



Design and Simulation of a Ship Propulsion System Using High Performance Drives Controlled Induction Motor

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ABSTRACT

This paper is about the use of induction motor for ship propulsion system replacing the old mechanical system of using gear box. The Direct Torque Control (DTC) of induction motor can be used to simulate the ship propulsion system. This can be achieved by controlling the output of a 3-phase induction motor using 3-phase inverter. The DTC will be used to control the induction motor speed and torque by comparing the outputs of the inverter and the induction motor. The mechanical output of the induction motor will be transmitted to the ship propeller via a meshing gear system. The circuits and mathematical models of the various building blocks of the project such as the 3-phase induction motor, 3 phase inverter, DTC, meshing gear system and propeller were formulated. The formulated models were used simulated using Matlab and Simulink.

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INTRODUCTION

Ship propulsion is a key area for both military and merchant shipping industries. Over the years, ships using mechanical propulsion system were commonly in use. Later, the direct current (DC) motor propulsion systems became the first type of electric propulsion for ships. The electric propulsion system has been frequently selected as the propulsion system of choice for various types of war ships and auxiliary ships in several navies worldwide especially advanced nations.

The direct current electric motor propulsion system has been the earliest form of electric propulsion before the advent of the induction motor. With the development in field of vector control of induction, it was seen that the Induction motor could actually be controlled like a direct current motor. Induction motor has been recently used for many industrial applications. These include for cranes, conveyors and ship propulsion. The control of induction motors for industrial application has been a major field of research over the years.

The ability to control the induction motor gives about the flexibility in its application in various

fields. The common method of ship propulsion has been mechanical in nature. Considering the fact that war ships require high maneuverability, high speed, less noise and limited space for machineries, there is a need to design systems which can meet up with these requirements. The electric propulsion of ship will help overcome the limitations associated with mechanical propulsion of ships.

METHODOLOGY

The system comprises of; Power supply and rectifier unit, Voltage source inverter (VSI), Space Vector Modulation (SVM), Direct Torque Control module, three Phase (3 ϕ) Induction Motor and ship propeller. The meshing gears which are used to match the induction motor to the propeller will also be described. The approach used is by first creating the mathematical models of the various building blocks. These mathematical models are then used for simulation using The Matlab/Simulink blocks.

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Mathematical Model of an Induction Motor

The dynamic equivalent circuit of the induction motor is represented in the rotating reference frame based on the dq axis. Let d be the direct axis and q the quadrature axis. The mathematical model of three phase induction motor is shown in figure 3.1. However, the following assumptions were made;

1. Balanced rotor and stator windings with sinusoidal distributed mmf.
2. Uniform air gap.
3. Inductance against rotor position is sinusoidal.
4. Saturation and parameter changes are neglected.

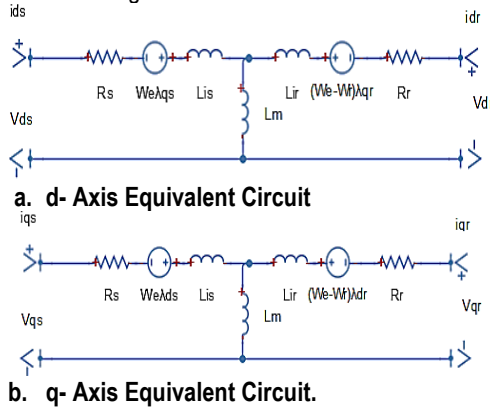


Figure 1: d-q Equivalent Circuits of the Induction Motor.

The descriptions of parameters are:
 V_{ds} = d-axis stator voltage. V_{qs} = q-axis stator voltage. V_{dr} = d-axis rotor voltage. V_{qr} = q-axis rotor voltage. i_{ds} = d-axis stator current. i_{qs} = q-axis stator current. i_{dr} = d-axis rotor current. i_{qr} = q-axis rotor current. R_s = Stator resistance. R_r = Rotor resistance. ω_e = angular velocity of the reference frame. ω_r = angular velocity of rotor frame. λ_{ds} , λ_{qs} , λ_{dr} , λ_{qr} = flux linkages.

Differential Equations of Three Phase Induction Motor

The differential equations of three phase induction motor model are;

$$V_{ds} = R_s i_{ds} + \frac{d\lambda_{ds}}{dt} - \omega_e \lambda_{qs} \quad (1)$$

$$V_{qs} = R_s i_{qs} + \frac{d\lambda_{qs}}{dt} - \omega_e \lambda_{ds} \quad (2)$$

$$V_{dr} = 0 = R_r i_{dr} + \frac{d\lambda_{dr}}{dt} - (\omega_e - \omega_r) \lambda_{qr} \quad (3)$$

$$V_{qr} = 0 = R_r i_{qr} + \frac{d\lambda_{qr}}{dt} + (\omega_e - \omega_r) \lambda_{dr} \quad (4)$$

Where:

$$\lambda_{ds} = L_s i_{ds} + L_m i_{dr} \quad (5)$$

$$\lambda_{qs} = L_s i_{qs} + L_m i_{qr} \quad (6)$$

$$\lambda_{dr} = L_r i_{dr} + L_m i_{ds} \quad (7)$$

$$\lambda_{qr} = L_r i_{qr} + L_m i_{qs} \quad (8)$$

Where L_s is the stator self-inductance that is equal $L_m + L_{ls}$ and L_r is the rotor self-inductance that is equal $L_m + L_{lr}$. L_m is the magnetizing inductance, L_{ls} is the stator leakage inductance and L_{lr} is the rotor leakage inductance. Thus, the current machine can be written as:

$$i_{ds} = \frac{L_r}{L_r L_s - L_m^2} \lambda_{ds} - \frac{L_m}{L_r L_s - L_m^2} \lambda_{dr} \quad (9)$$

$$i_{qs} = \frac{L_r}{L_r L_s - L_m^2} \lambda_{qs} - \frac{L_m}{L_r L_s - L_m^2} \lambda_{qr} \quad (10)$$

$$i_{dr} = \frac{L_s}{L_r L_s - L_m^2} \lambda_{dr} - \frac{L_m}{L_r L_s - L_m^2} \lambda_{ds} \quad (11)$$

$$i_{qr} = \frac{L_s}{L_r L_s - L_m^2} \lambda_{qr} - \frac{L_m}{L_r L_s - L_m^2} \lambda_{qs} \quad (12)$$

The induction motor model can be produced by using the following differential equations written in terms of flux linkage as:

$$\frac{d\lambda_{ds}}{dt} = V_{ds} - \frac{R_s L_r}{L_r L_s - L_m^2} \lambda_{ds} + \frac{R_s L_m}{L_r L_s - L_m^2} \lambda_{dr} + \omega_e \lambda_{qs} \quad (13)$$

$$\frac{d\lambda_{qs}}{dt} = V_{qs} - \frac{R_s L_r}{L_r L_s - L_m^2} \lambda_{qs} + \frac{R_s L_m}{L_r L_s - L_m^2} \lambda_{qr} - \omega_e \lambda_{ds} \quad (14)$$

$$\frac{d\lambda_{dr}}{dt} = -\frac{R_r L_r}{L_r L_s - L_m^2} \lambda_{dr} + \frac{R_r L_m}{L_r L_s - L_m^2} \lambda_{ds} + (\omega_e - \omega_r) \lambda_{qr} \quad (15)$$

$$\frac{d\lambda_{qr}}{dt} = -\frac{R_r L_s}{L_r L_s - L_m^2} \lambda_{qr} + \frac{R_r L_m}{L_r L_s - L_m^2} \lambda_{qs} - (\omega_e - \omega_r) \lambda_{dr} \quad (16)$$

Induction Motor Torque

The design of the induction motor involves taking two torques into considerations. These torques are:

- Electromagnetic Torque T_e .
- Rated Load Torque T_L .

The electromagnetic torque can be calculated with respect to the rotor speed ω_r . This denoted by:

$$T_e = T_L + \frac{2Jd\omega_r}{pdt} \quad (17)$$

$$\frac{d\omega_r}{dt} = \frac{p}{2J} (T_e - T_L) \quad (18)$$

In terms of the stator and rotor currents in the dq axis the torque can be written as;

$$T_e = \frac{3}{4} PL_m (i_{qs} i_{dr} - i_{ds} i_{qr}) \quad (19)$$

The mechanical power is;

$$P_m = T\omega_r \quad (20)$$

Where

$$\omega_r = \frac{2\pi N}{60}$$

P = number of poles

J = Inertia of rotor

ω_r = rotor speed

P_m = mechanical power in watts by manufactures.

N= rated rpm

However, T_L is to be matched with Ship's propeller. T_e developed by the motor drives T_L . If there is a mismatch between the electromagnetic torque T_e and T_L , the differential torque accelerates the rotor mass.

Simulation Model of Induction Motor

The induction Motor was simulated using equations 1 to 16 and the parameters in table 1. The speed as well as the torque of the motor were taken as outputs of the simulation. PI was used to generate the reference speed and torque.

Table 1: Simulation Parameters of the Induction Motor.

S/N	Parameter	Value	Remarks
1	Power	5HP	
2	Rated KVA	4.668KVA	
3	Rated Power	3.734KW	
4	Speed	1500 rpm	
5	Number of poles	4	
6	Rated voltage	500V	
7	Number of phases	3	
8	f	50Hz	
9	Rated current	8A	
10	R_s	1.405	
11	R_r	1.395	
12	L_{is}	0.005839H	
13	L_{ir}	0.005839H	
14	L_m	0.1722H	
15	J	0.0131kgm ²	

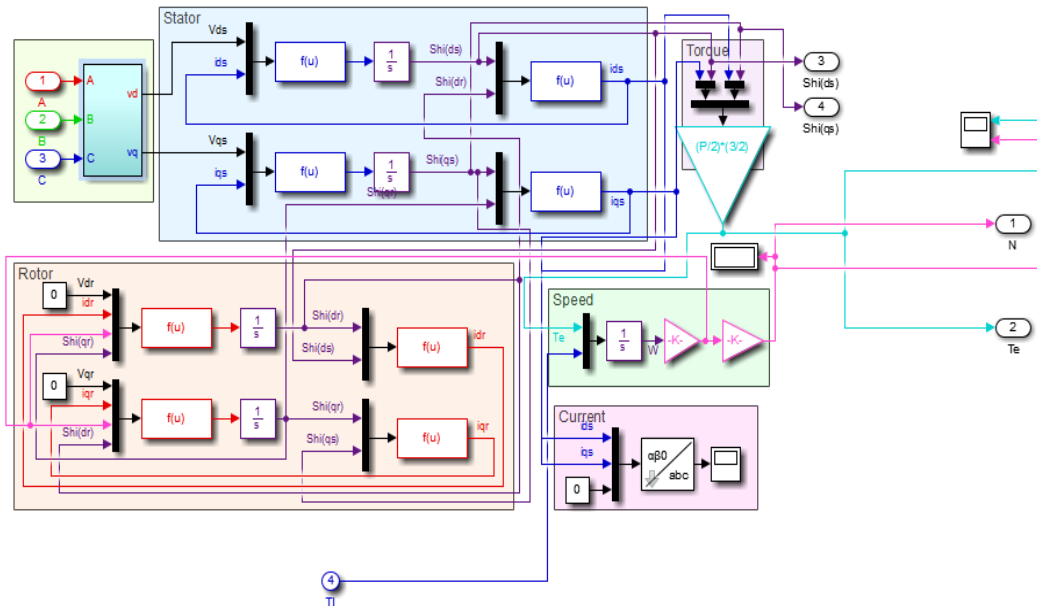


Figure 2: Simulink Model of Induction Motor Voltage Source Inverter

The Voltage Source Inverter is used in the design. The 3 Φ Voltage Source Inverter (VSI) is presented in figure 3. Figure 4 is used to analyse the switching signals for the SPWM VSI. IGBT or MOSFET transistors are used with switching variables (S_1 to S_6). S_1 to S_6 are the six power switches that shape the output. These are controlled by the switching variables a, a', b, b', c, c' . When an uer transistor is switched on, the corresponding a', b' or c' is 0. Therefore the on and off states of the uer switches S_1, S_3, S_5 can be used to determine the output voltage. The outputs from closed-loop current controllers are v_a^*, v_b^* and v_c^* . Only 1 switch is on at a certain time which leads to 3 switching variables. There are three switching variables which are S_a, S_b and S_c (i.e. one per phase).

One switch is on in each inverter leg at a time. If both are on at same time, the dc suly will be shorted. If both are off at same time, output voltage will be undetermined. Each of the inverter legs can assume two states only. For example, when $S_a = 1$ if S_1 is ON and S_4 OFF and when $S_a = 0$ if S_1 OFF and S_4 ON. There are a total of 8 states in all. The eight states are as shown figure 5. Therefore, the voltage vectors for all the 8

inverter states can be obtained. Note for states $[000]$ and $[111]$, voltage vector is equal to zero. The available eight different switching states of three phase inverter are depicted in the Fig 3.4. Six out of these eight states (V_1 to V_6) produce a nonzero output voltage and are known as active switching states and the remaining two states (V_0 and V_7) produce zero output voltage and are known as zero switching states. The Voltage Vectors for 8 Inverter States is shown in table 2.

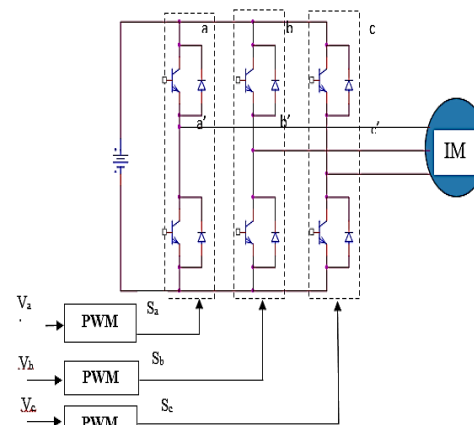


Figure 3: Three Phase Voltage Source Inverter.

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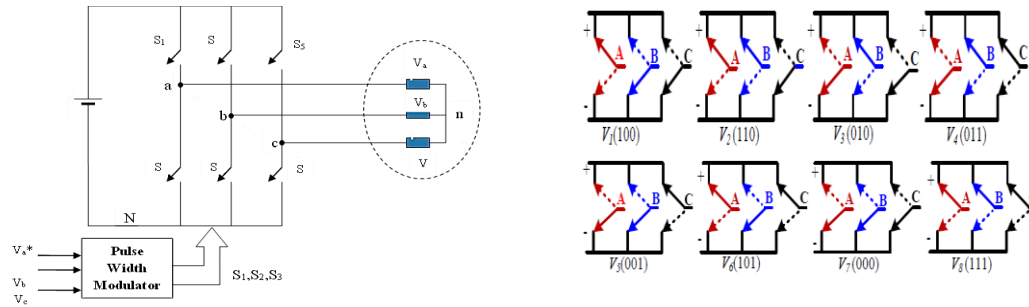


Figure 4: Switching Signals for the Voltage Source Inverter.

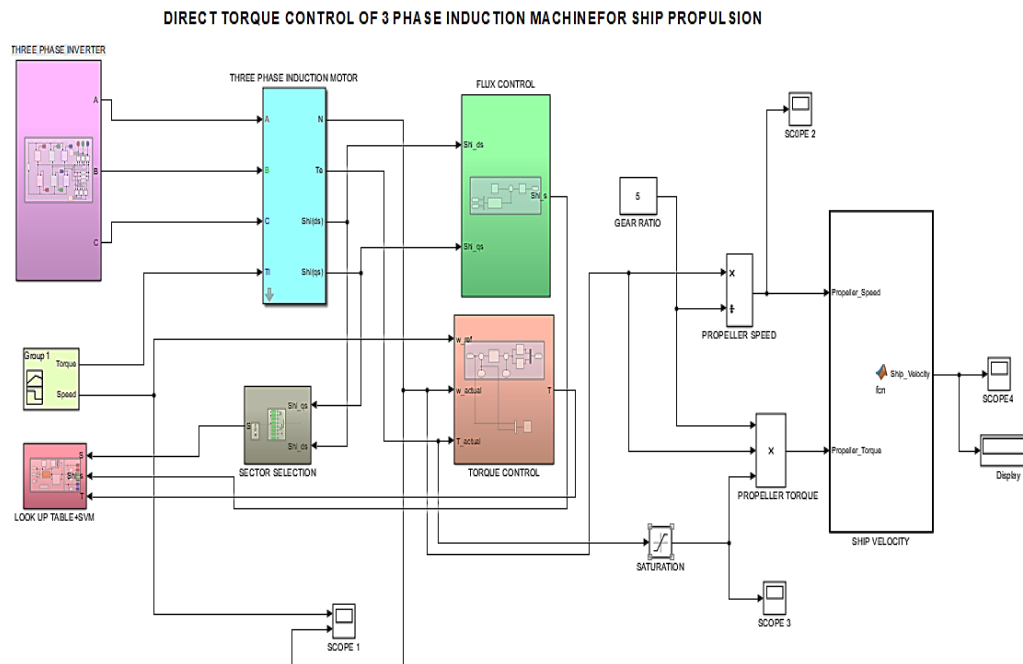


Figure 5: Switching states for two-level VSI fed Induction Motor

Table 2: Voltage Vectors for 8 Inverter States Simulation Model of Voltage Source Inverter

Voltage Vector	Inverter State [$S_a S_b S_c$] ₂
V_0	State 0 = [000] ₂
V_1	State 4 = [100] ₂
V_2	State 6 = [110] ₂
V_3	State 2 = [010] ₂
V_4	State 3 = [011] ₂
V_5	State 1 = [001] ₂
V_6	State 5 = [101] ₂
V_7	State 7 = [111] ₂

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The inverter was simulated using the concept in 3.3 and table 3.2. The 500VAC, three phase inverter simulation model is shown in figure 3.6.

Space Vector Representation

To achieve the model simulation of three phase inverter it is presented on the basis of space vector representation. The space vector representation of three-phase quantities $x_a(t)$, $x_b(t)$ and $x_c(t)$ with space distribution of 120° apart is given by:

$$X = \frac{2}{3}(x_a(t) + ax_b(t) + a^2x_c(t)) \quad (21)$$

Simulation and Discussion of Results

The Simulink models and MATLAB codes are developed for all the aforementioned modules.. In the Simulink model varying speed was simulated for the ship movement using the Simulink signal builder. The simulation was carried out in five modules. These modules are; Signal Builder, Induction Motor, Three Phase Voltage Source Inverter, DTC and Ship Propeller and Velocity.

Matlab Code for Ship Velocity Calculation

```
function Ship_Velocity = fcn (Propeller_Speed,
Propeller_Torque)
%PROPELLER PARAMETERS AT CONSTANT
SEA FACTORS
P= 1023.6; % water density;
Kt=0.2;% Thrust coefficient;
D=1.5; % propeller diameter in meters;
No=0.85; %Propeller Efficiency;
Np=Propeller_Speed; % in rpm;
Q=Propeller_Torque; % in Nm;
W=(2*pi*Np)/60; %Propeller angular Velocity in
rad/sec;
V=(W*D/2); % Propeller Linear Velocity in m/s;
Ship_Velocity = (No*2*pi*Q)/(Kt*P*V*(D)^4);s
```

Figure 6: Simulink Model for Direct Torque Controlled Induction Motor for Ship Propulsion System Signal Builder

The signal builder is used to simulate the command signal for the induction to follow. It generates varying speed and torque which gives

rise to varying velocity of the ship. The signal builder was used to simulate command for increase, decrease as well as constant speed in the forward direction for the ship. Figure 7 shows the signal builder used for the simulation.

Induction Motor Simulation

The model was created using simulink subsystems and blocks such as the integrator, gain, summer among others. The torque and speed responses of the induction motor were simulated as outputs. The graph of the Torque and speed responses against time is gotten from the scope of Simulink model as shown figure 8 and figure 9.

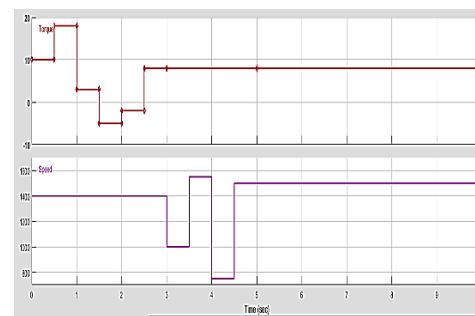


Figure 7: Signal Builder for Torque and Speed.

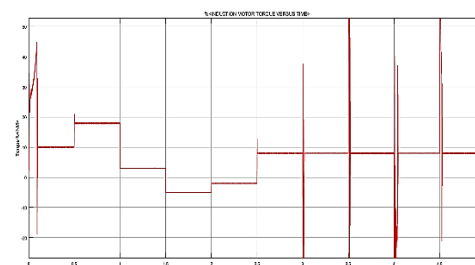


Figure 8: Torque Developed by the Induction Motor versus Time.

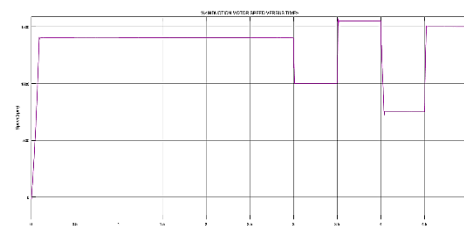


Figure 9: Speed vs Time Graph of the Induction Motor.

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Three Phase Voltage Source Inverter

The Simulink was used to simulate a three phase and 500V AC voltage to power the induction motor. The three phase output voltage was observed from the scope. The output of the three phase inverter voltage is shown in figure 10.

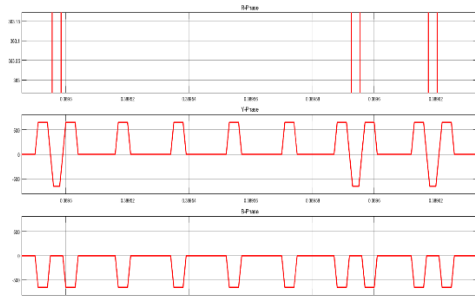


Figure 10: Output of the Three Phase Voltage Source Inverter.
Direct Torque Control Module

The DTC makes use of the flux and torque control to drive the induction motor. The major parameter to drive the ship is the torque which is fed into the propeller via the meshing gears.

Propeller Model and Ship Velocity

The output from the motor in form of torque and velocity was fed to the propeller via the meshing gears. The output of the overall system is the ship velocity. The Matlab function code for the propeller model was used to find the ship velocity at any point in time. The propeller speed and torque against time gotten from the simulation are shown in figures 11 and 12. The ship's velocity was computed by the Matlab function and a plot of ship velocity versus time is at figure 13. The plot shows the movement of the ship at different speeds.

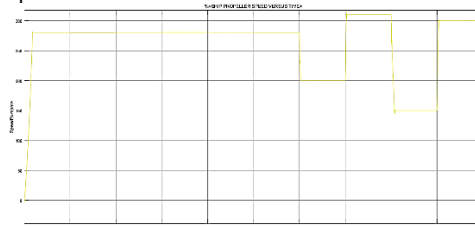


Figure 11: Plot of Propeller Speed against time.

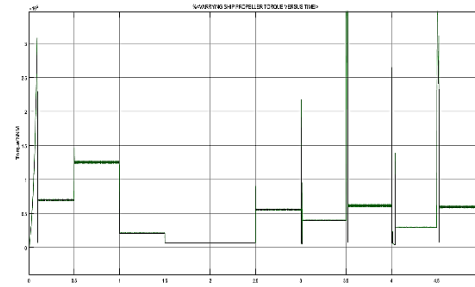


Figure 12: Plot of Propeller Torque against Time.

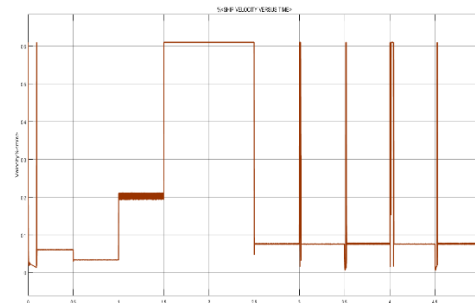


Figure 13: Plot of Ship Velocity against Time.

CONCLUSIONS

The project was to model and simulate a DTC controlled induction motor for ship propulsion. It was aimed at using high performance electric drives and induction motor to design an electric ship propulsion system. The performance evaluation of electric drives could be seen from the simulations. The design is simple and would be cheaper to implement when compared to a mechanical ship which are commonly in use in the Nigerian Navy and Merchant shiing industries.

The project will help to eliminate the associated problem with internal combustible engine for ship propulsion such as size, noise and cost of maintenance amongst others. The project if implemented can help to preserve the ecosystem by reduction of marine air pollution associated with mechanical ships. This aspect of research can be harnessed by the Nigerian Navy and other indigenous industries for the design and construction of Electric ships. The fact that electric ships generate less noise which makes them difficult to detect, gives them the good characteristics of a war ship.

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RECOMMENDATIONS

1. The development in renewable energy and breakthrough in electric drives technology could be harnessed by the Navy and the Merchant shipping industries for the construction of electric ships.
2. Focus should be given to research in field of electric machines and drives which are the major area required for design and construction of electric cars and ships.
3. Consideration can also be given to ships which use alternate means of power generation such solar power as a means of electricity generation onboard ships thereby serving as initial step towards migration to the design and construction of electric ships by the Nigerian Navy.

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