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Super Eco Ship using Green Technology for Energy Conservation Onboard Ship

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***Abstract*— The importance of shipping industry is very much traced for international transportation. It is generally acknowledged that more than 90 percent of international trade is carried by sea. Throughout the last century the shipping industry has seen a general trend of increases in total trade volume. Advances in technology have also made shipping an increasingly efficient and swift method of transport. The shipping industry is facing ever greater challenges, especially regarding energy. Other than economical issues there are some environmental issues which are resulted due to burning of more fuel. In recent years, sustainability in a climate and an environmental perspective has become an issue of highest priority. It is estimated that 4 % of the global CO2, SOx and NOx emissions come from international shipping. The world wide increase in the price of oil has especially affected the shipping industry. Because the burning of diesel fuel ultimately generates the energy required onboard ship. Each kilo-watt of energy saved onboard has a direct effect on the consumption of diesel and the total operating cost. Therefore ship operators will put higher pressure on ship owners to obtain fuel efficient ships. These in turn will put pressure on ship yards to supply fuel efficient ships. As a result, we expect to see an improvement in the fuel consumption on ships. Shipping installations having higher fuel efficiency in all operational stages will be increasingly favored and will presumably have great potential for future growth. Parts of these requirements can easily be met by controlling the speed of electric motors used for centrifugal pumps onboard ship using variable frequency drives. This VFD uses Space vector pulse width modulation to generate three phase AC with fewer harmonics for controlling speed of three phase Induction Motor and Variable Flow output from CF Pump for ballast operation.**

***Index Terms*— Green Technology, Variable Frequency Drive, SVPWM Control, Energy Conservation.**

I. INTRODUCTION

Advances in technology have made shipping an increasingly efficient and swift method of transport. The amount of goods actually loaded aboard ships has reached up to 10 billion tons. Like all industrial sectors, shipping industry has also witnessed the worst global recession in over seven decades and the sharpest decline in the volume of global merchandise trade. The improvement of energy efficiency has become most important in shipping industry to achieve excellence in cost competitiveness. Energy cost is one of the major component not only necessities the installation of energy efficient technology but also inculcate energy efficient practices and methods to be used for eco-friendly sailing. Here we have developed a latest technique using advanced technology for sustainable energy conservation onboard ship.

Now a day's energy is a critical input for production & consumption activities in an economy. In spite of the increase in prices of electricity, consumption has also gone up. Substantial saving of electrical energy can be achieved by using methods such Variable speed drive.

Other than economical issues there are some environmental issues which are resulted due to burning of more fuel. In recent years, sustainability in a climate and an environmental perspective has become an issue of highest priority. As almost 90 % of the world trade is carried by ship. It is estimated that 4 % of the global CO2, Sox and Nox emissions come from international shipping. The world wide increase in the price of oil has especially affected the shipping industry. Because the burning of diesel fuel ultimately generates the energy required onboard ship. Each kilo-watt of energy saved onboard has a direct effect on the consumption of diesel and the total operating cost. Therefore ship operators will put higher pressure on ship owners to obtain fuel efficient ships. These in turn will put pressure on ship yards to supply fuel efficient ships. As a result, we expect to see an improvement in the fuel consumption on

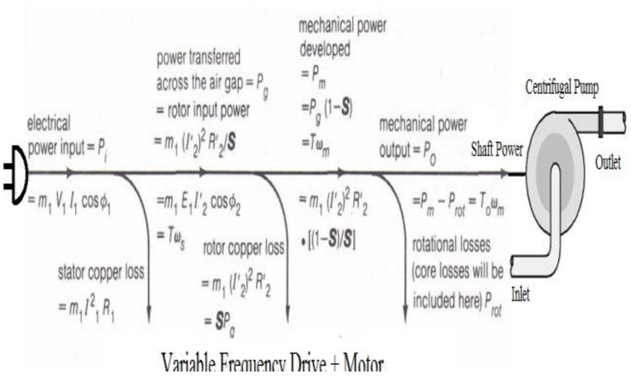

Fig.1. Transfer of Power from VFD to Pump

On board ships, there are a great number of pumps serving multiple purposes. The vast majority of pumps used today are the centrifugal type. These pumps are used for water cooling systems, cargo and ballast operation onboard ship. Cooling water pumps are especially dimensioned to have their rated capacity at a water temperature of 30 °C to 40 °C. When

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operating in cooler seas, this means that unnecessary high volumes of cooling water are pumped through the systems, resulting in high cost of energy and wear of the mechanical equipment. Vessels used for transporting fruit require very stable temperature. In passing through climatic zones with changing temperature conditions, a Marine frequency converter controlled cooling system will ensure constant storage room temperature.

On board passenger and cruise vessels, considerable energy is used for ventilation and air conditioning. Day cycles and changing environmental temperatures mean the motor power requirement for systems of this kind will undergo large variations. With temperature control, only the required motor power will be used to maintain the desired temperature.

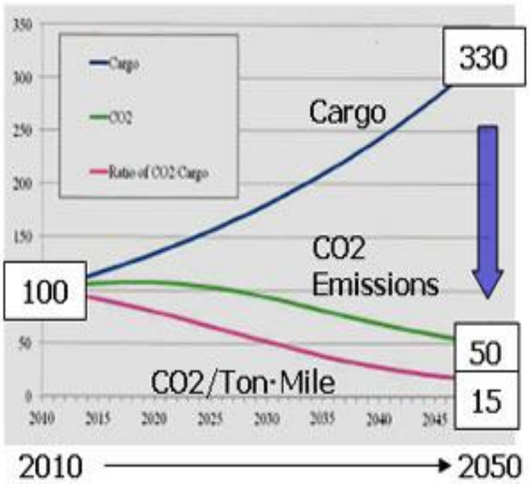

Fig.2. Carbon emission expected till 2050

For supply vessels, the ballast pumps, cargo pumps for fuel, brine and mud, etc. are installed with speed regulation using Marine frequency converters. The use of Marine frequency converters in regulating engine room temperature has also proved to provide great savings in energy. The shipping industry is facing ever greater challenges, especially regarding energy saving and the environment. Lurking in the background are political shadows like CO2 duties and dire predictions concerning the cost of fuel in ten years time. Authorities and owners are consequently focusing more and more on shipping concepts involving less environmental risk and energy saving. Shipping installations having higher fuel efficiency in all operational stages will be increasingly favored and will presumably have great potential for future growth. Additionally, the requirements of reliability, redundancy, maneuverability and concerning long maintenance intervals and short service response time are gradually becoming stricter.

Competence is a key factor in smooth sailing. Parts of these requirements can easily be met by controlling the speed of electric motors. The Centrifugal pumps used on board ship for ballast operation, cargo operation, Sea water cooling operation, savage operation etc are major consumers of electrical power. In the past 10 years, variable speed control for fans, pumps, chillers and HVAC systems has become an affordable way to save energy, thanks to advances in microelectronics and control technology.

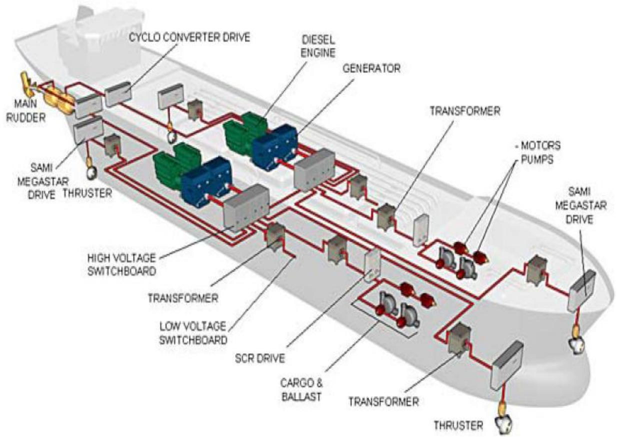

Fig.3. Ship layout with motors and pump for ballast operation

Variable frequency drives (VFDs) are gradually being recognized by maritime industries as one of the most effective tools for energy savings. Significant energy benefit can be realized from VFDs driven sea water cooling systems because the ambient sea water temperature varies greatly as ships travel through different sea areas. This research study of environmental issues and energy management is aimed at reducing energy consumption and pollution onboard ship and at sea.

II. Ballast Operation

Ballast is any material used to weight and/or balance an object. Ships have carried solid ballast, in the form of rocks, sand or metal, for thousands of years. Since modern times, ships have used water as ballast. Shipping moves over 80% of the world's commodities and transfers approximately 3 to 5 billion tones of ballast water internationally each year. Ballast water is absolutely essential to the safe and efficient operation of modern shipping, providing balance and stability to un-laden ships. It is much easier to load on and off a ship, and is therefore more efficient and economical than solid ballast. When a ship is empty of cargo, it fills with ballast water. When it Loads cargo, the ballast water is discharged.

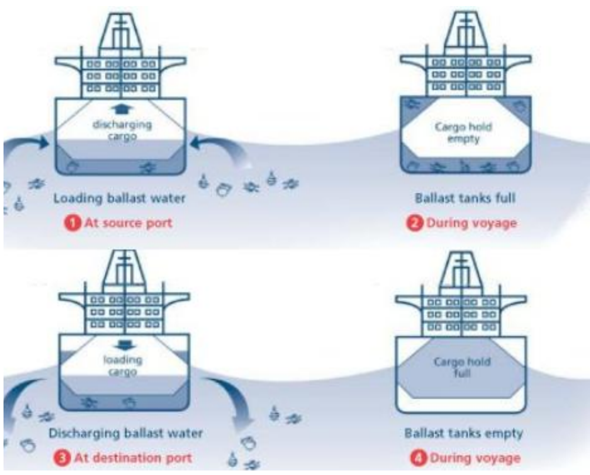

Fig.4. Cross section of ship showing ballast water cycle

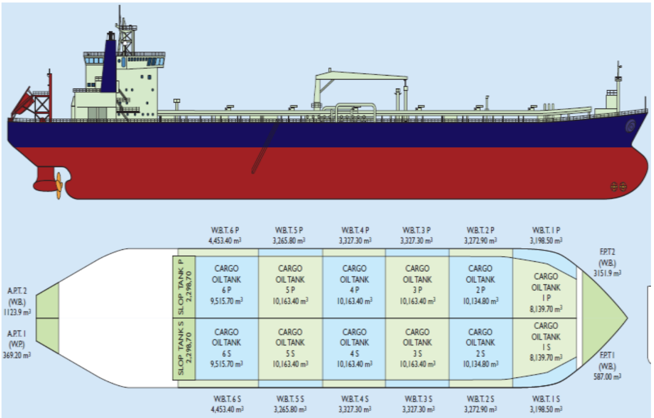

Fig.5. Arrangement of ballast tank onboard ship

TABLE I. Ballast water capacities for different types of ships

VESSEL TYPE	DWT	BALLAST CONDITION NORMAL (tonnes)	% of DWT	HEAVY (tonnes)	% of DWT
Bulk carrier	250,000	75,000	30	113,000	45
Bulk carrier	150,000	45,000	30	67,000	45
Bulk carrier	70,000	25,000	36	40,000	57
Bulk carrier	35,000	10,000	30	17,000	49
Tanker	100,000	40,000	40	45,000	45
Tanker	40,000	12,000	30	15,000	38
Container	40,000	12,000	30	15,000	38
Container	15,000	5,000	30	n/a	
General cargo	17,000	6,000	35	n/a	
General cargo	8,000	3,000	38	n/a	
Passenger/RORO	3,000	1,000	33	n/a	

TABLE II. Typical pumping requirement for ballast water management

Ballast needs	Vessel types	Typical pumping rates (m3/h)
Ballast replaces cargo Ballast required in large quantities, primarily for return voyage.	Dry bulk carriers	5,000–10,000
	Ore carriers	10,000
	Tankers	5,000–20,000
	Liquefied-gas carriers	5,000–10,000
	Oil bulk ore carriers	10,000–15,000
Ballast for vessel control Ballast required in almost all loading conditions to control stability, trim, and heel.	Container ships	1,000–2,000
	Ferries	200–500
	General cargo vessels	1,000–2,000
	Passenger vessels	200–500
	Roll-on, roll-off vessels	1,000–2,000
	Fishing vessels	50
	Fish factory vessels	500
	Military vessels	50–100

The centrifugal pumps are used onboard ship for loading and unloading ballast water. These pumps are traditionally controlled by throttling valve control, hydraulic and pneumatic control systems, bypass control systems etc. These systems have few limitations and disadvantages. Therefore to improve the overall efficiency of ballast operation, we need to use advanced technology that will reduce fuel consumption, emission of CO2, NOx, Sox, save energy. This can be done by using Variable frequency drive and three phase induction motor for controlling centrifugal pump onboard ship. As suggested power electronic technology reduces the emission of CO2, NOx, Sox and fuel consumption, we call this as eco-friendly system and green technology used for ballast water management.

III. Variable Frequency Drive

Induction motors, the workhorses of shipping industry [1], rotate at a fixed speed that is determined by the frequency of the supply voltage. Alternating current applied to the stator windings produces a magnetic field that rotates at synchronous speed. This speed may be calculated by dividing line frequency by the number of magnetic pole pairs in the motor winding. A four-pole motor, for example, has two pole pairs, and therefore the magnetic field will rotate 60 Hz / 2 = 30 revolutions per second, or 1800 rpm. The rotor of an induction motor will attempt to follow this rotating magnetic field, and, under load, the rotor speed "slips" slightly behind the rotating field. This small slip speed generates an induced current, and the resulting magnetic field in the rotor produces torque. Since an induction motor rotates near synchronous speed, the most effective and energy-efficient way to change the motor speed is to change the frequency of the applied voltage. VFDs convert the fixed-frequency supply voltage to a continuously variable frequency, thereby allowing adjustable motor speed. A VFD converts 60 Hz power, for example, to a new frequency in two stages: the rectifier stage and the inverter stage. The conversion process incorporates four functions:

Rectifier stage: A full-wave, solid-state rectifier converts three-phase 60 Hz power from a standard 208, 460, 575 or higher utility supply to either fixed or adjustable DC voltage.

Breaking chopper: The DC output of rectifier is controlled by chopper i.e. DC to DC converter. This output DC acts as input to three phase Inverter.

Inverter stage: IGBT/IGCT power transistors or thyristors switches the rectified DC on and off, and produce AC current and voltage waveform at the desired new frequency. The amount of distortion depends on the design of the inverter and filter. The output of inverter is variable voltage variable frequency with minimum harmonics.

Control system: It models a direct torque control (DTC) induction motor drive with space vector pulse width modulation. The particularity of this modified version is that the DTC is no longer based on hysteresis regulation that implies switching at variable frequency but on a fixed frequency PMW inverter. An electronic circuit receives feedback information from the driven motor and adjusts the output voltage or frequency to the selected values. Usually the output voltage is regulated to produce a constant ratio of voltage to frequency (V/Hz).

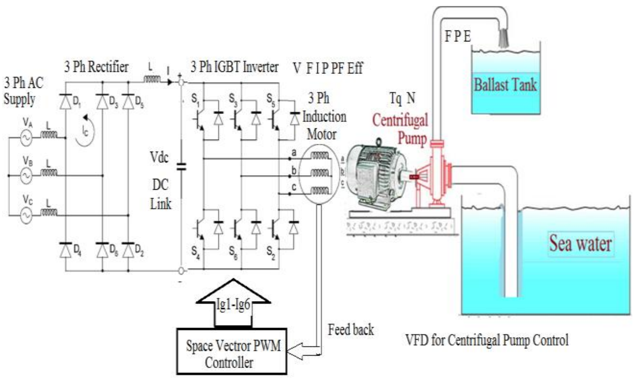

Fig.6. Ballast water management using VFD

Controllers may incorporate many complex control functions. Inverters use Space Vector Pulse Width Modulation (SVPWM) because the output current waveform closely approximates a sine wave. IGBT switches DC voltage at high speed, producing a series of short-duration pulses of constant amplitude. Output voltage is varied by changing the width and polarity of the switched pulses. Output frequency is adjusted by changing the switching cycle time. The resulting current in an inductive motor simulates a sine wave of the desired output frequency. The high-speed switching of a SVPWM inverter results in less waveform distortion and, therefore, lowers harmonic losses. Low voltage variable speed drives offer powerful and accurate performance for any application in powers of 0.55 up to 5600 kW [7].

Induction motors: Three Phases high efficiency induction motors offers a comprehensive range up to 18000 kW are reliable. These machines are commonly used onboard ship as prime movers for centrifugal pumps. IM consume about 35% of the total energy consumption. The simplicity of these machines allows them to be perfectly engineered according to requirements for application areas that include special and hazardous environments.

Centrifugal Pump: The load for the IM is variable torque type centrifugal pump. In the simulated model 500 HP Pump with maximum of 3000 m^3/hr flow rate is controlled using SVPWM controlled Variable Speed Drive. Thus we can adjust flow rate of ballast water system using VFD and reduce the consumption of energy and fuel.

IV. Affinity Laws

The affinity laws for specific pumps are, the volume (Flow) is proportional to speed. The Pressure (head) is proportional to square of the speed and the power absorbed is proportional to cube of the speed [2].

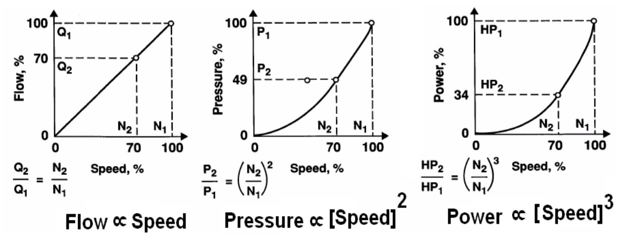

Fig.7. Affinity laws for pump

The affinity curve shows that at 100% rated speed and a fully loaded pump the horsepower consumption is maximum. If a 30% reduction in speed is allowable by the system process requirements then the pump may be driven at 70% of the maximum motor RPM with a nominal power consumption of 34.0% of the full load, full speed consumption. i.e. Power consumed = $(0.7)^3$ = 0.343 = 34.3%. For 60 Hz / 2 Pole IM, If we reduce 1 Hz frequency then Speed will reduce by 60 RPM i.e. 10% reduction in speed can reduce power consumption up to .9x.9x.9=72.9 % i.e. Saving = 27.1% power. Thus VFD is useful in energy saving because it reduces the motor speed as demand decreases and saves fuel and energy. The pump and driving motor must then develop enough torque to actually move the fluid [3].

V. Modeling of Induction Motor

A variable frequency drive (VFD) is used to change the supply frequency. As a result, motor speed changes. For various frequencies; speed, output torque, power factor, efficiency are studied. Graphs are generated to describe the behavior. An induction motor can be considered like a transformer with an air-gap. The equivalent circuit can be used to form a mathematical model. In this simulation, the motor of following specifications is studied. A three phase Y connected 220-V (line to line voltage) 7.5 kW, 60 Hz, 6 pole induction motor has the following values in Ω/phase referred to the stator. r1=0.294, r2=0.144, x1=0.503, x2 = 0.209, Xm = 13.25. The total friction, windage and core losses may be assumed as 6.5% of the power input at any given load. At 2% slip (loading condition), the motor offers its best performance [6].

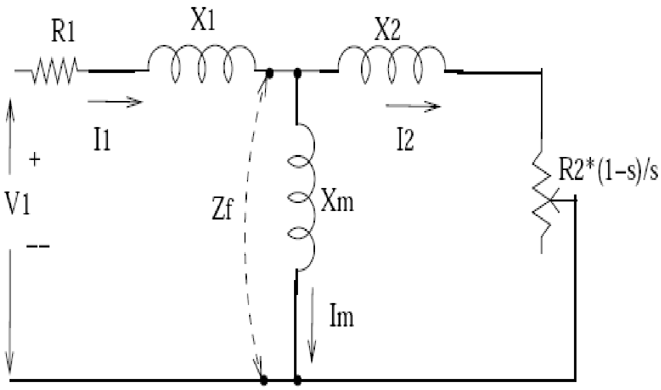

Fig. 8. Modified equivalent IM Model

It is assumed that the motor is tested for No Load and Blocked rotor tests at 60 Hz, because the motor is designed for this frequency and rated line voltage 220V. We are interested in predicting its behavior at various supply frequencies from a variable frequency drive. The range of frequencies will be 30 Hz to 90 Hz. For simplicity, we assume that the wave shape is a pure sinusoid. The user can select the loading condition (no load to overload) by mentioning the slip in the range 0 to 0.1. The best performance is obtained at slip = 0.02. From the No load and Blocked rotor tests, the user finds X1, X2, R2 and Xm. R1 can be measured using an ohmmeter. The reactance values are for 60 Hz. From the reactance we can find the inductances L1, L2, M. This helps to calculate the values of reactance at different frequencies. Following equations and concepts play vital role in the script.

The Total power transferred across the air gap from the stator is,

$$P_{gap} = 3 * I_2^2 * \left(\frac{R_2}{S}\right) \qquad \text{.. (1)}$$

$$P_{rotor} = 3 * I_2^2 * R_2 = S * P_{gap}$$

$$= 3 * I_2^2 * R_2 = S * P_{gap} \qquad \text{.. (2)}$$

Therefore the mechanical power output is given by

$$P_{mech} = P_{gap} - P_{rotor}$$
$$= 3 * I_2^2 * R_2 = S * P_{gap} \qquad \ldots\ldots\ldots\ldots\ldots\ldots (3)$$
$$= 3 * I_2^2 * \frac{R_2}{S} - 3 * I_2^2 * R_2$$
$$= 3 * I_2^2 * R_2 * \frac{1-S}{S} = (1-S) * P_{gap}$$

and the mechanical torque is given by

$$T_{mech} = \frac{P_{mech}}{\omega_m} = \frac{P_{gap}}{\omega_2}$$
$$= 3 * I_2 * \frac{R_2}{S * \omega_2} \qquad \ldots\ldots\ldots\ldots\ldots\ldots (4)$$

i.e the shaft power and shaft torque is given by

$$P_{shaft} = P_{mech} - P_{rotor} \qquad \ldots\ldots\ldots\ldots\ldots\ldots (5)$$
$$T_{shaft} = \frac{P_{shaft}}{\omega_m} = P_{mech} - P_{rotor} \qquad \ldots\ldots\ldots\ldots\ldots\ldots (6)$$

i.e. the stator input power (Pin) is given by

$$P_{in} = 3 * [V_1 * I_1] \qquad \ldots\ldots\ldots\ldots\ldots\ldots (7)$$

and Efficiency (η) is given by

$$\eta = \frac{P_{shaf}}{P_{in}} \qquad \ldots\ldots\ldots\ldots\ldots\ldots (8)$$

All the above parameters are fixed except the slip. We can change the slip value within the range 0 to 0.1 (No load to overload) and see the behavior of the motor.

VI. SIMULATION USING MATALB

It models a direct torque control (DTC) induction motor drive with a braking chopper for a 200HP AC motor. The induction motor is fed by a SVPWM voltage source inverter using IGBT. The speed control loop uses a proportional-integral controller to produce the flux and torque references for the DTC block. The DTC block computes the motor torque and flux estimates and compares them to their respective reference. The comparators outputs are then used by an optimal switching table which generates the inverter switching pulses. Motor current, speed, and torque signals are available at the output. After the simulation, we can observe the motor stator current, the rotor speed, the electromagnetic torque and the DC bus voltage on the scope. The speed set point and the torque set point are also shown. At time t = 0 s, the speed set point is 500 rpm. Observe that the speed follows precisely the acceleration ramp. At t = 0.5 s, the full load torque is applied to the motor shaft while the motor speed is still ramping to its final value. This force the electromagnetic torque to increase to the user-defined maximum value 1200 N. m and then to stabilize at 820 N. m once the speed ramping is completed and the motor has reached 500 rpm. At t = 1 s, the speed set point is changed to 0 rpm. The speed decreases down to 0 rpm by following precisely the deceleration ramp even though the mechanical load is inverted abruptly, passing from 792 N. m to - 792 N. m, at t = 1.5 s. Shortly after, the motor speed stabilizes at 0 rpm. Finally, note how well the DC bus voltage is regulated during the whole simulation period. The power system has been discretised with a 2 us time step. The speed controller uses a 140 us sample and the DTC controller uses a 20 us sample time in order to simulate a microcontroller control device. In order to control centrifugal pump using VFD controlled three phase IM, pump system is also modeled and simulated for 3000m^3/Hr flow rate [4].

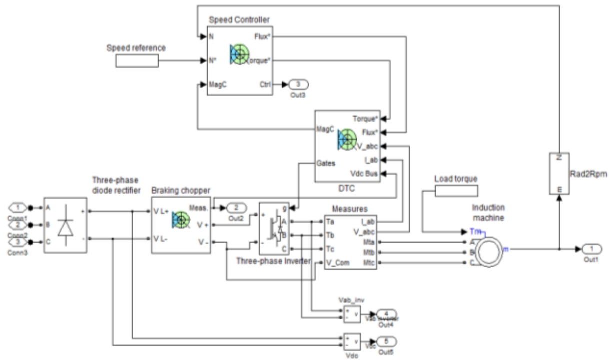

Fig.9. DTC based VFD control for three phase IM.

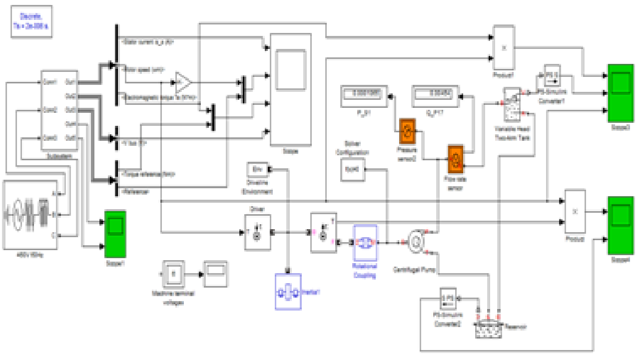

Fig.10. VFD controlled centrifugal pump

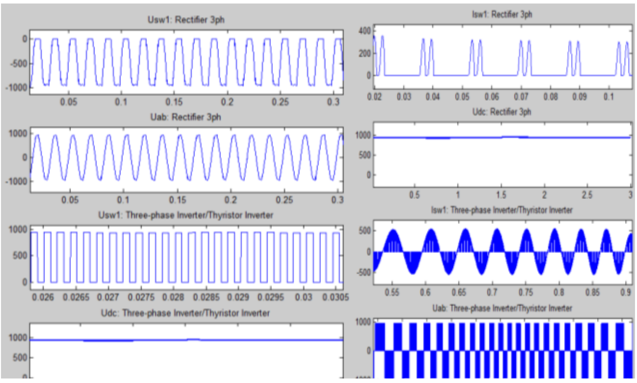

Fig.11. Rectifier I/O and Inverter I/O waveforms

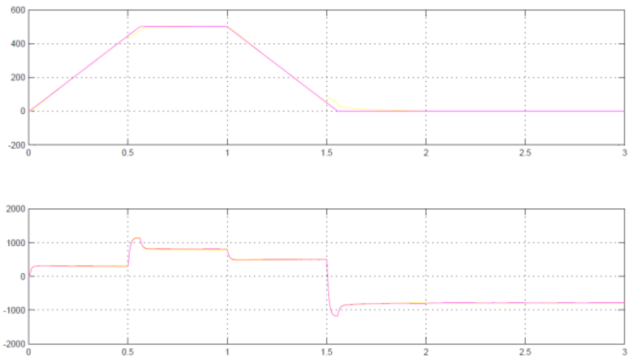

Fig.12. Speed and torque response

VII. EXPERIMENTATION

The VFD controlled centrifugal pump with 400 HP power, 50 Hz, 380 V AC nominal voltage, 2 poles and 2900 RPM nominal speed squirrel cage three phase induction motor of 500 HP is used for validation of results. VFD efficiency is 98 %, IM efficiency is 90% and Pump efficiency is 80%. Maximum head can be 30 meter. Pressure sensor is a 0-10 Bar ranged pressure switch in constant speed control strategy and an analog piezoelectric pressure transmitter with 24 V DC feed voltage and 4-20 mA output current in variable speed control strategy.

Table III. VFD & Throttling valve comparison, energy in kW

Flow	%	Throttled	VFD Static head in feet			
GPM	Flow	Valve	0 Ft	60 Ft	140 ft	210 Ft
170	50	19.7	3.2	6.35	10.44	14.08
204	60	20.95	5.46	8.7	12.7	16.02
238	70	22.21	8.68	11.75	15.42	18.3
272	80	23.47	13.06	15.58	18.61	20.9
306	90	24.73	18.83	20.31	22.31	23.77
340	100	25.99	26.19	26.02	26.52	26.89

Table IV. Percentage energy saved

Sr. No.	0 Ft	60 Ft	140 Ft	210 Ft
1	83.75635	67.7665	47.00508	28.52792
2	73.93795	58.47255	39.37947	23.53222
3	60.91851	47.0959	30.57181	17.60468
4	44.3545	33.61738	20.70729	10.95015
5	23.85766	17.87303	9.785685	3.881925
6	-0.76953	-0.11543	-2.03925	-3.46287

Table V. Total cost saved in a year

Sr. No.	Cost saved /year @ 0.06 $ for 8 Hrs/250 days			
Head in Feet	0 Ft	60 Ft	140 Ft	210 Ft
1	1485	1201.5	833.4	505.8
2	1394.1	1102.5	742.5	443.7
3	1217.7	941.4	611.1	351.9
4	936.9	710.1	437.4	231.3
5	531	397.8	217.8	86.4
6	-18	-2.7	-47.7	-81

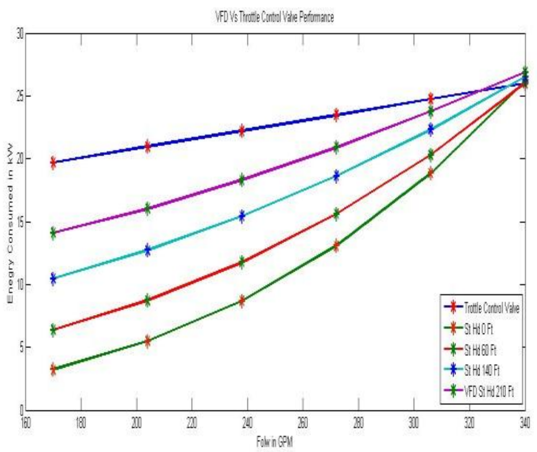

Fig. 13. Energy consumed using VFD and Throttling Valve.

Table VI. Variation of speed and energy saving

SPEED	VOLUME OR FLOW	I/P HP
100%	100%	100%
90%	90%	73%
80%	80%	51%
70%	70%	34%
60%	60%	22%
50%	50%	13%
40%	40%	6%
30%	30%	3%

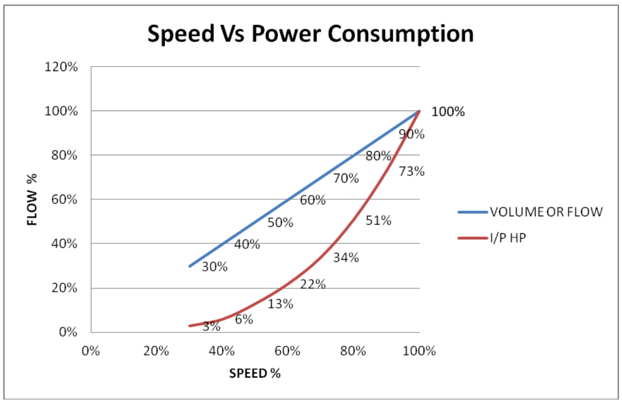

Fig. 14. Power consumption at various speeds

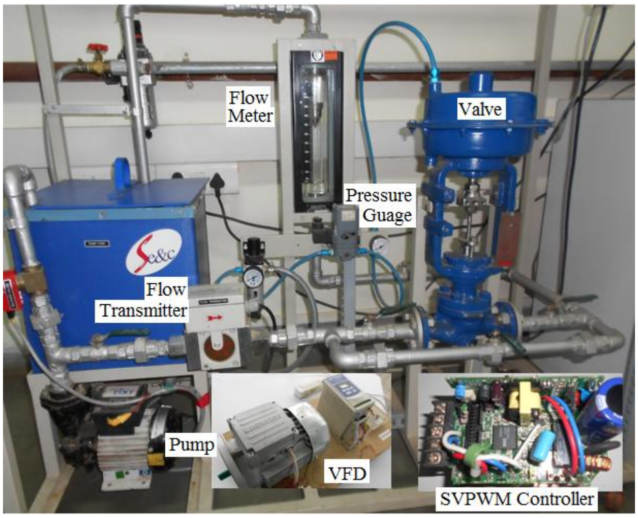

Fig. 15. Experimental setup for controlling pump using VFD

VIII. CONCLUSION

A variable speed drive regulates the speed of the motor, and in turn the speed of the pump, by controlling the energy that goes into the motor, rather than restricting the flow of a process running constantly at full speed. A variable speed drive can save over 50% of the energy. This is possible as it controls the energy at source, only using as much as is necessary to run the motor with the required speed and torque. Therefore variable speed drives are gaining much more importance for controlling centrifugal pumps and to conserve energy onboard ship [5]. Use of VFD improves process variability, VFD is faster, more linear and is invulnerable to backlash, reduced energy consumption, the pump supplies only enough energy to overcome the system head, the energy wasted across the control valve is eliminated, reduced maintenance costs, since the pump will operate close to the BEP over the entire operating range, reliability and efficiency are complementary. VFD improves the efficiency of motor-driven equipment by matching speed to changing load requirements and continuous process control over a wide range of speeds. In addition to saving of energy, it reduces consumption of CO/CO2, Sox and NOx etc. Therefore this eco-friendly power electronics technology act as green technology to protects environment in around at sea.

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