of DFAM. The grid side converter (GSC) and rotor side converter (RSC) is to control the DC-link voltage and to provide variable AC supply to rotor respectively. Similarly, the low voltage DC excitation to the stator is supplied from the DC-link through unidirectional parallel chopper. For switching the stator winding connections, three main and auxiliary contactors (L&T MNX32 & MNXA1) with the relay and driver circuit is

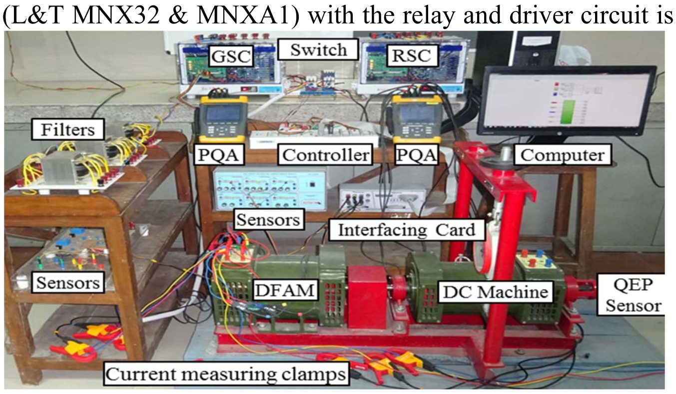


Fig.2 Snap shot of the experimental arrangement

used. The FPGA based real time controller (dSPACE-1202) interfaced with Matlab/Simulink software is used for generating the PWM pulses to converters and chopper circuit. Also, the controller is used to provide the signals for controlling the changeover switch in accordance with the load variation. All the PWM pulses and control signals are isolated from the power switches using Opto-coupler driver circuits. The Hall Effect sensors with active filtering circuit is used to obtain the current and voltage feedback signals to the controller. The quadrature encoder pulse (QEP) sensor is connected to the machine's shaft to provide the speed signals to the controller. Likewise, three phase power quality analyzers (PQA – Fluke 435) are connected on both stator and rotor side for measuring and recording various input electrical quantities. The recorded results are analyzed using Fluke view software. The schematic diagram of the proposed strategy is shown in Fig. 6 and the rating of the machine is tabularized in the Table 1.

TABLE 1 MACHINE RATINGS

Ratings	DFAM** *(Experimental & Simulation)*	DFAM* *(Simulation)*
Machine rated power	2.2 kW	2 MW
Stator voltage	415 volts	690 volts
Stator current	4.7 amps	1760 amps
Rotor voltage	185 volts	2070 volts
Rotor current	7.5 amps	7.5 amps
Frequency	50 Hz	50 Hz
Speed	1500 rpm	1500 rpm
Pole Pairs	2	2
Inertia (J)	13.695 gm^2	140000 gm^2
Friction Factor	0.033 gm^2/s	0.003 gm^2/s
Machine parameters (in ohms)		
2.2 kW*	R_1=3.678, R'_2 = 1.3, $X_1 = X'_2$ =7.813#, X_m=88.57	
2 MW*	R_1=0.0026, R'_2 = 0.0261, $X_1 = X'_2$ =0.00258#, X_m=0.002	

R_1 and X_1 are the resistance and the reactance of the stator,
R'_2 and X'_2 are the resistance and the reactance of rotor referred to the stator,
X_m is the magnetizing reactance.
** Hardware and Simulation; * Simulation
# Machine is considered as class A for empirical distribution of leakage reactance. [IEEE Std. 112-2004]

IV. IMPLEMENTATION OF ENERGY SAVING STRATEGY

In view of the fact that the electrical machines are designed to attain maximum efficiency around the full load, however, for various applications the motors rarely operated at full load [5]. Therefore, the energy savings strategies are usually applied to the machines running with partial loads.

In this paper, the energy saving on DFAM based EP system is obtained through injecting the low voltage DC supply to the stator windings. This technique makes the system to save a substantial amount of energy as well to operate in the full speed range without affecting the performance of the machine. Usually, the stator winding is connected directly to the fixed AC supply and the rotor winding is connected to the power converters (variable supply). The rating of the power converters is scaled and designed to handle the slip power [9]. In the introduced energy saving strategy, the stator windings are switched to the low voltage DC supply instead of AC supply

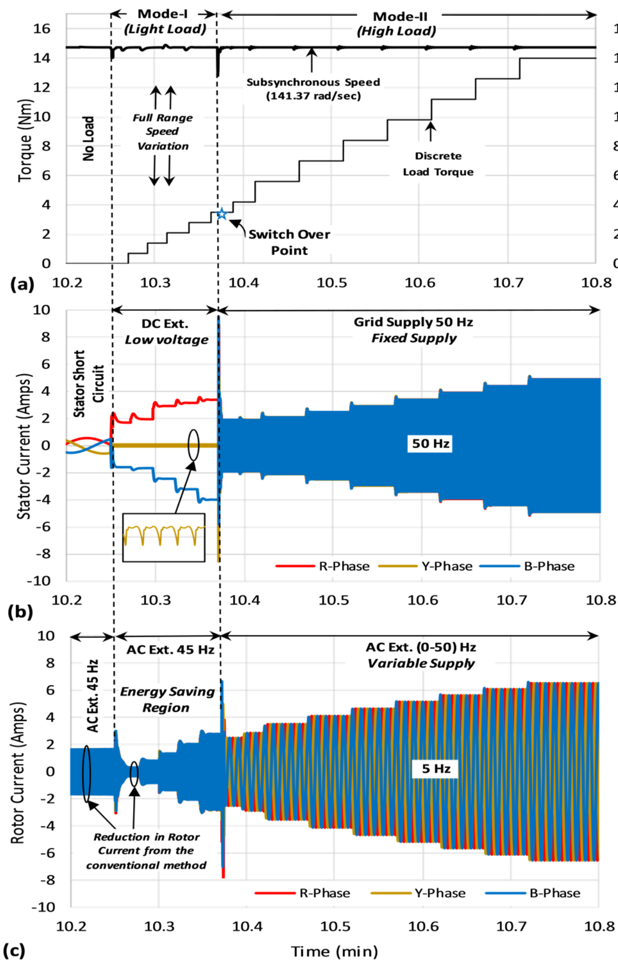


Fig. 3 Experimental results of proposed strategy
(a) speed and torque variation with respect to time; (b) stator current;
(c) rotor current

and the rotor is connected to the variable AC supply (RSC) under lightly loaded condition. Whereas in the high load, the stator windings are switched to AC supply and the rotor connection remains same. Adopting the proposed DC injection strategy in the light load region, full-scale speed variation can be attained with respect to the torque and the power rating of the converter. In the course of load variation from no load to full load an experiment is carried out in sub synchronous mode with the proposed strategy. The electrical quantities (stator current and rotor current) and the mechanical quantities (speed and torque) with respect to the time is shown in Fig. 3.

At no load region, the stator windings are short circuited and the machine is energized from the rotor power converters. In this region, the machine will perform as the conventional slip ring induction motor. The speed of the machine can be varied by controlling the rotor side power converter. However, due to slip losses the power wastage will occur in this region shown in Fig. 3.

At light load region (Mode-I), the stator is excited by the DC supply from the DC link through a unidirectional parallel chopper. And the rotor is energized by the rotor side power converter. This operation allows the machine to achieve full scale speed variation with a significant amount of power conservation, shown in Fig. 4. The boundary of this region depends upon the rating of power converters and the load value as in (13) and (14).

At high load region (Mode-II), the stator is switched to the grid supply and the rotor is excited by the power converter with variable supply. This mode of operation is similar to the conventional doubly fed asynchronous motor where the speed variation is limited by the power converter's rating.

The power from the grid side converter (P_R) equals the summation of DC chopper power and rotor side converter power given in (13). Similarly, the speed and torque of the motor depend up on motor's input (power from the rotor side converter and the DC link chopper) and motor's efficiency given in equation (14). Further, the rating of the grid side power converter can be increased to enhance the range of speed and torque variation.

$$P_R = (P_{dc} + P_r) \tag{13}$$

$$(P_R + P_{cl}) \geq (\omega \times \tau)\,\eta \tag{14}$$

Where, P_R is the power of the grid side converter, P_r is the power of the rotor side converter, P_{dc} is the power of DC link chopper, P_{cl} is the losses of power converter, ω is the rotor speed, τ is the shaft torque and η is the efficiency of the machine.

The Fig. 4 shows the power profile of a linearly loaded doubly fed asynchronous machine provided with AC/DC supply at the stator windings. The profile is obtained through the experimenting of 2.2 kW DFAM with stator AC supply (conventional) and stator DC supply (proposed) in the laboratory. From the profile, it can be observed that the proposed DC insertion strategy consumes less power than the conventional AC supply at a light load region (Mode-I). The boundaries of Mode-I and Mode-II are decided by (14). Similarly, the switching between these modes are carried out through the developed control strategy. The control strategy is based on the current mode of operation, type of supply and the load value (total input power). The implementation of the control strategy consists of the following process,

Step (i): Check the mode of operation, type of the supply and the load value of the machine.

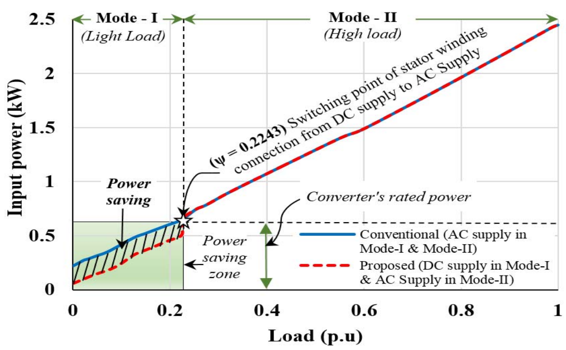


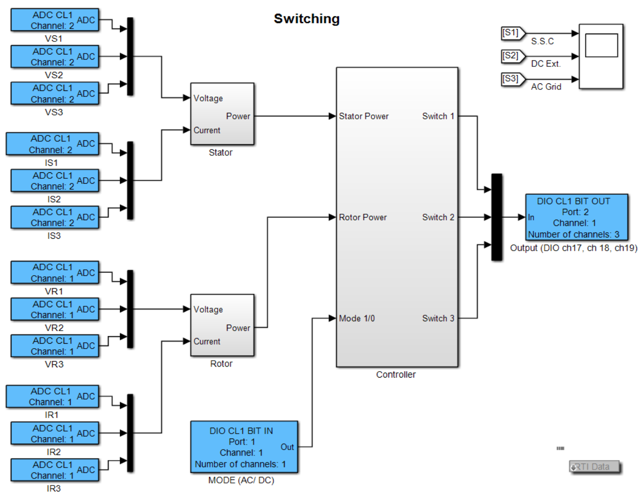
Fig. 4 Power profile of 2.2 kW DFAM with AC and DC stator supply

Step (ii): Switch the stator supply AC/DC corresponding to the load value of the machine.

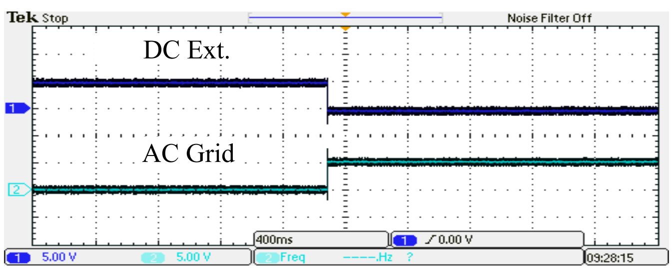
Step (iii): Control the rotor power corresponding to the stator supply.

Step (iv): Go to step (i)

The control of switches is carried out through Matlab/Simulink interfaced real time control shown in Fig. 6a. At Mode-I, the controller senses the input electrical quantities (current and voltage) of the stator and rotor to calculate the average input power. Depending upon the input power and threshold value, the switching between Mode-I and Mode-II is carried out. During Mode-I, the behavior of the machine is equivalent to a wound field synchronous machine [9]. During the Mode-I operation, the significant amount of energy is conserved. The magnitude of the DC excitation provided to the stator windings depends upon the speed and the load values. This magnitude variation is controlled automatically by the developed control algorithm. The control loop is based on traditional inner/outer loop control where the inner loop is used to control currents and outer loop is used to control the flux and the modes of operation (Mode-I/Mode-II). In Mode-II, the machine behaves like a doubly fed asynchronous machine. Additionally, reactive power can be controlled in AC mode, which gives added flexibility in system design. Once the stator is switched to AC supply, unlike in DC mode, the stator flux in the machine is very much determined. Along with the proposed DC injection strategy, machine can be operated by short circuiting the stator during light load region without providing DC supply to the stator.



(a) Control of AC/DC switch through RTI in Matlab/Simulink



(b) Control signals for switching DC Ext. to AC grid supply.

Fig. 5 Implementation of switching strategy

V. Energy Conservation Analysis – A Case Study

A tug boat load profile is considered for the energy conservation analysis. The tug boat is a multi-utility vessel used in harbors for maneuvering large ships, firefighting, etc. Although, the tugboat meant for operating with heavy thrust, most of the time it operates with lower loads [5]. Currently various researches are ongoing to reduce the fuel consumption of the engine through optimization the loads, but energy conservation on propulsion drive were not initiated yet. The suggested energy conservation strategy could be adopted for reducing the input power of the propulsion system which indirectly increases the fuel conservation and life span of the system. As the energy requirement of aforesaid applications depends upon the thrust, there will be wavering in energy demand. Therefore, an estimable energy conservation can be obtained by adopting the proposed DC injection strategy to the DFAM based electric propulsion system (Fig. 6). During light load, less torque is sufficient to drive the vessel. Whereas during high load, high torque is mandatory to drive the propeller. This non-linear characteristic load profile (Fig. 7) is considered for energy conservation analysis. According to the presumed load schedule, the tug boat sailing from port to vessel and returning back to the port once assisting the vessel is considered as one cycle (140 min.). The to and fro sailing period of the tug is 60 minutes, during the time being the EP is loaded with 0.15 p.u. load. Likewise, the waiting period counted as 30 minutes and during the time propulsion system is under a rest. Following to that the tug boat assists the vessel with 0.6 p.u. load and full load in 50 minutes. Employing a 2 MW doubly fed asynchronous propulsion drive with the presumed load curve, the energy conservation analysis was made. From the power profile (Fig. 4), it is evident that the proposed DC injection strategy can be applied only to the lofting period in the load curve (Fig. 7). Therefore, applying the strategy in lofting mode (0.15 p.u), the 0.42 MWhr of energy could be saved per cycle. Assuming 360 days of operation per year with 7 cycles of operation per day and 140 minutes per cycle, 1059.9 MWhr of energy could be saved with the proposed DC injection strategy. Overall, it is found that the proposed system reduced 18.92 % of energy consumption from the existing system.

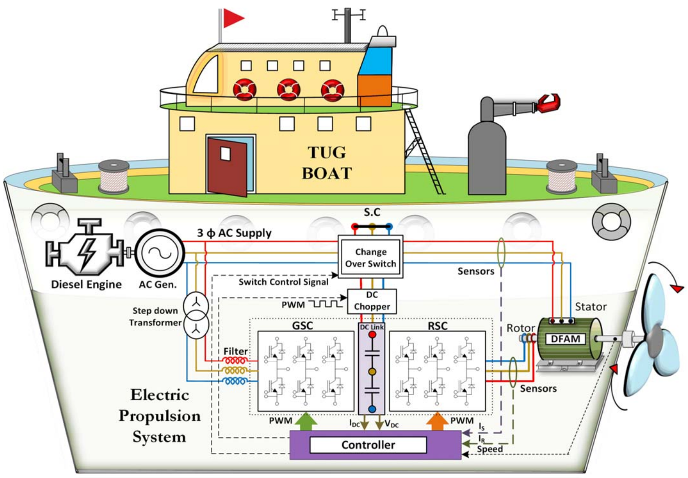


Fig.6 Schematic diagram of the proposed EP strategy

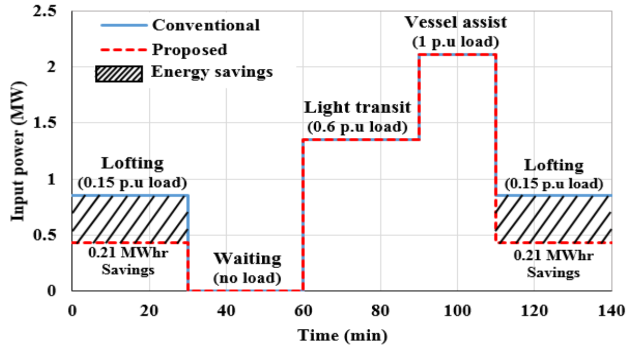


Fig. 7 Presumed per cycle load curve of the electric propulsion drive

VI. Conclusion

From the energy conservation analysis, it is evident that the significant amount of energy is conserved in the light load region by adopting the proposed strategy. This method can be easily adopted in the existing DFAM based system without any extensive modification. In addition to this, the full-scale speed variation is achieved in light load condition without increasing the rating of the power converters. Also, it is found that low voltage DC injection reduces the vibration of the machine which is the prime factor of marine system.

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