

# Power Conditioning System for EMALS Application

Deeksha Rajvanshi

*B Tech, Final Year, EE College of Technology GBPUAT, Pantnagar*  
*E-mail: deeksharajvanshi@yahoo.in*

---

**Abstract:** *Electromagnetic Aircraft Launch System (EMALS) is a Navy's launch choice for Ford-Class aircraft carriers, replacing present steam catapults used on current and prior generations of aircraft carriers. EMALS lowers overall operating costs and reduces maintenance over current steam catapults and provides less 'Wear and Tear' on carrier based aircraft. The U.S. Navy is presently developing electromagnetic launch technology. EMALS is a fully integrated system consisting of an energy storage system, a power electronics system, a linear launch motor and a control system etc. This paper describes the various configurations available and preliminary design aspects of power conversion system.*

## 1. INTRODUCTION

This section describes the various configurations available and design aspects of power conditioning unit.

The U.S. Navy is presently developing electromagnetic launch technology to replace the existing steam catapults on current and future aircraft carriers. The steam catapults are large, heavy and operate without feedback control. An Electromagnetic Aircraft Launch System offers higher launch energy capability, as well as substantial improvements in areas other than performance.

## 2. EMALS (ELECTROMAGNETIC AIRCRAFT LAUNCH SYSTEM)

EMALS is a fully integrated system consisting of an energy storage system, a linear launch motor and a control system, a power electronics system. The energy storage system takes energy from the ship distribution system over a specified period of time and stores it for pulse discharge over two to three second launch event

The power electronics system takes the power from energy storage system and conditions it for use in the linear launch motor (Linear Induction Motor); which accelerates the aircraft to fly away speed. The aircraft is attached to a shuttle that is propelled down the length of catapult track by an electromagnetic field produced by the linear motors. The introduction of EMALS would have an overall positive impact on the ship. The launch engine is capable of a high thrust density, as shown by the half scale model that demonstrated 1322 psi over its cross section. This is compared to the

relatively low 450 psi of the steam catapult. The same is true with energy storage devices, which would be analogous to the steam catapult's steam accumulator. The low energy density of the steam accumulator would be replaced by high energy density flywheels. These flywheels provide energy densities of 28 KJ/KG. The increased densities would reduce the system's volume and would allow for more room for vital support equipment on the host platform.

### 2.1 Major Subsystems of EMALS

- **Prime Power Interface:** This system provides inter connection with the ship's electrical distribution system and delivers power to drive the energy storage generators.
- **Launch Motor:** Developed in a linear induction motor configuration, the launch motor is a compact, modular, integrated flight – deck structure that converts electrical current into the electromagnetic force to accelerate the aircraft along the launch stroke. The motor design will tolerate the range of conditions experienced in the flight – deck environment and operating scenario. A simple moving shuttle will interface with the aircraft in the same manner as the existing catapults. After the aircraft launches, the electric current in the motor will reverse and brake the shuttle to a complete halt without the use of a weight brake.
- **Power Conversion Electronics:** the power conversion electronics derive power from the energy stored and convert this power to a traveling wave of energy of the appropriate voltage and current to drive the shuttle along the launch stroke.
- **Launch Control:** The EMALS uses a state of the art system to control the current into the launch motor in real time. More precise end speeds are achievable over a wider range of aircraft types and weights over those of steam catapults.
- **Energy Storage:** the required energy for a launch is drawn from the energy storage devices during each two to three second launch. The energy storage devices are recharged from ship's power between launches.
- **Energy Distribution System:** this system delivers the energy from the power conversion system to the launch motor and comprises of cables, connectors, terminations, protection and switch gear system.

### 3. POWER CONVERSION SYSTEM

During launch, the power conversion system releases the stored energy from the disk alternators using a frequency based changer. These power converters provide a controlled rising frequency and voltage to the LIM, energizing only the small portion of stator coils that affect the launch carriage at any given moment.

The power conversion electronics derive power from the energy stored and convert this power to a travelling wave of energy of the appropriate voltage and current to drive the shuttle along the launch stroke. The power-conditioning system feeds current with a rising voltage and frequency, through inverters, to the linear motor. A moving electromagnetic wave is created by powering just the coils in the portion of the motor where the travelling armature is located. The electromagnetic field set up by the current in the stators accelerates the armature. The field simultaneously pushes and pulls the armature and its carriage down the length of the motor until the attached aircraft reaches launch speed, disengages, and flies off.

For conversion from a three-phase mains source/ energy storage element to a three phase voltage load with an arbitrary frequency and amplitude, converter systems with either a voltage or current DC-link are mainly used today. It can be done in various methods:

1. Cyclo-converter: Single stage converter
2. Power conditioner: Double stage converter

#### 3.1 Double Stage Converter

The variable input voltage from energy storage devices (Flywheel/ super capacitor) shall be given to front end AC to DC converter. Front end converter will convert AC voltage to DC voltage and DC output from the converter is fed to the IGBT based PWM inverter for getting quality AC power output with appropriate filters so as to suppress the DC content at the output. The output of the filter will be a pure sine wave at constant voltage and constant frequency.. This DC voltage is then subsequently inverted into AC voltage by high speed inverters using IGBTs (Insulated Gate Bipolar Transistor) which is the latest fourth generation semiconductor device. IGBTs are high speed switching devices having fast response time & low losses. With recent advent of IGBTs, switching frequencies in the range of tens of kilohertz is now possible with minimal switching losses. This is particularly important in sinusoidal output systems because size & cost of the filter varies inversely with switching frequency. The frequency on the output is controlled by the inverter while the amplitude is controlled by the rectifier.

### 4. DESIGN OF POWER CONVERSION SYSTEM

The PCS takes the input from flywheel Alternator which is variable source. Following specifications are considered for design calculations , it may change at actual .

Table 1: Specifications

Parameters	Range	Unit
Input Phase From Disk Alternator/ Capacitor		
Voltage(phase to phase)	2300	Volts
Input Frequency (max)	500	Hz
input frequency (min)	334	Hz
Output from PCS to LEM		
Output Voltage	3400	Volts
Output Frequency	300	Hz
Switching Frequency	5000	Hz
Power Output	20MW	Watts
Voltage Regulation	1%	
Frequency Regulation	1%	
Transient Response		
TVD/TVR	10	
Recovery Time	less than 300 ms	
Overall efficiency	Not less than 90 %	

Note: The actual requirement of Linear motor is in the range of hundreds of MW(tentatively 250 MW) , The following design calculations are done for 20 MW, 300Hz, 3300V V, 3 ph, power conditioning unit. To increase the capacity in power range number of such modules can be increased as per requirement.

### 5. CALCULATIONS OF ENTIRE SCHEME

#### 5.1 Scheme 1

Using uncontrolled rectifier

STEP 1 Calculate the input current from flywheel

$$\text{REAL POWER} = \text{REACTIVE POWER (P)} * \text{PF}$$

$$P = \sqrt{3} * V * I$$

$$25000000 = 1.73 * 2300 * I_L$$

$$I_L = 6282.986 \text{ Amps (input current to PCS)}$$

STEP 2 THIRD HARMONIC FILTER DESIGN AT INPUT

$$\text{Harmonic\_freq} = 3 * f_{in}$$

$$V_{ph} = V_{in} / 1.732$$

$$\text{Inductance (Lf)} = \frac{V_{ph}}{2 * 3.14 * \text{Harmonic\_freq} * I_L}$$

$$\text{Capacitance(Cf)} = \frac{1}{4 * \pi^2 * \text{Harmonic\_freq}^2 * L_f} \text{ (condition of resonance)}$$

#### RESULTS

S.No Parameter  
value Unit

1	Per phase Voltage	1329.479769	Volts
2	Harmonic Frequency (max)	1500	Hz
3	Harmonic Frequency (min)	1002	Hz

4	Per phase current	6282.985675	Amps
5	Filter Inductor1 (max)	1.29843E-05	Henry
6	Tuned Capacitor1 (max)	0.00086792	Farad
7	Filter Inductor2 (min)	1.94376E-05	Henry

### STEP 3 AC TO DC COVERSION

#### CONFIGURATION 1 :USING UNCONTROLLED RECTIFIER

For a three phase full bridge rectifier the average value of dc voltage can be obtained over a  $\frac{\pi}{3}$  radian interval.

$$V_{dr} = \frac{1}{\pi} \int_{-\frac{\pi}{6}}^{\frac{\pi}{6}} \sqrt{2} V_{in} \cos \omega t d\omega t$$

$$V_{dr} = 1.35 * V_{in}$$

$$V_{dr} = 1.35 * 2300 = 3105 \text{ Volts}$$

$$V_{\text{positive\_p}} = \sqrt{2} * V_{in}$$

$$V_{\text{neg\_p}} = V_{\text{positive\_p}} * \cos 30^\circ$$

$$V_{pp} = V_{\text{positive\_p}} - V_{\text{neg\_p}}$$

Harmonic freq of diode =  $6 * F_{in}$   
(for six pulse converter)

Parameters	Value	Units
Input Voltage	2300	Volts
Rectified Voltage( $V_{dr}$ )	3105	Volts
Peak reverse voltage of diode	3105	Volts
Peak Voltage( $V_{\text{positive\_p}}$ )	3252.2	Volts
Peak Neg Voltage( $V_{\text{neg\_p}}$ )	2816.5	Volts
Peak to peak voltage ( $V_{pp}$ )	435.7122	Volts

### STEP 4 Calculate the current of inverter

We know,

Parameters	Range	Unit
Output Voltage	3400	Volts
Output Frequency (max)	300	Hz
Output frequency (min)	200	Hz
Power	20	MW

$$\text{REACTIVE POWER (P)} = \frac{20000000}{0.8} = 25000000 \text{ MVA}$$

Using equation (2)

$$25000000 = 1.73 * 3400 * I$$

$$I = 4250.255 \text{ Amps (output current of inverter)}$$

### STEP 5 Calculate the desired dc voltage for inverter

The amplitude modulation ratio ( $ma$ ) =  $V_{\text{cont.}} / V_{\text{tring.}} = 1$

line to line rms voltage at the fundamental frequency due to 120° phase displacement between Phase voltages can be written as

$$V_{LL} = \frac{\sqrt{3}}{\sqrt{2}} (V_{AN}) = \frac{\sqrt{3}}{2\sqrt{2}} ma V_d$$

$$V_{LL} = 0.612 ma V_d \text{ (} ma \leq 1.0 \text{)}$$

$$\therefore \text{DC I/P Voltage (} V_d \text{)} = \frac{V_{LL}}{0.612 * ma}$$

$$V_d = \frac{3400}{0.612 * 1} = 5556 \text{ Volts}$$

But  $V_{dr}$  from equation (8) comes out to be 3105V which is less than the desired  $V_d$  5556V.

Therefore, we connect a booster

### STEP 6 Booster calculations

$$\text{Duty ratio (D)} = \frac{V_d - V_{dr}}{V_d} \dots \dots \dots \text{eq (16)}$$

$$T_{on} = D * T_{total}$$

$$T_{off} = T_{total} - T_{on}$$

$$I_o = \frac{P_{\text{booster}}}{V_d}$$

$$I_{dc} = \frac{I_o}{1-D}$$

$$R = \frac{V_d}{I_o}$$

$$LB = \frac{T_{total} * V_d * D * (1-D)^2}{2 * I_o}$$

$$V_{\text{ripple}} = 0.01 * V_d$$

$$C = \frac{I_o * D * T_{total}}{V_{\text{ripple}}}$$

$$\tau = R * C$$

### STEP 7 Calculations for inverter design

$$\text{DC I/P Voltage (} V_d \text{)} = \frac{V_{LL}}{0.612 * ma}$$

$$\text{We know that, } P = \sqrt{3} V_{LL} I_o \cos \phi$$

$$I_o = 4245.3 \text{ Amps}$$

Peak rating of switch

$$V_T = V_d \text{ max}$$

$$I_T = \sqrt{2} I_o \text{ max}$$

DC side current (Drive input current) –

$$\text{Inverter\_id} = \frac{3 * V_{LL} * I_o}{V_d * 0.8}$$

Switch utilization factor –

Total switch utilization ratio of all six switches combines is-

$$\text{SUR} = \frac{(V_A)_{3\text{-Phase}}}{6 V_T I_T} = \frac{\sqrt{3} V_{LL} I_o \text{ max}}{6 * V_d \text{ max} * \sqrt{2} I_o \text{ max}}$$

$$= \frac{1}{2\sqrt{6}} * \frac{V_{LL}}{V_d \text{ max}} = \frac{1}{8} ma$$

### Results

Parameter	Value	Unit
$V_{out}$	3400	Volts

Ma (Modulation Index)	1	Amplitude Modulation Index	
Output frequency	300	Hz	
Output current	4245.3	Amps	
Peak rating of switch	8873.9	Amps	
switching frequency	5	Khz	
DC side current	3600	Amps	
Switch utilization factor	0.1249	12.49%	

#### STEP 8 Design of output harmonic filter

Design is similar to that of input filter. Just the values of output frequency are changed.

#### STEP 9 Calculations for snubber circuits

$$X_s = \frac{0.05 \cdot V_{LL}}{I}$$

$$X_c = \frac{0.05 \cdot V_{LL}}{\sqrt{3} \cdot I_{dc}}$$

$$I_{rr} = 0.09 \cdot I_{dc}$$

$$L_c = \frac{X_c}{2 \cdot \pi \cdot f_{out}}$$

$$C_{base} = L_c \cdot \left( \frac{I_{rr}}{V_{LL}} \right)^2$$

eq (34)

$$C_s = \frac{0.6 \cdot I_{dc}}{V_{LL}}$$

$$R_s = \frac{1.3 \cdot \pi \cdot V_{LL}}{I_{rr}}$$

$$W_{snubber} = 3 \cdot C_s \cdot V_{LL}^2$$

#### STEP10 HEAT CALCULATIONS

R<sub>thJC</sub> - thermal resistance junction-case;

T<sub>j(max)</sub> - maximum junction temperature.

T<sub>C</sub> - case temperature

$$\Delta T = P_{tot} \cdot R_{thJC}$$

The difference between junction and case temperature is

$$P_{tot} = \frac{\Delta T}{R_{thJC}} = \frac{T_j - T_c}{R_{thJC}}$$

Power dissipation of IGBT :

Following Parameters are considered from manufactures data sheet ;

$$R_{thJC} = 0.055 \text{ K/W}$$

$$T_{j(max)} = 150 \text{ }^\circ\text{C}$$

$$T_c = 25 \text{ }^\circ\text{C for 565 Amps (from manufactures data sheet)}$$

$$P.D = 150-25$$

$$0.055$$

$$P.D = 2272.72 \text{ watts for 565 amps}$$

We are using these power devices at 400 Amps max

Hence T<sub>c</sub> = 80 °C for 400 Amps (from manufactures data sheet)

$$P_{total} = P.D = 150-80$$

$$0.055$$

$$P_{total} = 1.27 \text{ kW}$$

#### 6. MATLAB PROGRAM FOR SCHEME 1

```
% Drive design using a matlab program(uncontrolled rectifier)
clear all;
clc;
% Assign necessary constants and parameters
sm = 1.2;
pie = 3.14;
ma = 1;
pf = 0.8;
% Assign the input for front end converter
Vin = input('Enter the input voltage(in volts) = ');
Power = input('Enter the power for which drive is to be
designed(in watts)= ');
Fin_min = input('Enter the min input frequency(in hertz)= ');
Fs = input('Enter the switching frequency(in hertz)= ');
h = input('Enter the value of harmonics=');
RthJC = input('Enter the thermal resistance junction case =');
Tj = input('Enter the max junction temp =');
Tc = input('Enter the case temp =');
Fout = input('Enter the output freq (in hertz)');
% Assign the desired voltage for motor
VLL = input('Enter the desired voltage (in volts) = ');
% Calculations from the above parameters
IL = Power/(1.732*Vin*pf);
Iout = Power/(1.732 * VLL *pf);
% Design of uncontrolled rectifier as front end converter
Vdr = 1.35*Vin;
disp(Vdr)
Vpositive_p = 1.414*Vin;
Vneg_p = Vpositive_p*cosd(30);
Vpp = Vpositive_p - Vneg_p;
Is = IL/1.414;
Id = Is/.816;
Is1 = (1/(pie*(6^.5)))*Id;
Ish = Is1/h;
L = input('Enter the value of inductor =');
Vdr1 = (1.35*VLL) - (3/(pie*2*pie*Fin_min*L*Id));
Isc = (VLL/1.732)/(2*pie*Fin_min*L);
Vdmax = 2*1.414*Vin;
Drating = 1.732*Vin*sm;
Diode_freq = 6* Fin_min;
% Harmonic filter design at input
H_freq_min = 3*Fin_min;
Vph = Vin/1.732;
Lf_min = Vph/(2*pie*H_freq_min*IL);
Cf_min = 1/(4*(pie^2)*(H_freq_min^2)*Lf_min);
% Calculate the input desired for inverter
Vd = VLL/(0.612*ma);
disp(Vd)
```

```

disp('Since Vdr is less than Vd we need a booster : ')
%Calculations for booster circuit
efficiency = .95;
Pow_inverter = Power/efficiency;
Pbooster = Pow_inverter;
Io = Pbooster/Vd;
D = (Vd-Vdr)/Vd;
Ttotal = 1/Fs;
Ton = D*Ttotal;
Toff = Ttotal-Ton;
Idc = Io/(1-D);
R = Vd/Io;
Lb = Ttotal*Vd*D*((1-D)^2)/(2*Io);
Vripple = .01*Vd;
C = (Io*D*Ttotal)/Vripple;
Tau = R*C;
% Design of inverter
disp('Output Voltage :')
disp(VLL)
SUR=VLL/(2*(6^5)*Vd);
SURmax = ma/8;
Inverter_id=Power/Vd1;
Vt=Vd;
It=1.414*IL;
Mf=Fs/Fout;
%Design of output filter
Third_harmonic=3*Fout;
Lout=Vph/(2*pie*Third_harmonic*IL);
Cout=1/(4*(pie^2)*(Third_harmonic^2)*Lout);
XLout=2*pie*Third_harmonic*Lout;
Xcout=1/(2*pie*Third_harmonic*Cout);
% Design of snubber circuits
Xs=.05*VLL/Iout;

```

```

Xc=.05*VLL/(1.732*Idc);
Irr =0.09*Idc;
Lc=Xc/(2*pie*Fout);
Cbase=Lc*((Irr/VLL)^2);
Cs=.6*Idc/VLL;
Rs=(1.3*1.414*VLL)/Irr;
Wsnubber=3*Cs*(VLL^2);
% Calculation of thermal loss
To= Tj-Tc;
Ptot= To/RthJC;

```

## REFERENCES

- [1] R. Bhatia, H. U. Krattiger, A. Bonanini, et al., Adjustable Speed Drive with a Single 100-MW Synchronous Motor.
- [2] W. C. Rossmann and R. G. Ellis, Retrofit of 22 Pipeline Pumping Stations with 3000-hp Motors and Variable-Frequency Drives, IEEE Transactions on Industry Applications.
- [3] S. Malik and D. Kluge, ACS1000 World's First Standard AC Drive for Medium-Voltage Applications, ABB Review, No. 2, pp. 4–11, 1998.
- [4] IEEE Standard 519-1992, IEEE Recommended Practices and Requirements for Harmonic Control In Electrical Power Systems, IEEE Inc., 1993.
- [5] J. K. Steinke, Use of an LC Filter to Achieve a Motor-Friendly Performance of the PWM Voltage Source Inverter, IEEE Transactions on Energy Conversion, Vol. 14, No. pp. 649–654, 1999.
- [6] N.Mohan.T.M.Undeland and W.P.Robbins, Power Electronics: Converters, Applications and Design, John Wiley & Sons, Inc, New York, 1995
- [7] Muhammad H. Rashid , Power Electronics Handbook, Second Edition.