Control Strategy for Fuel Saving in Asynchronous Generator Driven Electric Tugboats

B. Anil Kumar[1], K. Anil Kumar[1], T. Radha[1], T. R. Chelliah[1], D. Khare[1], U. S. Ramesh[2]
[1]Hydropower Simulation Laboratory, Dept. of Water Resources and Development, IIT Roorkee, India.
[2]Indian Maritime University, Visakhapatnam, India.

***Abstract*—Usually electric tugboats are equipped with diesel engine based electric generator for power production, battery for supplying power to auxiliary loads and electric motors for propulsion. This paper proposes control strategies for diesel engine and electric generators used in electric tugboat to improve energy efficiency of the system. Doubly fed induction machine (DFIM), asynchronous in nature, is considered in this research which serves as generator (power production). The speed of diesel engine is controlled in accordance with the power demanded by the tug. Output voltage and frequency of generator during sub-synchronous operation are regulated by controlling its rotor current with the help of power electronic convertors. Comparison of fuel consumption at fixed and variable speeds of operation is performed. From the test results, it is observed that the variable speed operation of diesel generator offers significant reduction in fuel consumption.**

Keywords— Doubly fed induction machine, Diesel engine, Optimization, Tugboat, Variable speed technology.

I. INTRODUCTION

For past few decades there has been a tremendous increase in power demand for various applications in power sector. With the growth of port trading, competition among port have been increased for attracting more vessels to berth, making the tugboat operation an essential part of port operation.Worldwide growing concern for climatic change, increasing strict emission norms have motivated toward efficient power utilization schemes for various transport-vehicles (on-road vehicles, hybrid vehicles, maritime vessels,etc.,).

Since the diesel engine is the prime energy source of any marine vessels the fuel consumption of the engine should be reduced, for reducing running cost. Invention of technologies in micro-grid [1] and machine drives [2] have gained a high level of attention in marine sectors for power utilization. Technology like the hybrid electric vehicle (HEV) has also came up, in which power is generated by multiple energy sources and are capable of harnessing the energy from regenerative braking. Consequently much research has been carried out in the field of power management and sizing of HEVs, with the objective of achieving reduced cost/emissions and fuel consumption [3]. Various power management strategies and control algorithms have been employed in marine electro-mechanical system in [4], and different static and dynamic optimization methods are proposed in [5 – 7]. The power management of tugboat is carried out with constant speed diesel engine generator (DEG) where optimization has been carried out with repeated switching of machines [8]. This frequent switching will cause high wear and tear and also consequent to more fuel consumption due to high starting surge, which altogether affects life span of the engine and also increases greenhouse gases emission.

Diesel engine generators (DEG) in small tugboat produce 500-2500kW for driving the propeller. DEG efficiency mainly depends on its operating speed and power delivery. The speed of diesel engine can be varied depending on its loading conditions for fuel saving with less emission. Considerable amount of fuel can be saved under low load if the engine speed is adjusted [9]. The repercussion of varying engine speed, fluctuates voltage and frequency which must be regulated to standard value as per the requirement of the load. This raises the necessity of power converters in the system.

In this brief, the concept of doubly fed induction machine (DFIM) based variable speed technology is proposed for minimizing fuel consumption. In electric tugboat the power optimization problem is formulated for tugboat operation to effectively schedule the power from generators and battery to meet their load profile. Optimization results in optimal scheduling which consequent to minimum fuel consumption for both fixed speed operation and DFIM based variable speed operation in tugboat.

The brief study of DFIM and its applications are detailed in Section II. Section III details about the electric tugboat and its load profile, followed by the diesel engine characteristics in section IV. Objective function is formulated for optimization in section V. Subsequently optimization is carried for fixed speed system and variable speed technology (VST) for optimal scheduling in section VI and VII respectively. At last fuel consumption in both the cases are calculated and detailed in conclusion.

II. DOUBLY FED INDUCTION MACHINE

The development of power electronic components, such as multilevel voltage source convertors with high power ratings have given raise in various application of VST. Earlier DFIM was used in wind turbines to maximize its operating efficiency against the stochastic nature of wind [10, 11]. Recently in variable speed application with DFIM is gaining popularity in hydropower systems at both generating and motoring modes with higher efficiency and stability [12].

Typically DFIM is a wound rotor induction machine where the power can be recovered/feed through slip rings. The stator of the DFIM is connected to the load and the rotor is fed through back to back PWM voltage source inverters with a common DC link. The rotor side convertor (RSC) regulates the voltage and frequency required by the system, and the DC link voltage is

978-1-4673-8888-7/16/$31.00 ©2016 IEEE

stabilized using load side convertor (LSC) and should be able to provide essential reactive power. However for insuring proper power flow suitable control technique have to be adopted for operation of convertors. Similar to induction generator it requires reactive power for setting up magnetic field. Various methods have been detailed in [13, 14] for providing initial excitation. Basic block diagram of DFIM is shown in Fig. 1

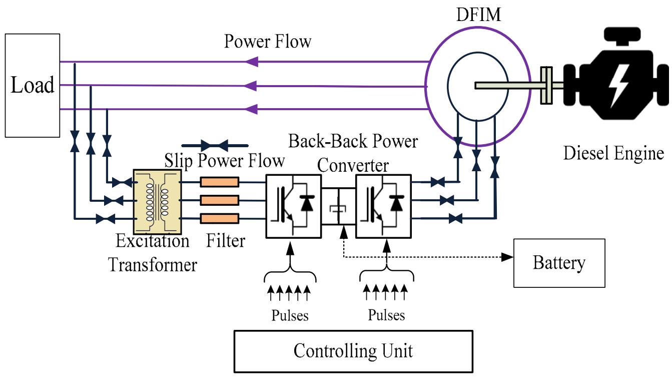

Fig. 1. Doubly fed asynchronous machine.

DFIM can operate as a generator or as a motor in both sub-synchronous and super-synchronous speeds, thus giving four possible operating modes. Application of these modes in pumped storage plant have improved its overall efficiency. In this brief DFIM as generator in sub-synchronous mode is considered. DFIM when used for power production/electric propulsion purposes, contributes fuel saving and low emission when compared to synchronous [15], and modelling and control strategy are discussed in [16]. DFIM based marine propulsion system was suggested in [17].

III. Tugboat Load Profile

Tugboats are called as ports workhorses. Though they are small in size, but are powerful enough for towing big ships in and out of berth. In general, according to the length of vessel number of tugboats based on their capacity are assigned for maneuver them, as shown in Table I [18]. This cycle of tugboat is repeated several times which depend on number of vessel to be towed and the number of tugboat available at the harbor. As the tugboat carry the same task repeatedly, the load demand profile of the tugboat can easily be estimated beforehand. About 40%-45% of the generated energy on the tugboat is utilized by the auxiliary system such as fans, lights, pumps, compressors, and so on, whereas 50-60% of power is used for propulsion system. Some preliminary work has done in [7] for power optimization in tugboat, and some improvements have be carried out in this paper.

TABLE I. Number of Tugboat Required for Towing According to Vessel Length [18].

Vessel length	Number of Tugboat	Tugboat power in hp
≤ 100 m	1	≥ 1200 hp
100 – 200 m	2	≥ 2600 hp
200 – 250 m	2	≥ 3200 hp
250 – 300 m	2	≥ 3400 hp
> 300 m	2	≥ 4000 hp

Fig. 2 shows a typical operational load profile of a tugboat cycle [3]. It can be observe that the tugboat goes through 4 modes to complete a cycle of work. Loitering and waiting mode require low power demand i.e. nearly 15% and 10% of the maximum load respectively, which account 64% of total time duration per load cycle. This illustrates the tugboats are operated under light loads for significantly long duration which causes reduction in fuel efficiency. The objective of this paper is to improve fuel efficiency particularly at light loads. However, in low assist and high assist modes generator are loaded to their rated capacities.

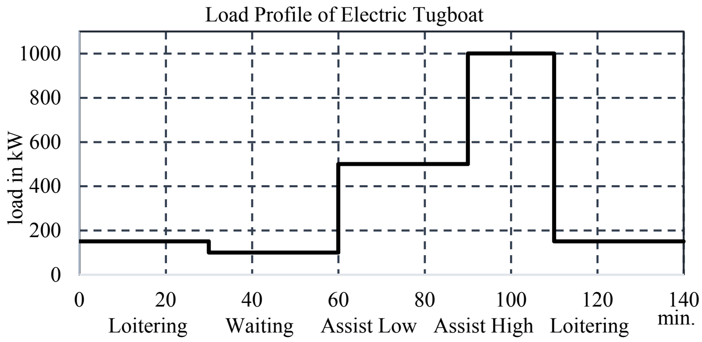

Fig. 2. Tugboat load profile [3].

IV. Diesel Engine Features

Diesel engines coupled with synchronous generators are widely used to generate constant voltage at constant frequency regardless of the loading conditions. Even though low load can be accommodated by generator at less speed to have minimum fuel consumption however the speed of the engine has to be maintained constant for constant frequency. Therefore engine is not usually operated at the optimal speed where the fuel consumption can be minimum for a given loading condition. In this fuel consumption characteristics and emission characteristics are getting poorer. In order to improve these characteristic speed of diesel engine has to be varied according to the load [19]. DEG speed adjustment has been proposed in [3, 20] which in turn can increase fuel efficiency and reduces air pollution. A fuel consumption characteristics curve plotted between engine-speed and output-power of a diesel engine (26kW, 1800rpm) is shown in Fig 3.

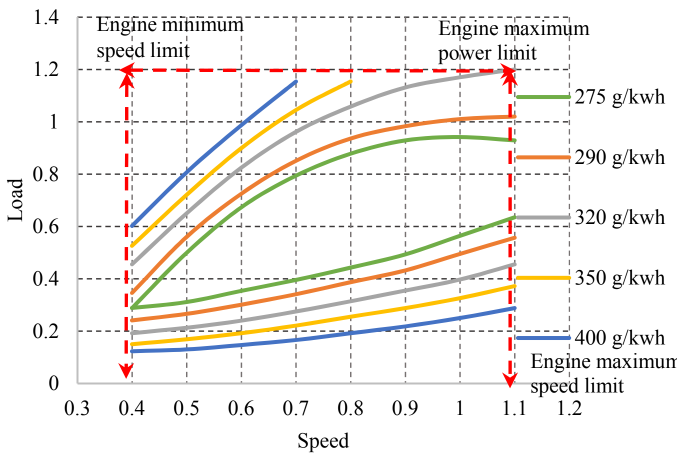

Fig. 3. Specific fuel consumption curve of a typical 26kw diesel engine [9].

When the DEG is loaded at 0.4 p.u., it consumes 3.4, 3.6, 4, and 4.4 L of fuel at 0.66, 0.77, 0.97, and 1.1 p.u. of speed respectively where the specific gravity of diesel oil is taken as 0.8 kg/L. Near about 21% of fuel saving can be achieved if the speed of diesel engine is reduced with reference to the loading condition [9]. However, output power fluctuation may occur in the case of sudden load change since the change of the engine speed is not as fast as the change in electrical load. To improve the power quality of the system against sudden load power surges storage system based on the supercapacitor bank is adopted [9]. Supercapacitor are able to supply additional power required during inrush current of the electric load for a few second without increasing the engine power capacity. This paper is not considered super capacitors as the fluctuation are overcome by the rotor side control of DFIM.

V. PROBLEM FORMULATION

Optimization problem is formulated for electric tugboat equipped with two generators driven by their respective diesel engine, and a battery to meet the load demand. Generator and storage unit are controlled by switchboard unit which basically schedules generators and battery. A schematic representation of tugboat unit is shown in Fig 4.

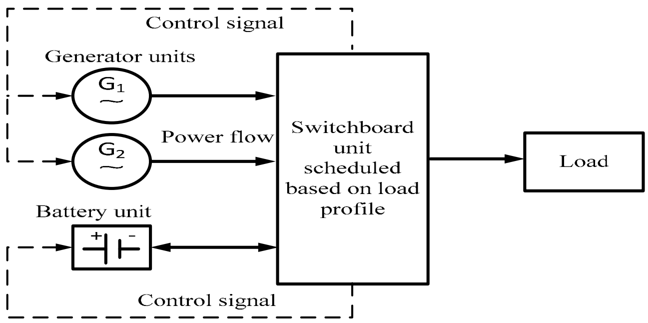

Fig. 4. Schematic of tugboat arrangement.

Switchboard unit mainly schedules the generator output by switching and also controls battery charring and discharging periods depending upon the load demand and state of charge (SOC) of battery. Fixed and variable speed setup is shown in Fig. 6. and Fig. 8. respectively. For the ease of calculation some of the assumptions have been made such as: The efficiency of generator and battery is assumed to be 100%, diesel engine generator and battery can respond instantaneously by reaching their set power ratings and transient introduced due to engine, battery and switchboard are neglected. But these phenomena are to be considered during future studies. Objective function formulated for this problem is split in to three sections as given below.

A. Fuel Consumption

Fig. 5 shows a typical fuel consumption versus engine load curve provided by an engine manufacturer [3]. Objective function considered in this paper is the minimum specific fuel consumption (SFC). The parameters a_i, b_i, and c_i are evaluated for the engine speed [4]. However for fixed speed operation in a marine vessel the engine speed and frequency are kept constant. Therefore the above said parameters are assumed to be constant. The fuel consumed in term of energy produced from duration [0, Δt] is given by;

$$\sum_{k=n\Delta t}^{n\Delta t+T_h}\left(\sum_{i=1}^{n}(a_i(\frac{E_i^p(k)}{E_i^{pr}})^2 + b_i\frac{E_i^p(k)}{E_i^{pr}} + c_i\right)E_i^{pr}H)\Delta t \quad (1)$$

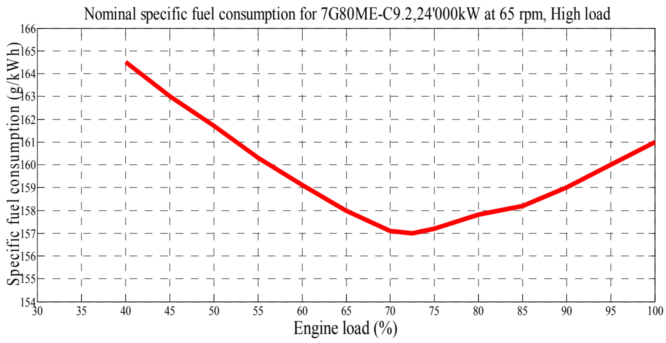

Fig. 5. Fuel consumption curve of a typical diesel engine [3].

B. Battery

The energy added by the battery during tugboat operation can be purchased from the grid at shore or can be generated by diesel generator itself during its runtime. Proper control mechanism is provided to maintain rated energy storage in battery at each load cycle. However the battery losses are assumed to be negligible when compared with the losses occurring in the diesel engine set. The SOC of the battery is kept in the permissible limit as done in [9]. SOC of battery is calculated using the equation$SOC(k) = SOC(k-1) - (B^p(k-1)/B^{p\,rated})100$. Function of battery power is given as;

$$\sum_{k=n\Delta t}^{n\Delta t+T_h} B^p(k)\Delta t \quad (2)$$

C. Wastage of Energy

The main purpose of this function is to minimize the wastage of energy i.e. to minimize the energy produced by the engines that cannot be used by the battery or the load. Therefore this function consist of difference between power supplied from engines, battery and power demand is given by;

$$\sum_{k=n\Delta t}^{n\Delta t+T_h}\left(E_i^p(k) + B^p(k) - D^p(k)\right)\Delta t \quad (3)$$

The objective function formulated is the combination of above three sub-objectives. In other words, the objective function is chosen to minimize the cost and by maximize the diesel engine fuel efficiency, by proper usage of battery under low load, and also minimizing power wastage by ensuring good load tracking. Therefore the objective function is given by;

$$J = \sum_{k=n\Delta t}^{n\Delta t+T_h}((\sum_{i=1}^{n}(a_i(\frac{E_i^p(k)}{E_i^{pr}})^2 + b_i\frac{E_i^p(k)}{E_i^{pr}} + c_i)E_i^{pr}H)\Delta t + \alpha\left(E_i^p(k) + B^p(k) - D^p(k)\right)\Delta t + \beta(B^p(k)\Delta t)) \quad (4)$$

Where $E_i^p(k), B^p(k), D^p(k)$ are power generated by ith engine, the power supplied by the battery and the power demand respectively during kth interval of time.

α, β = Penalty weights

H= Heating value of diesel oil

E_i^{pr} = Rated power of the engine

E_i^{pmin}, E_i^{pmax} = Minimum and Maximum limits of engine

$B^{p\,rated}$= Battery rated power

$B^{dchmax}(k)$ = Battery discharging rate

$B^{pchmax}(k)$ = Battery charging rate
i= i[th] Number of generator
Δt = Sampling time
K= Sampling step
T_h = Total time period
$SOC\ (k)$ = State of Charge at sample time
SOC^{max}, SOC^{min} = Maximum and Minimum limits of SOC
$DFIM_\omega$= DFIM rotor speed
$DFIM_\omega^{max}, DFIM_\omega^{min}$ = Maximum and minimum speed limit of DFIM

The following set of constraints has been considered for the objective function evaluation for the engine limits, battery limits and for response between load and demand.

$$E_i^{pmin} \leq E_i^p \leq E_i^{pmax} \quad (5)$$
$$B^{pchmax}(k) \leq B^p(k) \leq B^{pdhmax}(k) \quad (6)$$
$$SOC^{max} \leq SOC \leq SOC^{min} \quad (7)$$
$$E_i^p(k) + B^p(k) \geq D^p(k) \quad (8)$$
$$DFIM_\omega^{min} \leq DFIM_\omega \leq DFIM_\omega^{max} \quad (9)$$

Operating rage of the engine E_i^p should always be in its permissible range (5). To maintain the battery life the operating range should be in between boundary limits provide by the manufactures and the power supplied to the battery should be in permissible limit of maximum and minimum charging and discharging rates (6). Similarly the state of charge of the battery should be kept in suitable bounded range (7). All these limits are given in following section. To ensure the power generation meets the load demand the power generated by engine and battery should be greater than the load demand at any particular time 'k' (8). Speed constraint in (9) is considered only for variable speed optimization problem. The variable speed of the rotor should be in the limits which subjects to convertor rating.

Tugboat is powered by two engine with same power rating E_i^{pr}= 550kW where i=1, 2, and for auxiliary power supply/storage battery packs of total capacity 100kWh is provided. Capacity of battery is limited because of its size, weight and economic constrain. Maximum and minimum engine rated power output are chosen as E_i^{pmax}550kW, E_i^{pmin}= 100kW. Battery maximum recommended state of charge $SOC^{max}$is 80%, minimum recommended SOC is SOC^{min}= 20%. The maximum battery charging rate is 200kW and maximum discharging rate are chosen as 600kW. This charging and discharging rate are chosen based on relative size with the engine power, more details are provided with the manufacturer [3]. Fuel consumption curve constant parameters ai, bi, ci are 60.65, -91.14, 191.7 respectively which calculated for diesel engine model type 7G80ME-C9. Heating value of diesel oil H is 43.2 MJ/kg. The penalty weights α and β are chosen as 0.8 and taken as 0.2 respectively. For variable speed operation $DFIM_\omega^{max}, DFIM_\omega^{min}$are chosen as 1800 rpm and 1260 rpm respectively, assuming the rotor converter can provide 30% of frequency variation. The objective function consists of three variables that are power output of engine $E_i^p$where i=1, 2 and battery power$B^p(k)$, which have to be optimally found in the search space.

VI. FIXED SPEED SYSTEM

In fixed speed operation power generation is carried through two synchronous generator driven by respective diesel engine. Objective function detailed in above section is solved by using Matlab optimization tool box considering all constraints mentioned above. Generated output power of the engine E_i^p and schedule of battery power B^p are optimized according to the load profile. The objective function is considered minimum switching phenomenon, to improve the machine life span, and improved fuel consumption efficiency as the machine consumes more fuel during each start up. However, repeated switching of machine can be mitigated by keeping the machine ideal, but letting the diesel engine idle for more duration is not economical as the machine will consume fuel during this period and the consumed fuel during this duration will not combust completely which increase the environmental pollution. Optimization program run both the generators most efficiently by tracking fuel efficiency curve shown in Fig. 5 to achieve minimum SFC.

The result obtained for fixed speed operation is shown Fig: 7. here the battery is assumed to be initially charged to 80%. Batteries are given priority to accommodate low loads until it reaches to its minimum SOC limit. Switching of generators take place when the battery is unable to meet the load supplying power to both battery and tugboat. Results show the minimum switching action of DEG throughout the cycle. Battery is ensured to be continuously charged and discharged within its limits. It is noted that the battery has enough charge at the end of each load cycle.

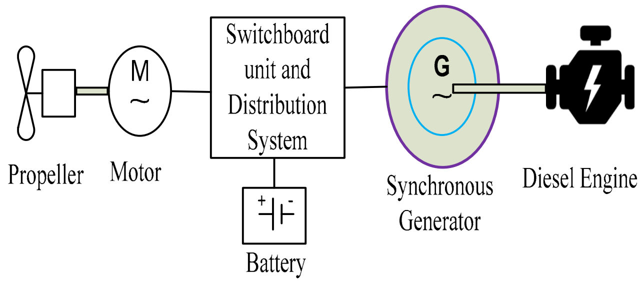

Fig. 6. Fixed speed schematic arrangement.

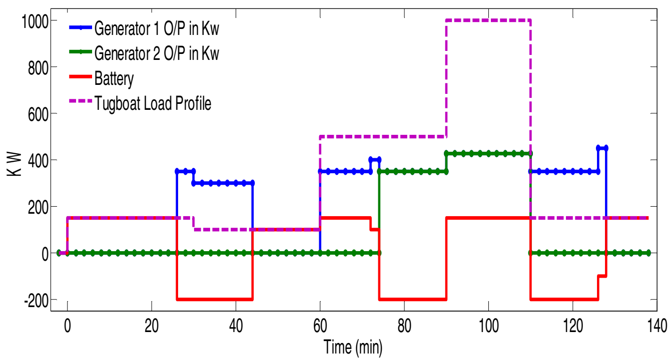

Fig. 7. Power management considering fixed speed system.

VII. VARIABLE SPEED SYSTEM

The system is modified by considering 550kW Doubly-Fed Induction Generator (DFIG) driven by a variable speed diesel engine i.e. a fixed speed generator (550kW) and a DFIG to meet the loads. The advantages of DFIM are stated in previous section. DFIG can generate desired voltage and frequency independent of loads as well as of its prime mover speed.

Schematic diagram for variable speed setup is shown in Fig. 8. In case of synchronous generator its field has to be excited with constant dc voltage but in DFIM the rotor power is fed via battery (at starting) and can be later fed by the generated power of stator. In this case, battery is assumed to be charged sufficiently to accommodate initial startup of the machine. DFIG rotor power depends on its loading and speed. In this case rotor power is considered to be not more than10%.

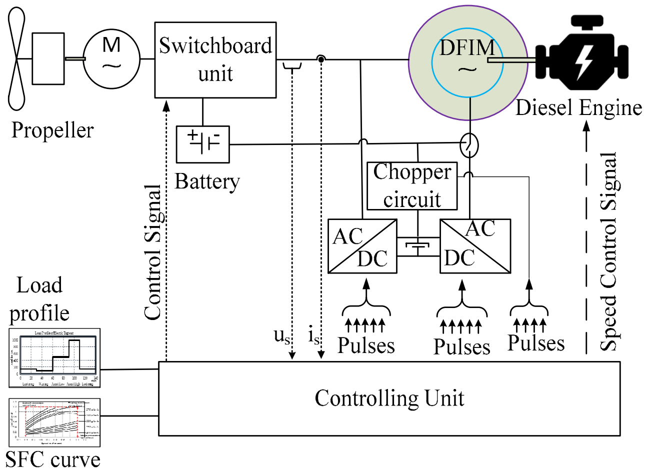

Fig. 8 variable speed schematic arrangement.

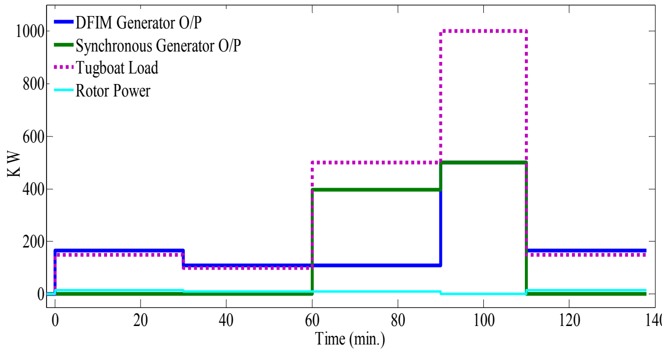

Fig.9 Power management considering variable speed system.

Synchronous generator is loaded according to the fuel consumption curve at low assist and high assist mode, and remaining loads are supplied by DFIM. Generated power and speed of DFIM are obtained by optimization model executed in Matlab. The optimization result is shown in Fig. 9. Scheduling of generators and their speeds at various load points are given in Table II. Calculated fuel consumption at fixed and variable speed technologies are tabulated in Table III.

TABLE II. SCHEDULING OF GENERATORS

Mode	DIFIG (G1)		SG (G2)	
Loitering	On	1260 rpm	Off	--
Waiting	On	1260 rpm	Off	--
Assist low	On	1260 rpm	On (396 kw)	Rated Speed
Assist high	On	Rated Speed	On (492 kw)	Rated Speed
Loitering	On	1260 rpm	Off	--

TABLE III. FUEL CONSUMPTION PER LOAD CYCLE

Mode	Fuel consumption in Liter
Fixed Speed (2*SG)	305 L
Variable Speed (1*DFIG + 1*SG)	297 L

VIII. CONCULSION

Fixed speed DEG is widely used in marine application regardless of its running cost. In this paper the optimization problem for scheduling generation in electro-mechanical tugboat operation was formulated for attaining minimum fuel consumption subject to minimum switching operations of energy sources. Doubly-Fed Induction generator was considered for power production and the speed of diesel engine coupled with the generator is adjusted to get reduction in fuel consumption. Rotor side converter is controlled in such a way that the generator was produced desired voltage and frequency when sub-synchronous operation of generator. From the test results, it was observed that fuel consumption for a typical tugboat is reduced by 2.6% per cycle.

ACKNOWLEDGMENT

This research is supported by Ministry of Shipping, Government of India vide grant number MSR-912-WRC.

REFERENCES

[1] H. Jiayi, J. Chuanwen, and X. Rong, “A review on distributed energy resources and MicroGrid,” in Renew. Sustain. Energy Rev., vol. 12, no. 9, Dec. 2008, pp. 2472–2483.

[2] R. Raja Singh, T. Raj Chelliah, and P. Agarwal, “Power electronics in hydro electric energy systems – A review,” in Renew. Sustain. Energy Rev., vol. 32, Apr. 2014, pp. 944–959.

[3] T. L. Vu, A. A. Ayu, J. S. Dhupia, L. Kennedy and A. K. Adnanes, “Power management for electric tugboats through operating load estimation,” in IEEE Transactions on Control Systems Technology, vol. 23, no. 6, Nov. 2015, pp. 2375-2382.

[4] S. D. Farrall and R. P. Jones, “Energy management in an automotive electric/heat engine hybrid powertrain using fuzzy decision making,” in Proc. IEEE Int. Symp. Intell. Control, Chicago, IL, USA, Aug. 1993, pp. 463–468.

[5] C. Kim, E. NamGoong, T. Kim, H. Kim, and S. Lee, “Fuel economy optimization for parallel hybrid vehicles with CVT,” in SAE Tech., 1999, Paper 1999-01-1148.

[6] G. Paganelli, G. Ercole, A. Brahma, Y. Guezennec, and G. Rizzoni, “General supervisory control policy for the energy optimization of charge-sustaining hybrid electric vehicles,” in JSAE Rev., vol. 22, no. 4, Oct. 2001, pp. 511–518.

[7] C.-C. Lin, J.-M. Kang, J. W. Grizzle, and H. Peng, “Power management strategy for a parallel hybrid electric truck,” in IEEE Trans. Control Syst. Technol., vol. 11, no. 6, Nov. 2003, pp. 839–849.

[8] W. Koczara, “Adjustable speed generator systems - an emerging technology for efficient electrical energy generation,” in 7th Internatonal Conference on Power Electronics, Daegu, 2007, pp. 43-52.

[9] J. H. Lee, S. H. Lee and S. K. Sul, “Variable-speed engine generator with supercapacitor: isolated power generation system and fuel efficiency,” in IEEE Transactions on Industry Applications, vol. 45, no. 6, Nov.-dec. 2009, pp. 2130-2135.

[10] Y. z. Sun, J. Lin, G. j. Li and X. Li, “A review on the integration of wind farms with variable speed wind turbine systems into power systems,” in International Conference on Sustainable Power Generation and Supply, Nanjing, 2009, pp. 1-6.

[11] Tao Sun, Zhe Chen and F. Blaabjerg, “Flicker study on variable speed wind turbines with doubly fed induction generators,” in IEEE

Transactions on Energy Conversion, vol. 20, no. 4, Dec. 2005, pp. 896-905.

[12] A. C. Padoan et al., “Dynamical behavior comparison between variable speed and synchronous machines with PSS,” in IEEE Transactions on Power Systems, vol. 25, no. 3, Aug. 2010, pp. 1555-1565.

[13] F. Abdoune, D. Aouzellag, and K. Ghedamsi, “Terminal voltage build-up and control of a DFIG based stand-alone wind energy conversion system,” in Renew. Energy, vol. 97, 2016, pp. 468–480.

[14] T. Mesbahi, A. Ouari, T. Ghennam, N. Berkouk EL,Rizoug, N. Mesbahi,M. Meradji, “A stand-alone wind power supply with a Li-ion battery energy storage system,” in Renew. Sustain. Energy Rev., vol. 40, 2014, pp. 204-213.

[15] J. C. Dermentzoglou and J. M. Prousalidis, “Contribution to a detailed modeling and more reliable simulation of a ship's shaft machine,” in International Conference on Electrical Systems for Aircraft, Railway, Ship Propulsion and Road Vehicles (ESARS), Aachen, 2015, pp. 1-6.

[16] J. C. Dermentzoglou, “Investigating the incorporation of a doubly fed induction machine as a shaft generator into a ship's system: Application of a vector control scheme for controlling the doubly fed induction machine,” in International Conference on Electrical Machines (ICEM), Berlin, 2014, pp. 2319-2324.

[17] M. Debbou and M. Pietrzak-David, “VSI loss evaluation of DFIM drives for electrical naval propulsion,” in IECON 2014 - 40th Annual Conference of the IEEE Industrial Electronics Society, Dallas, TX, 2014, pp. 943-949.

[18] Z. Liu, “Hybrid evolutionary strategy optimization for port tugboat operation scheduling,” in Third International Symposium on Intelligent Information Technology Application (IITA), Nanchang, 2009, pp. 511-515.

[19] J. Leuchter, V. Rerucha, Z. Krupka and P. Bauer, “Dynamic behavior of mobile generator set with variable speed and diesel engine,” in IEEE Power Electronics Specialists Conference, Orlando, FL, 2007, pp. 2287-2293.

[20] L. M. Grzesiak and J. Sobolewski, “Electrical energy source with variable speed diesel engine, controlled by using the neural voltage regulator,” in European Conference on Power Electronics and Applications, Dresden, 2005, pp. 9.