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MECHANICAL CONSIDERATIONS – PART 6
Drive
Motor
Coupling
Machine
Flow of Power
THERMAL ANALYSIS – PART 7
POWER STAGE DESIGN – PART 8
MOTOR CONTROL PROBLEMS AND SOLUTIONS – PART 9
FIRMWARE DEVELOPMENT – PART 10
Day Two Topics
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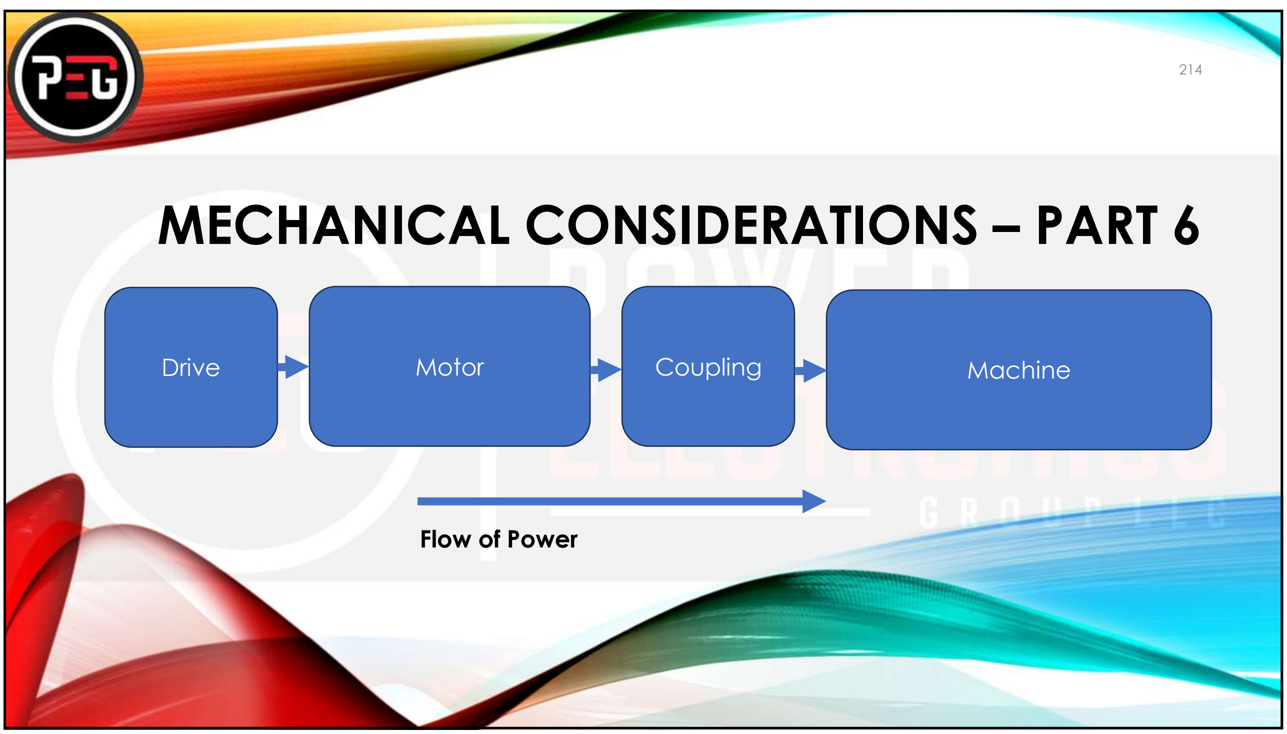
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MECHANICAL CONSIDERATIONS – PART 6
Drive
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AGENDA

- Motor Sizing - General Considerations.
- Torque-Speed Profile;
- Dynamics of Mechanical Drive Systems;
- Power Transmission Systems;
- Gearing Systems;
- Modes of Mechanical Failure and Preventive Treatment

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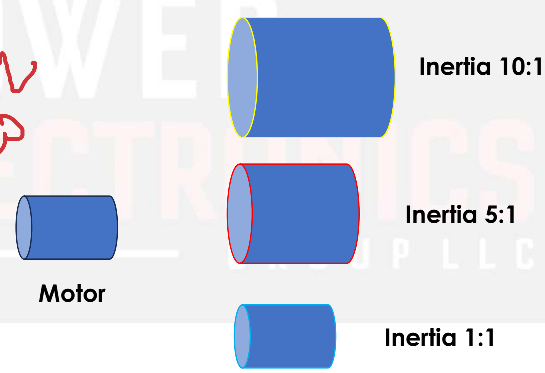
GENERAL LOAD REQUIREMENTS

- Motor Sizing
  - Load inertia (moment of inertia)
  - Required torque and speed
    - Peak torque;
    - Root mean square torque;
    - Maximum speed.
  - Acceleration and deceleration profiles
  - Duty cycle and thermal limits
  - Friction and external forces
  - Mechanical losses;



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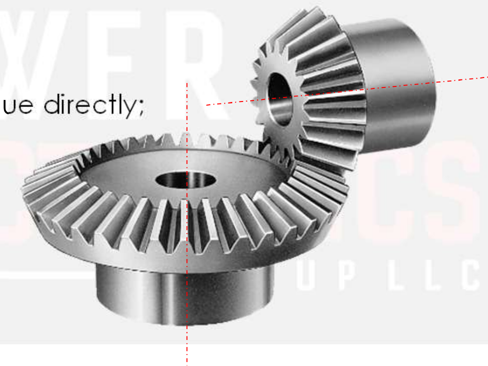
GENERAL LOAD REQUIREMENTS

- Horizontal Motion axis;
  - Gravitational forces don't influence drive torque directly;
- Vertical Motion axis;
  - motor must counteract gravitational force.



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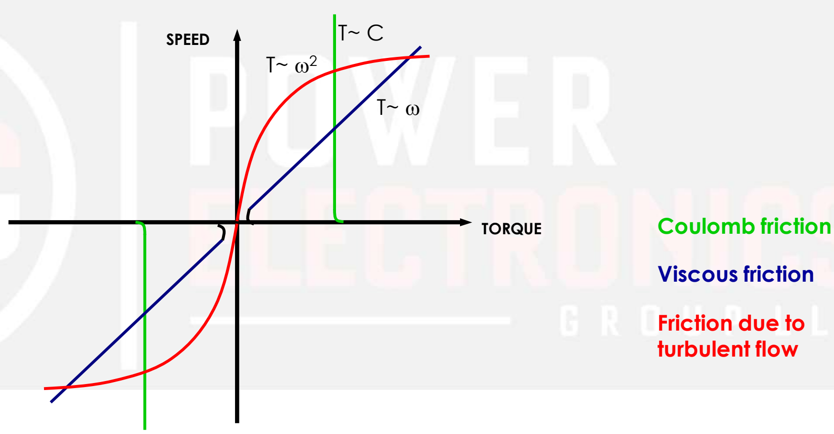
TORQUE-SPEED CHARACTERISTIC



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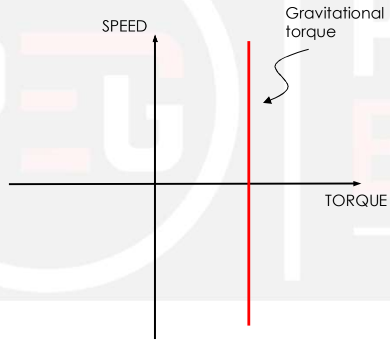
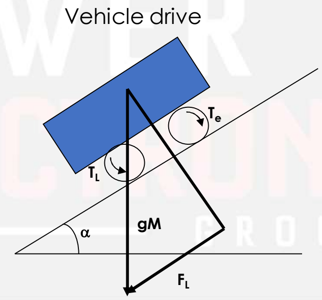
TORQUE-SPEED CHARACTERISTIC





$T_L = rF_L = r\,g\,M \sin\alpha$

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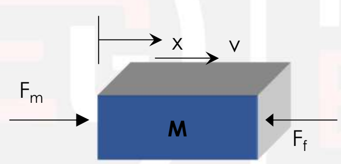
DYNAMICS OF MECHANICAL DRIVE SYSTEM



Newton's law

$$F_m - F_f = \frac{d(Mv)}{dt}$$

$$F_m - F_f = M\frac{d(v)}{dt} = M\frac{d^2x}{dt^2} = Ma$$

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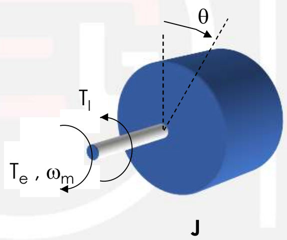
DYNAMICS OF MECHANICAL DRIVE SYSTEM

Rotational motion



$$T_e - T_l = \frac{d(J\omega_m)}{dt}$$

$$T_e - T_l = J\frac{d(\omega_m)}{dt} = J\frac{d^2\theta}{dt^2}$$

DYNAMICS OF MECHANICAL DRIVE SYSTEM

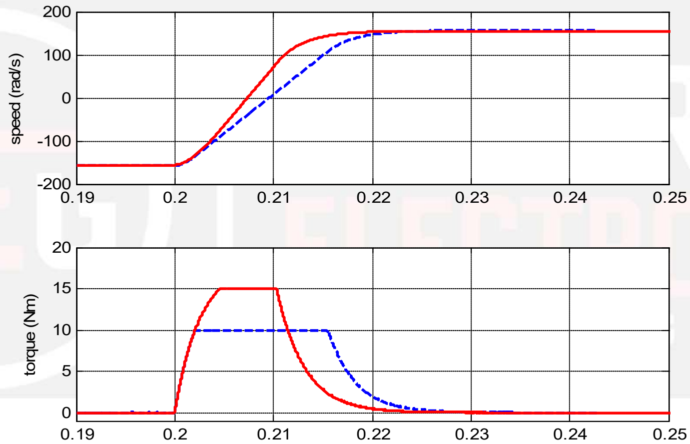
For constant J,

$$T_e = T_l + J\frac{d\omega_m}{dt}$$

$J\frac{d(\omega_m)}{dt}$ Torque dynamics – present during speed transient

$\frac{d(\omega_m)}{dt}$ Angular acceleration

DYNAMICS OF MECHANICAL DRIVE SYSTEM



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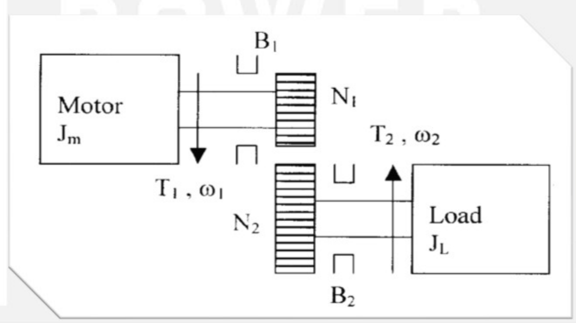
GEAR BOXES

$$T_2 = nT_1$$



Relation b/w the i/p and o/p of a single stage gear

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GEAR BOXES

Resultant mechanical constants at the shaft are,

$$J = J_m + \left[\frac{N_1}{N_2}\right]^2 J_1 \qquad B = B_1 + \left[\frac{N_1}{N_2}\right]^2 B_2$$

Inertia **Frictional Forces**

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GEARS

- **Spur Gears**
  - Simplest and most common type of gears.
  - Their teeth are Straight, and Parallel to the gear axis.
  - No significant force is generated along the shaft's axis (axial or thrust force)

Spur gears

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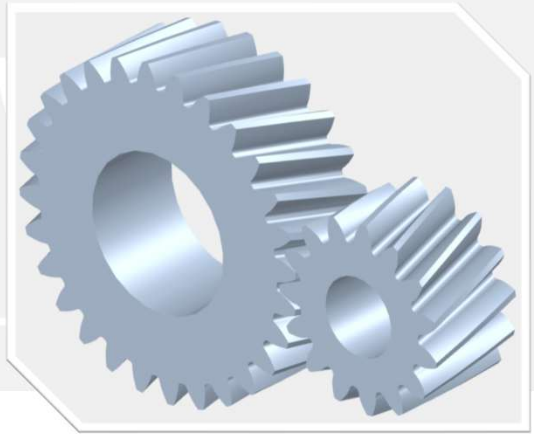
GEARS

- Helical Gears
  - High contact ratio

Spur Gears	Helical Gears
Cheaper, simpler, noisier	Quieter, stronger, needs thrust bearings
No axial forces	Produces axial forces
Good for low-cost systems	Ideal for high-speed or precision drives



Helical Gears

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PLANETARY GEAR BOX

- Torque thru equally spaced planetary wheels;
- Gearbox has no bending moments;
- Smaller size.

Planetary gear box

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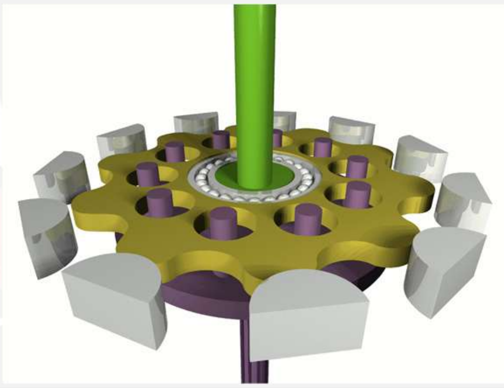
CYCLOID SPEED REDUCER

- Plain disc rolling around a stationary ring;
- Follows an eccentric path at speed n1;
- Rotation in the opposite direction with n2.



Major components of cycloid speed reducer

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LEAD SCREW

- Lead is equal to the pitch;
- Direct contact between the screw and the nut;
- Inefficient Drive.

Lead screw

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Ball Screw

- Low Friction;
- Good Dynamic Performance.

Ball screw

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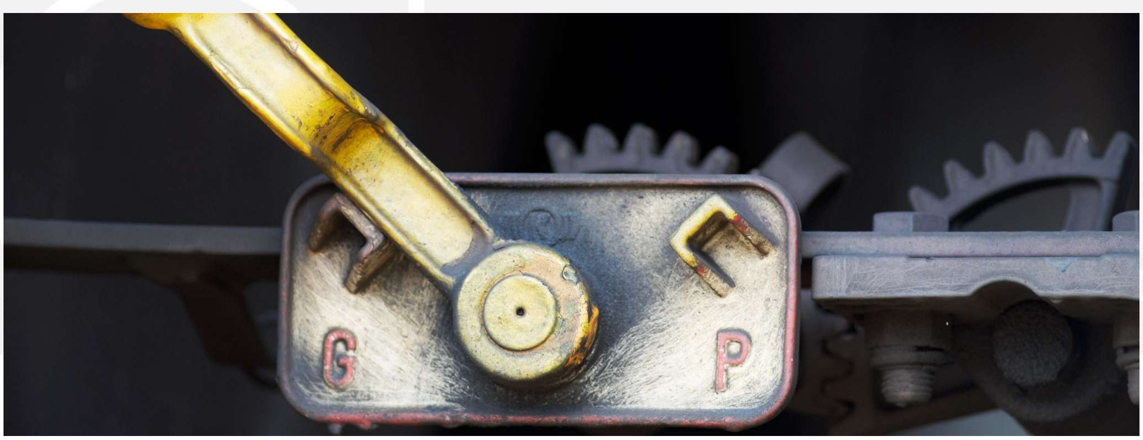
MOTOR MOUNTING TECHNIQUES AND VIBRATION ISOLATION



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INTRODUCTION

- Mounting Principle;
- Mounting methods with applications;
- Role of coupling;
- Drives;
- Torque bar;
- Vibration isolation.

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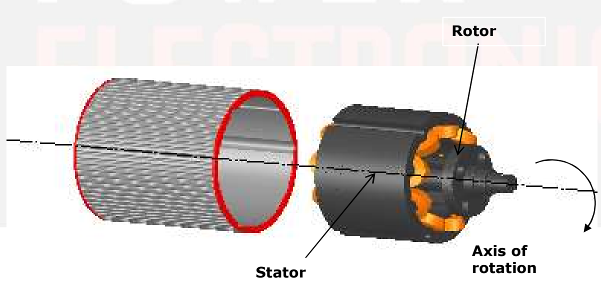
MOUNTING PRINCIPLE

- Axis of stator and rotor and that of rotation should be the one and same.



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MOUNTING PRINCIPLE

- Flat Surface
- Rigid Surface

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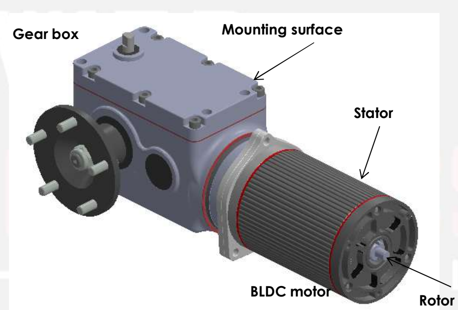
WHEELCHAIR MOTOR MOUNTING

- Surface mounting.
- Inner runner motor.



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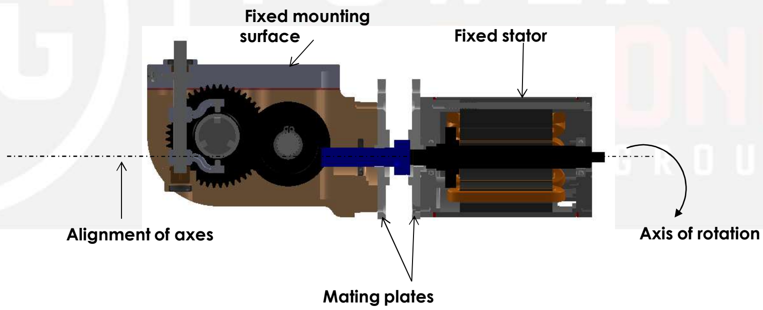
WHEELCHAIR MOTOR MOUNTING

- Critical mating plate;
- Fixed stator.



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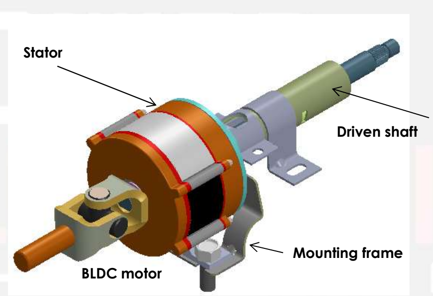
POWER STEERING MOTOR MOUNTING

- Mounting frame;
- Inner runner motor.



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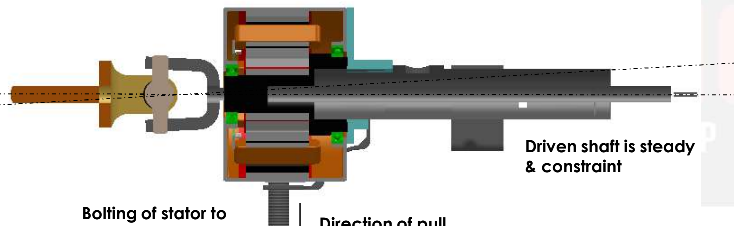
VIOLATION OF THE PRINCIPLE

- Pulling forces;
- Dynamics of Eccentricity.



POOR MEHTOD OF MOUNTING

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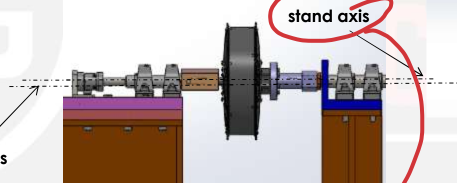
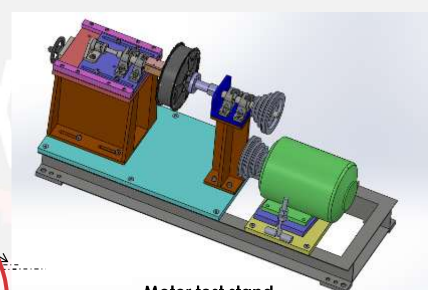
VIOLATION OF PRINCIPLE

- Axis are not same.





Motor test stand

POOR MEHTOD OF MOUNTING

significance of stand axis?

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ROLE OF COUPLINGS

- Connecting shafts & power transmission;
- Mechanical flexibility;
- Reduce transmission of shock loads from one shaft to another.

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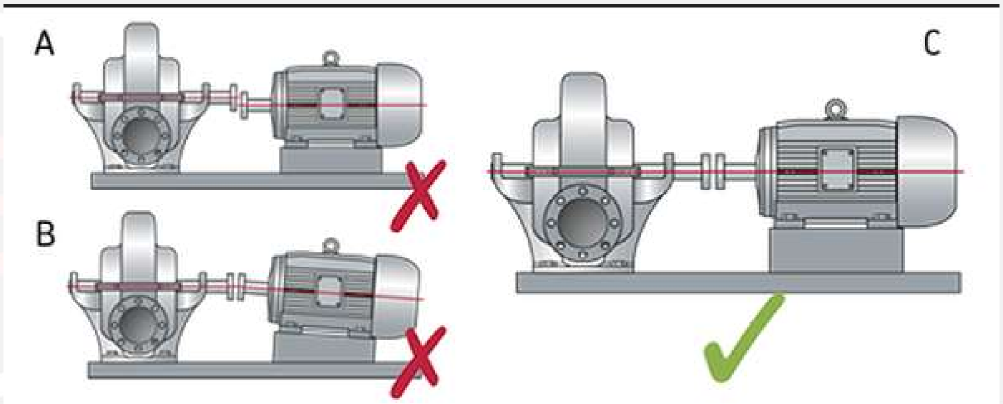
mounting v/s coupling?

ROLE OF COUPLINGS



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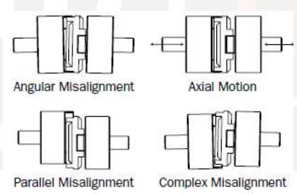
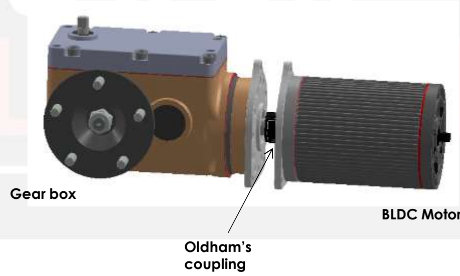
FLEXIBLE COUPLINGS

- Oldham's couplings:
- Shock/vibration absorber.





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DRIVES

- Belts & pulleys;
- Gear drives;
- Chain & sprockets.

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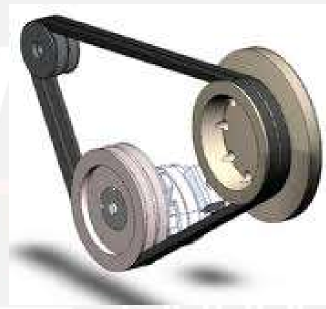
BELTS & PULLEY'S

- Flexible, shock absorber;
- Efficient;
- Long distance power transmission;



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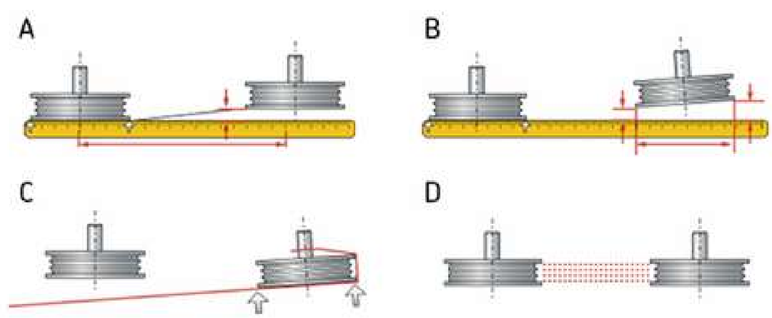
BELTS & PULLEYS



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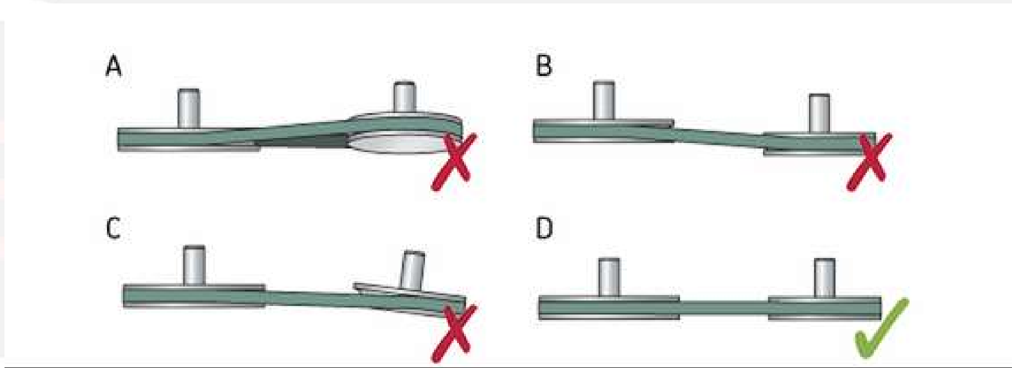
BELTS & PULLEYS



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GEAR DRIVE MOUNTING

- Axis of power transmission is one and same.
- Rigid mounting.

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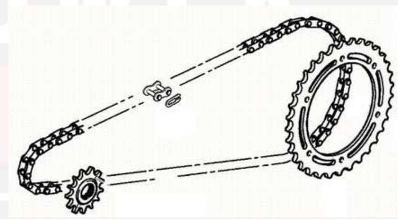
CHAIN & SPROCKETS

- Employed for long & short distance;
- Load on shafts is less;
- Multiple shaft can work.



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VIBRATION ISOLATION

- Mechanical Causes
  - Unbalanced loading
  - Damaged bearing
  - Air-gap
  - Loose Hardware
  - Foundation/Uneven mounting surface
  - Lack of lubrication

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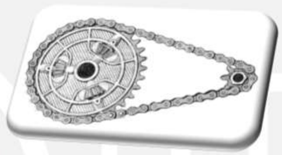
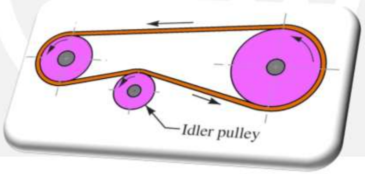
COUPLINGS/GEARING


Toothed Gear


Roller Chain Drive


Silent Chain Drive


V-Belt Drives



Flat Belt with Idler


Open Flat Belt Drive


Friction Drive

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POWER TRANSMISSION

- Need for Drives
    - Speed
    - Torque
    - Different Axis of Rotation

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TYPES OF POWER TRANSMISSION

- Mechanical
- Hydraulic
- Pneumatic
- Electrical

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TYPES OF MECHANICAL DRIVES

- Mode of power transmission
  - Transmission by friction
    - With Direct Contact, e.g., Friction Drive
    - With Flexible connection, e.g., Belt Drives

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TYPES OF MECHANICAL DRIVES

- Mode of power transmission
  - Transmission by mesh
    - With Direct Contact, e.g., toothed and Worm gears
    - With flexible connection, e.g. Chain Drives

TYPES OF MECHANICAL DRIVES

- Mode of power transmission
  - By the change of the Velocity Ratio
    - Step by Step Change
    - No Change
    - Variable speed drives e.g., Automotive Vehicles

TYPES OF MECHANICAL DRIVES

- Mode of power transmission
  - By the position of shaft-
    - Parallel shaft
    - Shafts at right angles
    - Intersecting shafts

CONCEPT OF PERIPHERAL SPEED

- Peripheral speed can be calculated by,

$v_1=\omega D_1/2$

or $v_1=\pi D_1 n_1/60$

Peripheral speed of the driven member,

$v_2= \omega_2 D_2/2$

CONCEPT OF PERIPHERAL SPEED

or $v_2 = \pi D_2 n_2/60$
Without slipping, the peripheral speeds should be same
v1=v2
i.e. $\omega_1 D_1/2 = \omega_2 D_2/2$
or $\pi D_1 n_1/60 = \pi D_2 n_2/60$

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CONCEPT OF PERIPHERAL SPEED

Whence,
$\omega_1/\omega_2 = D_2/D_1 = n_1/n_2$
Where D_1 and D_2 diameters
$\omega_1(n_1)$ and $\omega_2(n_2)$ are angular speeds

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CONCEPT OF PERIPHERAL SPEED

- Angular speed ratio or velocity ratio
  $(VR)_{1,2}=\omega_1/\ \omega_2=n_1/n_2=D_2/D_1$
- Sign of VR will depend on the directions of the angular velocities

EFFICIENCY OF POWER TRANSMISSION

- **Output Power**

$P_o=P_i \times \eta_i$

M_t= torsional moment, Nm

ω=angular speed , radians/s

M_t=kWx1000/ω
=kW x 1000/(2 π f)
=9550xkW/rev/min (Nm)

EFFICIENCY OF POWER TRANSMISSION

$Mt_i.\omega_i = Mt_1.\omega_1.\eta_{1i}$

Hence

$Mt_i = Mt_1.\omega_1 / \omega_2.\eta_{1i}$

$= Mt_1.(VR)_{1,}i.\eta_{1i}$

Mt_2=torsional moment on the second shaft

$= Mt_1.(VR)_{1,2}.\eta_{1,2}$

EFFICIENCY OF POWER TRANSMISSION

- Total Speed Ratio,

  $(VR)_{1,n} = (VR)_1 \times (VR)_2 \times (VR)_3 \ldots\ldots\ldots\ldots (VR)_n$

- Total efficiency of the multistage drive,

  $\eta_{1,n} = \eta_1 . \eta_2 . \eta_3 \ldots\ldots\ldots\ldots \eta_n$

SELECTION OF A MECHANICAL DRIVE

- Power transmission
- Angular velocities
- Distance
- Overall dimensions

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VELOCITY RATIO

- Velocity ratio obtained by
  - Toothed wheel gears
  - Worm gears

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VARIOUS DRIVES IN SERIAL ORDER ARE

1	Toothed Gears	Velocity Ratio	From 4 to 20
2	Roller Chain Drives	Velocity Ratio	From 6 to 10
3	Silent chain Drives	Velocity Ratio	Up to 15
4	V-belt Drives	Velocity Ratio	From 8 to 15
5	Flat belt with idler	Velocity Ratio	Up to 10
6	Open flat belt drive	Velocity Ratio	Up to 5
7	Friction Drives	Velocity Ratio	From 5 to 1

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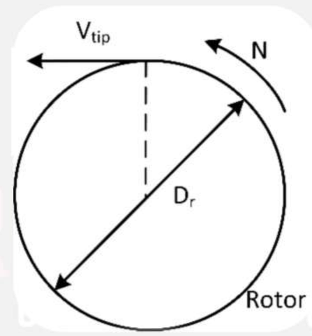
PERIPHERAL VELOCITY IMPACT

- Transmitted Power is Proportional to Peripheral Velocity
  - Centrifugal force increases with speed
    - Belt load increases & tension reduces
  - Limiting factors for chain drives
    - Increased Teeth wear and tear in gear drives



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MAXIMUM PERIPHERAL SPEEDS FOR VARIOUS DRIVES

- Flat Belts= v_{max} ≤25 m/s
- Belt (artificial fiber)= v_{max} ~50 m/s
- V belts= v_{max} ~ 25 to 30 m/s
- V belt (steel wire core)= v_{max} =40 m/s
- Chain Drives= v_{max} =25-30 m/s

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TRANSMITTED POWER

- Power transmission can be increased by
  - Worm gear
  - Toothed gears
  - V belt & chain drives

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MAXIMUM TRANSMITTED POWER FOR VARIOUS APPLICATIONS

Sr.No.	Application	Maximum Transmitted Power (kW)
1	V Belt	735 to 1100
2	Flat Belt	1835
3	Chain Drives	3670
4	Friction Drives	150 to 225

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LOSSES IN TRANSMISSION

- Two parts of losses
    - Constant Part
    - Variable Part

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LOSSES IN TRANSMISSION

Sr. No.	Type of Drive	Losses in %
1	Toothed Gears	1
2	Chain Drive	2
3	Flat-belt Drives	2.5
4	V-belt Drives	4
5	Friction Drives	4
6	Worm Gear	10 to 25

Over time these losses increase

WEIGHT, SIZE AND COST OF DRIVES

- Coupling Sizes (based on distance)
  - Decreasing Centre distances for various Drives
    - Flat belt (**Largest**)
    - Flat belt with idler pulley
    - V-Belt
    - Chain Drive
    - Toothed Gears
    - Worm Gears (**Smallest**)

WEIGHT, SIZE AND COST OF DRIVES

- Coupling Sizes (Based on Width)
  - Size in decreasing order of the wheels or pulleys
    - Chain (**Largest**)
    - Flat Belt
    - Flat belt with idler pulley
    - Toothed Gears
    - V-Belts
    - Worm gear (**Smallest**)

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WEIGHT, SIZE AND COST OF DRIVES

- **Weight of the drives**
  - Worm gear (Least)
  - Toothed gears (Largest)

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WEIGHT, SIZE AND COST OF DRIVES

- **Cost of the Couplings/Drives**
- V-belt drive is taken as unity, then for other drives
    - Flat Belt- 1.06
    - Flat Belt with idler pulley- 1.25
    - Worm gear-1.25
    - Chain drive-1.40
    - Toothed gear-1.65

CHARACTERISTICS OF BASIC TYPES OF DRIVES

Type of drive	Transmitted Power kW	Peripheral Speed m/s	Speed Ratio	Efficiency
1. Friction	upto 20 (100)	upto 20	upto 7 (25)	0.80—0.92
2. Flat belt	upto 100 (1500)	5—30 (100)	upto 4 (10)	0.92—0.98
3. V-belt	upto 50 (1000)	5—30	upto 7 (15)	0.87—0.97
4. Straight tooth gear	upto 10000	25	upto 6 (10)	0.92—0.99
5. Helical tooth gear	upto 50000	25 (140)	upto 7 (20)	0.94—0.99
6. Worm gear	upto 100	upto 35	8—100 (1000)	0.75—0.90
7. Chain	upto 200 (5000)	upto 25	upto 15	0.94—0.98

Note : The highest known values are given in brackets.

CHARACTERISTICS COMPARISON

Characteristics	Belt Drive	Gear Drive
1. Initial cost	Cheaper	Costly
2. Maintenance cost	Low	Considerable
3. Lubrication	None	Must
4. Shock absorption	Better	Not so good, depends upon gear material.
5. Life	1—5 years	Depends upon materials. Longest service life if properly lubricated, is generally more than 10 years.
6. Environment	Can not work under all types of conditions	If properly lubricated, can work under any condition and also under high temperature.
7. Noise	Low	Can be maintained low with proper lubrication and by adjusting shaft distances.
8. Force or Loads	Very heavy loads cannot be transmitted under normal conditions	Quite heavy loads can be transmitted as the gear size is practically unlimited.
9. Direction of input and output	Can be changed but not that easily and efficiently	Can be changed easily.

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MODES OF MECHANICAL FAILURE AND PREVENTIVE TREATMENT

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INTRODUCTION

- Mechanical failure;
- Various mechanical failure modes;
- Reasons behind motor failure & prevention.

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MECHANICAL FAILURE

- Complex interaction of ***load***, ***time***, and ***environment***.
- Corrossive environments

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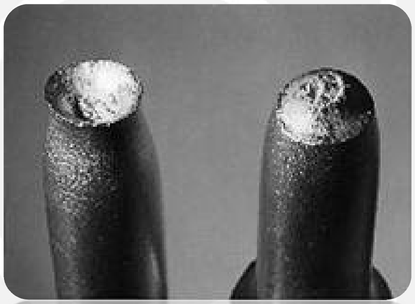
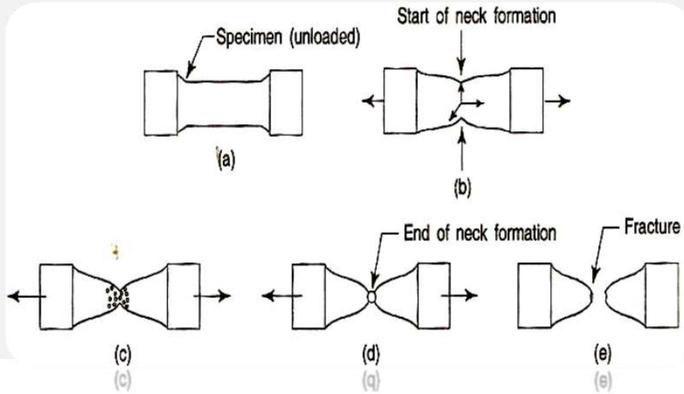
MODES OF MECHANICAL FAILURE

- Ductile fracture (High Energy Absorption)





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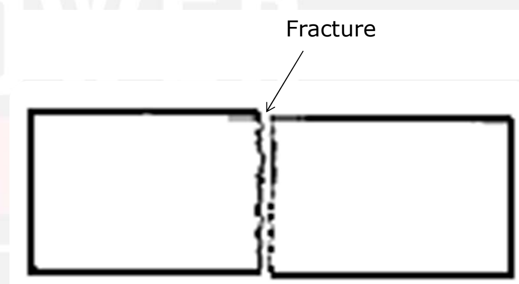
MODES OF MECHANICAL FAILURE

- Brittle fracture (Low Energy Absorption)



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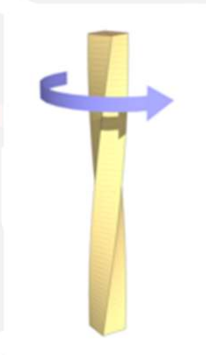
MECHANICAL FAILURE

- Torsion Failure



➢ Yielding Failure

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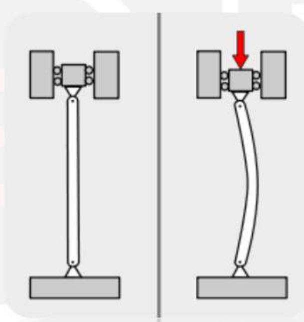
MECHANICAL FAILURE

- Buckling



➢ Corrosion

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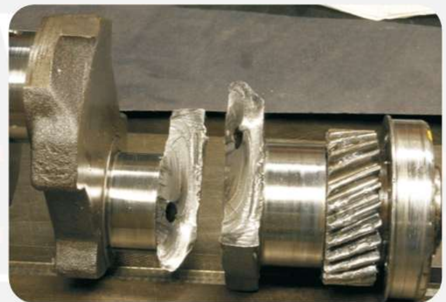
MECHANICAL FAILURE

- Wear

➢ Fatigue (Repeated)



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MODES OF FAILURE IN BLDC MOTORS

- Stator & Rotor Faults.
- Bearing faults.
- Shaft misalignment.

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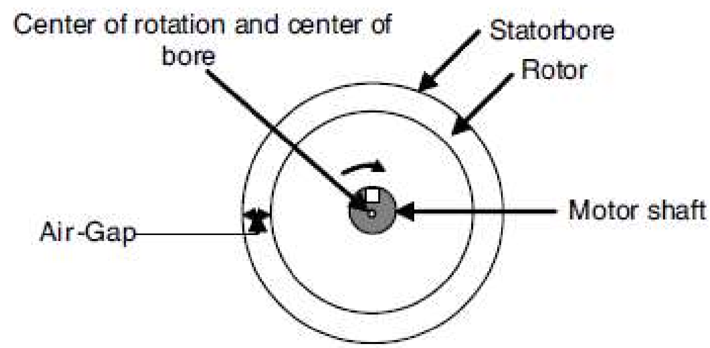
STATOR & ROTOR FAULTS

- Eccentricity



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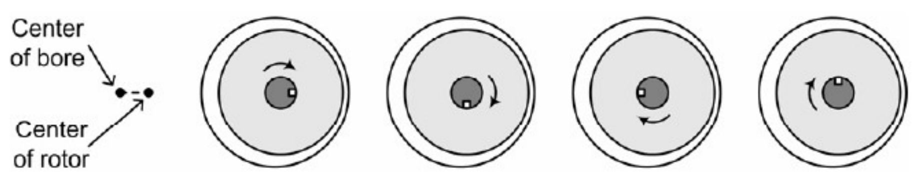
STATOR & ROTOR FAULTS

- Static Eccentricity



Static air-gap eccentricity

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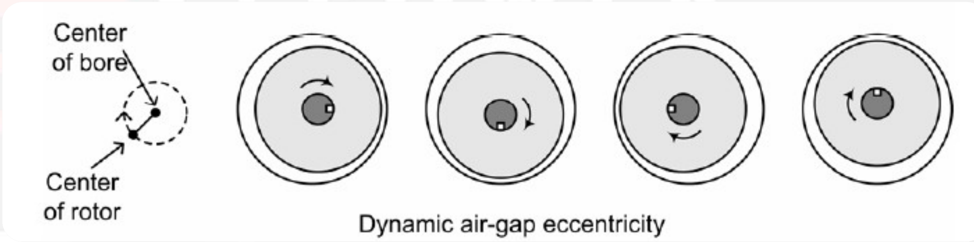
STATOR & ROTOR FAULTS

- Dynamic Eccentricity
  - Tolerances, Bent Shaft, Bearing Wear



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STATOR & ROTOR FAULTS

- Damaged rotor Magnets

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PREVENTION

- Preventive treatment
  - ✓ Improve the assembly methods.
  - ✓ Balancing the load.
  - ✓ Dynamic analysis of rotor & stator.
  - ✓ Less handling of material.

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BEARING FAULTS

Flaking

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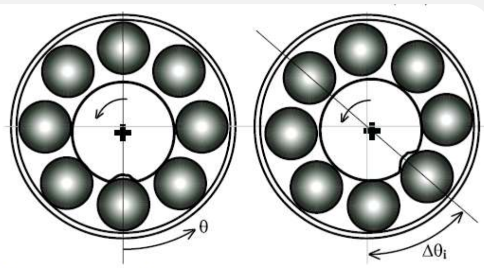
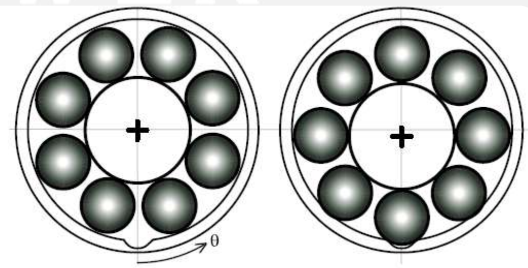
BEARING FAULTS



Radial rotor movement due to an inner bearing raceway defect.



Radial rotor movement due to an outer bearing raceway defect.

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BEARING FAULTS

- Preventive treatment
  - ✓Revaluate interference
  - ✓Review the precision of shaft & housing
  - ✓Improve assembly methods
  - ✓Prevent misalignment
  - ✓Time to time inspection & maintenance

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BEARING FAULTS

- Cause
  - Excessive load
  - Improper mounting
  - Insufficient clearance
  - Improper lubrication

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BEARING FAULTS

- Cause
  - Contamination
  - Rust
  - Drop in hardness due to variable
  - temperature
  - Improper precision in shaft & housing

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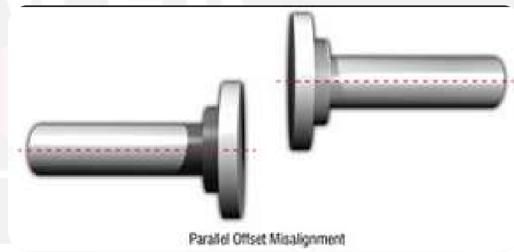
SHAFT MISALIGNMENT

Angular offset alignment



Parallel offset alignment

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SHAFT MISALIGNMENT

- **Causes:**
  - Reaction forces and torques in the coupling, and finally torque oscillations and dynamic air gap eccentricity in the driving machine.
- **Effect:**
  - Cause a slight unbalance in the rotor and produce undesired vibrations. Such vibrations eventually weaken the coupling and cause it to fail.
  - They also stress the motor bearings thereby lowering their life.

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SHAFT MISALIGNMENT

- **Preventive Treatment**
  - ✓ Reduce excessive axial and radial forces on the bearings to insure longer bearing life and rotor stability under dynamic operating conditions;
  - ✓ Maintain proper internal rotor clearances;
  - ✓ Eliminate the possibility of shaft failure from cyclic fatigue;
  - ✓ Improve assembly methods & handlings;
  - ✓ Improve the precision of shaft & housing.

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THERMAL ANALYSIS – PART 7

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STEADY STATE THERMAL BEHAVIOR

$$T_{ss} = 80.(A_s)^{-0.7}.P_{loss}^{\ \ 0.85}$$

A_s is in in^2;
T_{ss} is in degree Celsius;
P_{loss} is in Watts.

Note: A_s- Surface area of the entire body is to be considered here;

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STEADY STATE THERMAL BEHAVIOR

$$T_{ss} = 80.\left(\frac{A_s}{2.54^2.10^2}\right)^{-0.7}.P_{loss}^{\ \ 0.85}$$

A_s is in mm^2;
T_{ss} is in degree Celsius;
P_{loss} is in Watts.

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ASSUMPTIONS

- Object is a black body;
- Natural Air Cooling;
- Object is vertical;
- Natural air flow is not obstructive;
- Prominent heat flow is through natural convection.

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WHAT DOES THIS MEAN

- Assume Surface Area of 1 in^2 and 1 Watt of Power Loss
  - Temperature Rise = 80 deg. C
- Double the surface area
  - Temp Rise = 50 deg. C
- Double it again
  - Temp Rise = 30 deg. C

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WHAT DOES THIS MEAN?

- 10 Watts, 50 deg. C Temp Rise
  - Surface Area = 32 in^2 (20,680 mm^2)

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ESTIMATE LOSSES BASED ON MOTOR DIMENSIONS

- D = 90mm
- L = 100mm
  - Surface Area = 636,172 mm^2
  - For Temp Rise = 50 deg. C
  - Max Ploss = 168 Watts
  - Adding ribs could greatly increase power dissipation.

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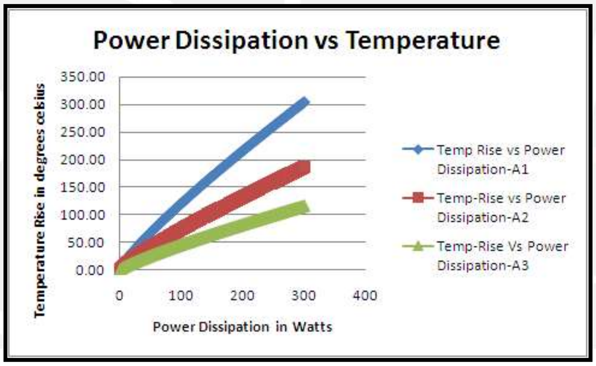
ESTIMATE LOSSES BASED ON MOTOR DIMENSIONS TSA



A1=98,000 sqmm;
A2=196,000 sqmm;
A3=392,000 sqmm;

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TRANSIENT BEHAVIOR

- Temp Rise of the Windings

$$T_{ss} = 80.(A_s)^{-0.7}.P_{loss}^{0.85}$$

$$\Delta T = (T_{ss}).(1 - e^{-\frac{t}{\tau_w}})$$

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WINDING THERMAL ANALYSIS

- Estimate Winding Losses
  - Copper Losses
  - Core Losses
- Estimate Thermal Time Constant

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MODES OF HEAT TRANSFER

- Three modes of Heat Transfer
  - Conduction
  - Convection
  - Radiation

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CONDUCTION

- Through a conduction medium
  - Air;
  - Metal;
  - Liquid;
  - Etc.

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CONVECTION

- Natural air;
- Forced Air;
- Natural Liquid;
- Forced Liquid.

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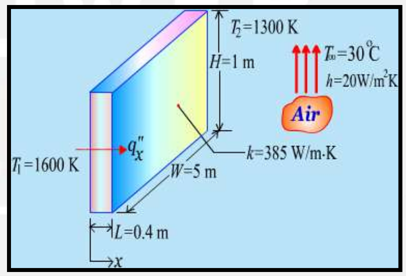
CONDUCTION

$$\frac{Q}{A} = k.\frac{(T1 - T2)}{L}$$ **Heat Flux**

$$\frac{Q}{A} = 385\frac{W}{m}K.\frac{(1600 - 1300)}{0.4}$$

$$\frac{Q}{A} = 385{,}000\frac{W}{m^2}$$



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CONDUCTION

- Q= Heat in Watts;
- A=Area of cross section (in contact with source) in sq-meter;
- T= Temperature in Kelvin or deg. C;
- L=Thickness in meter;
- W=Width in meter;
- H=Height in meter;
- k=Thermal conductivity of the material in W/m°K;
- R_{th}=Thermal resistance in °K/W;

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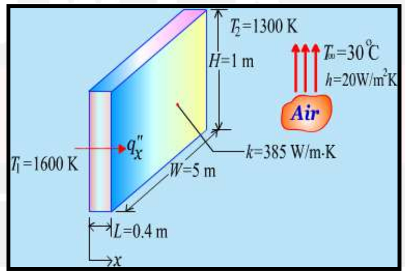
CONVECTION

$$\frac{Q}{A} = h.(T1 - T2)$$

$$\frac{Q}{A} = 20\frac{W}{m^2}K.(1300 - 273 - 30)$$

$$\frac{Q}{A} = 19{,}940\frac{W}{m^2}$$



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CONVECTION

- h = convective heat transfer coefficient
  - Forced Air Convection = 200W/m^{2}K;
  - Free Convection with Water = 1000W/m^{2}K;
  - Forced Convection with Water = 10,000W/m^{2}K;

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RADIATION

$$P = \varepsilon.\sigma.A_s.T^4$$

$$\varepsilon = Emissivity$$

$$\sigma = Stefan - Boltzan$$

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THERMAL ANALYSIS

- The above three are sufficient to define the steady state heat transfer model.
- How do we build a time dependent model?

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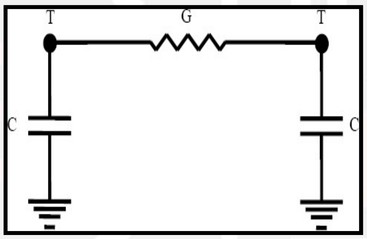
THERMAL NETWORK ELEMENTS



$$C = \rho . V . C_p$$

Conductive heat transfer;

$$R_{th} = \frac{\Delta T}{Q} = \frac{L}{A_s k}$$

Convective heat transfer;

$$R_{th} = \frac{\Delta T}{Q} = \frac{1}{A_s h}$$

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THERMAL NETWORK ELEMENTS

- Q= Heat in Watts;
- A_s=Area of cross section in sq-meter;

  Note: A_s=Surface area in contact with the heat source only;
- T= Temperature in Kelvin;
- L=Thickness in meter;
- k=Thermal conductivity of the material in W/m°K;

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THERMAL NETWORK ELEMENTS

- Rth=Thermal resistance in °K/W;
- h=Convective heat transfer coefficient in W/m^2°K;
- C=Specific heat capacity of the body in J/°K;
- Cp=Specific heat constant in J/Kg°K;
- ρ=Density of the material in Kg/m^3;
- V=Volume in m^3;

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THERMAL NETWORK ELEMENTS

Meaning	Material Properties	Natural Air	Aluminum	Stainless steel	Silicon steel	Steel chr	Steel carbon	copper	NdFeB
Thermal conductivity	k in W/mK	0.024	250	16	31	16	16	401	8.9551
Convective heat transfer co-eficient	h in W/m2K	5 to 25							
Specific heat capacity	Cp in J/KgK	287	900	510	490	460	482	383.1	502
Density	p in Kg/m3	1	2700	8000	7650			8954	7500

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THERMAL MODEL OF THE EBIKE MOTOR

- eBike Motor Thermal Model;
- Empirical Results;
- P-Spice Simulation;

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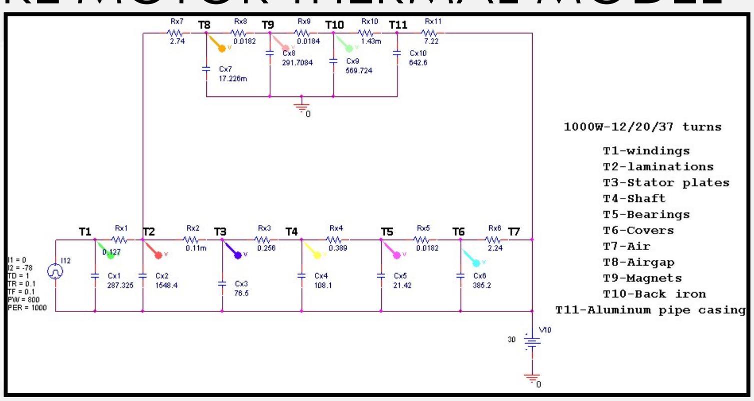
EBIKE MOTOR THERMAL MODEL



Rph=0.065 ohms, Turns=12, Irms/ph=14.14A/ph, Ploss=65W+20%=80W;

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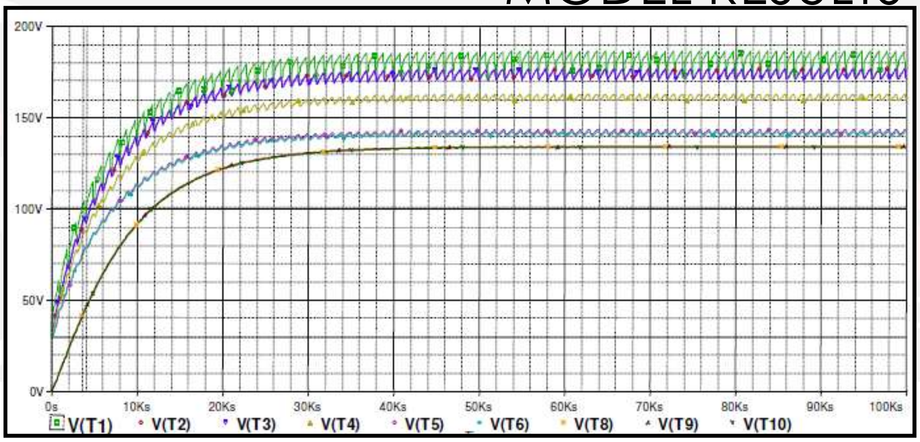
EBIKE MOTOR LUMPED THERMAL MODEL RESULTS



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EBIKE MOTOR LUMPED THERMAL MODEL RESULTS

- Winding Temp=100 deg at 60min with 80W of Ploss considering h=5(worst case) & D=80%;
- Winding Temp=100 deg at 90min with 80W of Ploss considering h=25(optimistic case) D=100%;

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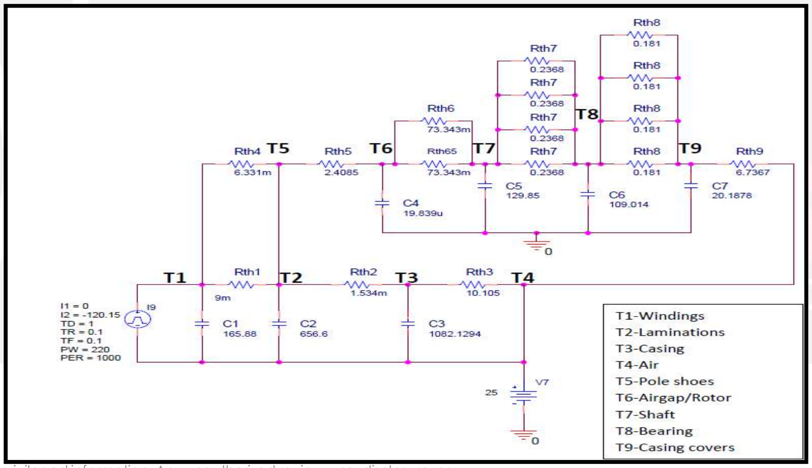
INNER ROTOR MOTOR THERMAL MODEL



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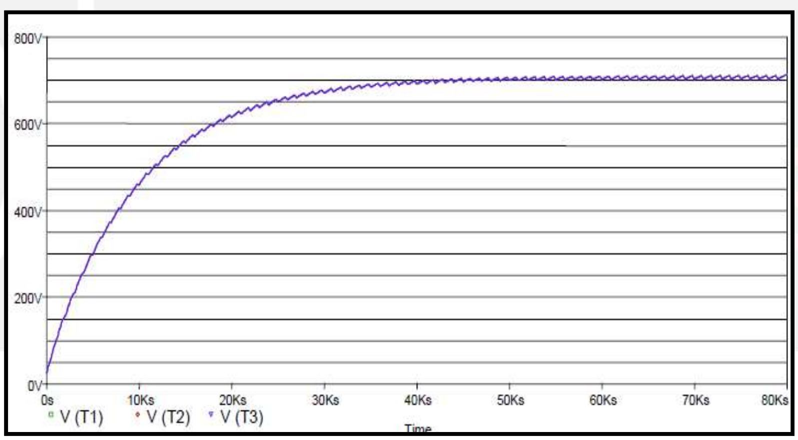
LUMPED THERMAL MODEL RESULTS



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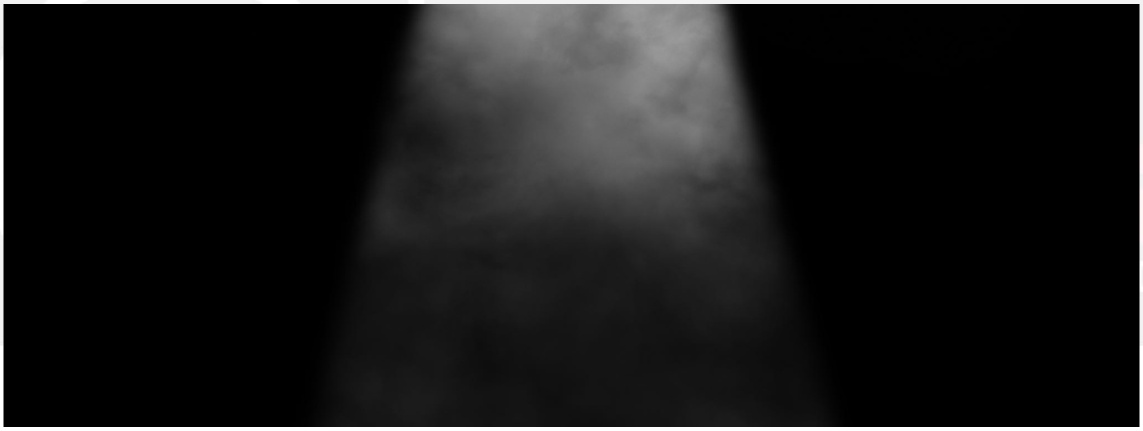
POWER STAGE DESIGN – PART 8



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AGENDA

- Basic Sinusoidal Control;
- 3-Phase Inverter;
- MOSFET Gate Driver Devices;
- Current Feedback Measurement;
- Inverter Design;
- Layout Considerations for Low Voltage Drives;
- EMI Filter Design;

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MOTOR DRIVE TOPOLOGIES

- Low Voltage Drives
  - Quarter-Bridge (1-Switch per Phase);
  - Half-Bridge (2-Switches/Phase);
  - Full-Bridge (4-Switched/Phase);

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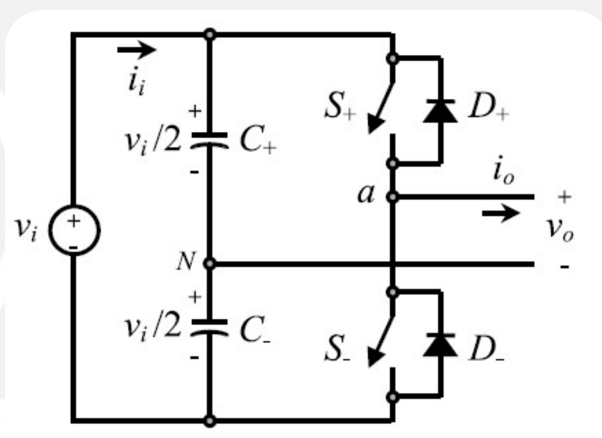
TYPES OF BRIDGES – HALF BRIDGE



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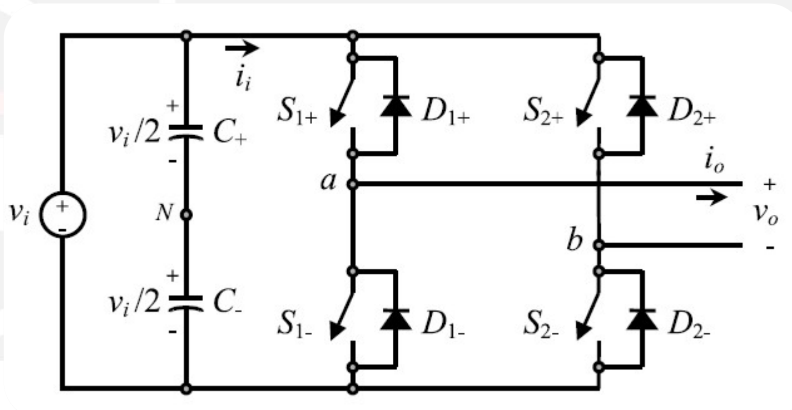
TYPES OF BRIDGES – FULL BRIDGE



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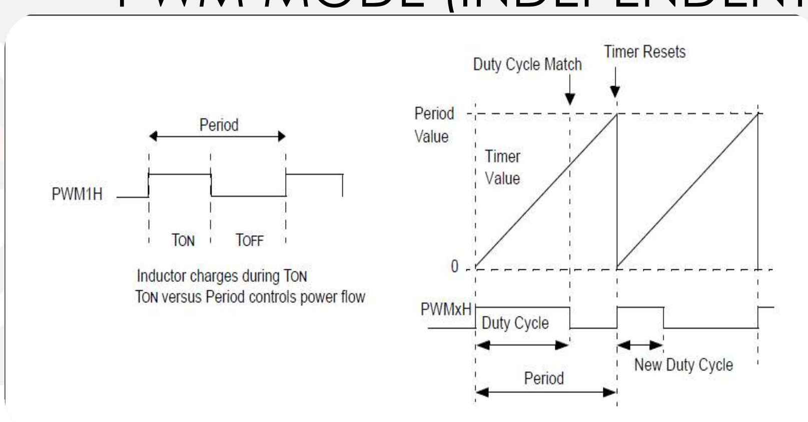
PWM TECHNIQUES – EDGE ALIGN PWM MODE (INDEPENDENT)



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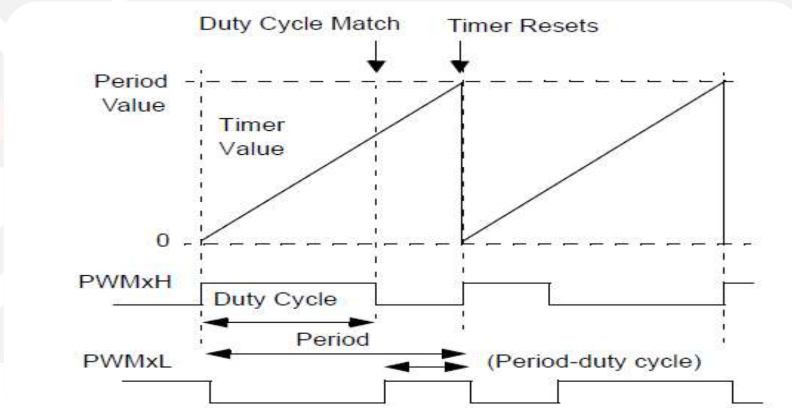
PWM TECHNIQUES – EDGE ALIGN PWM MODE (COMPLIMENTARY)



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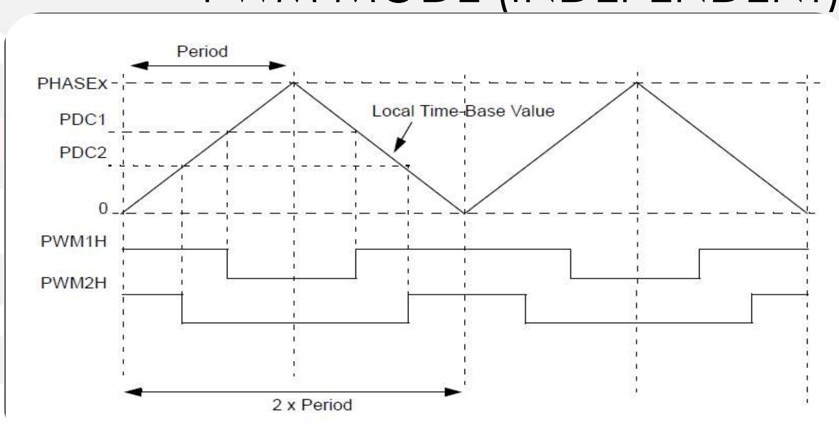
PWM TECHNIQUES – CENTER ALIGN PWM MODE (INDEPENDENT)



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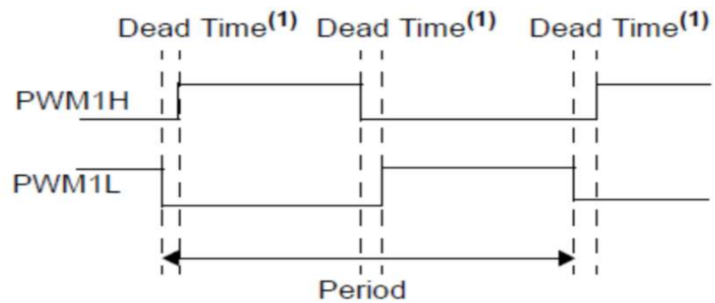
PWM TECHNIQUES – CENTER ALIGN PWM MODE (COMPLIMENTARY)



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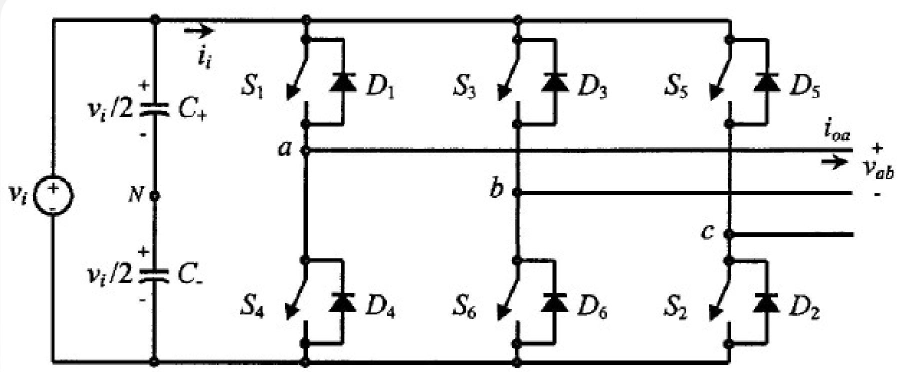
3-PHASE INVERTER



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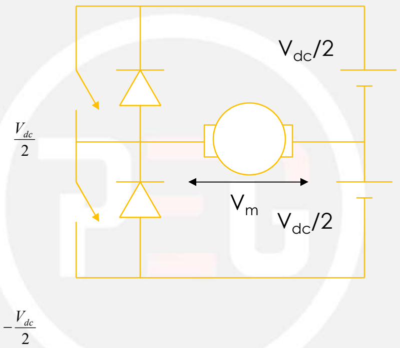
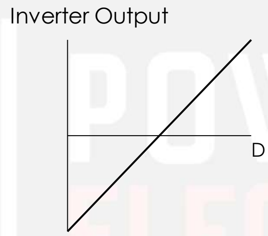
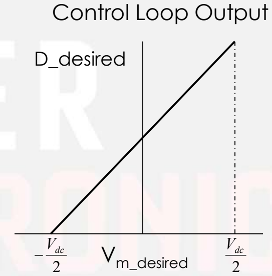
3 PHASE SINE INVERTER: GENERATING D







$$V_m = \frac{V_{dc}}{2}.[2.D - 1]$$

$$D\_desired = \left(\frac{2.V_{m\_desired}}{V_{dc}} + 1\right) \Big/ 2$$

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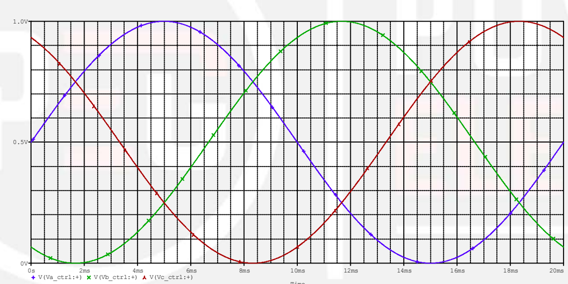
3 PHASE SINE INVERTER: GENERATING D

Amplitude Modulation Ratio:

$$m_a = \frac{V_m}{V_{dc}/2}$$



$$V_{a\_ctrl} = \frac{1}{2}.\frac{V_m}{V_{dc}/2}.Sin(w_e.t) + \frac{1}{2}$$

$$V_{b\_ctrl} = \frac{1}{2}.\frac{V_m}{V_{dc}/2}.Sin(w_e.t - 120^o) + \frac{1}{2}$$

$$V_{c\_ctrl} = \frac{1}{2}.\frac{V_m}{V_{dc}/2}.Sin(w_e.t - 240^o) + \frac{1}{2}$$

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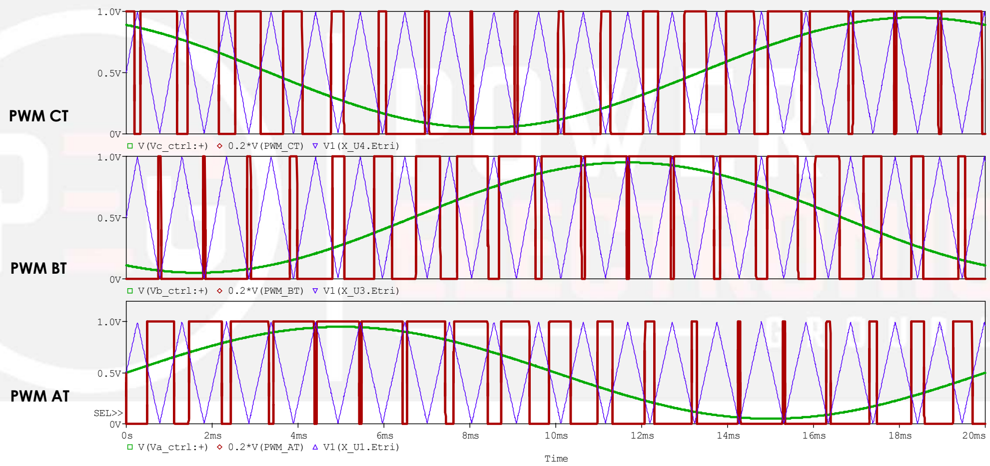
3 PHASE SINE INVERTER: GENERATING D



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GATE DRIVE CIRCUIT DESIGN FOR MOSFETS

- **Switching Losses**: As the operating frequency of inverter increases, the MOSFET's required gate voltage must be driven to its final value in as short a period as possible (within EMI constraints) to minimize switching losses.
- **Drive Circuit Impedance**: The driver circuit should act as a low impedance voltage source, to enable the gate capacitance to be charged and discharged as quickly as possible.
- **Sourcing and Sinking**: It must also have the capability of sourcing and sinking high transient gate currents - possibly several amps, in tens of nanoseconds.

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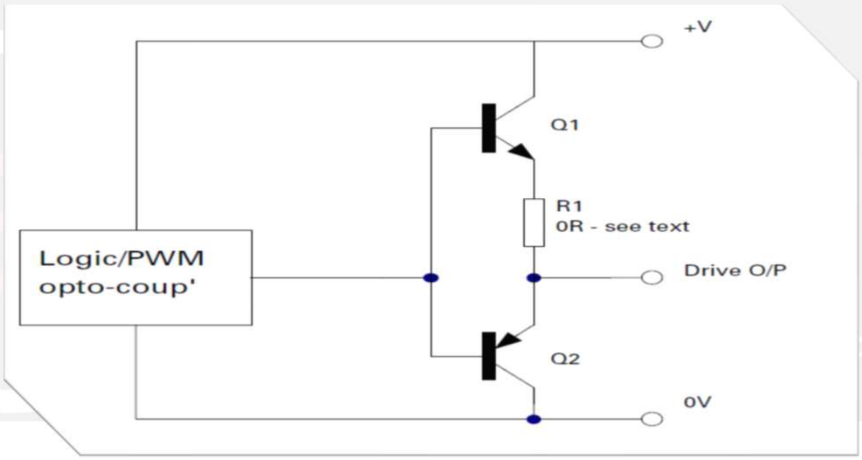
PUSH-PULL DRIVE



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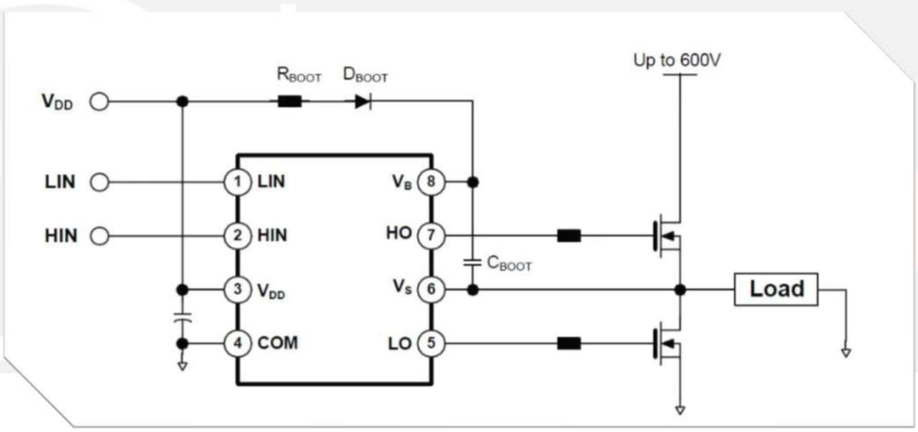
MOSFET DRIVER



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MOSFET DRIVER

- To apply pulses of exact voltage and time period;
- To avoid misfiring of the MOSFETs;
- To insert dead time;

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BOOTSTRAP CAPACITOR

- Most widely used method;
- Significantly positive charge ($V_{GS} > V_{DS} + V_{th}$) applied to the gate in order to turn on.

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BOOTSTRAP CAPACITOR

- Simple and low cost;
- Problem when negative voltage is present at the source of the switching device;

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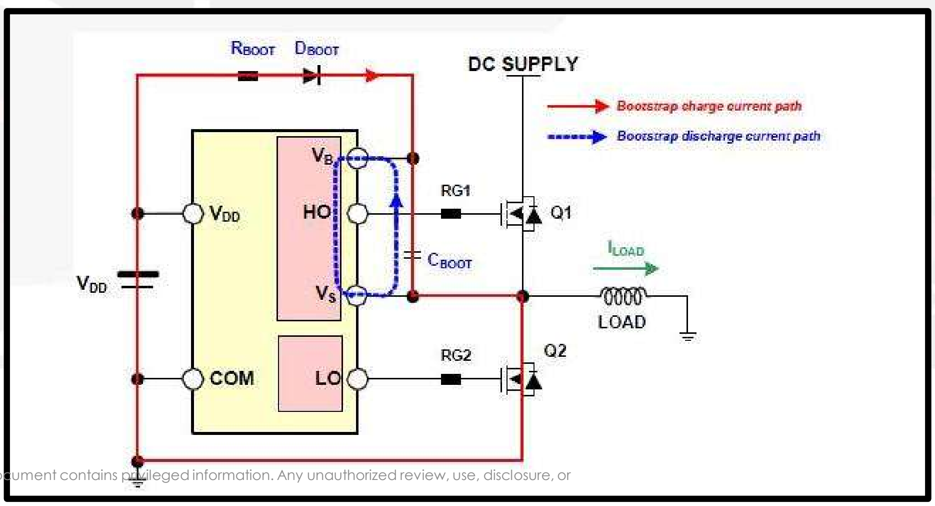
BOOTSTRAP DRIVER CIRCUIT OPERATION



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DECIDING ITS CORRECT VALUE OF A BOOTSTRAP CAPACITOR

$\Delta V_{BOOT} = V_{DD} - V_F - V_{GSMIN}$

where, ΔV_{BOOT} = maximum allowable voltage drop depends on the minimum gate drive voltage for high side switch to maintain;

where, V_{DD} = Supply voltage of the gate drive IC;
where, V_F = Bootstrap diode forward voltage drop;
where, V_{GSMIN} = Minimum gate−source voltage;

The Value of Bootstrap Capacitor is calculated as:
$C_{BOOT} = Q_{TOTAL}/\Delta V_{BOOT}$
Q_{TOTAL} is total amount of charge supplied by the capacitor;
$Q_{TOTAL} = (I_{LKCAP} + I_{LKGS} + I_{QBS} + I_{LK} + I_{LKDIODE}).T_{ON} + Q_{LS}$

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EXAMPLE

$Q_{total} = 210*10^{-9}$

$\delta V_{boot} = 7.33V$

$C_{boot} = \frac{210*10^{-9}}{7.33} = 28.649*10^{-9}F$

4 Mosfets for one leg

$C_{boot} = 28.649*10^{-9}*4$

$C_{boot} = 0.1uf$

we have to choose 10 times of the calculated

$C_{boot} = 0.1uf*10 = 1uf.$

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DECIDING ITS CORRECT VALUE OF A BOOTSTRAP CAPACITOR

- The suggested values are within the range of 100nF to 570nF, but the right value must be selected according to the application as, when the capacitor is too large, the charging time slows and the low side time might not be long enough to reach the bootstrap voltage.

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CURRENT SENSORS

Master the Art of Motor, Inverter, Hardware & Firmware Design

April 22 – 24, 2025

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CURRENT FEEDBACK MEASUREMENT

- Sensors for Current Measurement:
  - Shunt Resistors;
  - Hall Effect Sensors;
  - Current Transformers.

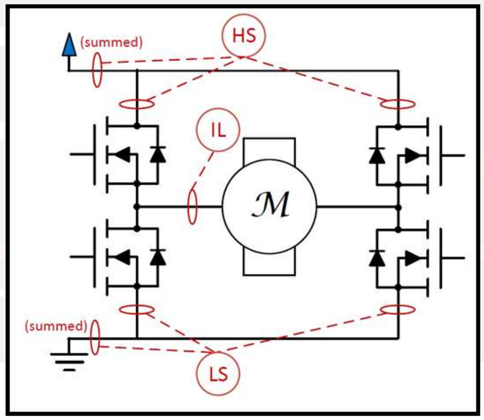

Image Source: https://www.allegromicro.com/-/media/files/application-notes/an296276-current-sensing-in-motor-drives.pdf

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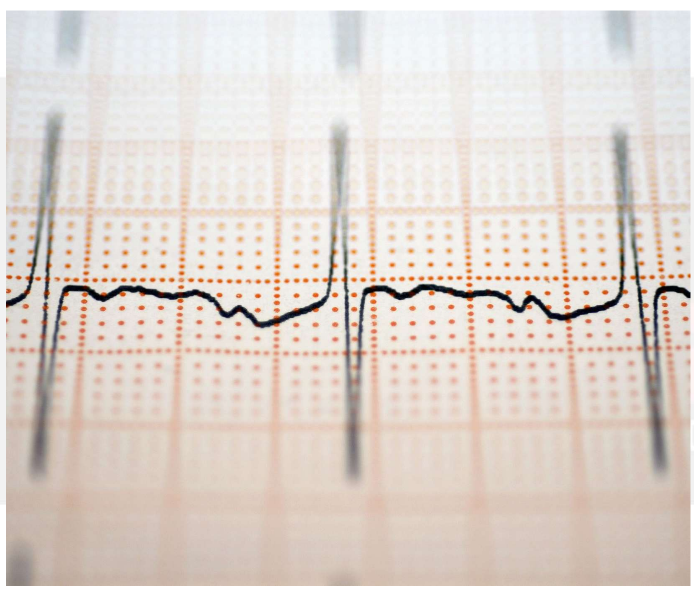
CURRENT FEEDBACK MEASUREMENT USING SHUNT RESISTOR

Methods of Measurement:

High Side Current ;
Low Side Current;
Phase Current



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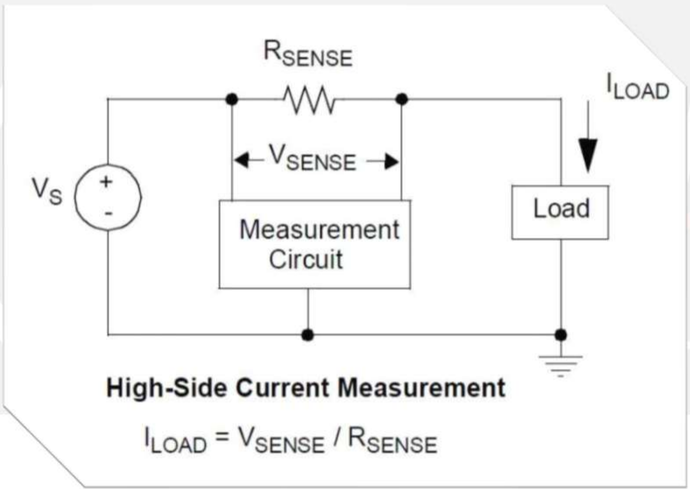
HIGH SIDE CURRENT MEASUREMENT



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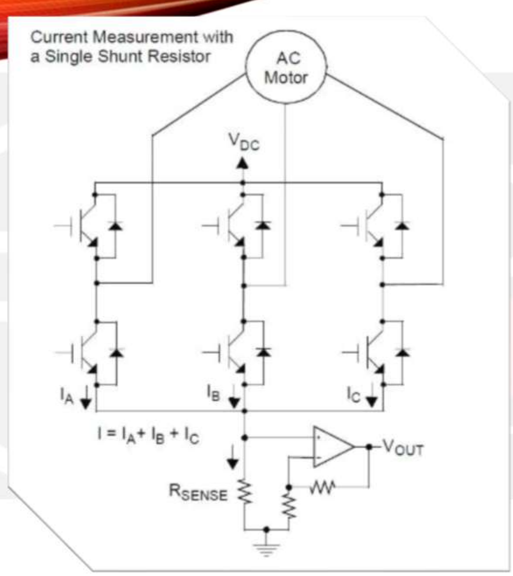
LOW SIDE CURRENT MEASUREMENT



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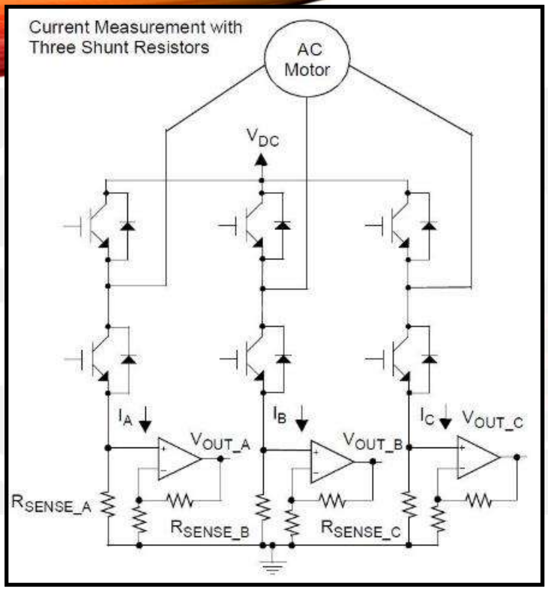
LOW SIDE CURRENT MEASUREMENT



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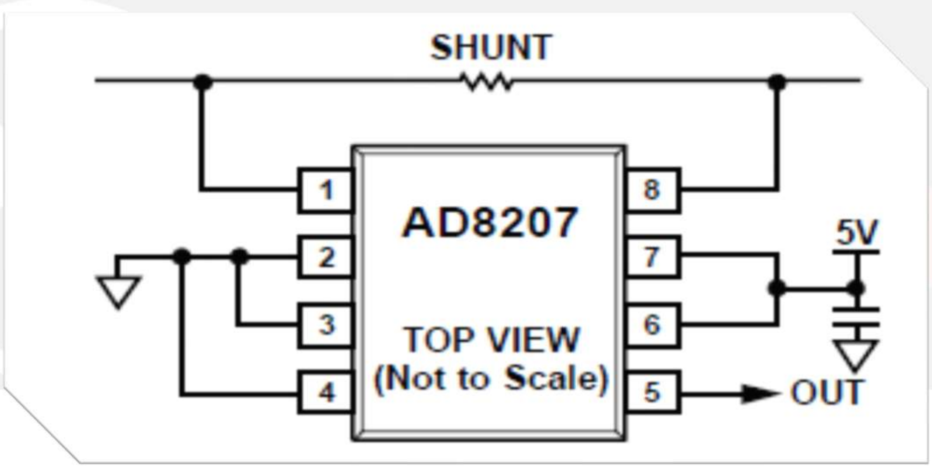
360

PHASE CURRENT MEASUREMENT



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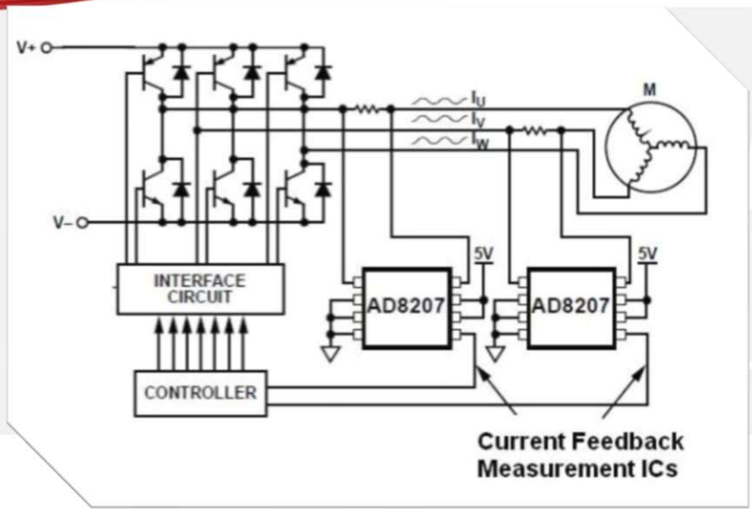
CURRENT FEEDBACK MEASUREMENT



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CURRENT FEEDBACK MEASUREMENT

- AD8207
  - For measuring the winding current;
  - Gain up to 20;
  - Bidirectional;
  - Rejection of High PWM Common Mode Voltage (-4V to +65V);

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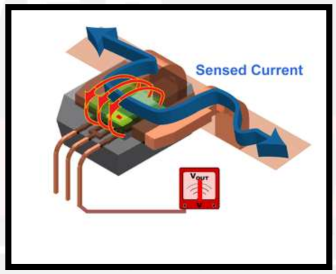
CURRENT FEEDBACK MEASUREMENT USING HALL EFFECT SENSOR

- An Easy way of sensing current in which O/P can be directly fed to ADC;
- Expensive;
- Accuracy varies with temperature;
- May Need more space.



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CURRENT FEEDBACK MEASUREMENT USING CURRENT TRANSFORMER

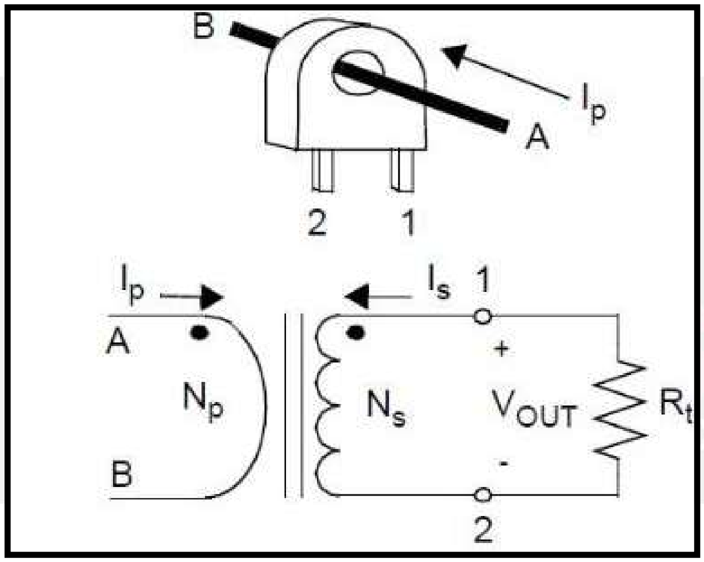
- Uses the principle of a Transformer;
- Provides Galvanic Isolation;
- Used only for AC Measurement.

364

CURRENT FEEDBACK MEASUREMENT USING CURRENT TRANSFORMER

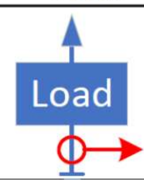
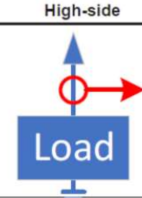
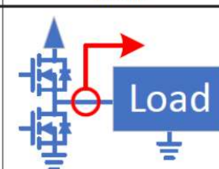
Is = Ip / N where, N = turns ratio;

VOUT = Is x Rt;



365

Current Sensing Options

Type	Low-side		High-side		In-line
Picture					
Detects short to GND	✗		✓		✓
Detects short to supply	✓		✗		✓
Asynch with PWM	✗		✗		✓
Voltage rating	Low (<20 V)		High, depends on supply		High, depends on supply
Bandwidth required	Higher than PWM		Higher than PWM		Higher than motor
Polarity	Unidirectional or Bidirectional		Unidirectional or Bidirectional		Bidirectional only
Possible configurations	1 per 1/2-H	1 summing	1 per 1/2-H	1 summing	1 per 1/2-H bridge
Measures LS brake	✓	✗	✗		✓
Measures HS brake	✗		✓	✗	✓
Measures in coast	✓ (bidirectional only)		✓ (bidirectional only)		✓
Measures in drive	✓		✓		✓
Magnetic solution comparison to shunt-based current sensing	Smaller solution size Fail open, protect from overvoltage stress		Smaller solution size Basic or reinforced isolation built-in		Smaller solution size Basic or reinforced isolation built-in PWM rejection

References: https://www.allegromicro.com/-/media/files/application-notes/an296276-current-sensing-in-motor-drives.pdf

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COMPARISON

Method	Shunt	Hall Sensor	CT
Accuracy	Good	Good	Medium
Cost	Low	High	Medium
Isolation	No	Yes	Yes
DC Offset Problem	Yes	No	No
Saturation	No	Yes	Yes
Power Consumption	High	Low	Low
Type	Both AD/DC	Both AD/DC	Only AC

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INVERTER DESIGN

- Selection of Switches (IGBTs/MOSFETs);
- Selecting IGBT/MOSFET Drivers;
- Selecting Current Feedback Measurement IC;
- Selecting Bus Capacitance;

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INVERTER DESIGN

- Power Stage Layout Considerations
  - Voltage Source Impedance;
  - Bus Voltage Capacitance;
  - MOSFET/IGBT Placement;
  - Gate Drive Selection;
  - Gate Drive Layout;
  - Current Sensor Selection;
  - Current Sensor Layout.

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INVERTER DESIGN

- Layout Considerations;
  - Ground Planes;
    - How many ground planes should you have?
    - How should they be connected?
  - Interfacing with the Digital World
    - What is the cardinal rule?

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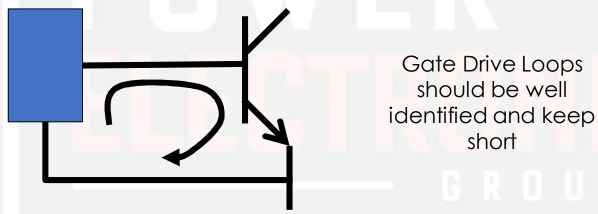
THE CARDINAL RULE

- Identify the Current Loops;
- Keep them short and sweet.



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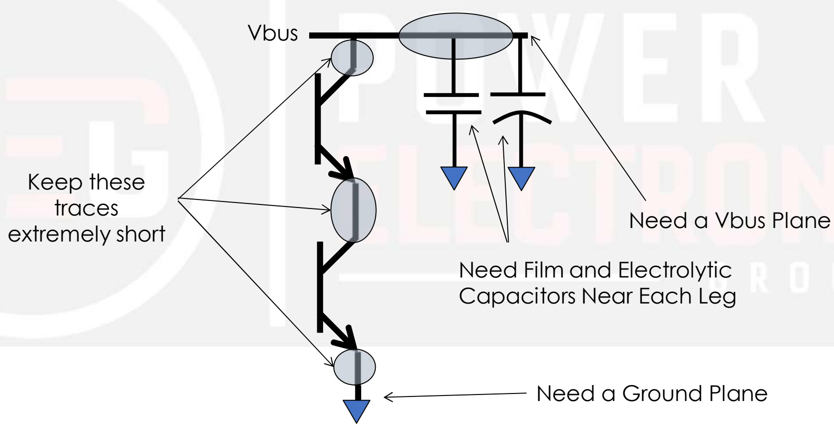
POWER SWITCHES



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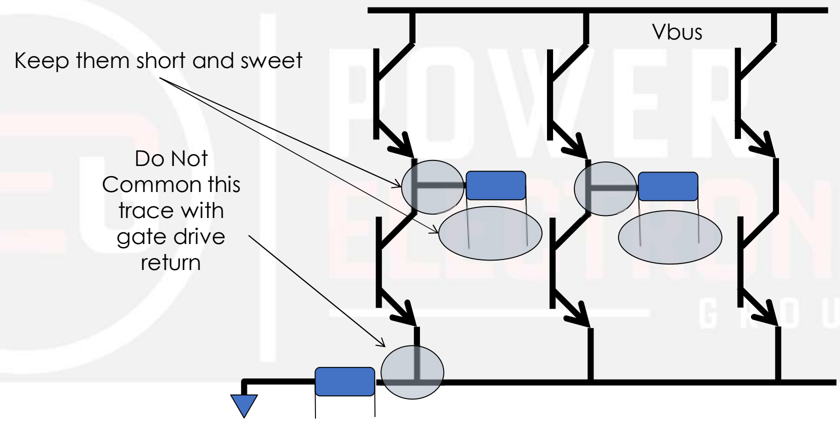
CURRENT SENSING



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SWITCHING FREQUENCY

- What should be your switching frequency?
  - Algorithm Execution Time;
  - Input Filter Capacitance;
  - Switching Losses;
  - Current Ripple;
  - EMI/RFI Considerations.

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SWITCH SELECTION

- How should you select your switch?

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SNUBBER SELECTION

- Would you need a snubber?

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EMI/RFI CONSIDERATIONS

- How do you do layout to reduce:
  - Conducted Emissions;
  - Radiated Emission.

377

EMI FILTER DESIGN

- 2-Wire input;
- 3-Wire input;
- Common Mode Noise;
- Differential Mode Noise;
- Multi-Stage Filter Design.

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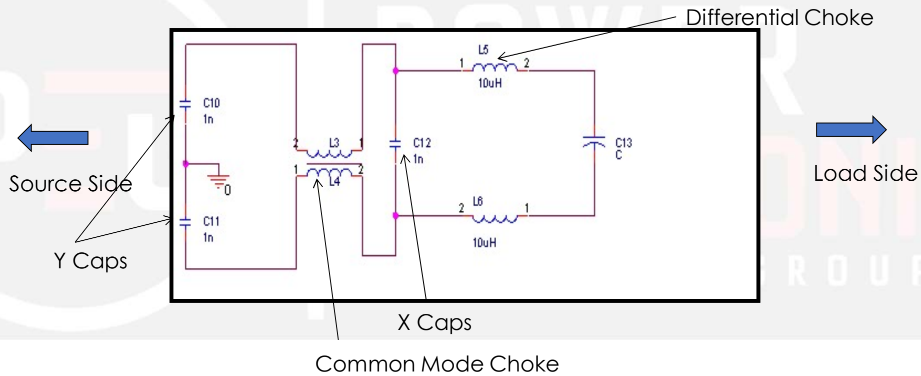
EMI FILTER



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EMI FILTER DESIGN – LAYOUT CONSIDERATIONS

- If traces are minimized, the filter requirements are reduced significantly;
- Common Mode Noise created by dV/dt;
- Differential Mode Noise created by di/dt.

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EMI FILTER DESIGN

- Measure
  - Common Mode Noise;
  - Differential Mode Noise;
- Calculate
  - Attenuation required;
  - Component Values.

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CHALLENGES IN GATE DRIVE DESIGN

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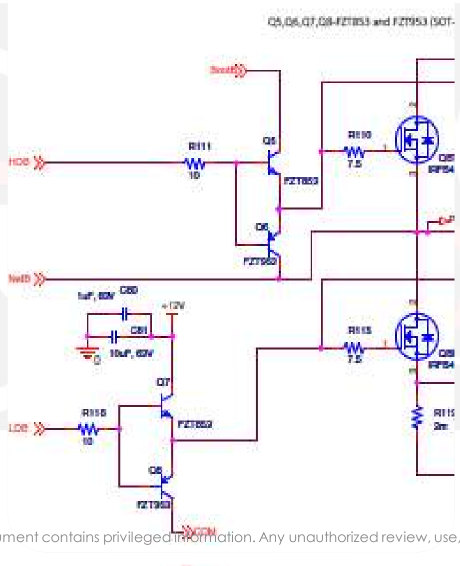
INVERTER LEG



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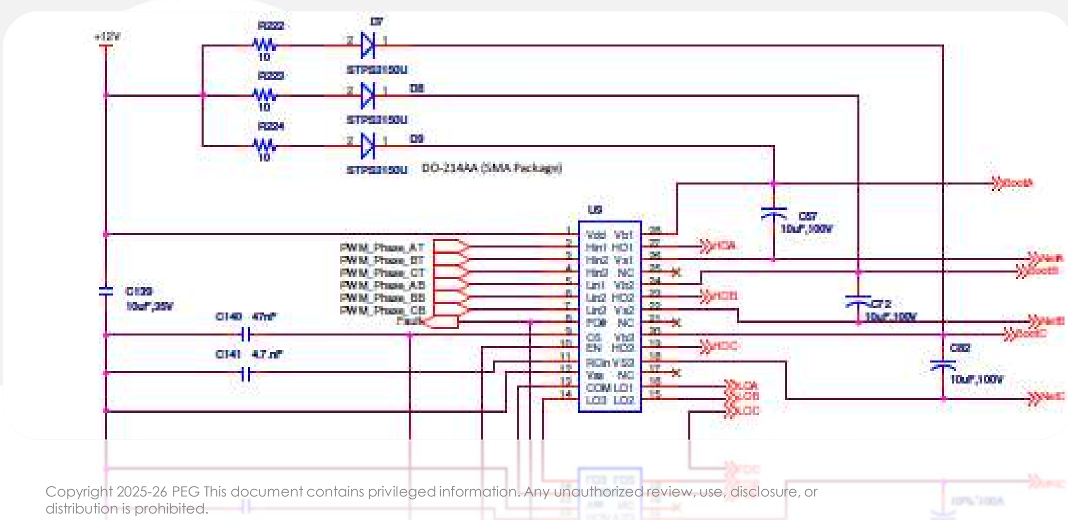
GATE DRIVER



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DATASHEET

Symbol	Parameter	Min.	Typ.	Max.	Units	Conditions
gfs	Forward Transconductance	160	—	—	S	V_{DS} = 50V, I_D = 75A
Q_g	Total Gate Charge	—	150	210		I_D = 75A
Q_{gs}	Gate-to-Source Charge	—	35	—	nC	V_{DS} = 50V
Q_{gd}	Gate-to-Drain ("Miller") Charge	—	43	—		V_{GS} = 10V ⑤
R_G	Gate Resistance	—	1.3	—	Ω	
$t_{d(on)}$	Turn-On Delay Time	—	25	—		V_{DD} = 65V
t_r	Rise Time	—	67	—	ns	I_D = 75A
$t_{d(off)}$	Turn-Off Delay Time	—	78	—		R_G = 2.6Ω
t_f	Fall Time	—	88	—		V_{GS} = 10V ⑤
C_{iss}	Input Capacitance	—	9620	—		V_{GS} = 0V
C_{oss}	Output Capacitance	—	670	—		V_{DS} = 50V
C_{rss}	Reverse Transfer Capacitance	—	250	—	pF	f = 1.0MHz
C_{oss} eff. (ER)	Effective Output Capacitance (Energy Related)⑦	—	820	—		V_{GS} = 0V, V_{DS} = 0V to 80V ⑦
C_{oss} eff. (TR)	Effective Output Capacitance (Time Related)⑥	—	950	—		V_{GS} = 0V, V_{DS} = 0V to 80V ⑥

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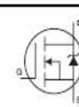
DATASHEET

Diode Characteristics

Symbol	Parameter	Min.	Typ.	Max.	Units	Conditions
I_S	Continuous Source Current (Body Diode)	—	—	170①	A	MOSFET symbol showing the integral reverse p-n junction diode. 
I_{SM}	Pulsed Source Current (Body Diode) ②	—	—	670		
V_{SD}	Diode Forward Voltage	—	—	1.3	V	T_J = 25°C, I_S = 75A, V_{GS} = 0V ⑤
t_{rr}	Reverse Recovery Time	—	50	75	ns	T_J = 25°C; V_R = 85V,
		—	60	90		T_J = 125°C; I_F = 75A
Q_{rr}	Reverse Recovery Charge	—	94	140	nC	T_J = 25°C; di/dt = 100A/μs ⑤
		—	140	210		T_J = 125°C
I_{RRM}	Reverse Recovery Current	—	3.5	—	A	T_J = 25°C
t_{on}	Forward Turn-On Time	Intrinsic turn-on time is negligible (turn-on is dominated by LS+LD)				

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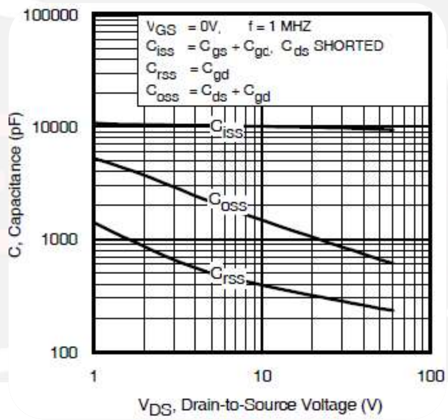
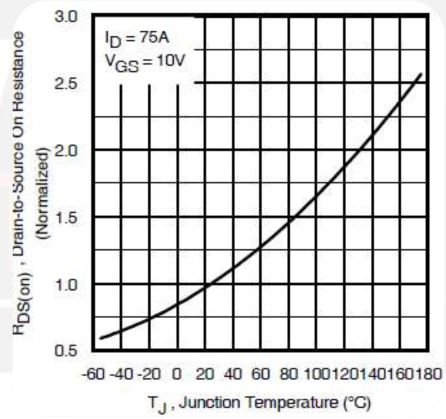
DATASHEET





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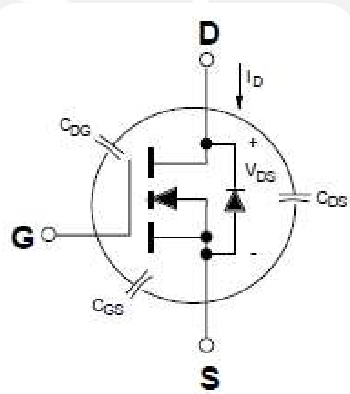
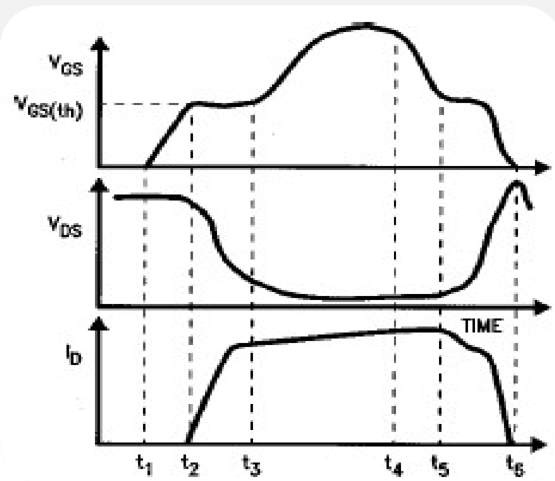
MOSFET FUNDAMENTALS





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PROBLEMS

- Cross conduction;
- Ph-B & Ph-C have longer(High Impedance) gate return path;
- Ringing effect;
- Body diode getting clamped;
- Extremely fast turn on of gate signals;
- Spikes observed on supply voltages & battery current;

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SOLUTIONS

- Increased the top Rg;
- Reduced bottom Rg;
- Provided low impedance path;
- RC-snubber to damp unnecessary turn ON;
- Diodes included to turn OFF faster;

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INVERTER AND PERIPHERAL CIRCUIT DESIGN

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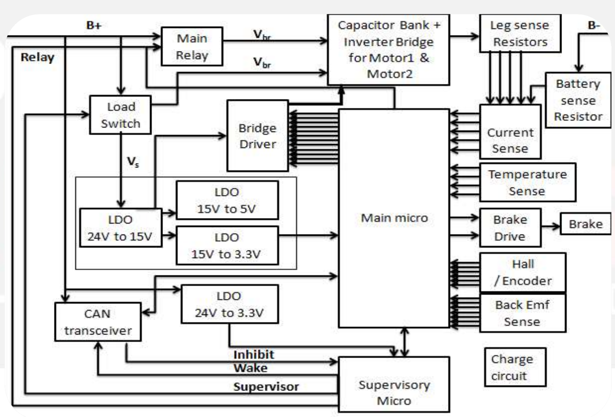
SYSTEM BLOCK DIAGRAM

- Dual uC
- Input Relay
- Start up Logic
- Sensors
- Encoder
- Communication
- Power Supply
- Charging
- Safety



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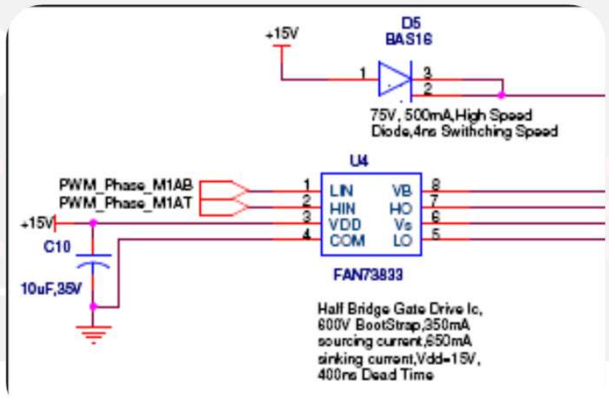
PHASE A – BRIDGE DRIVER

Bridge Drivers come in many varieties and features

For High Voltage, Isolation Requirements may need to be addressed.



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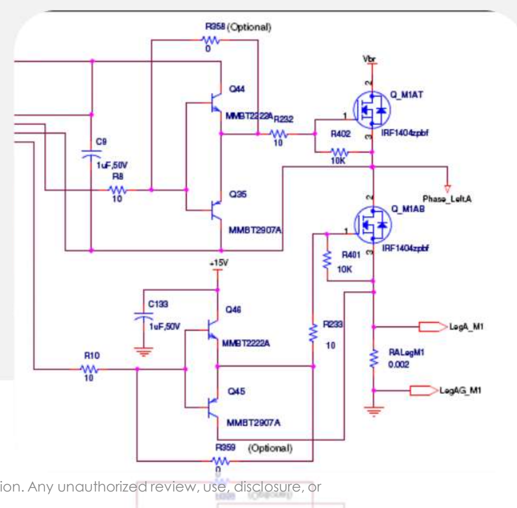
PHASE A – PUSH PULL + MOSFETS



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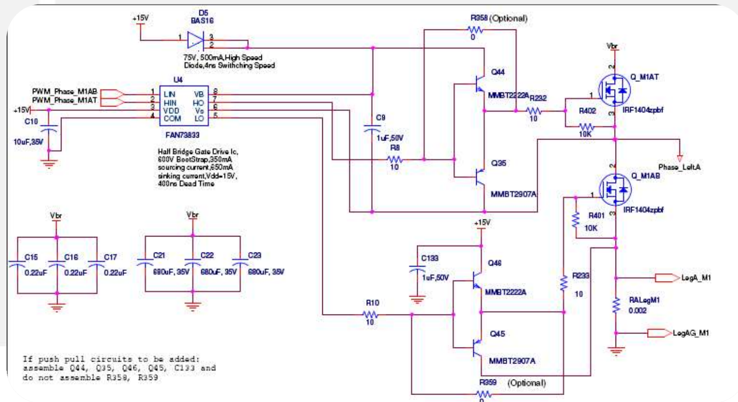
PHASE A – DRIVER + PUSH PULL + MOSFETS



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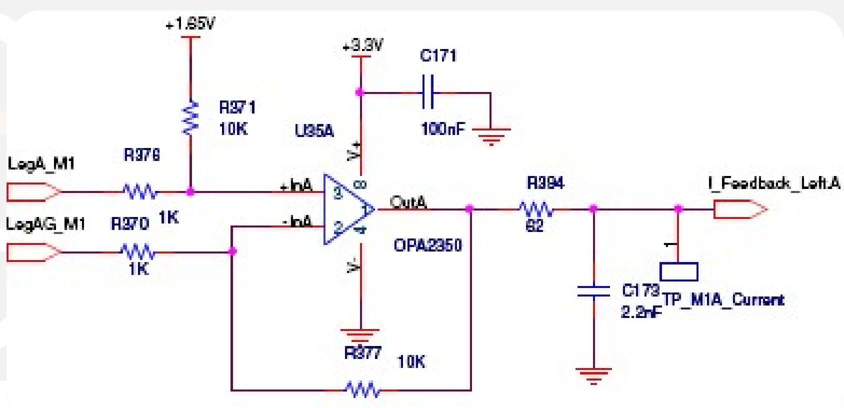
LEG CURRENT SENSING



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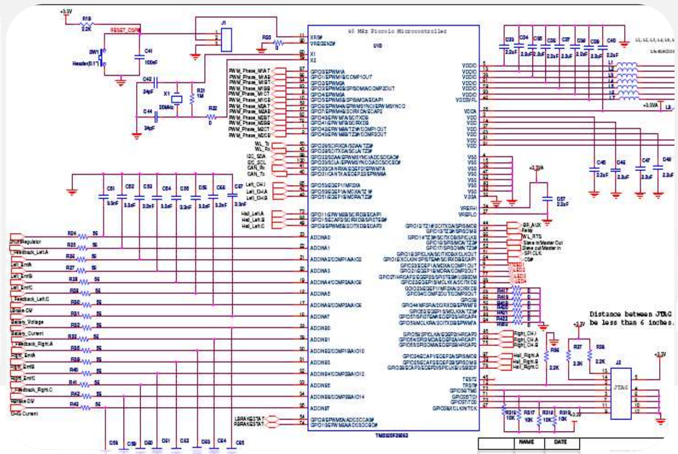
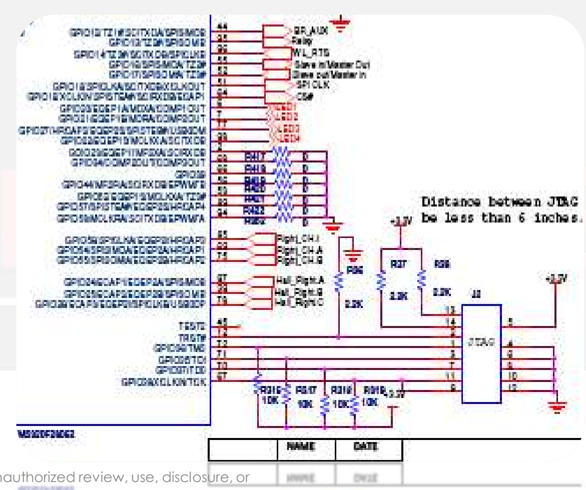
MCU WITH PERIPHERALS

- ADCs
- PWMs
- Crystal
- Power
- Position
- I/Os
- JTAG



397

MCU WITH PERIPHERALS
(DIGITAL I/OS + POSITION SENSING + JTAG)



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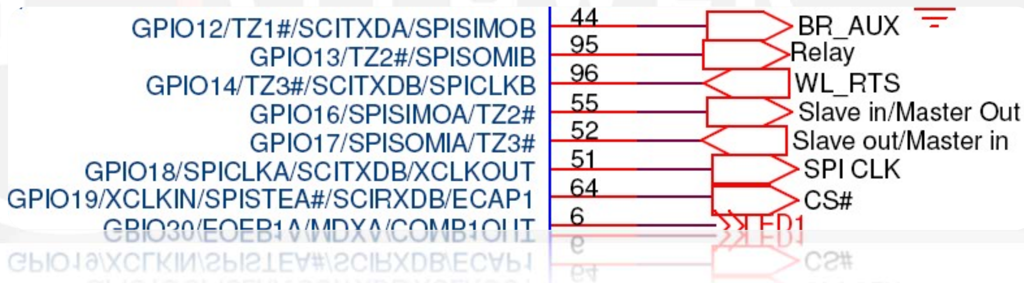
DIGITAL IOS + SERIAL COMMUNICATION



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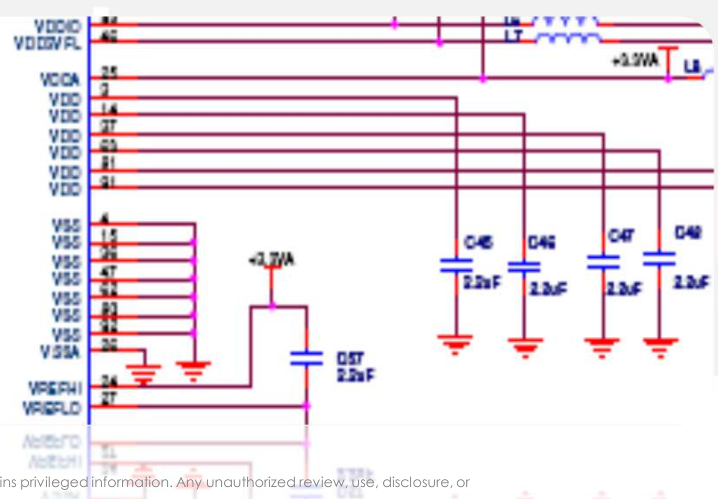
400

MCU WITH PERIPHERALS (FILTERING FOR POWER SUPPLY PINS)



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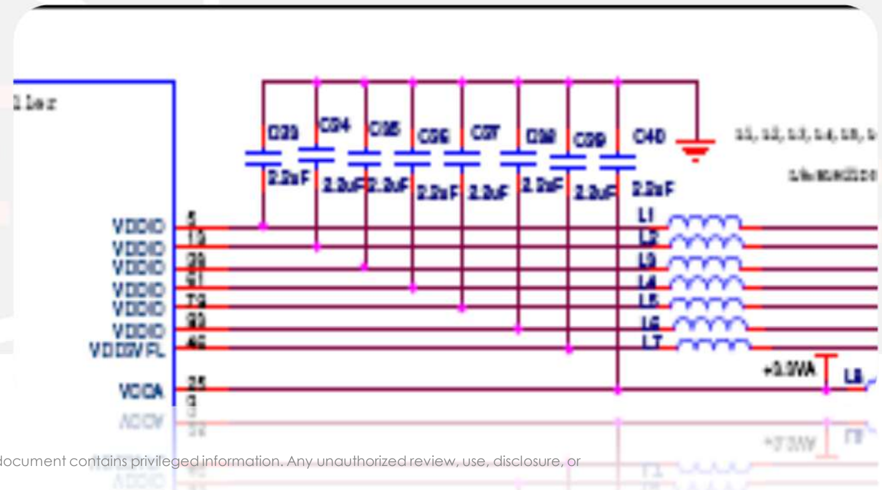
401

MCU WITH PERIPHERALS (FILTERING FOR POWER SUPPLY PINS)



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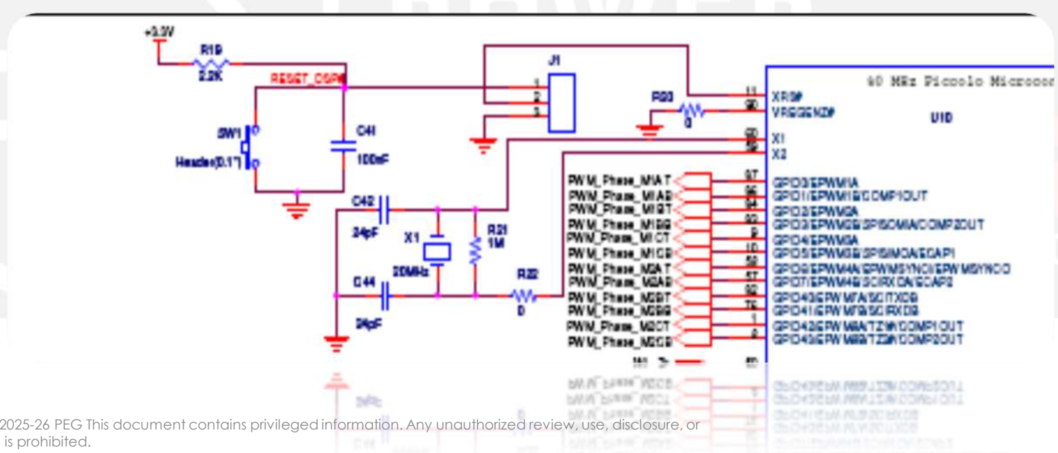
402

MCU WITH PERIPHERALS (CRYSTAL + PWM CONFIG)



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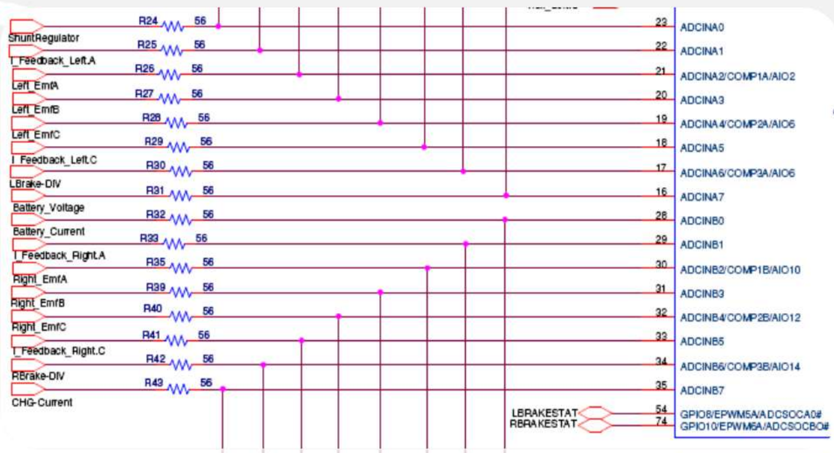
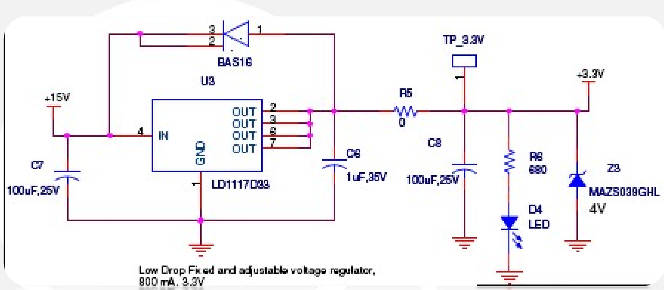
ADC CHANNELS



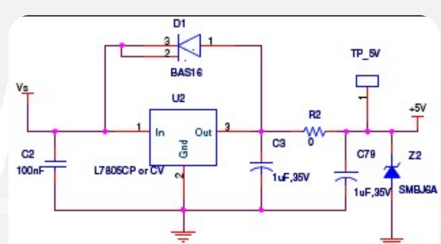
403

404

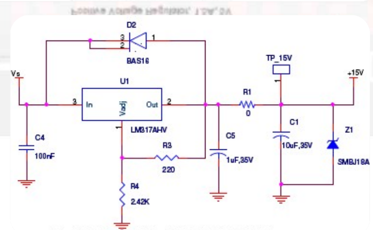
POWER SUPPLY SECTION



Low Drop Fixed and adjustable voltage regulator, 800 mA, 3.3V



Positive Voltage Regulator, 1.5A, 5V



3-Terminal Positive Adjustable Regulator, 1.5A, 1.2V to 57V, TO-220

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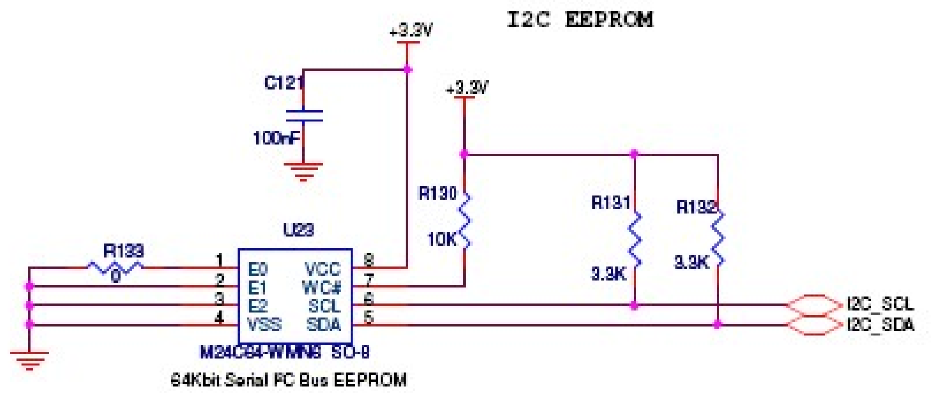
EEPROM



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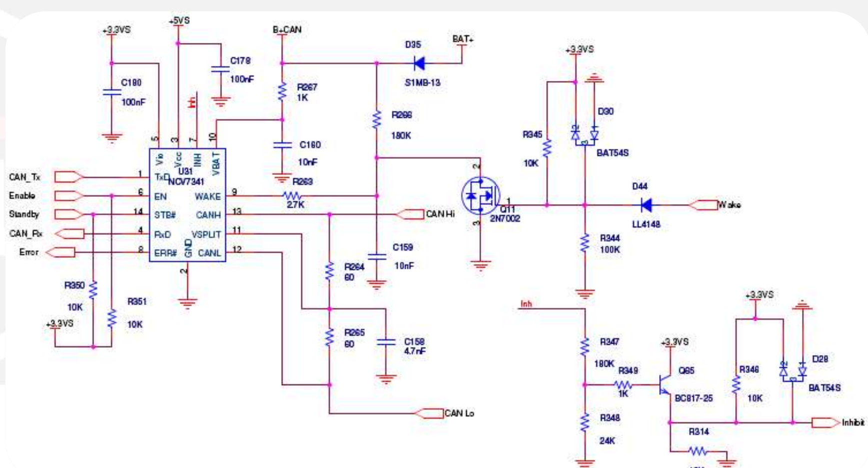
CAN INTERFACE



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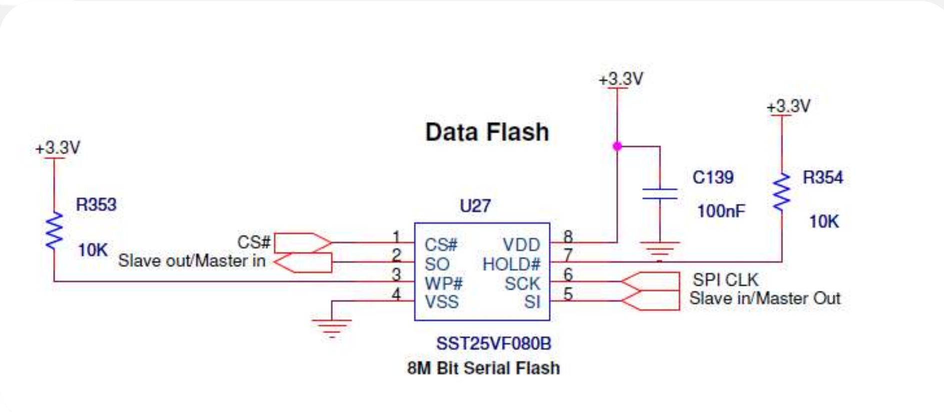
SPI INTERFACE WITH FLASH



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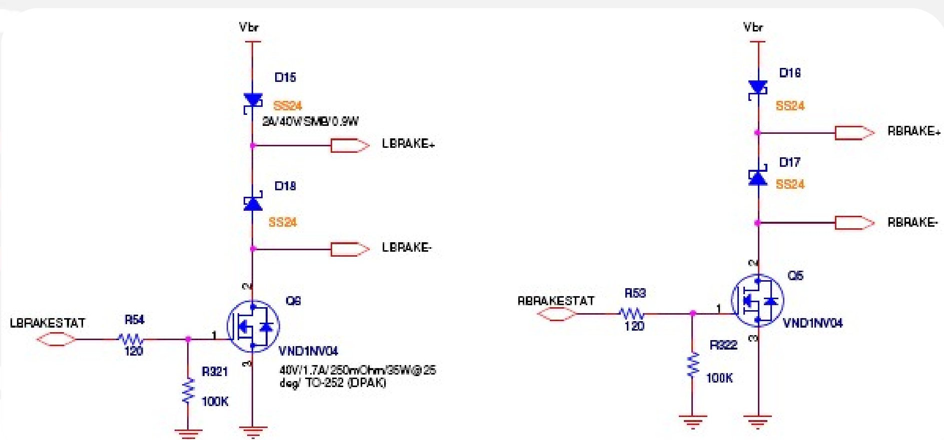
BRAKE SIGNAL



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LAYOUT CONSIDERATIONS

- No. of Layers
  - Total No. of Layers have to be 8.
- No. of Planes:
  - GND Plane;
  - +3.3V, +3.3VA, +3.3VS, +15V, SHUNT (if possible) (Four split planes + SHUNT);
  - +5V, +5VS, B+, BAT+, VBR, Motor Connections.

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LAYOUT CONSIDERATIONS

- Identifying Power Traces:
  - VBR, Motor Phase Connections, Ground.
- Track Width of Power Traces;
- EMI/EMC Related precautions.

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PLANES IDENTIFICATION

	Top	Bottom	Inner
B+	Yes	--	Yes
GND	Yes	Yes	Yes
Vbr	Yes	--	Yes
SHUNT	Yes	Yes	--
Motor Connection	Yes	Yes	Yes

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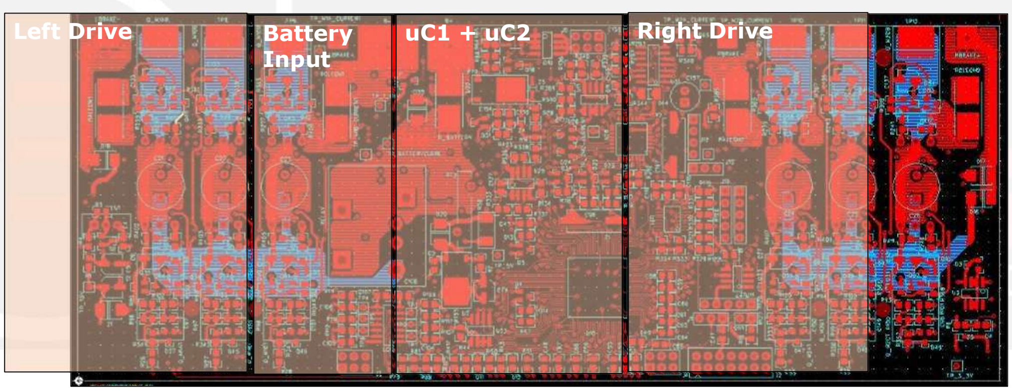
SECTIONS



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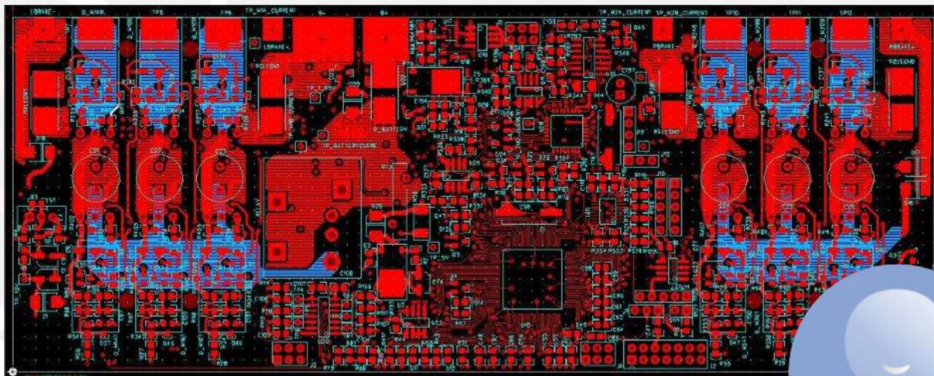
413

IDENTIFYING POWER TRACES (BRIDGE POWER FLOW)



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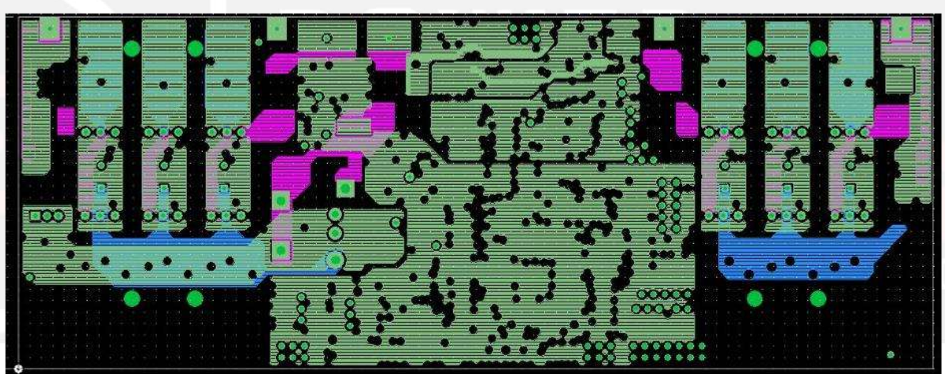
414

CONTINUED…. (BRIDGE POWER FLOW)



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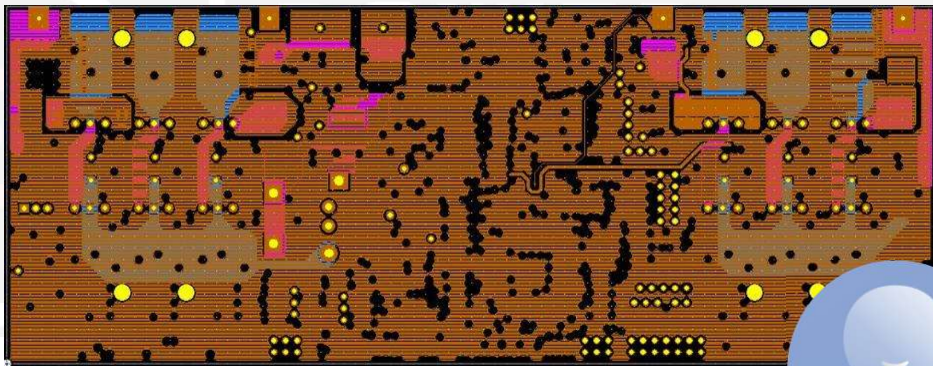
415

CONTINUED…. (COPPER PLANE)



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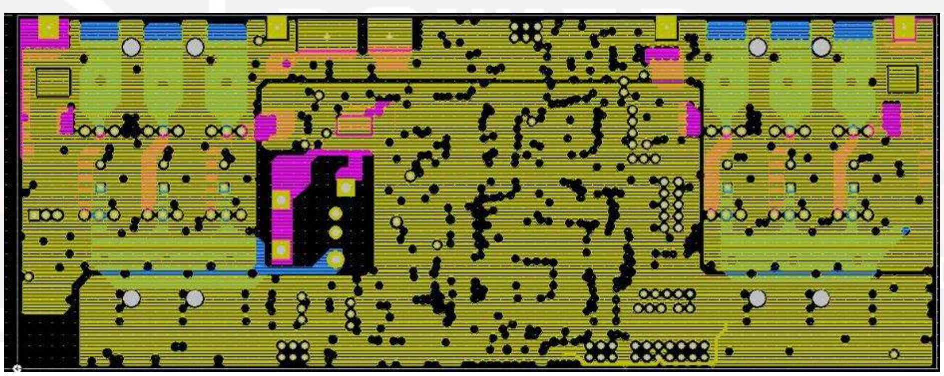
416

CONTINUED…. (SECTIONED POWER PLANES)



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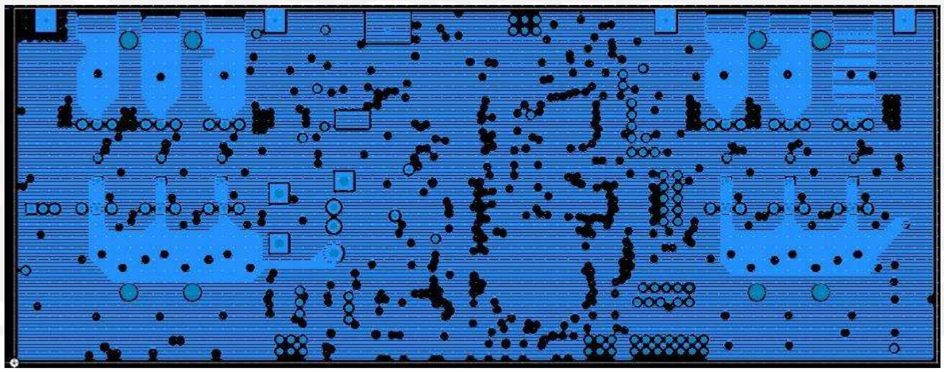
417

CONTINUED… (COPPER PLANE)



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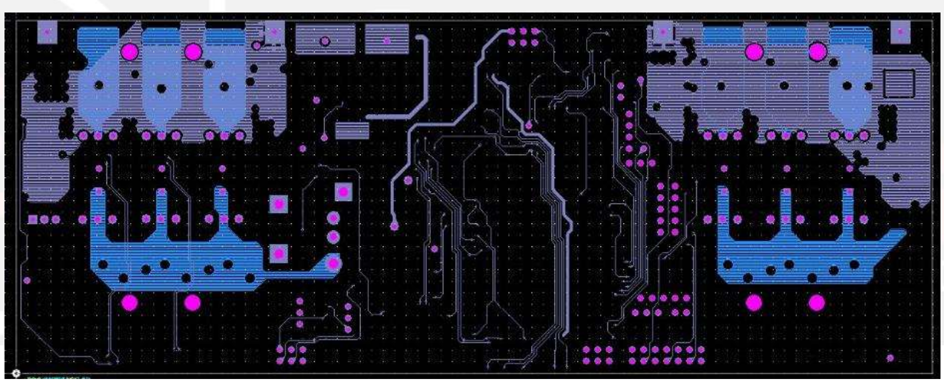
418

CONTINUED…. (COPPER POURS)



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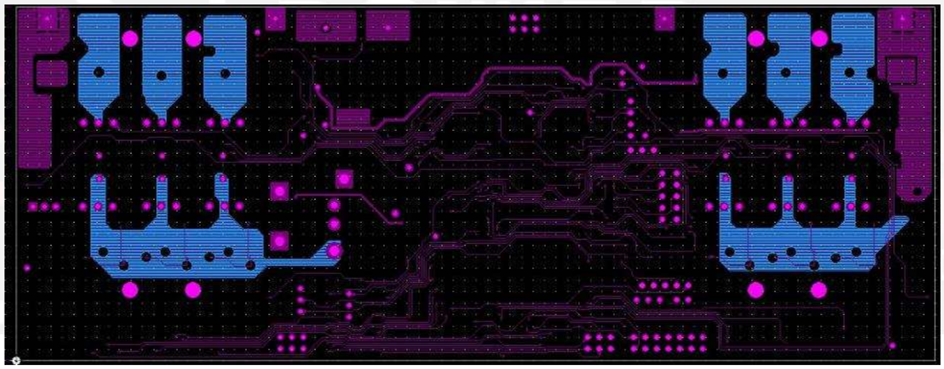
419

CONTINUED…. (COPPER POURS)



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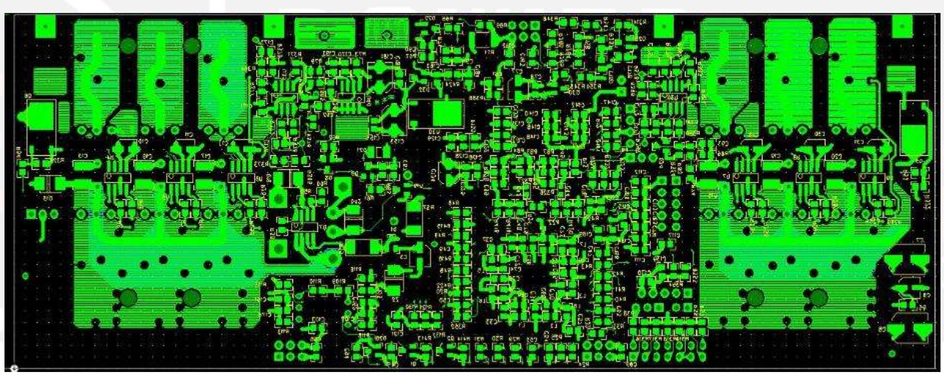
420

CONTINUED…. (COPPER POURS)



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421

HIGH VOLTAGE DESIGN EXAMPLE WITH PFC

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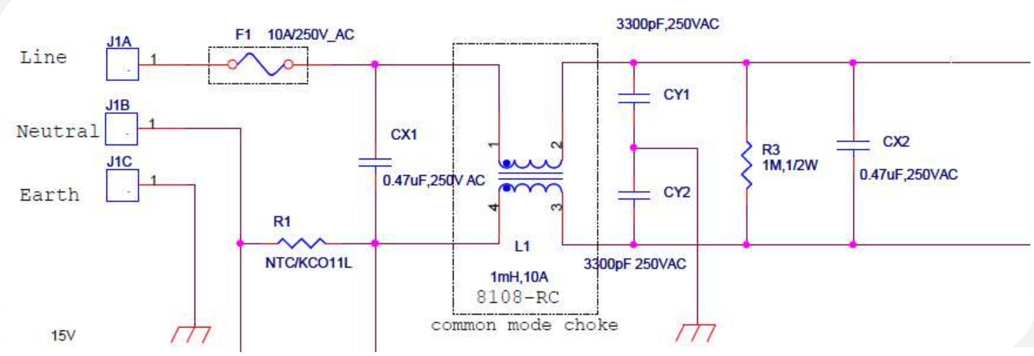
422

EMI FILTER



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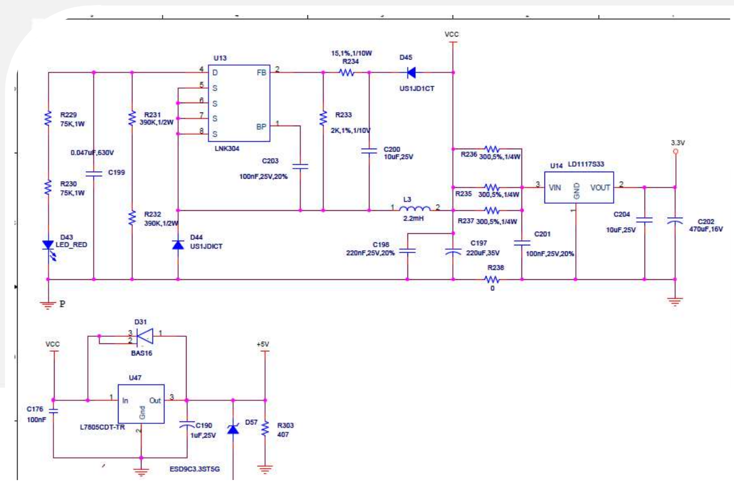
CONTROL POWER SUPPLY



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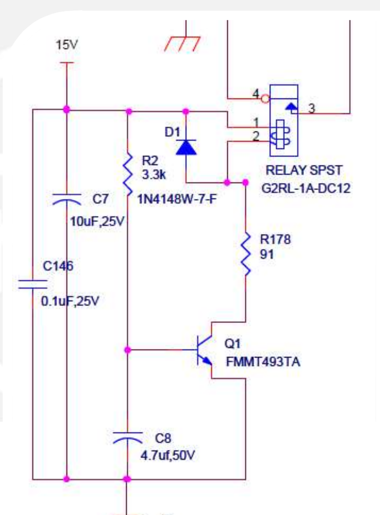
SLOW CHARGE CUT OFF



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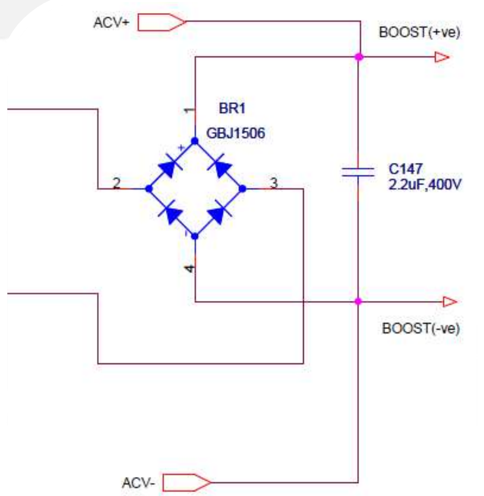
BRIDGE RECTIFIER



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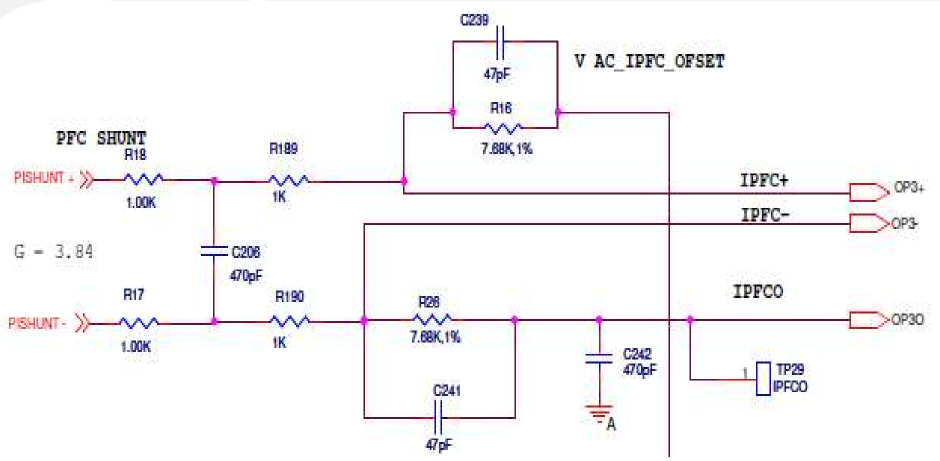
PFC CURRENT



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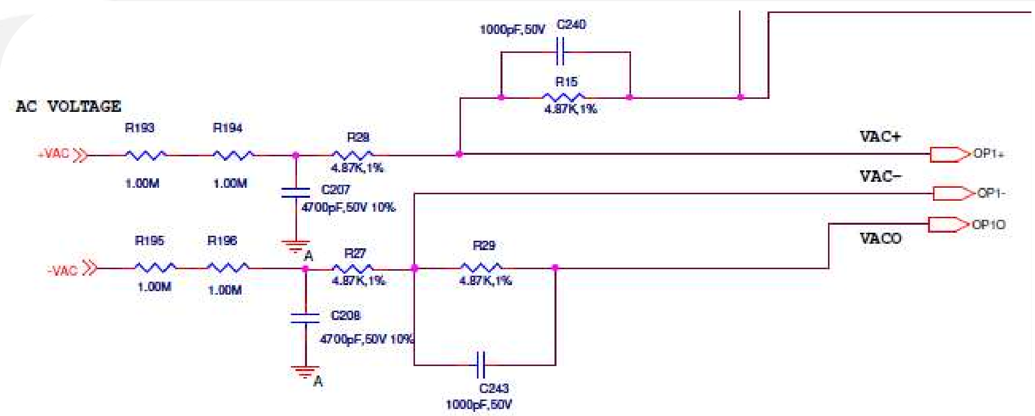
AC VOLTAGE



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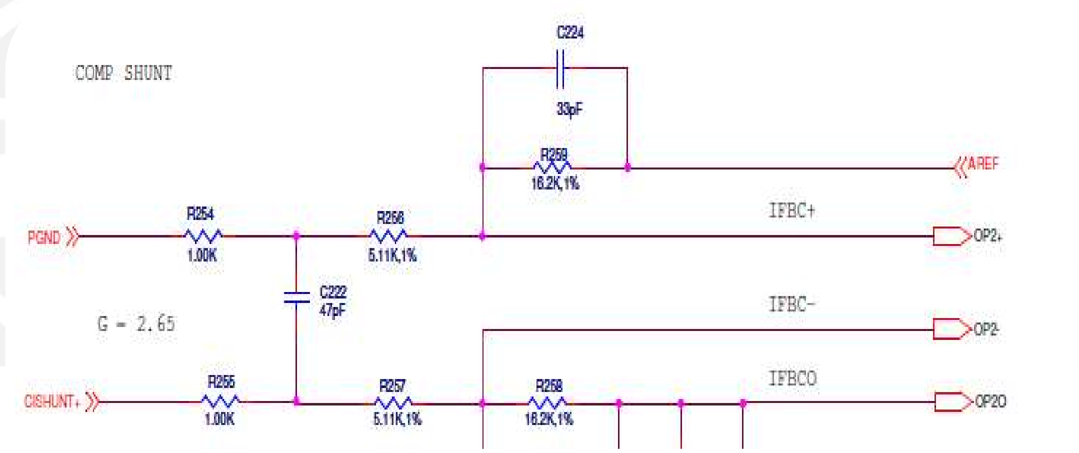
PHASE CURRENT



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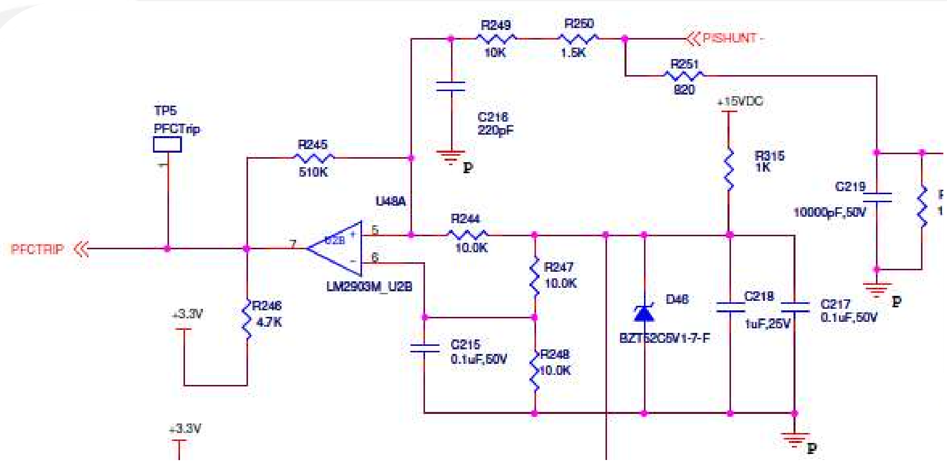
PFC CURRENT PROTECTION



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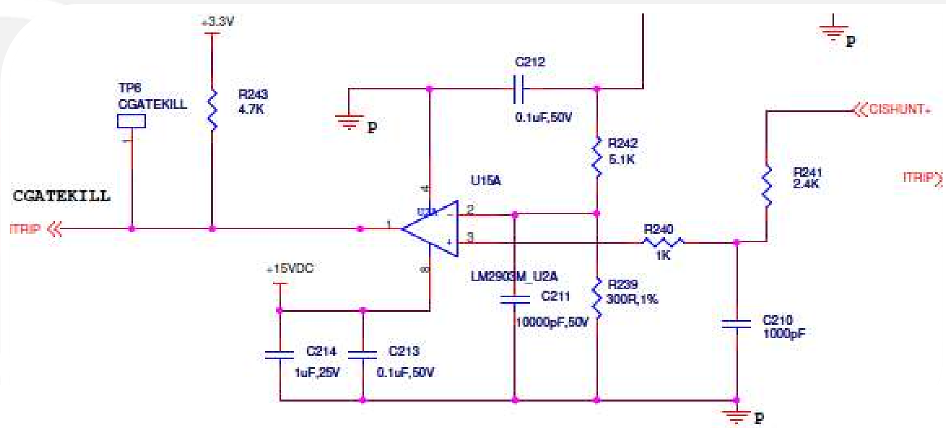
SYSTEM PROTECTION



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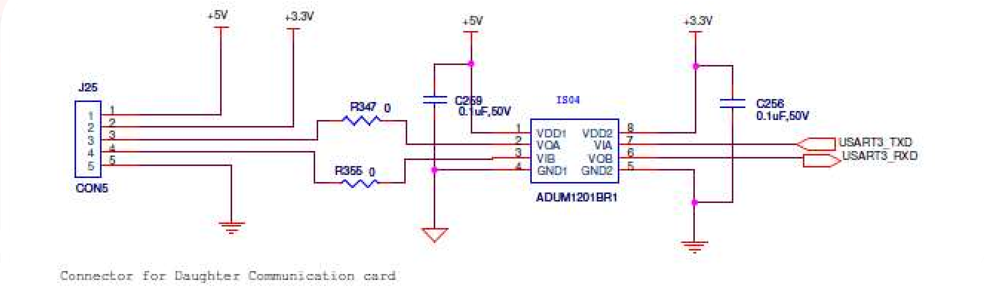
DIGITAL ISOLATION



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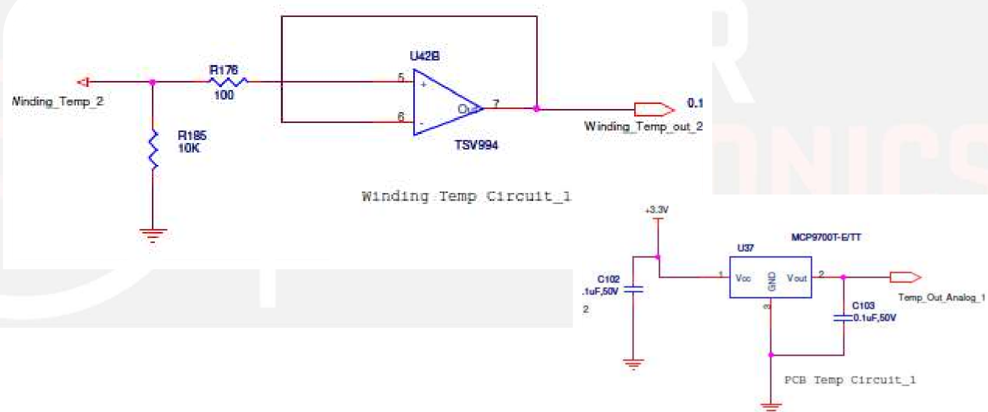
TEMPERATURE



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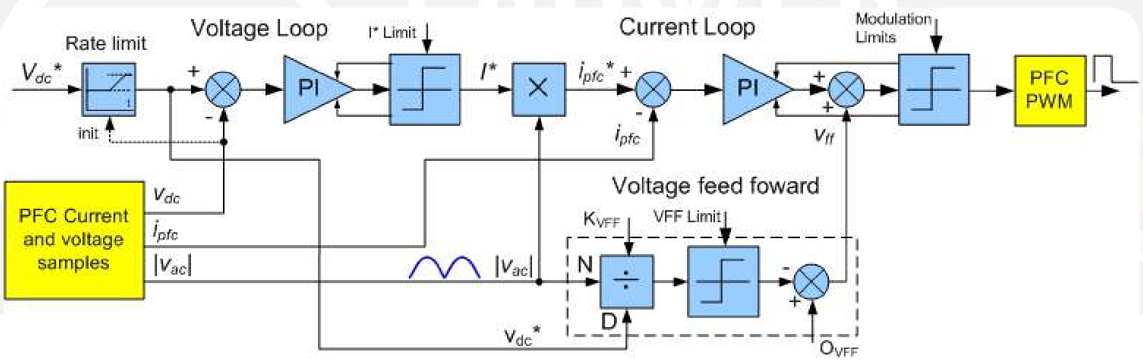
PFC CONTROL ALGORITHM



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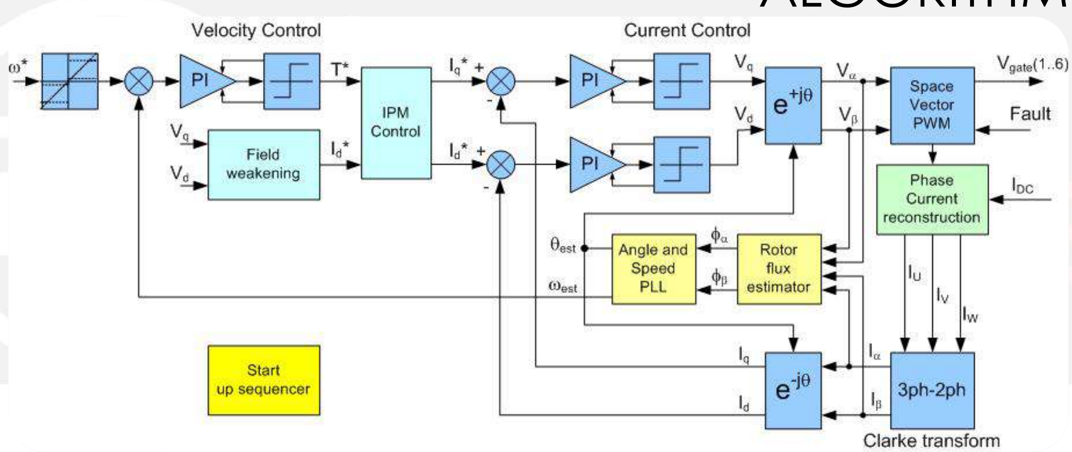
SENSOR LESS CONTROL ALGORITHM



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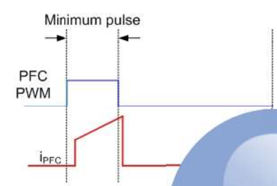
PFC CURRENT SAMPLE TIME

- Allows reliable sampling of PFC current pulse;
- Ensure proper current correction;
- Typically to set to 2uS for 18Khz PFC switching frequency;



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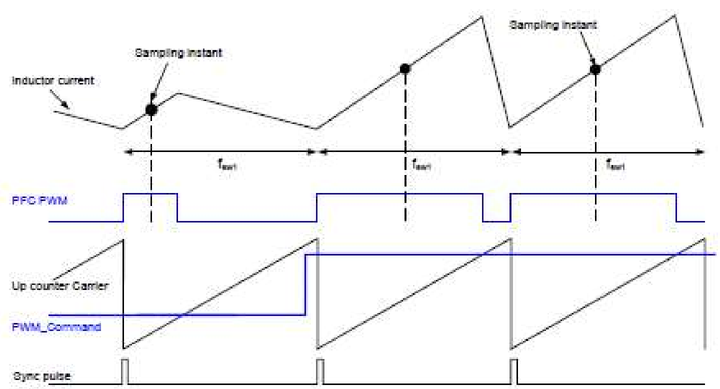
PFC SWITCHING CHARACTERISTICS



Note : Sync is interrupt generated

436

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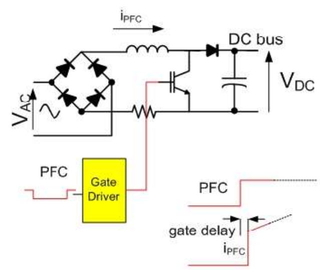
PFC GATING PROPAGATION DELAY

- Set the Propagating delay in gate drive circuit;
- For proper sampling of the PFC current;
- It is set to 0.3uS;



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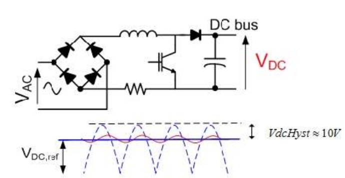
DC BUS VOLTAGE GAP

- Smaller Voltage gap allows PFC PWM to be active;
- PFC greater than 0.95;
- AC input Voltage is updated at every 50mS;
- Trade off between conduction & switching losses;
- Set to 10V;



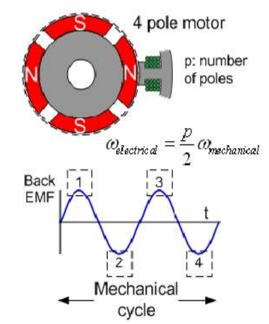
$$V_{DC} \approx DCBUS\_Ref \approx \sqrt{2} \cdot v_{AC} - VdcHyst$$

438

MOTOR PARAMETERS

- No of magnetic poles in full mechanical cycle;
- Electrical cycle for every pair of Magnetic poles;
- Check Bemf waveform Positive and Negative peak

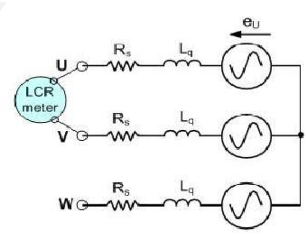
$$\omega_{electrical} = \frac{p}{2}\omega_{mechanical}$$



439

MOTOR STATOR RESISTANCE

- Measure per phase resistance of the stator windings;
- For star connected motor express in per phase;



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MOTOR R AND L

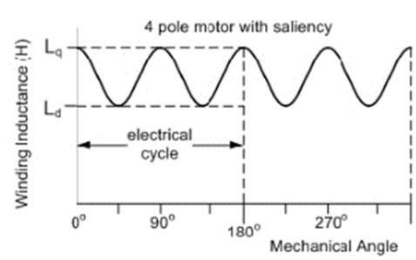
- Flux estimator depends on the R and L;
- Flux PPL loops time constant depends on R and L;
- Parking process uses L parameter to determine rotor position ;
- Motor open loop process used R value for start;
- Loop closing depends on R, L values with Rotor and flux information;

441

442

MOTOR LD INDUCTANCE

- This is per phase inductance of motor at rated current
- Important parameter in calculating Flux and Torque Parameters;



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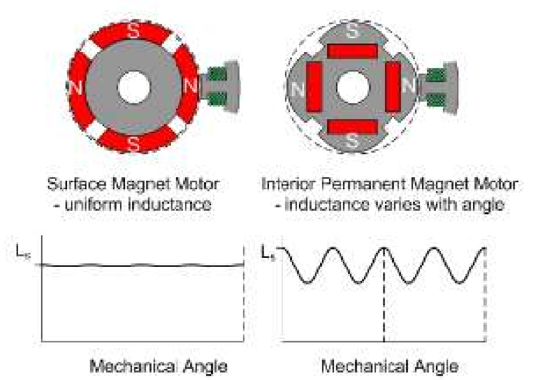
MOTOR LQ INDUCTANCE

- This is per phase inductance measured at rated current;
- For IPM motor inductance varies with Mechanical angle Lq > Ld;
- For SPM motor inductance remains the same Ld == Lq;
- Lq is maximum inductance of windings;



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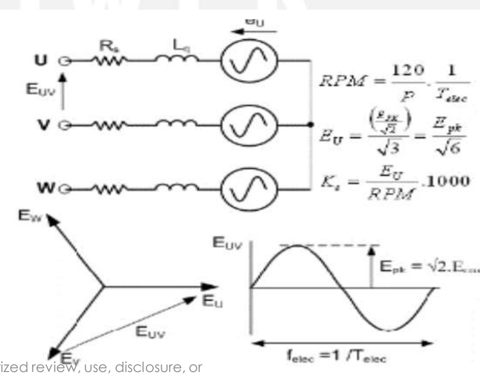
MOTOR BEMF CONSTANT KE

- Line to neutral Bemf constant expressed in Volts rms per 1000RPM;

$$K_e = 1000 * ([rmsVoltage]/\sqrt{3})([frequency]*120/poles)$$



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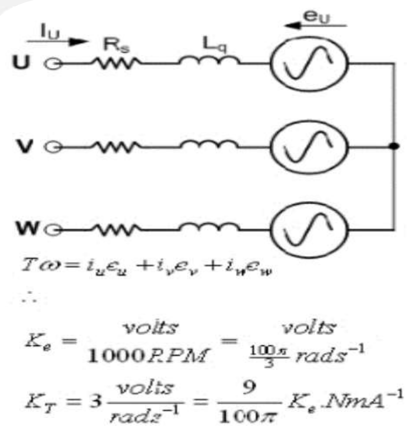
MOTOR TORQUE CONSTANT KT

- Kt is current dependent parameter;
- Measured in Nm per amps rms of line current;
- If Ld = = Lq;

$$K_t = \frac{(9 * K_e)}{(100 * \Pi)}$$



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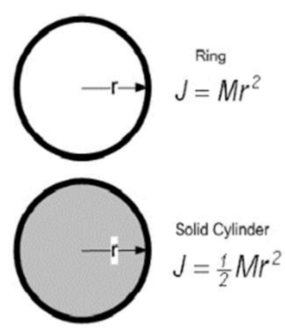
MOTORS TOTAL SHAFT INERTIA

- Used for start acceleration and speed regulation;
- Expressed in Kg-m^2;



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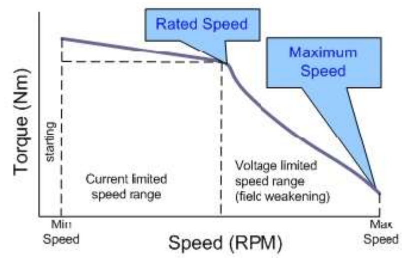
MOTOR MAX RPM;

- Maximum speed that Motor can Run;
- Speed Regulator will restrict speed below this value;
- Also used for Torque scaling;



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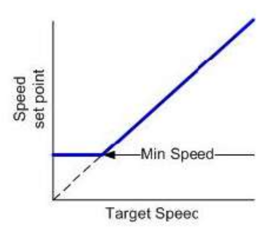
MINIMUM RUNNING SPEED

- Typically, 5% - 10% of rated speed;
- This minimum value is influenced by motor and Hardware;
- Reliability degrades at lower speeds;



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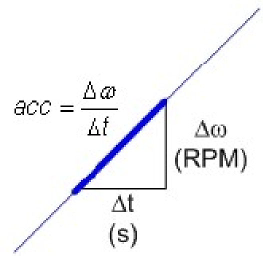
ACCELERATION RATE

- This set the rate of increase of speed in regulator reference;
- This acceleration rate is set to define the target speed profile;
- Actual acceleration depends on motor torque capacity



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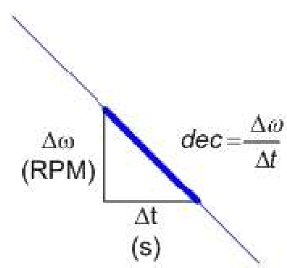
DECELERATION RATE

- This sets the rate of decrease in speed regulator reference;



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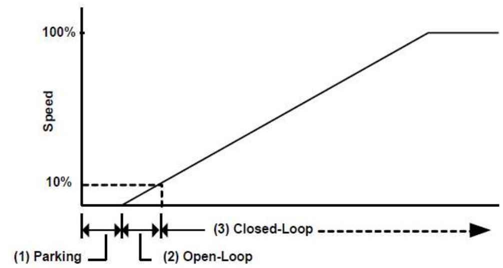
DRIVE START UP PROCESS

- Parking;
- Open loop speed & Bemf build up;
- Closed loop operation;



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PARKING PROCESS

- Rotor position is identified by forcing DC current into motor;
- This process makes shaft to park at a certain prescribed angle;
- Sets stator magnetizing vector at a fixed angle;
- Alignment torque tends to align with stator magnetizing vector;

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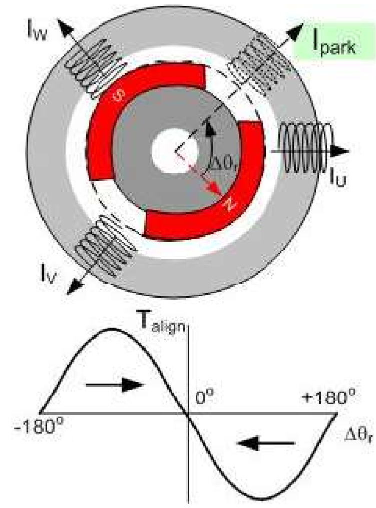
453

PARKING CONFIGURATION

Maximizes the torque at the start;

Parking current = 0.25*Irated;



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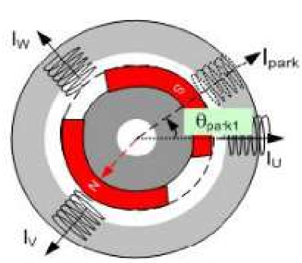
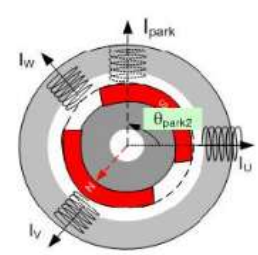
FIRST STAGE OF PARKING

- 2 angles are used to complete the parking process





First angle parking = 120

Second angle parking = 90

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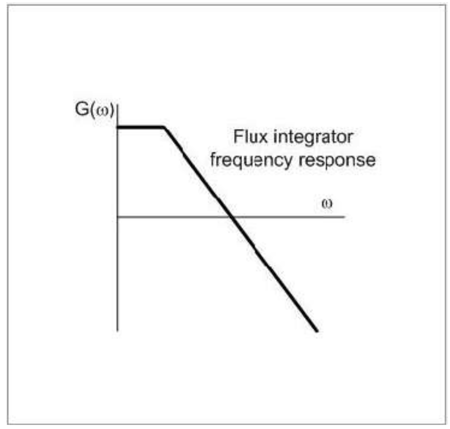
FLUX ESTIMATOR TIME CONSTANT

- Limits the low frequency response;
- Prevents from DC saturation;
- It is set to 15mS;



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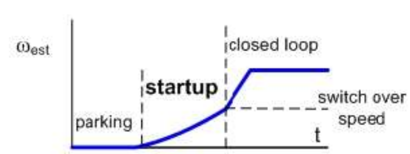
CLOSED LOOP SWITCH OVER SPEED

- Angle estimator closes the PLL loop;
- And uses rotor flux estimator as input;
- This value must be less than minimum speed;



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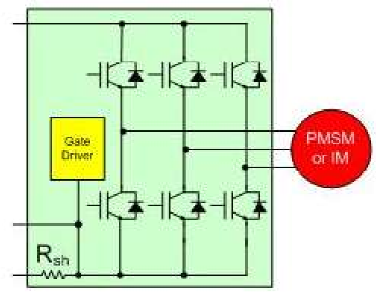
CURRENT FEED BACK SENSE

- Specify the value of the DC link current sense;
- Discrete component integrated into power module;



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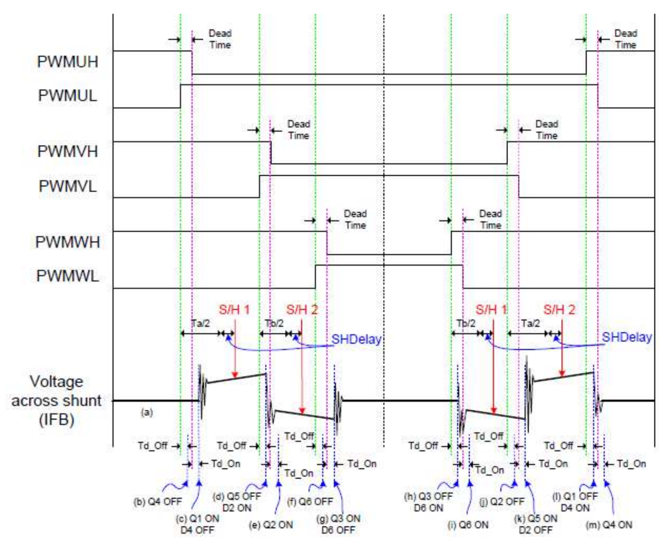
PWM SWITCHING PATTERN & CURRENT RECONSTRUCTION



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MOTOR CURRENT FEEDBACK AMPLIFIER GAIN

- Sets the gain of the current feedback difference amplifier;
- Gain is ratio of input & feedback resistance;
- Calculate the current of A/D converter saturation;
- Keep motor current less than A/D converter saturation current;
- For good control minimum current is 25% of A/D current;

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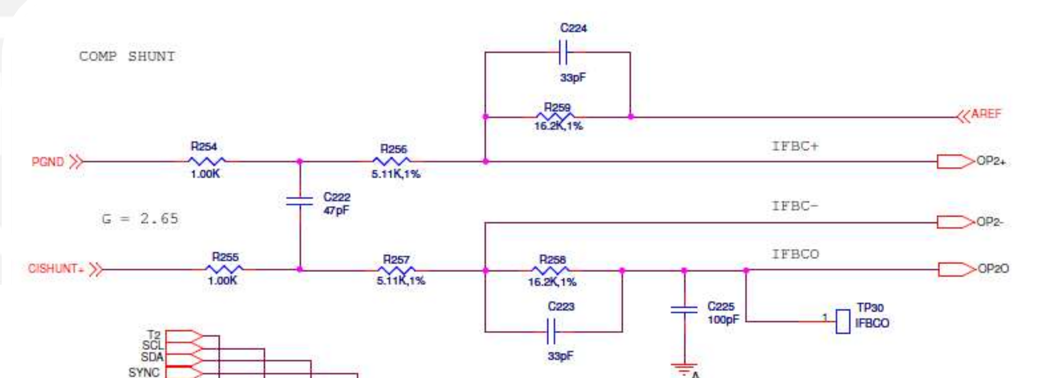
460

CALCULATION GAIN FOR MOTOR CURRENT F/B

- Motor current amplifier current feedback amplifier gain = $\frac{16.2k}{1.00k + 5.11k} = 2.65$



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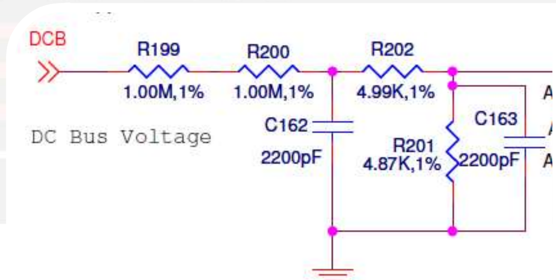
DC BUS FEEDBACK SCALING

- DC bus feedback gain
- Gain = 8.27 Counts/volts;
- 1.2V input = 4095 digital counts;

$$= 4095 * \left(\frac{4.87K}{1.00M + 1.00M + 4.99K + 4.87K} \right) \Big/ 1.2$$



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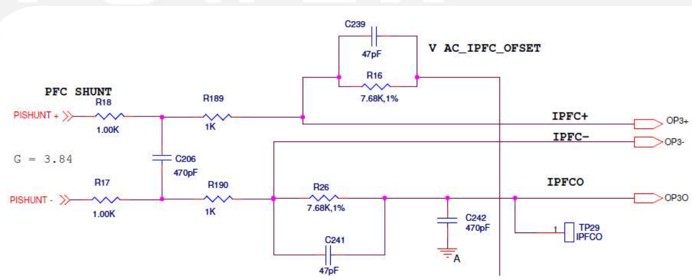
PFC CURRENT FEEDBACK AMPLIFIER GAIN

- Amplifier gain is determined from resistor network;
- Gain = $\frac{7.68k}{1.00k + 1k}$ = 3.84



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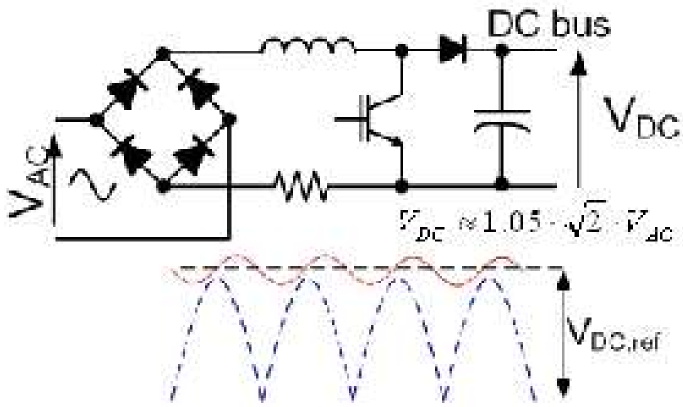
DC BUS VOLTAGE REFERENCE

In PFC mode DC bus Voltage > peak supply voltage;

PF >0.95 is obtained;

When supply varies from 220 – 240Vrms, DC reference is 385VDC

Varies between 360 – 385VDC;



463

DC BUS OVER VOLTAGE LEVEL

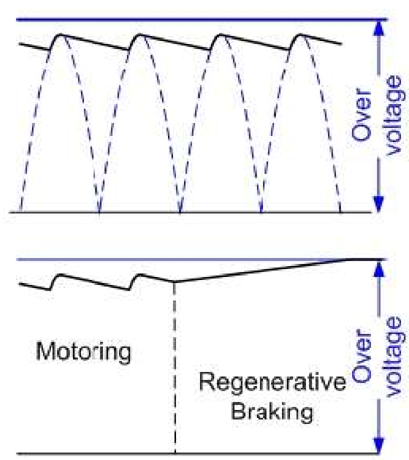
If bus voltage crosses this level control shut down inverter;

Motor speed is reduced to ZERO;

Protect the inverter component damage;

Typically it is set to 400V;

High voltage input may cause over voltage;



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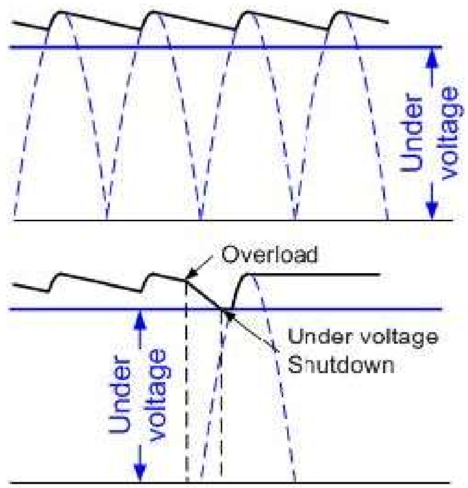
DC BUS UNDER VOLTAGE LEVEL

A low ac line will cause under voltage level;

Under voltage level is set to 120V;

Shut down the inverter and motor;

Avoid poor performance;



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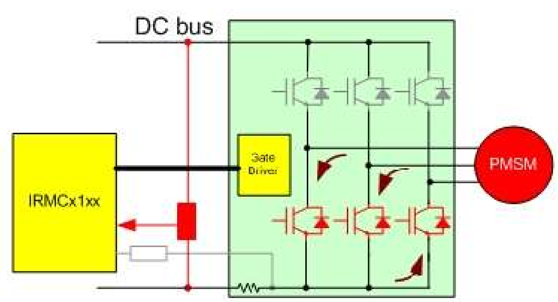
DC BUS CRITICAL VOLTAGE LEVEL

Controller applies zero vector braking;

Motor must be capable to withstand short circuit current

Turn ON all low side Transistor;

Protect the Boost PFC circuit;



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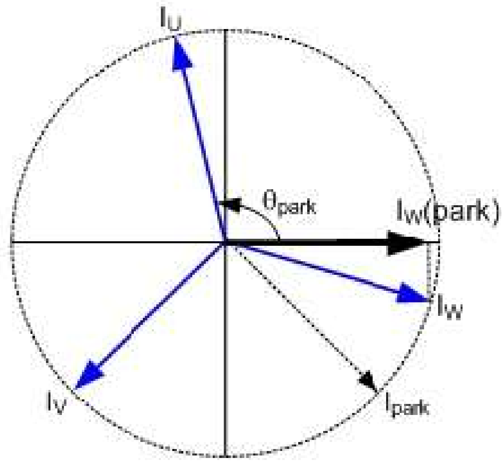
MOTOR PHASE LOSS DETECTION

Phase fault is detected during parking process;

If missing vector is identified, it generates fault;

Phase connection's fault is recorded;



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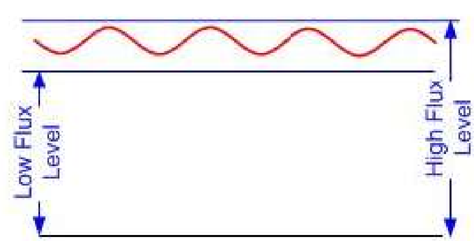
ENABLE START FAIL FAULT

- After loop is closed estimated rotor flux is compared with predefined limits;
- If flux is outside it generates the fault;
- Flux comparison is performed at every start up;



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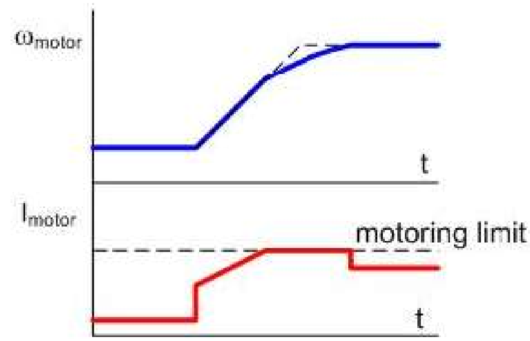
MOTOR CURRENT LIMIT

Current limit when motoring is expressed as percentage rated motor current;

Current regulator will not allow to go beyond this point;

Thermal capability for Motor & Inverter are considered



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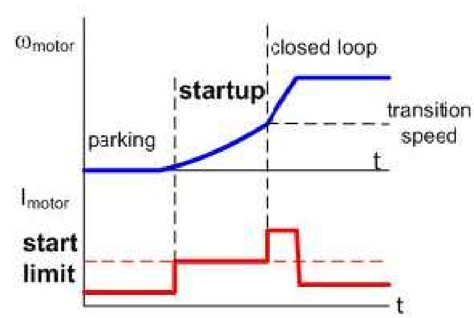
STARTING CURRENT LIMIT

- This is motor current limit at startup phase;
- It is expressed as %of rated current of motor;
- Current limit applies in closed loop;
- Set this value to lower for smooth start;



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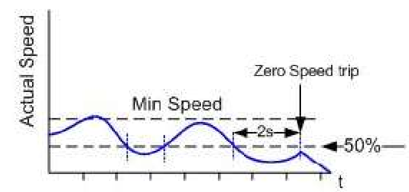
ZERO SPEED DETECTION

- Fault is generated is speed falls to half of minimum speed value;
- Minimum time period is 2 seconds;



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DRIVE PARAMETERS

new1 - Notepad

File Edit Format View Help

```
##MOTOR1_PARAMS
Mtr_Max_Speed               2500
Mtr_Rate_Amps               3.75
Mtr_Num_Poles               6
Mtr_Ke              35.00
##MOTOR1_REGS
MtrCtrlBits                 80
MtrCtrlBits_S               0
SysClk              800
PwmDeadTm                   80
PwmPeriodConfig             6666
Pwm2HiThr                   72
Pwm2LowThr                  51
PwmGuardBand                0
ActivePol                   32
TwoPhsCtrl                  0
GCChargePW                  240
GCChargePD                  40
GCChargeT                   100
MotorLim                    4095
RegenLim                    0
StartLim                    1229
KpIreg              4597
KpIregD             4597
KxIreg              8056
VdLim               722
VqLim               1324
VdcCompScale                69
KpSreg              42
KxSreg              80
SpdScl              768
SpdFiltBW                   195
SpeedScale                  85
AccelRate                   447
```


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MOTOR CONTROL PROBLEMS AND SOLUTIONS – PART 9

3-Day Workshop on Motor, Inverter, Hardware, and Firmware Design Techniques for Permanent Magnet Brushless Motors – A System Approach

April 22 - 25, 2025

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474

AGENDA

- Winding Overload;
- EMI & EMC Problems;
- Inverter Fault;
- Cogging Torque
- Torque Ripple
- Control Diagnosis

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WINDING OVERLOAD

- Symptoms
  - Does Not Start
  - Slow Speed Increase
  - Humming
  - Smoke
  - Smell

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EMI & EMC PROBLEMS

Cabling between drivers and motors;

Long Cables;

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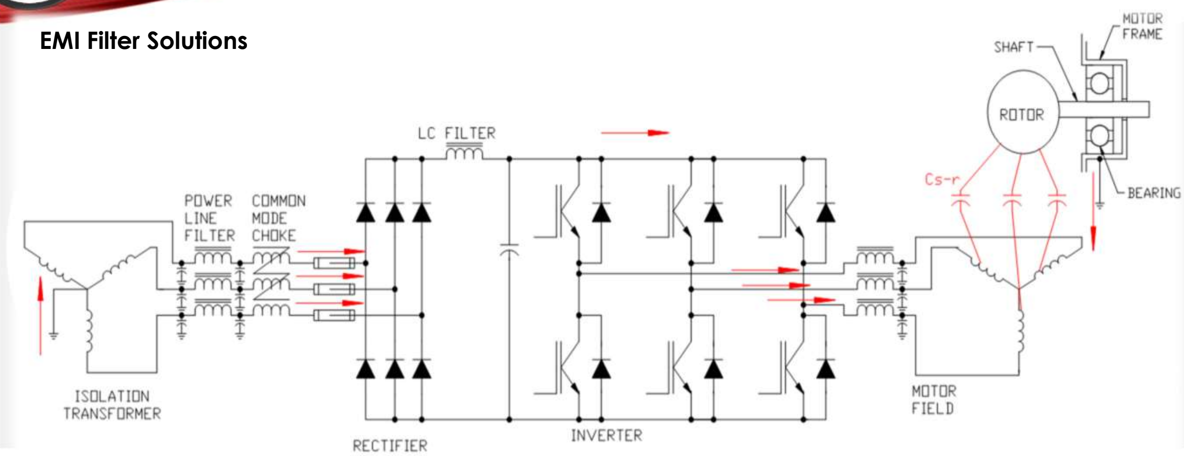
EMI Filter Solutions



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INVERTER FAULT MONITORING

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COGGING TORQUE SOLUTIONS

TIMING TECHNIQUE	• Dead Zone • Tooth notching
SMOOTHING TECHNIQUE	• Sinusoidal magnetization
GEOMETRIC TECHNIQUE	• Tooth crowning • Slot skewing

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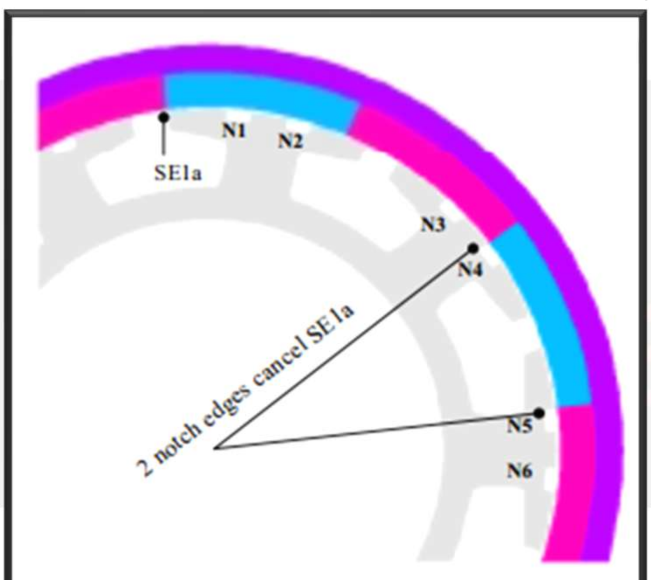
480

COGGING REDUCTION BY NOTCHES



480

481

Torque Ripple

Causes

Solutions

481

482

IMPROVED MOTOR DESIGN TECHNIQUES

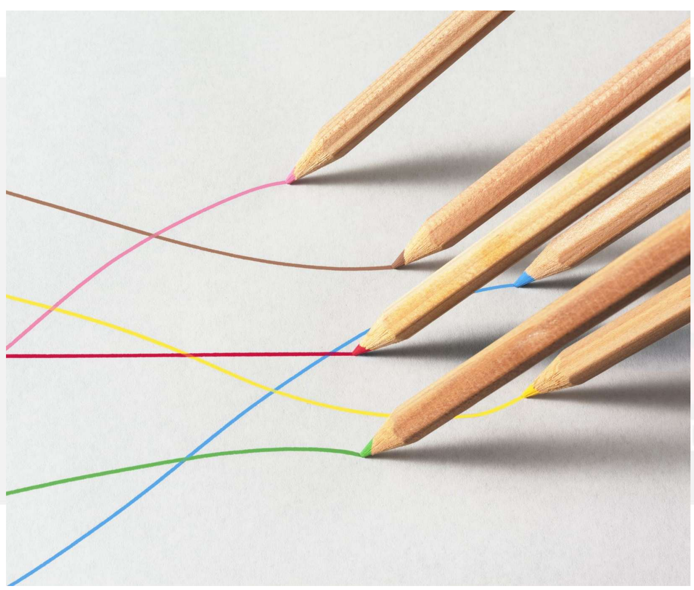
Skewing;

Fractional slot winding;

Short pitch winding;

Increased number of phases;

Air-gap windings;



482

483

IMPROVED CONTROL TECHNIQUES

- Modified PWM control technique;
- DC bus voltage control;
- Current control-based techniques;
- DTC (direct torque control);
- Phase conduction methods (for 6-step);

483

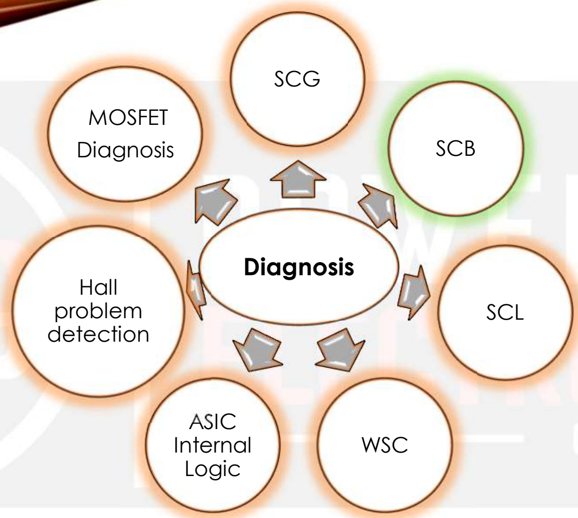
484

CONTROL SYSTEM FAULTS/DIAGNOSIS

- Short circuit conditions at motor terminals;
- Internal, external power supply voltages and over-temperature failure Conditions;

484

485



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486

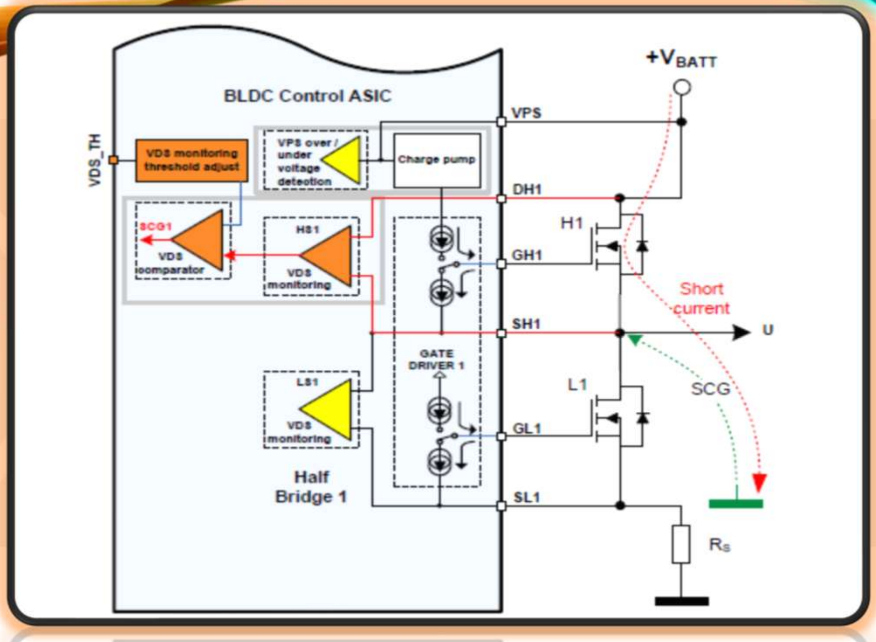
BLDC MOTOR DIAGNOSIS CONCEPTS

- ONSM (ON State Monitoring)
- OFSM (OFF State Monitoring)

486

SCG

$$I_{SC} \geq \frac{VDS_{TH}}{R_{DS\_ON}}$$



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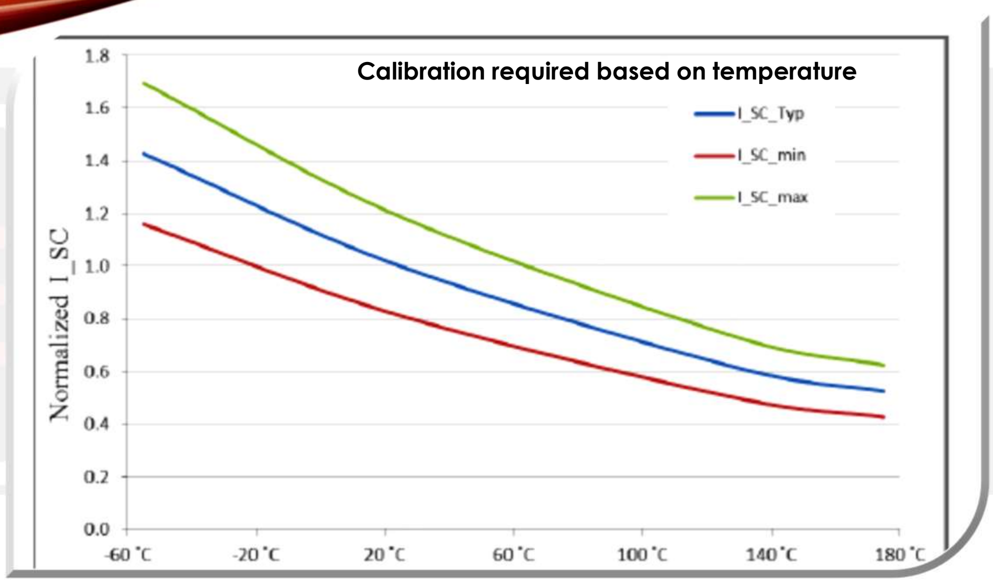

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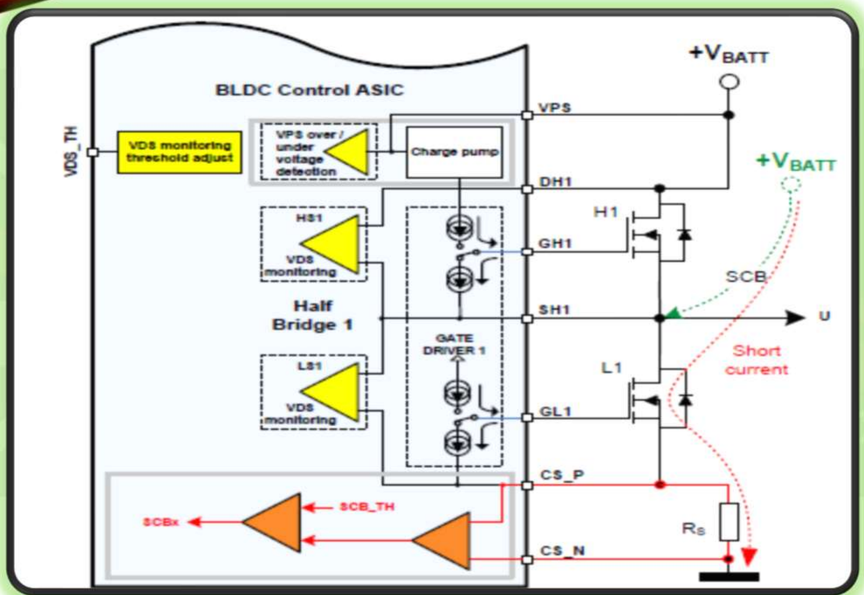
409

Short Circuit to Battery (SCB)



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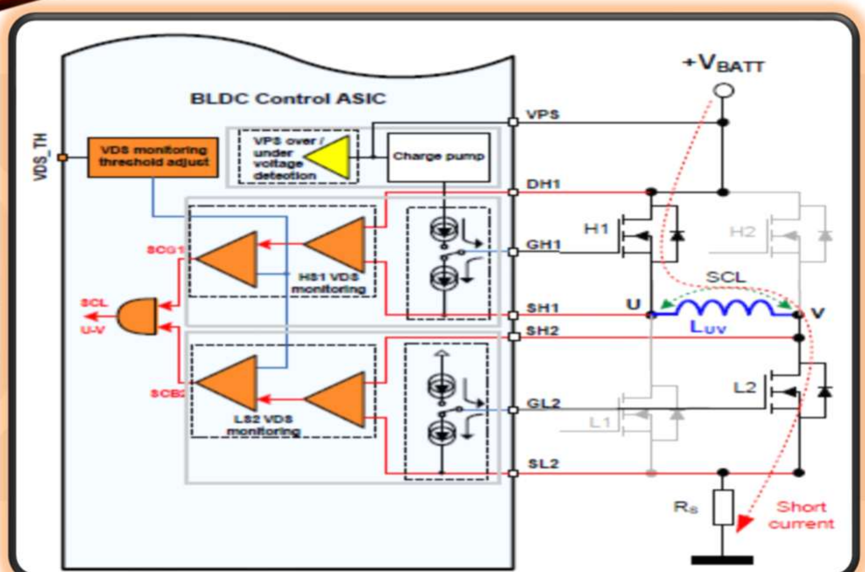
Short Circuit to Load (SCL)



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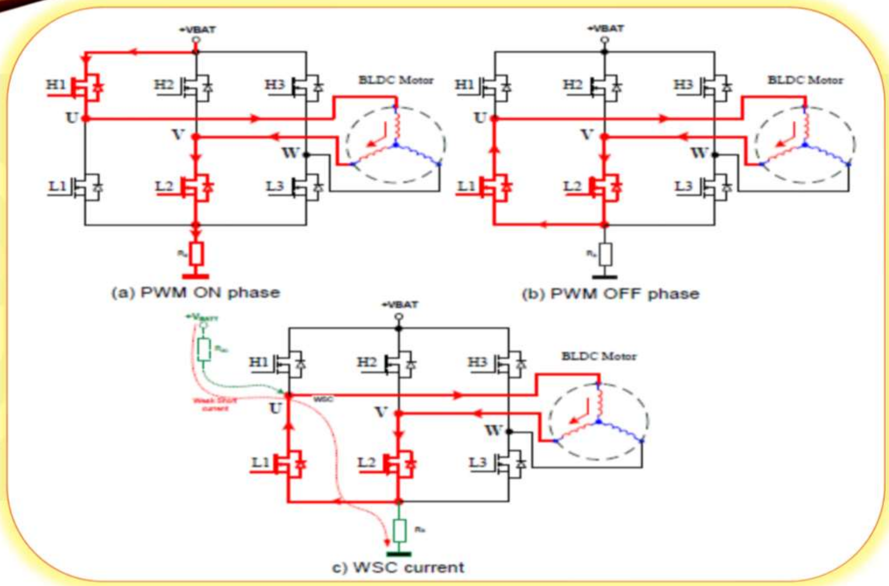
491

$$I_{WSC} \geq \frac{WSC\_TH}{R_S}$$

Weak Short Circuit (WSC)



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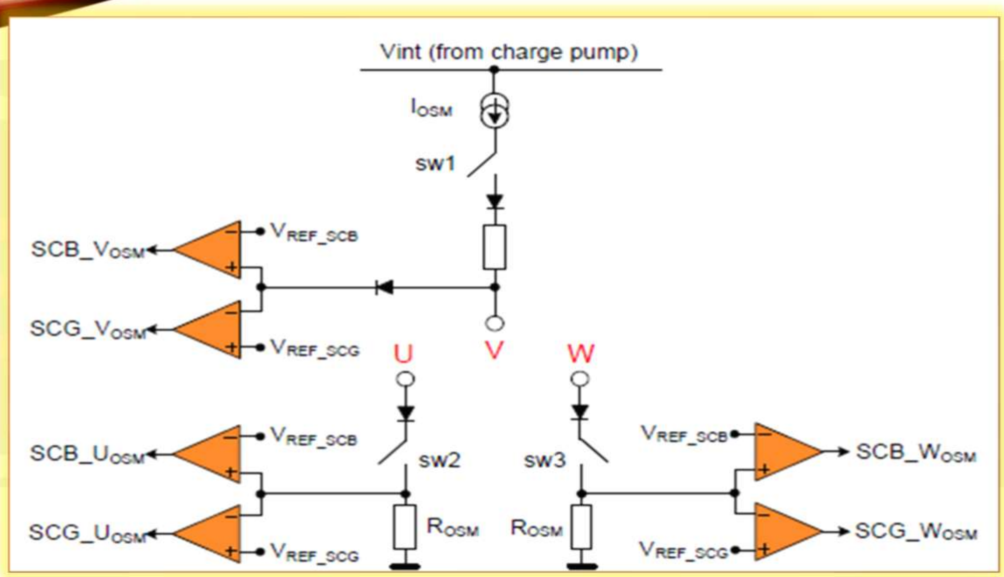


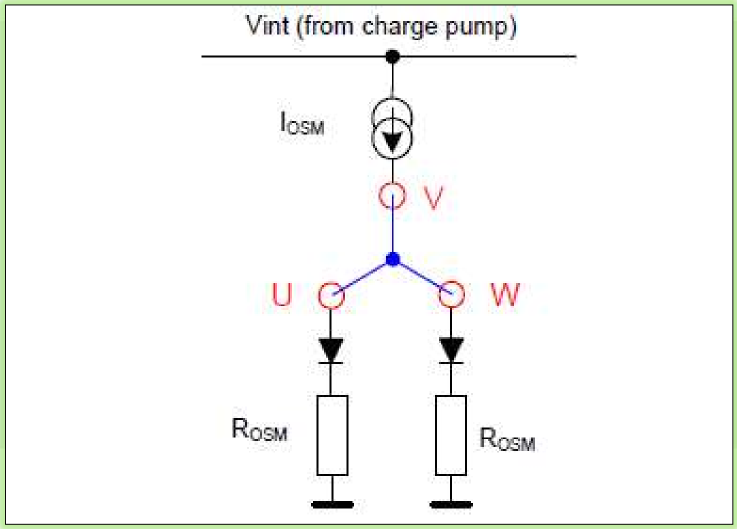
492

493

Phase Voltage Monitoring

$$V_{U\_OSM} = V_{V\_OSM} = V_{W\_OSM} = \frac{R_{OSM} \cdot I_{OSM}}{2} + V_D$$

These voltages will change under
SCB
SCG
WSC
Winding Fault



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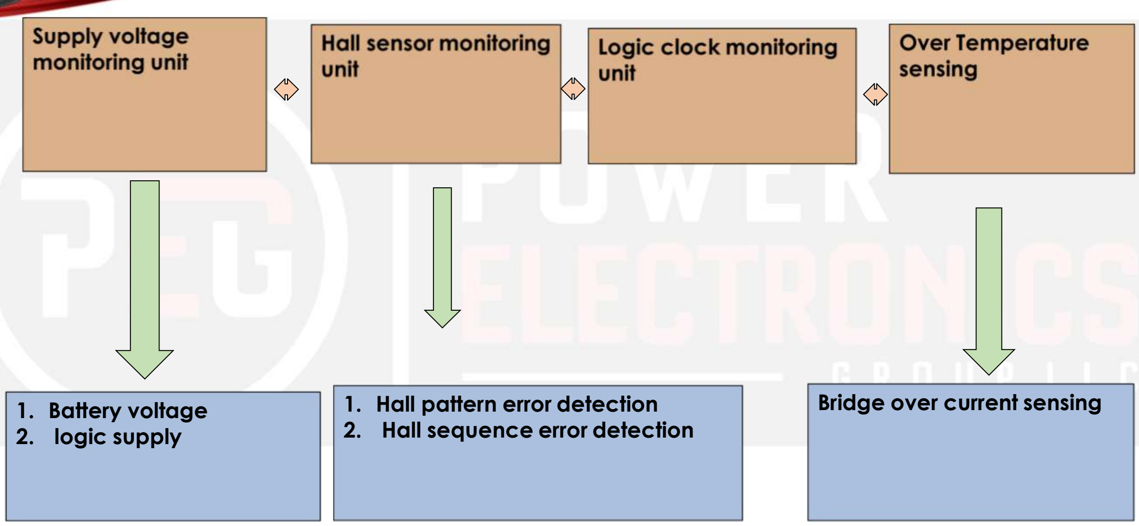

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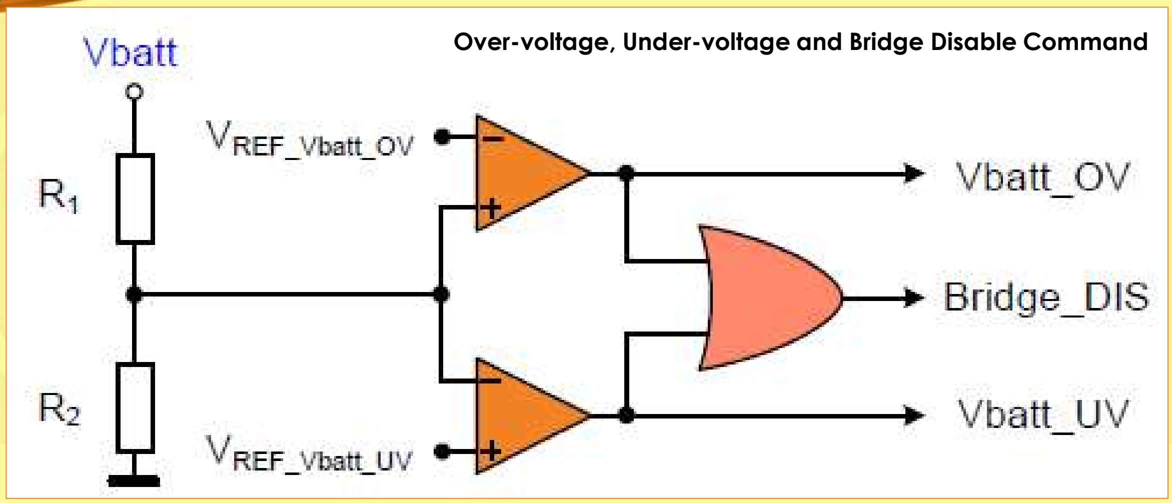

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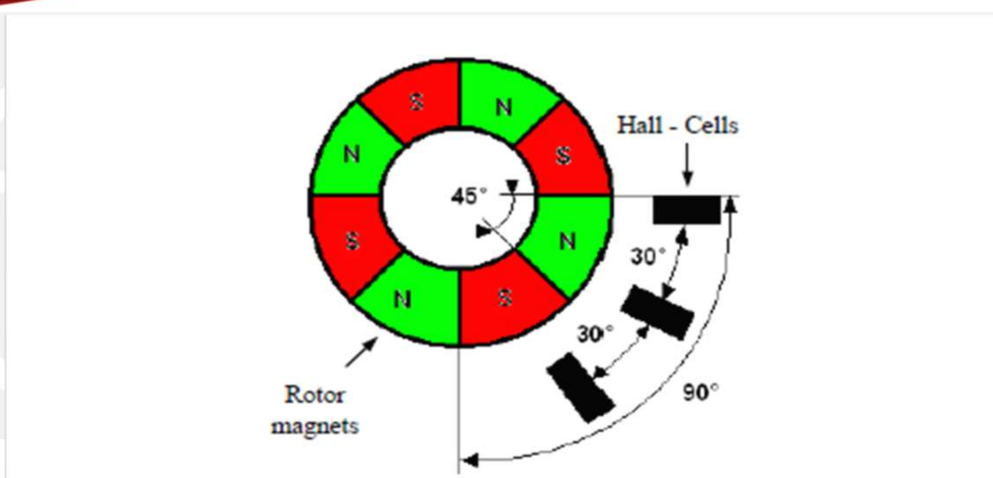

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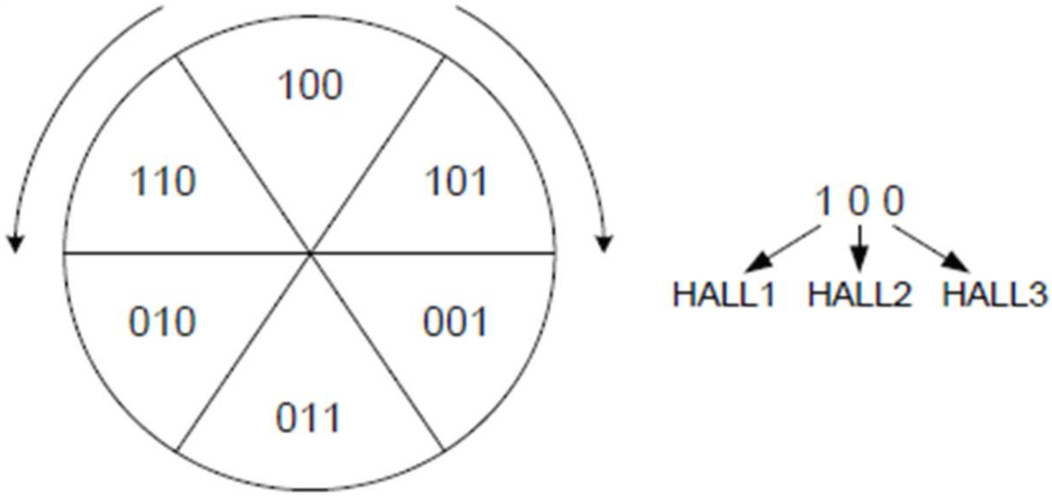
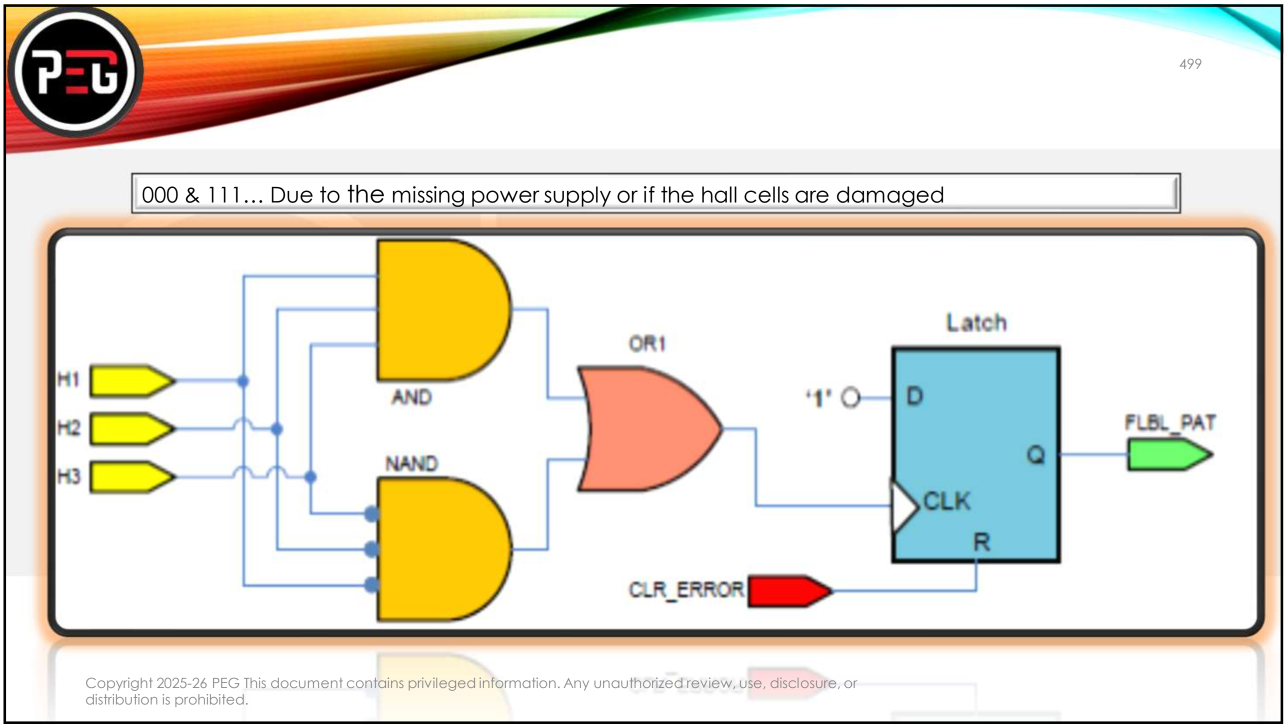


497

498

HALL1	HALL2	HALL3	
0	0	0	Invalid!
1	0	0	Sequence 1
1	0	1	Sequence 2
0	0	1	Sequence 3
0	1	1	Sequence 4
0	1	0	Sequence 5
1	1	0	Sequence 6
1	1	1	Invalid!

498


499
000 & 111… Due to the missing power supply or if the hall cells are damaged
H1
H2
H3
AND
NAND
OR1
Latch
'1'
D
Q
CLK
R
FLBL_PAT
CLR_ERROR
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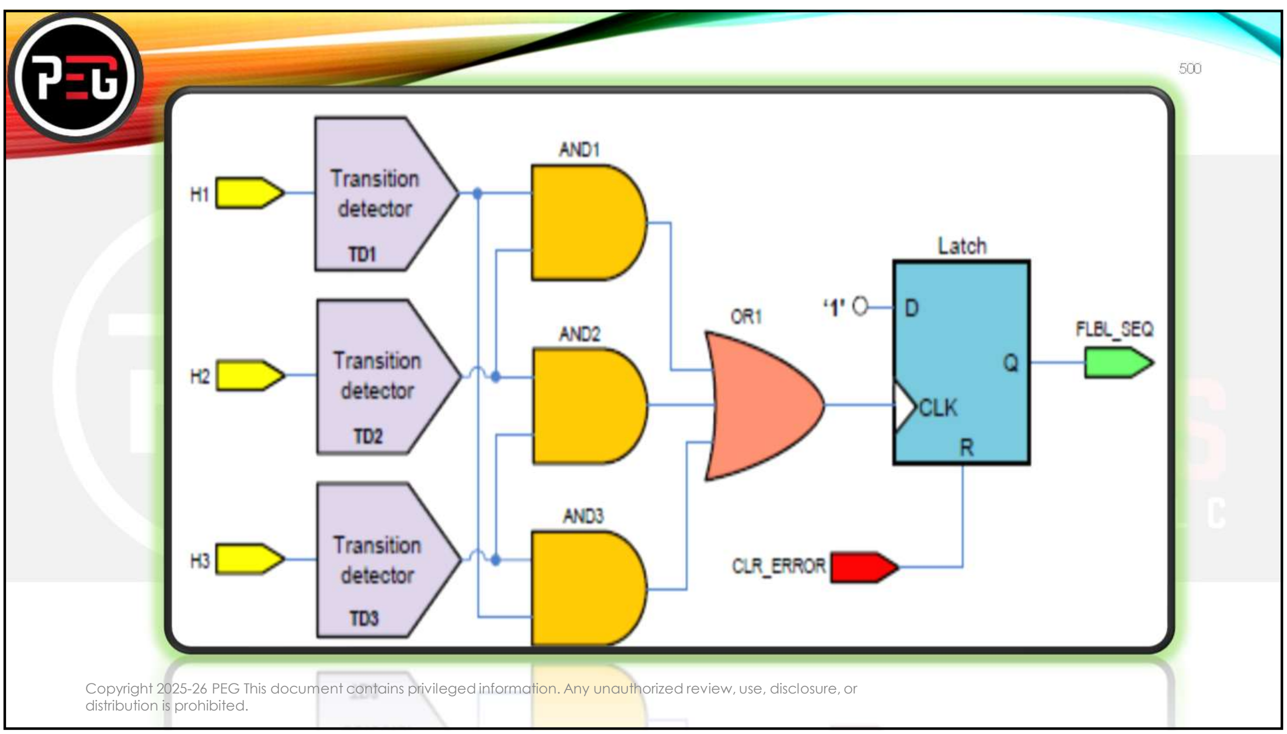
499


500
H1
H2
H3
Transition detector
TD1
Transition detector
TD2
Transition detector
TD3
AND1
AND2
AND3
OR1
Latch
'1'
D
Q
CLK
R
FLBL_SEQ
CLR_ERROR
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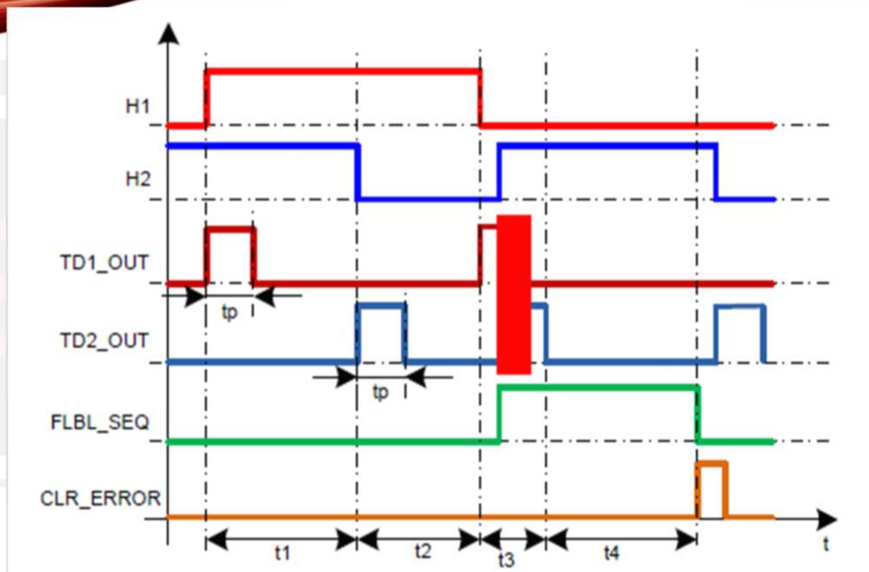
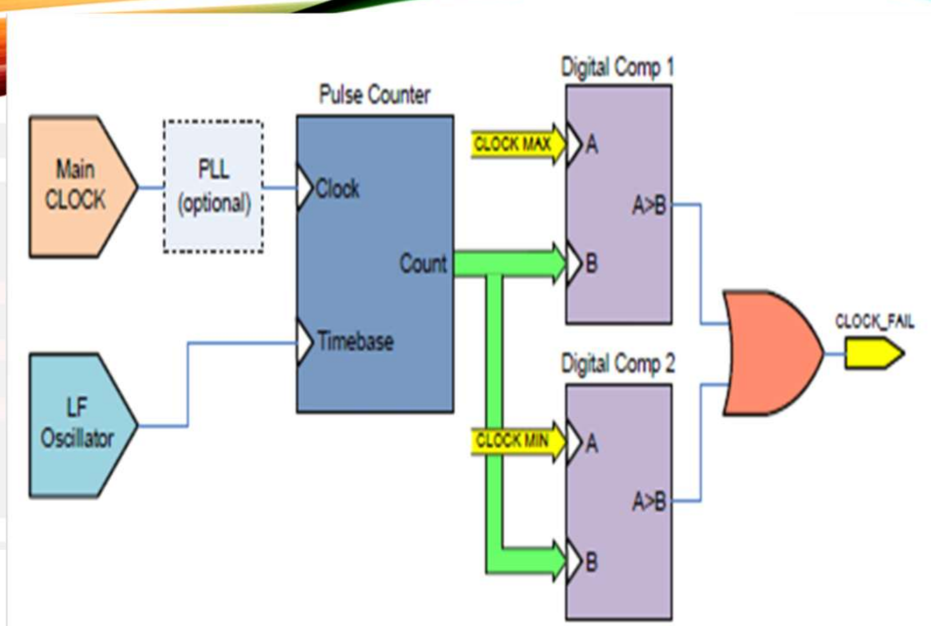

501
H1
H2
TD1_OUT
tp
TD2_OUT
tp
FLBL_SEQ
CLR_ERROR
t1
t2
t3
t4
t

501


502
Main CLOCK
PLL (optional)
Pulse Counter
Clock
Count
Timebase
LF Oscillator
Digital Comp 1
CLOCK MAX
A
B
A>B
Digital Comp 2
CLOCK MIN
A
B
A>B
CLOCK_FAIL

502

OVER TEMPERATURE SENSING

1. Power inverter block;
2. Controller;

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FIRMWARE DEVELOPMENT – PART 10

3-Day Workshop on Motor, Inverter, Hardware, and Firmware Design Techniques for Permanent Magnet Brushless Motors – A System Approach

April 22 – 24, 2025

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AGENDA

- Driving Algorithms;
  - Six Step Control using 8-bit uC;
  - Basic Sinusoidal Control;
  - Field Oriented Control;
  - Space Vector Modulation.
  - Stability Analysis;

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FIRMWARE DEVELOPMENT

LANGUAGE BASED

MODEL BASED

506

LANGUAGE BASED (8 TO 32-BIT)

Altera;	Infineon;	Microchip;	Nxp;
Renesas;	ST Microelectronics;	Texas Instruments;	Toshiba;

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MODEL BASED DESIGN

Tool	Control Design	Motor Modeling	Power Electronics	Code Generation	HIL Support	Real-Time Sim	Domain Focus	Supported Processors
Altair Activate	✓	✓	✓				Multi-Domain	Depends on Modelica backend
Altair Embed	✓	✓	✓	✓	✓	✓	Embedded Motor Control, Real-Time System Prototyping	TI C2000, STM32, ARM Cortex-M
DSHplus	✓	✓	✓				Fluid Power, Mechatronics	
dSPACE	✓	✓	✓		✓	✓	Embedded Systems, HIL	TI C2000, ARM Cortex-M, others via Simulink
Dymola	✓	✓					Multi-domain via Modelica	Via Simulink or external tools (TI, ARM)
EICASLAB	✓	✓					Control Design	ARM, DSPs (specifics less known)
JMAG-RT		✓					EM Simulation	Export models to Simulink/C code
LMS Imagine.Lab AMESim	✓	✓	✓				Multi-Physics	Via Simulink integration
MapleSim	✓	✓	✓				Symbolic Modeling	TI C2000, ARM (via connectors)
MATLAB and Simulink	✓	✓	✓		✓	✓	Industry Standard	TI C2000, STM32, ARM Cortex-M, NXP, Infineon, Microchip, Renesas
Modelica	✓	✓					Open Modeling Language	Depends on toolchain (Dymola, OpenModelica, etc.)
NI LabVIEW + VeriStand	✓				✓	✓	Test & Measurement	NI PXI, CompactRIO (x86, FPGA)
OpenModelica	✓	✓					Open Source Modeling	Depends on integration, not direct
PLECS (Plexim)	✓	✓	✓		✓	✓	Power Electronics	TI C2000, STM32, ARM Cortex-M (via PLECS Coder)
Scilab/Xcos	✓						Open Source Modeling	Custom C code generation possible
SimulationX	✓	✓	✓				Multi-Domain	Via co-simulation with Simulink
Synopsys SaberRD	✓	✓	✓				Mixed-Signal Systems	FPGA/DSP/ASIC (indirect via HDL tools)
TwinCAT 3	✓			✓		✓	Industrial Automation	x86, Beckhoff IPCs
Typhoon HIL		✓	✓		✓	✓	Real-Time HIL	No direct target code gen, HIL-focused
VisSim (Altair Embed)	✓	✓		✓	✓	✓	Embedded Systems	TI C2000, STM32, ARM Cortex-M

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ALGORITHM DEVELOPMENT

1. Real-Time Determinism (Timer Based Loop Execution)
2. Modular Architecture
3. Efficient Use of MCU Resources
4. Accurate Current Sensing
5. Position Estimation
6. Speed Estimation
7. PI Loop Procession
8. Duty Cycle Computation
9. Error Detection & Response
10. Testing, Tuning and Maintenance

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8-BIT MCU VS. 32-BIT DSP

	8-Bit MCU	32-Bit DSP
Timer Based Functions	Highly Critical	Less Critical
Code Efficiency	High	Low
ADC Execution Time	2uS	80nS
ADC Execution	Serial/Sequential	Parallel
PI Processing	20-40uS	<2uS
Active Filtering	80 to 90uS	<2uS
Wave shaping	Table Based	Function Based
Overall Execution Time (Scalar Control)	~90uS	~4uS
Scalability	Low	High
Cost	Low	High
Algorithm Adaptation	Low	High

510

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BASIC BLDC CONTROL ALGORITHM

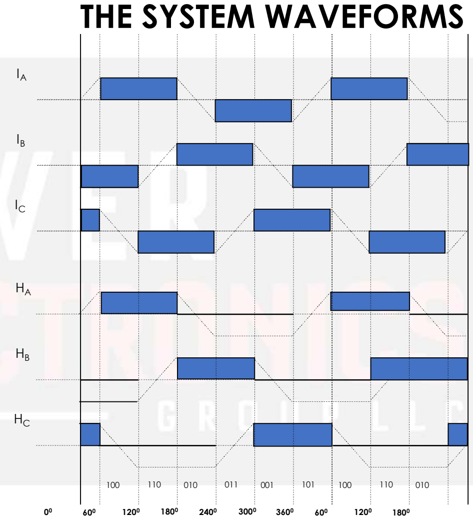
- One Shot Inverter State Determination;
- Choice of PWM Schemes (Top Side Vs. Bottom Side PWM etc.);
- Sensor-less Possible;
- Single ADC Channel Scan Requirement per PWM Cycle.

511

512

	100	110	010	011	001	101
A_T	1	1				
B_T			1	1		
C_T					1	1
A_B				1	1	
B_B	1					1
C_B		1	1			

THE SYSTEM WAVEFORMS



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BASIC SINUSOIDAL CONTROL

3-Day Workshop on Motor, Inverter, Hardware, and Firmware Design Techniques for Permanent Magnet Brushless Motors – A System Approach

April 22 – 24, 2025

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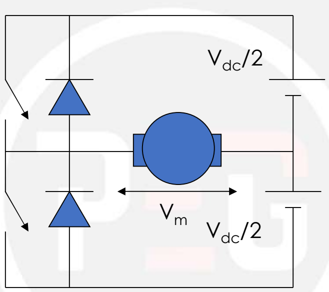
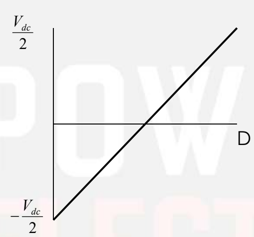
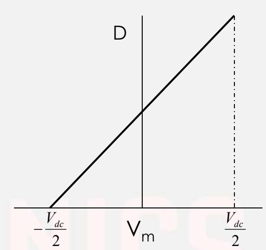
3 PHASE SINE INVERTER: GENERATING D







$$V_m = \frac{V_{dc}}{2}.[2.D - 1]$$

$$D = \left(\frac{2.V_m}{V_{dc}} + 1\right) \Big/ 2$$

514

515

3 PHASE SINE INVERTER: GENERATING D

Amplitude Modulation Ratio: $m_a = \frac{V_m}{V_{dc}/2}$

$$V_{a\_ctrl} = \frac{1}{2} \cdot \frac{V_m}{V_{dc}/2} . Sin(w_e . t) + \frac{1}{2}$$

$$V_{b\_ctrl} = \frac{1}{2} \cdot \frac{V_m}{V_{dc}/2} . Sin(w_e . t - 120^o) + \frac{1}{2}$$

$$V_{c\_ctrl} = \frac{1}{2} \cdot \frac{V_m}{V_{dc}/2} . Sin(w_e . t - 240^o) + \frac{1}{2}$$

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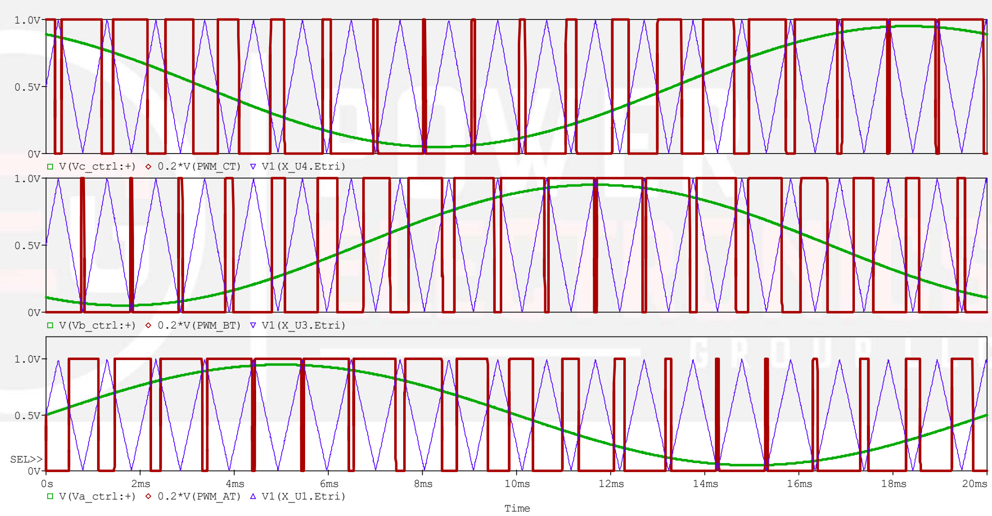
3 PHASE SINE INVERTER: GENERATING D

PWM CT

PWM BT

PWM AT



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FIELD ORIENTED CONTROL

3-Day Workshop on Motor, Inverter, Hardware, and Firmware Design Techniques for Permanent Magnet Brushless Motors – A System Approach

April 22 - 25, 2025

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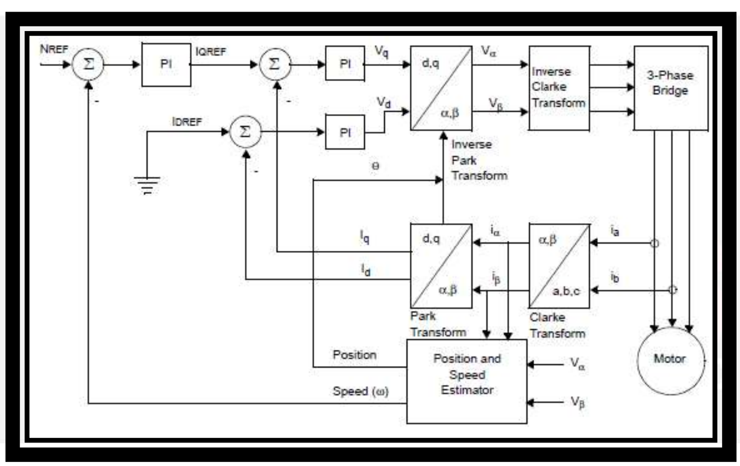
BLOCK DIAGRAM FOC CONTROL



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ADVANTAGES

- Quick response;
- Accurate position control;
- Phase Correction Alignment;
- Machine Models valid in Steady & Transient State;
- Independent Torque & Flux Control;
- PI Regulators neither Damage References nor introduce High Bandwidth noise.

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COMPARISON OF SCALAR & VECTOR CONTROL

Scalar Control	Vector Control
Controls only magnitude.	Controls both magnitude and phase.
Have sluggish response.	Have fast transient response.
Torque and flux are functions of frequency.	Torque and flux are independently controlled.
Accurate position control is not possible.	Accurate position control is possible.
Easy to implement.	Complex to implement.

520

521

FOC FUNDAMENTALS

- Motor is modeled into Synchronous Reference Frame;
- Stator Currents Serve as an input to these Models;
- Speed & Position are estimated from the Hall code;
- Excitation flux & Rotor flux are decoupled for Control;
- Objective is to control the motor similar to Separately excited DC motor;

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FOC FUNDAMENTALS

- I_d→ Flux producing component (direction of rotor flux phasor);
- I_q→ Torque producing component (orthogonal to rotor flux);

522

523

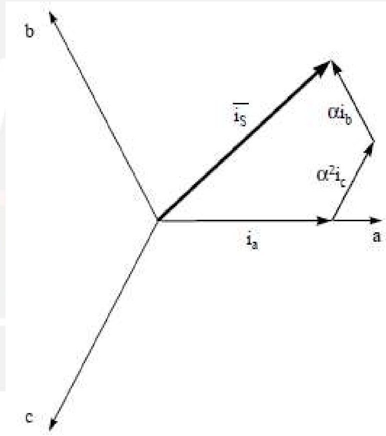
FOC FUNDAMENTALS

- The 3-phase currents are given by:

$$I_a = I_m \sin(\omega t)$$
$$I_b = I_m \sin(\omega t - 120)$$
$$I_c = I_m \sin(\omega t - 240)$$

- For a balanced system:

$$I_a + I_b + I_c = 0$$



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FOC FUNDAMENTALS

- The complex stator current vector is represented by:

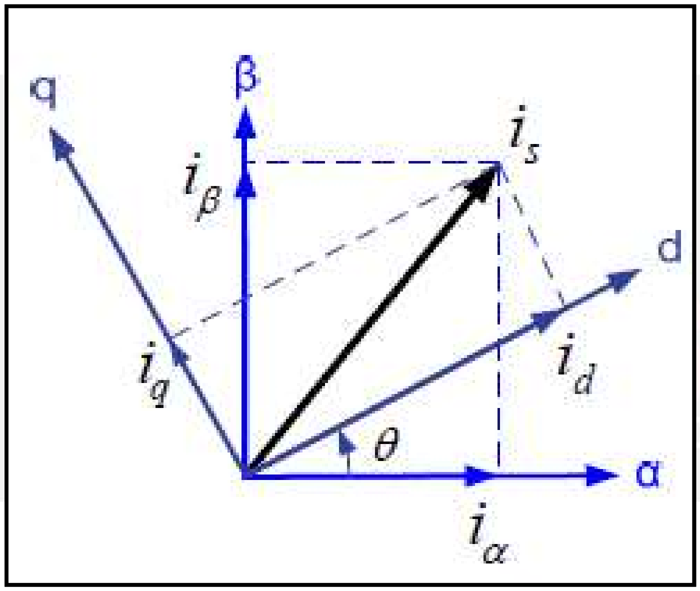
$$\bar{i}_s = i_a + \alpha i_b + \alpha^2 i_c$$

- Where $\alpha = e^{j2\pi/3}$ and $\alpha^2 = e^{j4\pi/3}$ are the spatial operators.

524

525

TRANSFORMATIONS



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TRANSFORMATIONS

Clarke's transformation

$$\begin{bmatrix} f\alpha \\ f\beta \end{bmatrix} = (2/3) \cdot \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \cdot \begin{bmatrix} fa \\ fb \\ fc \end{bmatrix}$$

Park's transformation

$$\begin{bmatrix} f_d \\ f_q \end{bmatrix} = \begin{bmatrix} \cos(\theta_e) & \sin(\theta_e) \\ -\sin(\theta_e) & \cos(\theta_e) \end{bmatrix} \cdot \begin{bmatrix} f_\alpha \\ f_\beta \end{bmatrix}$$

Where 'f' can be either Voltage or Current.

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COMPARISON OF PARK'S & CLARKE'S TRANSFORMATION

Clarke's transformation	Park's transformation
Projection of phase quantities onto stationary reference frame.	Projection of phase quantities onto rotating reference frame.
The converted quantities still depend on time & speed.	The converted quantities are time independent.

527

BLDC MOTOR: FOC MODEL

- Electrical equations:

$$V_{as} = V\cos(\omega t)$$
$$V_{bs} = V\cos(\omega t - 2\pi/3)$$
$$V_{cs} = V\cos(\omega t - 4\pi/3)$$

$$I_{as} = I\cos(\omega t)$$
$$I_{bs} = I\cos(\omega t - 2\pi/3)$$
$$I_{cs} = I\cos(\omega t - 4\pi/3)$$

$$\theta_e = \theta_m . p$$
$$\omega_e = \omega_m . p$$

$$v = Ri + \frac{d\lambda}{dt} = Ri + \frac{d}{dt}(Li + \lambda_m(\theta))$$

528

BLDC MOTOR: FOC MODEL

- The BEMF is given by:

$$\overline{E} = \begin{bmatrix} E_a(\theta) \\ E_b(\theta) \\ E_c(\theta) \end{bmatrix} = -\omega_e.\lambda_m. \begin{bmatrix} \sin(\theta_e) \\ \sin(\theta_e - 2\pi/3) \\ \sin(\theta_e - 4\pi/3) \end{bmatrix} = \omega_e.\lambda_m.[k(\theta_e)]$$

- →Magnetic flux of permanent magnet.

λ_m

BLDC MOTOR: FOC MODEL

$$T_e = \frac{3}{2}\frac{p}{2}(\lambda_d i_q - \lambda_q i_d) \qquad T_e = p[I_s]^t \lambda_m.[k(\theta_e)]$$

Since Rotor flux is oriented with d-axis, Id=0.

$$\lambda_d = \lambda_m$$

$$T_e = \frac{3}{2}\frac{p}{2}(\lambda_m i_q)$$ Hence by controlling Iq, Torque can be controlled.

- Mechanical equations:

$$T_e = T_l + k_e \omega_m + J\frac{d\omega_m}{dt}$$

BLDC MOTOR: FOC MODEL

Clarke's transformation

$$i_\alpha = \frac{2}{3}.(i_a - \frac{i_b}{2} - \frac{i_c}{2})$$

$$i_\beta = \frac{2}{3}.(\frac{i_b}{\sqrt{3}} - \frac{i_c}{\sqrt{3}})$$

$$V_\alpha = r_s i_\alpha + p\lambda_\alpha$$

$$V_\beta = r_s i_\beta + p\lambda_\beta$$

$$\lambda_\alpha = L_s i_\alpha + \lambda_{\alpha m} = L_s i_\alpha + \lambda_m \cos(\theta_e)$$

$$\lambda_\beta = L_s i_\beta + \lambda_{\beta m} = L_s i_\beta + \lambda_m \sin(\theta_e)$$

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BLDC MOTOR: FOC MODEL

Park's transformation

$$i_{ds} = i_{\alpha s}\cos(\theta_e) + i_{\beta s}\sin(\theta_e)$$

$$i_{qs} = -i_{\alpha s}\sin(\theta_e) + i_{\beta s}\cos(\theta_e)$$

$$V_{ds} = r_s i_{ds} - \omega_e \lambda_{qs} + \frac{d}{dt}\lambda_{ds}$$

$$V_{qs} = r_s i_{qs} - \omega_e \lambda_{ds} + \frac{d}{dt}\lambda_{qs}$$

$$\lambda_d = L_s i_d + \lambda_m$$

$$\lambda_q = L_s i_q$$

$\theta_e = \tan^{-1}\left(\frac{\lambda_\beta}{\lambda_\alpha}\right)$ →Rotor position.

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TRANSFORMATIONS

$$\begin{bmatrix} f_\alpha \\ f_\beta \end{bmatrix} = \begin{bmatrix} \cos(\theta) & -\sin(\theta) \\ \sin(\theta) & \cos(\theta) \end{bmatrix} \begin{bmatrix} f_d \\ f_q \end{bmatrix}$$ Anti-Park's transformation

$$\begin{bmatrix} f_a \\ f_b \\ f_c \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ -1/2 & \sqrt{3}/2 \\ -1/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} f_\alpha \\ f_\beta \end{bmatrix}$$ Anti-Clarke's transformation

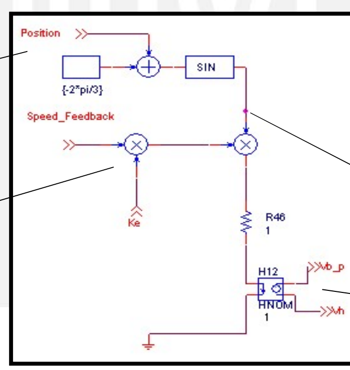
Where 'f' can be either Voltage or Current.

P-SPICE IMPLEMENTATION

- Sinusoidal BEMF modeling

Rotor position is added with an offset

Speed feedback is multiplied with K_e



Position based Sinusoidal Signal

BEMF signal

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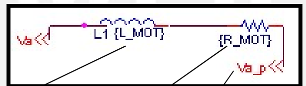
P-SPICE IMPLEMENTATION

- Developing a per phase Motor model



Motor Inductance per phase

Motor Resistance per phase

BEMF signal

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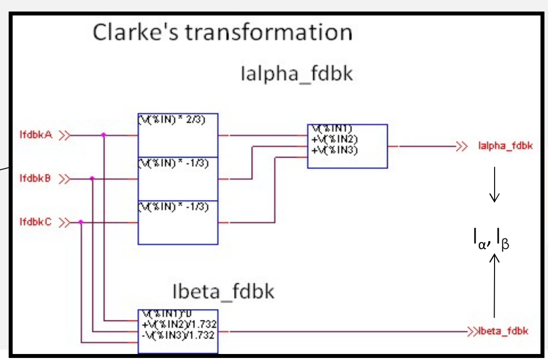
P-SPICE IMPLEMENTATION

- Clarke's Transformation.

3-Phase feedback currents



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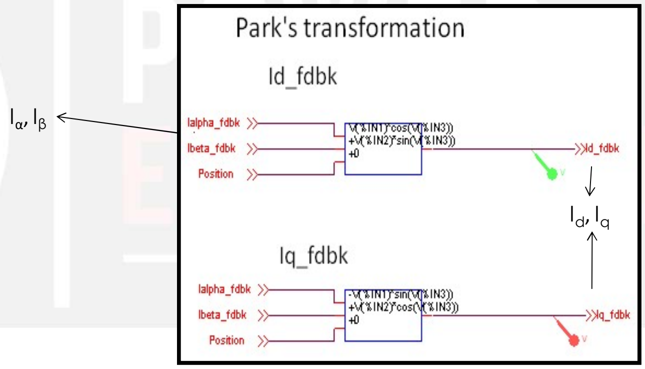
P-SPICE IMPLEMENTATION

- Park's Transformation



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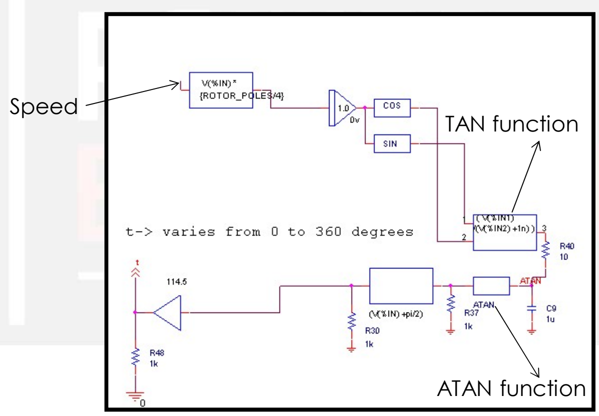
P-SPICE IMPLEMENTATION

- Generating Position Ramp



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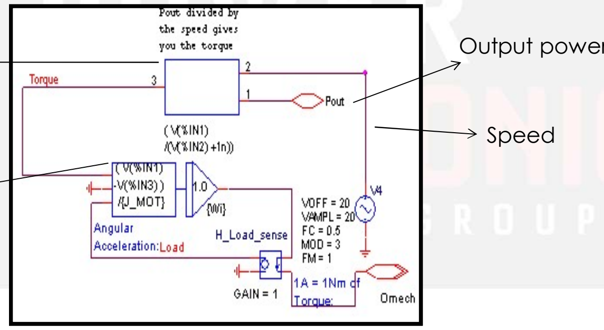
P-SPICE IMPLEMENTATION

- Generating Torque

$$T = \frac{P_{out}}{\omega}$$

$$\omega_{mech} = \frac{T - T_l}{J}$$



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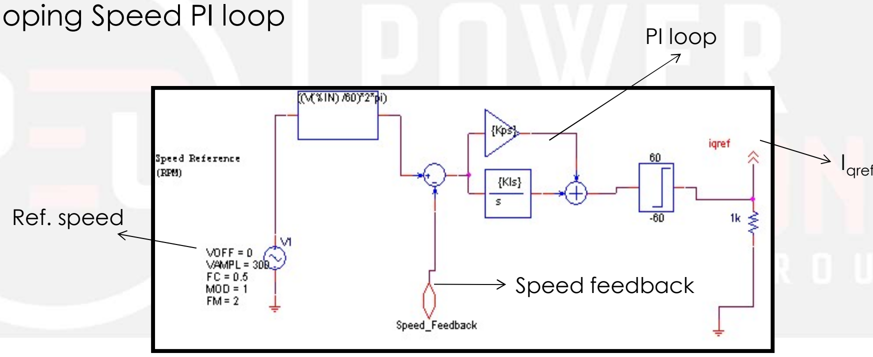
P-SPICE IMPLEMENTATION

- Developing Speed PI loop



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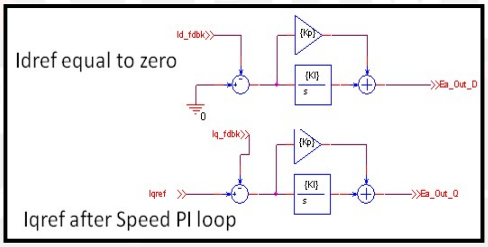
P-SPICE IMPLEMENTATION

- PI loop implementation



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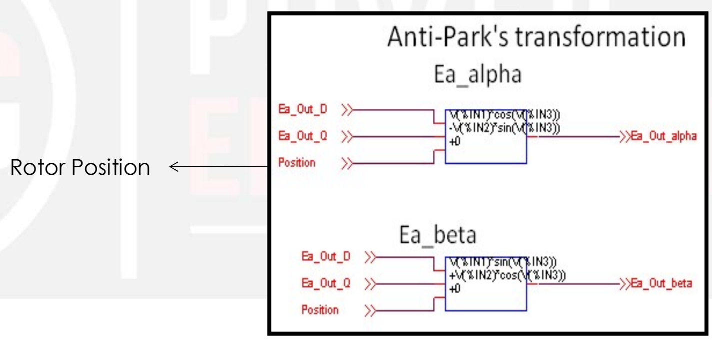
P-SPICE IMPLEMENTATION

- Anti-Park's transformation



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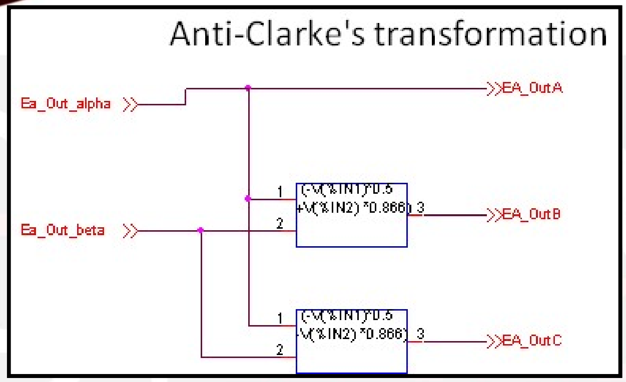

P-SPICE IMPLEMENTATION

Anti Clarke's transformation

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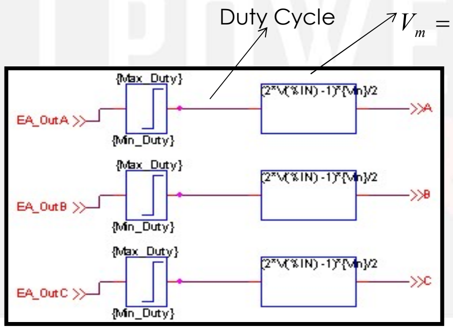
P-SPICE IMPLEMENTATION

- Generating Duty Cycle

Duty Cycle

$$V_m = \frac{V_{dc}}{2}[2.D - 1]$$



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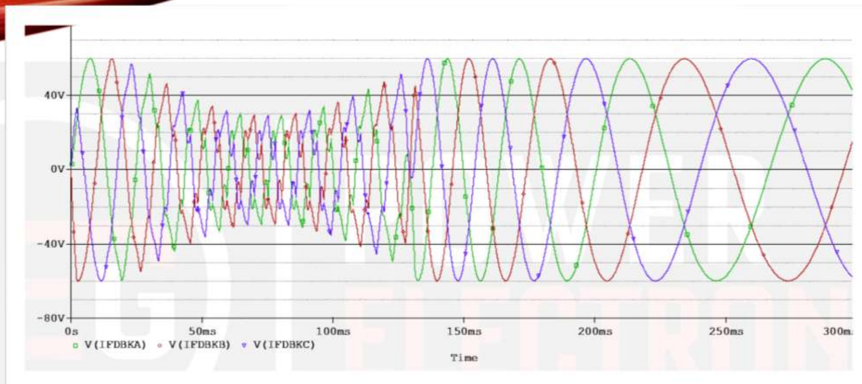

SIMULATION RESULTS

Feedback phase currents I_{α},I_b,I_c

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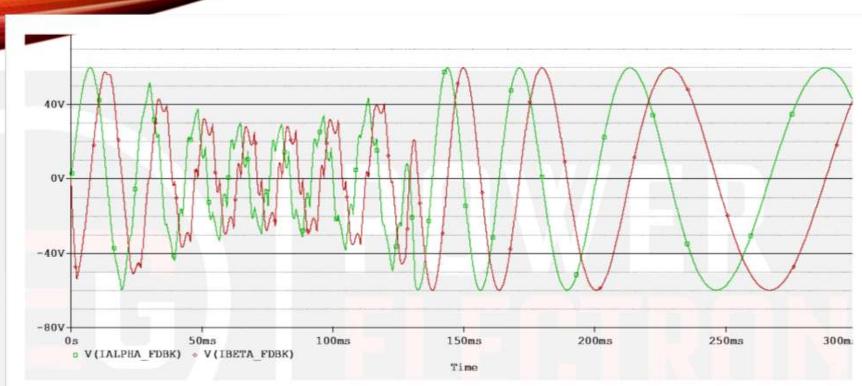

SIMULATION RESULTS

Clarke's transformation

I_{α},I_{β}

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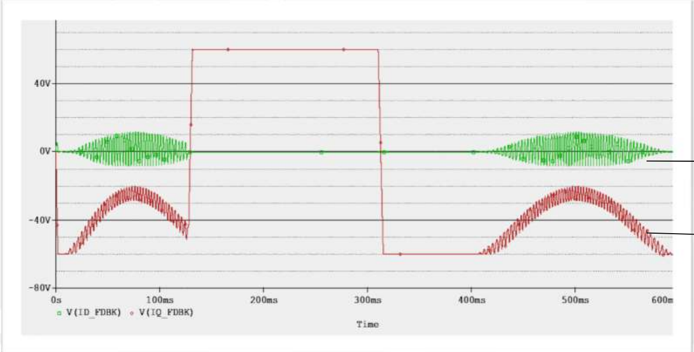
SIMULATION RESULTS



Park's transformation

I_d, I_q

I_d

I_q

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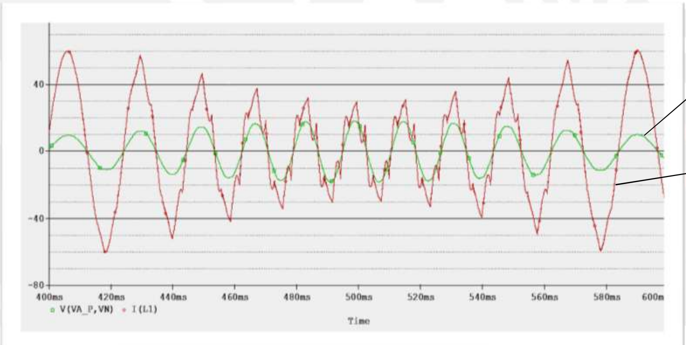
SIMULATION RESULTS



BEMF of phase-A

Phase-A current

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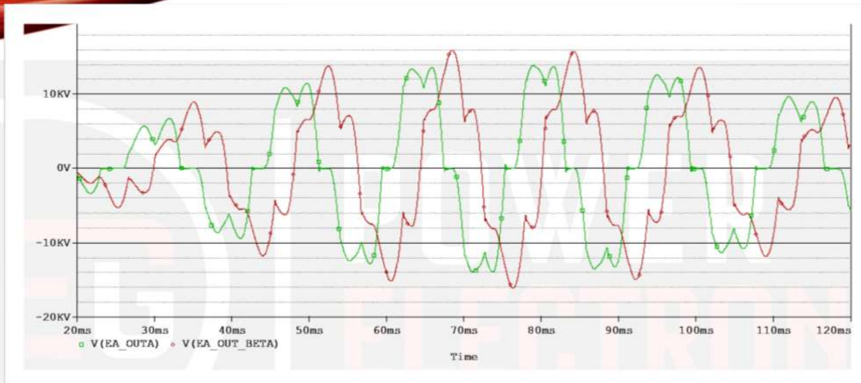

SIMULATION RESULTS

Anti-Park's transformation

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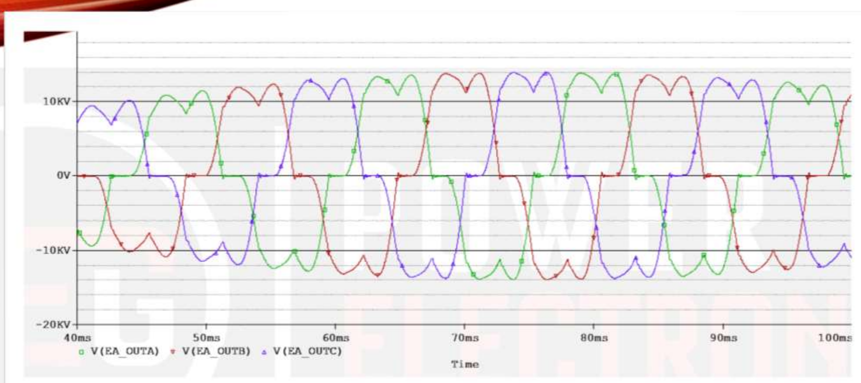

SIMULATION RESULTS

Anti-Clarke's transformation

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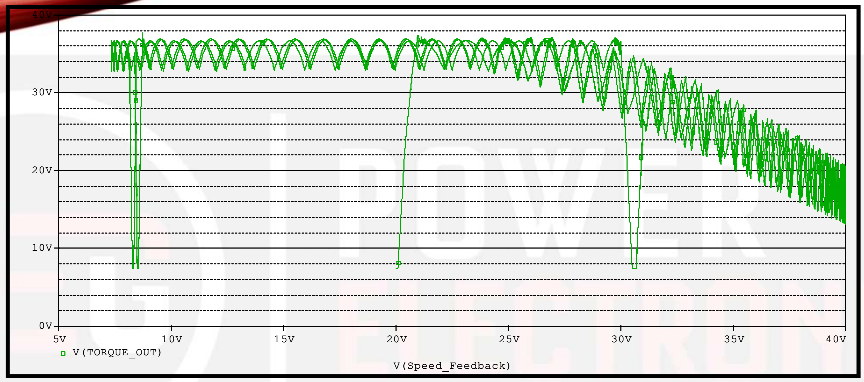

SIMULATION RESULTS

Torque-Speed characteristics

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SPACE VECTOR MODULATION

3-Day Workshop on Motor, Inverter, Hardware, and Firmware Design Techniques for Permanent Magnet Brushless Motors – A System Approach

April 22 - 25, 2025

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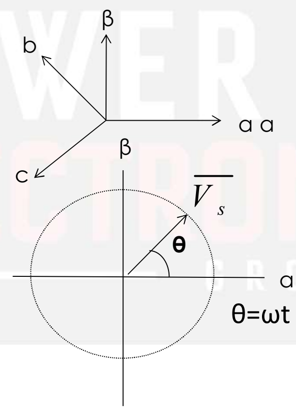
SPACE VECTOR REPRESENTATION

$$V_a = V_m \sin(\omega t)$$
$$V_b = V_m \sin(\omega t - 120)$$
$$V_c = V_m \sin(\omega t + 120)$$
$$V_a + V_b + V_c = 0$$
$$V_s = V_a + V_b e^{j.\frac{2\pi}{3}} + V_c e^{j.\frac{-2\pi}{3}}$$
$$\overline{V_s} = \frac{3}{2} V_m (\sin \omega t - j \cos \omega t)$$



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SVM FUNDAMENTALS

$$\overline{V_s} = V_\alpha + jV_\beta = |V_s| e^{j\omega t}$$

$$\begin{bmatrix} f_\alpha \\ f_\beta \end{bmatrix} = \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \cdot \begin{bmatrix} f_a \\ f_b \\ f_c \end{bmatrix}$$

- Where ‘f’ can be either voltage or current & $\overline{V_s}$ is the resultant vector.

$$\overline{V_\alpha} = V_a - \frac{1}{2}(V_b + V_c) = \frac{3}{2} V_a$$
$$\overline{V_\beta} = \frac{\sqrt{3}}{2}(V_b - V_c)$$

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SVM FUNDAMENTALS

- For a 3-phase total number of combinations are $2^3 = 8$
- Out of 8 states two are called null states;
  - All of the TOP switches (or) all of the BOTTOM switches ON at a time.
  - Remaining 6 states are called Active states.

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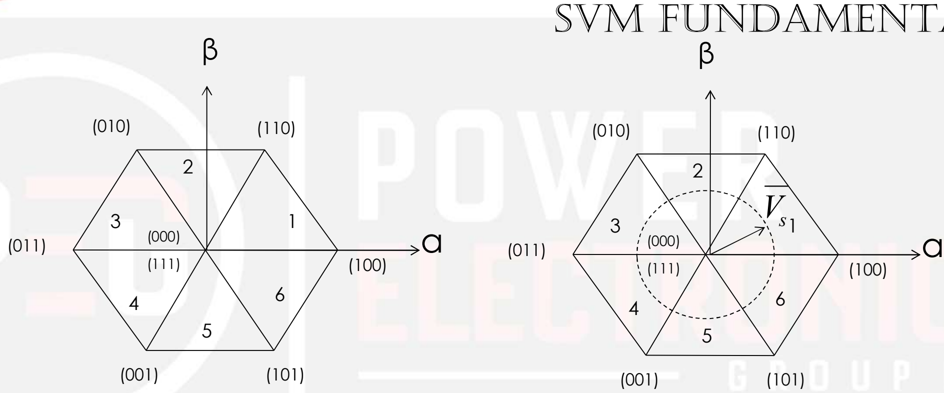
SVM FUNDAMENTALS



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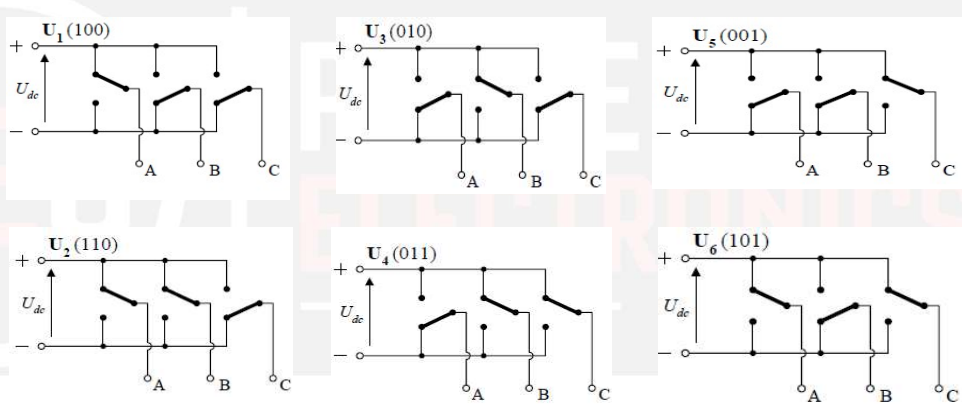
SVM FUNDAMENTALS

- Each switching state is treated as a Sector;
- Each Sector is framed by 2 vectors which are 60 degrees apart;
- Upper switch ON→'1';
- Lower switch ON→'0';
- 6 active vectors & 2 null vectors;
- Amplitude of all the vectors = V_{dc}.

SVM FUNDAMENTALS



1 to 6 Active states.

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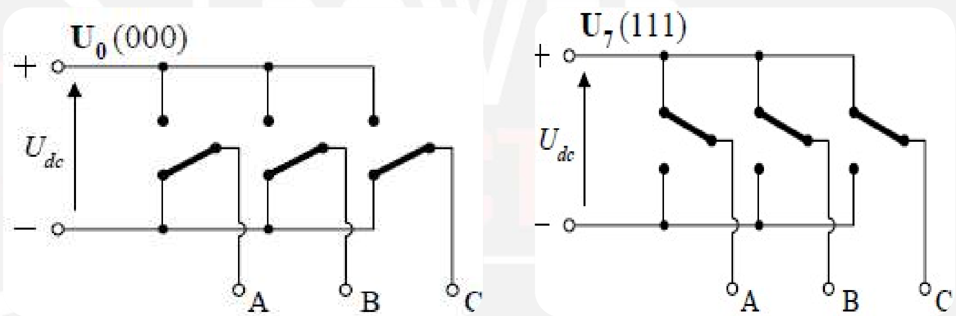
SVM FUNDAMENTALS

Null states



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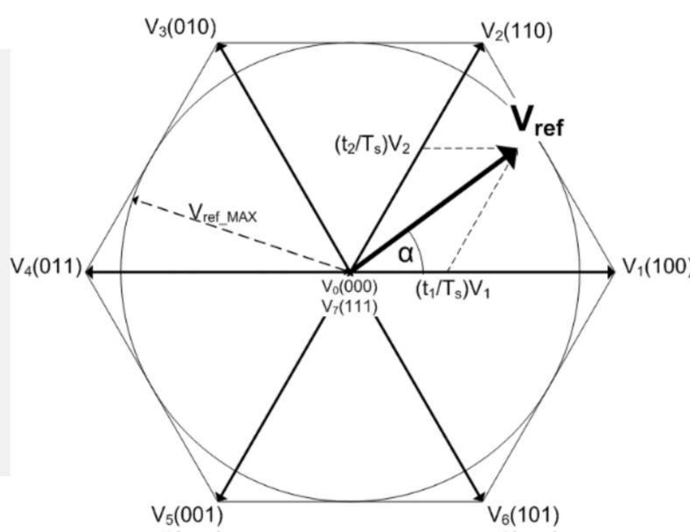
SVM FUNDAMENTALS



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SVM FUNDAMENTALS

Volt second balance equation along **α-axis**

$$\overline{V}_1.T_1 = \overline{V}_2.\cos(60).T_2 = |V_s|.T_s.\cos(\alpha)$$

Volt second balance equation along **β-axis**

$$\overline{V}_2.\sin(60).T_2 = |V_s|.T_s.\sin(\alpha)$$

Solving for T_1,T_2 & T_0

$$T_1 = T_s.\frac{|V_s|}{V_{dc}}\frac{\sin(60-\alpha)}{\sin(60)} = T_s.\frac{2}{\sqrt{3}}\frac{|V_s|}{V_{dc}}.\sin(60-\alpha)$$

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SVM FUNDAMENTALS

$$T_2 = T_s.\frac{2}{\sqrt{3}}\frac{|V_s|}{V_{dc}}.\sin(\alpha)$$

$$T_0 = T_s - (T_1 + T_2)$$

Where α varies from 0 to 60 Degrees.

$$dx = \frac{\sin(\frac{\pi}{3} - \alpha)}{\sin(\frac{\pi}{3})}$$

$$dy = \frac{\sin(\alpha)}{\sin(\frac{\pi}{3})}$$

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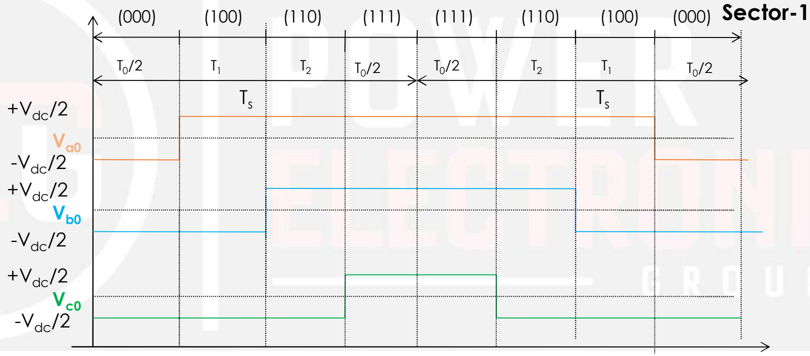
SVM FUNDAMENTALS



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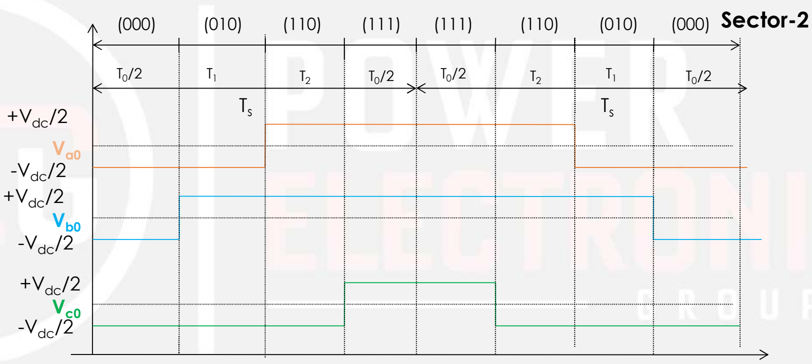
SVM FUNDAMENTALS



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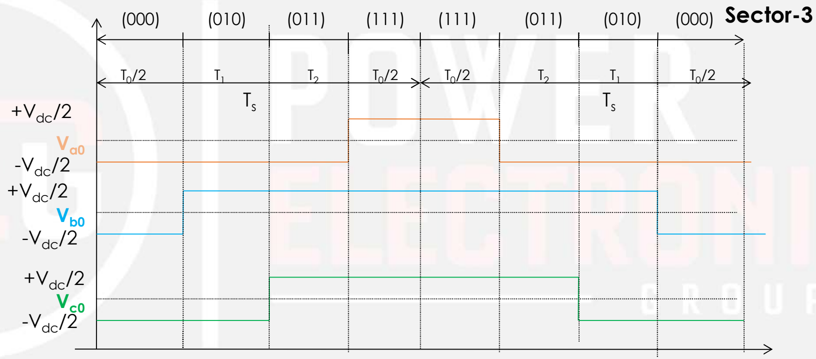
SVM FUNDAMENTALS



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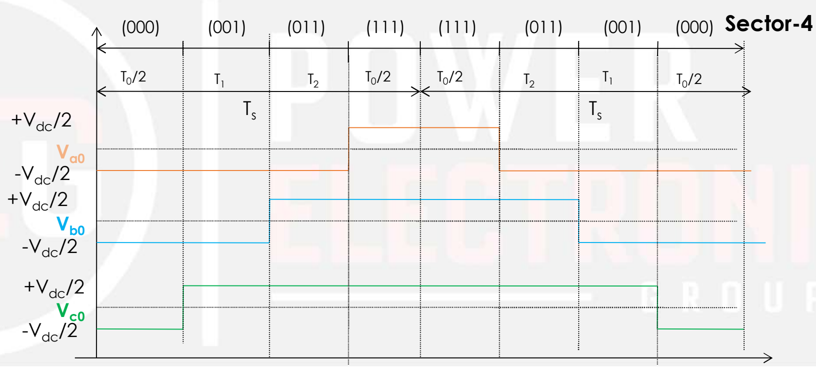
SVM FUNDAMENTALS



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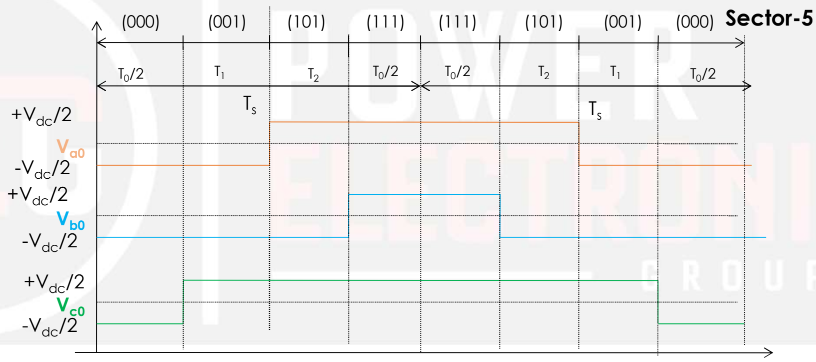
SVM FUNDAMENTALS



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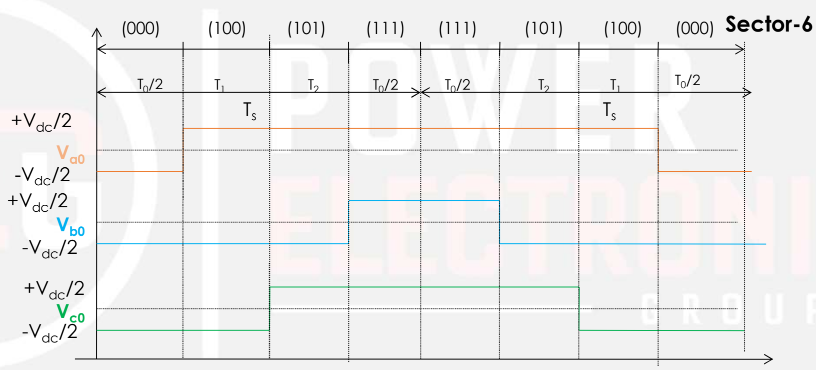
SVM FUNDAMENTALS



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SVM FUNDAMENTALS

Sector Number	PWM	Formula
1	A	(1-dx-dy)/2
	B	(1+dx-dy)/2
	C	(1+dx+dy)/2
2	A	(1-dx+dy)/2
	B	(1-dx-dy)/2
	C	(1+dx+dy)/2
3	A	(1+dx+dy)/2
	B	(1-dx-dy)/2
	C	(1+dx-dy)/2

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SVM FUNDAMENTALS

4	A	(1+dx+dy)/2
	B	(1-dx+dy)/2
	C	(1-dx-dy)/2
5	A	(1+dx-dy)/2
	B	(1+dx+dy)/2
	C	(1-dx-dy)/2
6	A	(1-dx-dy)/2
	B	(1+dx+dy)/2
	C	(1-dx+dy)/2

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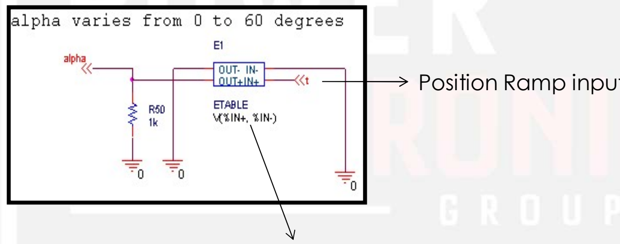
P-SPICE IMPLEMENTATION

- Angle α generation.



(0,0) (60,60) (60.1,0) (120,60) (120.1,0) (180,60) (180.1,0) (240,60) (240.1,0) (300,60) (300.1,0) (359.9,60) (360,0)

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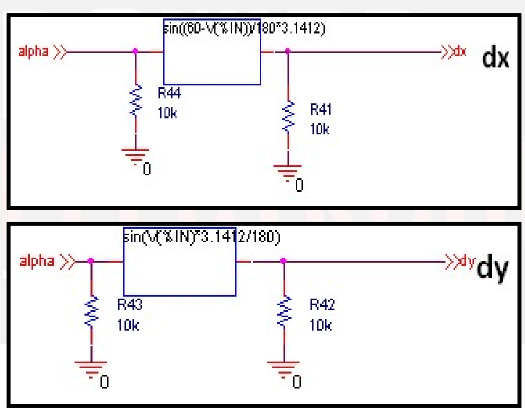
P-SPICE IMPLEMENTATION

- Duty cycle dx & dy generation.



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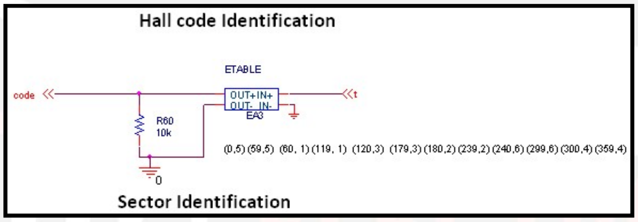
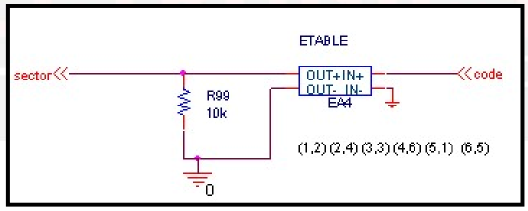
P-SPICE IMPLEMENTATION





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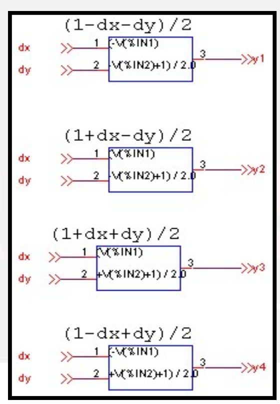
P-SPICE IMPLEMENTATION

- Duty cycle generating formulae.



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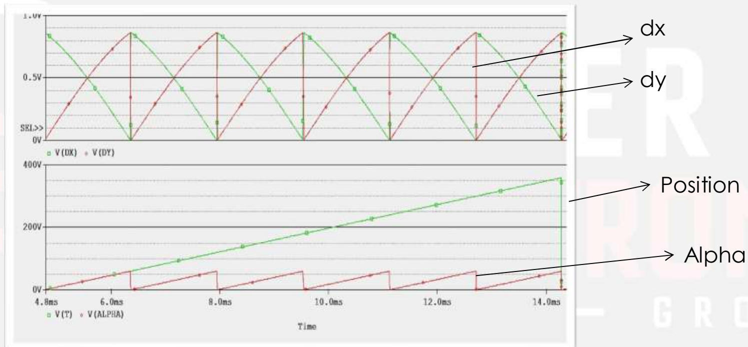
SIMULATION RESULTS



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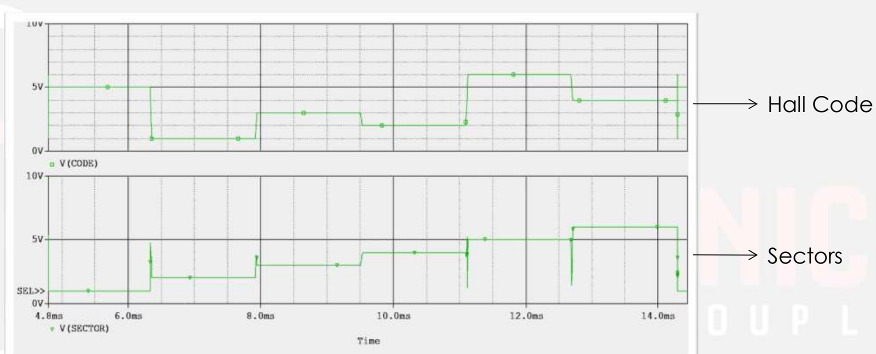
SIMULATION RESULTS



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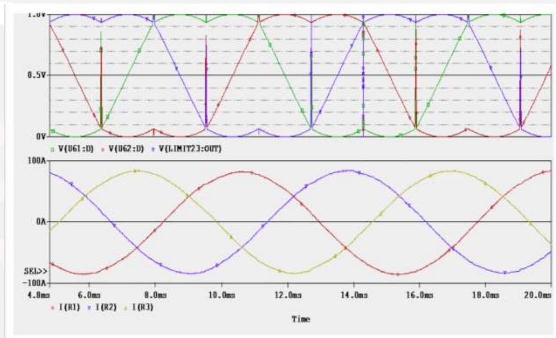
SIMULATION RESULTS



PWM-A,PWM-B,PWM-C

Phase Currents-I_a,I_b,I_c

$$For\ \frac{|V_s|}{V_{dc}} = 1$$

$$V_{dc} = 36V, |V_s| = 36V$$

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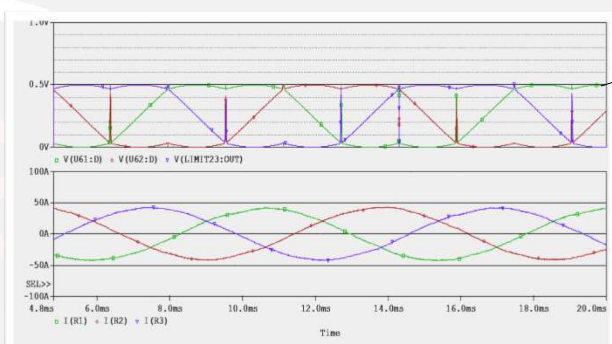
SIMULATION RESULTS



PWM-A,PWM-B,PWM-C

Phase Currents-I_a,I_b,I_c

$$For\ \frac{|V_s|}{V_{dc}} = 0.5$$

$$V_{dc} = 36V, |V_s| = 18V$$

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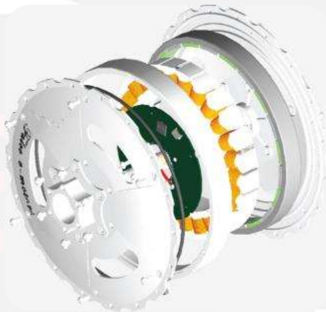
SCALAR VS. VECTOR CONTROL



5-Phase Drive
(Scalar Control)

3-Phase Dual Drive
(Vector Control)

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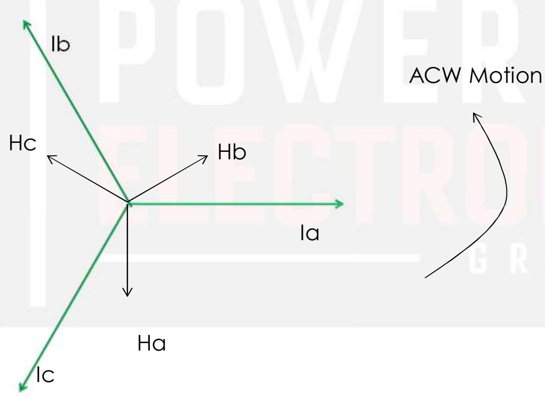
VECTOR DIAGRAM - ACW



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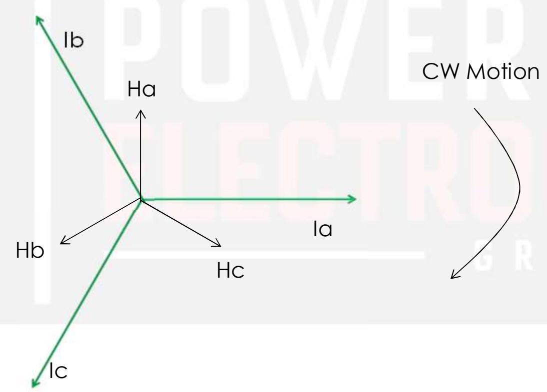
VECTOR DIAGRAM - CW



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KEY POINTS DIFFERENTIATING TWO SYSTEMS

5-Phase Drive	3-Phase Dual Drive
Scalar Control	Vector Control
No Direct Speed Control	Direct Speed Control
8-bit uC operating at 20 MIPS	32-bit uC operating at 80 MIPS
Simultaneous ADC Registers scanning not possible	Simultaneous ADC Registers scanning possible

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5-PHASE MOTOR DRIVE

- System Requirements:
  - Run the system using Throttle, Speed sensor, Pressure sensor;
  - Scalar control;
  - Regeneration/Braking;
  - System Lock as a security feature;
  - Wireless Interface;

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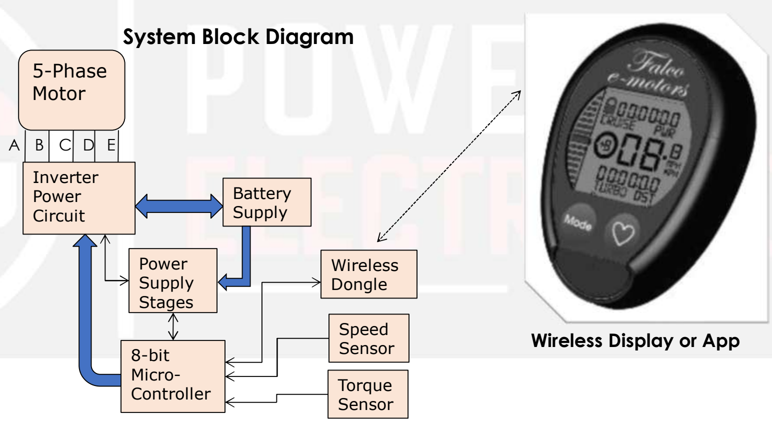
5-PHASE MOTOR DRIVE

System Block Diagram



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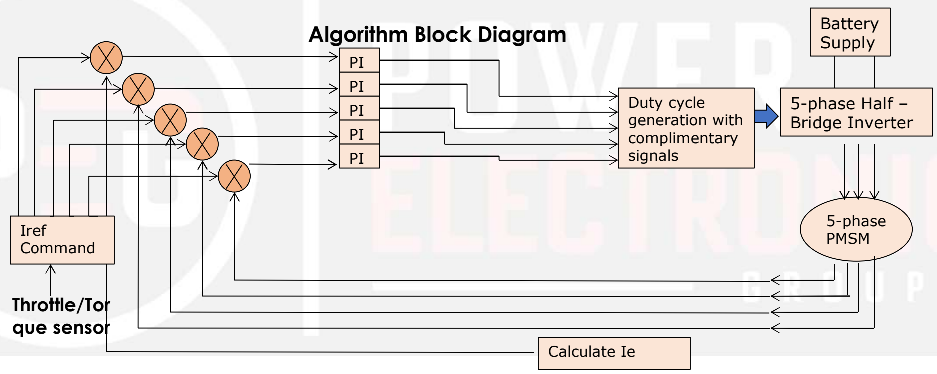
5-PHASE MOTOR DRIVE



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5-PHASE MOTOR DRIVE

- Challenges Faced: Hardware;
  - Problem with Hall-sensors installation;
  - Alignment problem of BEMF & Hall sensors;
  - Leg Current sensing;
  - PCB Layout;
  - Power Supply design;
  - Mechanical design;

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5-PHASE MOTOR DRIVE

- Challenges Faced: Firmware;
  - Different Current Profiles;
  - Timing;
  - Current sensing;
  - Stabilizing the PI loop;
  - Duty Cycle Calculation;
  - Limitations in floating point calculations;
  - Lower switching PWM frequency;

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5-PHASE MOTOR DRIVE

- **Features of 8-bit uC.**

Functionalities	8-Bit MCU
Timer Based Functions	Highly Critical
Code Efficiency	High
ADC Execution Time	2uS
ADC Execution	Serial/Sequential
PI Processing	20-40uS
Active Filtering	80 to 90uS
Waveshaping	Table Based
Overall Execution Time (Scalar Contrl)	~90uS
Scalability	Low
Cost	Low
Algorithm Adaptation	Low

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5-PHASE MOTOR DRIVE

- Milestones:
  - Hall Signals generation code;
  - Applying Sinusoidal currents into windings;
  - Linearization of Hall codes;
  - Open loop;
  - Closed loop;
  - Phase Advance Implementation;
  - Integration & system response optimization;

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5-PHASE MOTOR DRIVE

- Lessons Learnt:
  - Proper Capturing of Requirements;
  - Hardware Design Analysis;
  - Clear Strategy on Algorithm;
  - Flow Chart development;
  - Software Design Documentation;
  - Flexibility;
  - Smart Thinking;

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3-PHASE DUAL MOTOR DRIVE

- System Requirements:
  - Dual Brushless Motor Drive;
  - Joystick Controlled;
  - Operated from +24V Battery;
  - Hardware to handle 60A of peak current;
  - FOC to control motors in either directions;

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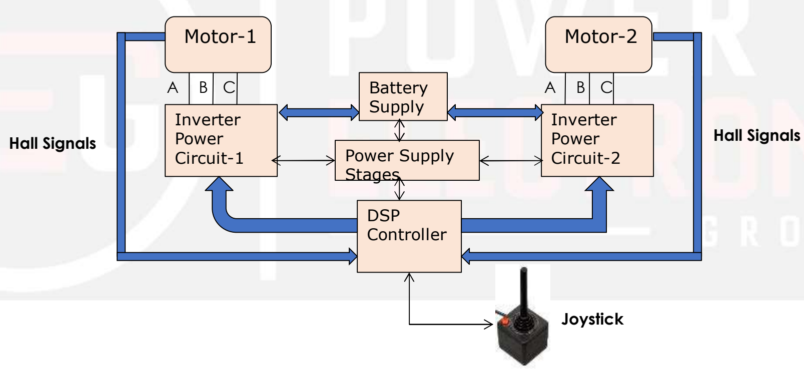
3-PHASE DUAL MOTOR DRIVE

System Block Diagram



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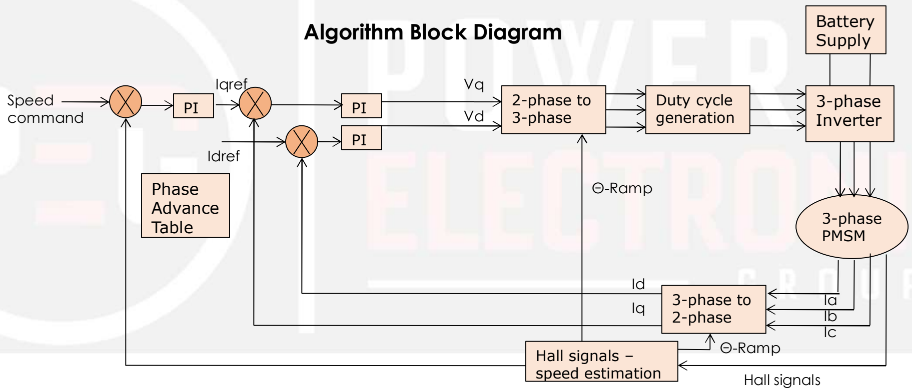
3-PHASE DUAL MOTOR DRIVE

Algorithm Block Diagram



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ADVANTAGES OF DSP

Functionalities	32-Bit DSP
Timer Based Functions	Less Critical
Code Efficiency	Low
ADC Execution Time	80nS
ADC Execution	Parallel
PI Processing	<2uS
Active Filtering	<2uS
Waveshaping	Function Based
Overall Execution Time (Scalar Contrl)	~4uS
Scalability	High
Cost	High
Algorithm Adaptation	High

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ALTAIR EMBED

3-Day Workshop on Motor, Inverter, Hardware, and Firmware Design Techniques for Permanent Magnet Brushless Motors – A System Approach

April 22 – 25 , 2025

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WHY ALTAIR EMBED?

- High level model-based programming;
- Dedicated C programmers not required;
- Speeds up edit-debug cycle;
- Simple & fast configuration;
- Increases consistency & reliability;
- Efficient code generation;
- Simulate & verify logic instantly;
- Hardware in loop (HIL) simulation;

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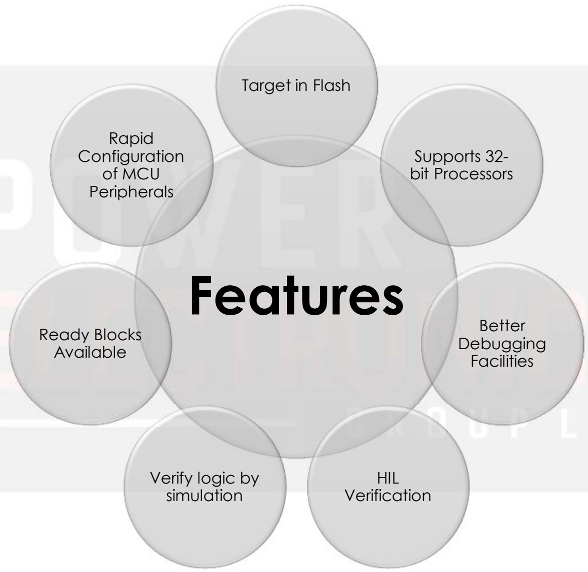

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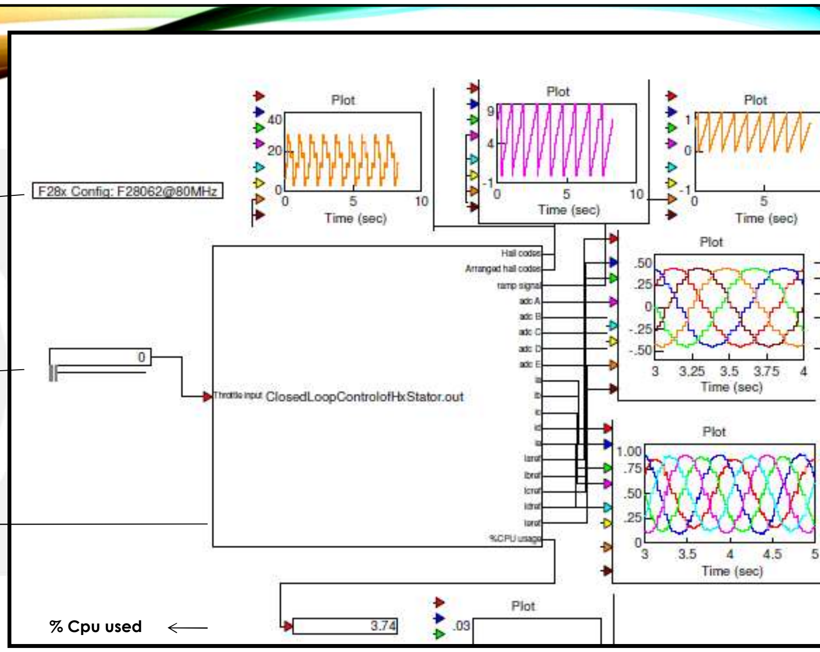
MCU target configuration

External Input to the block;

Final compound block & .out file;



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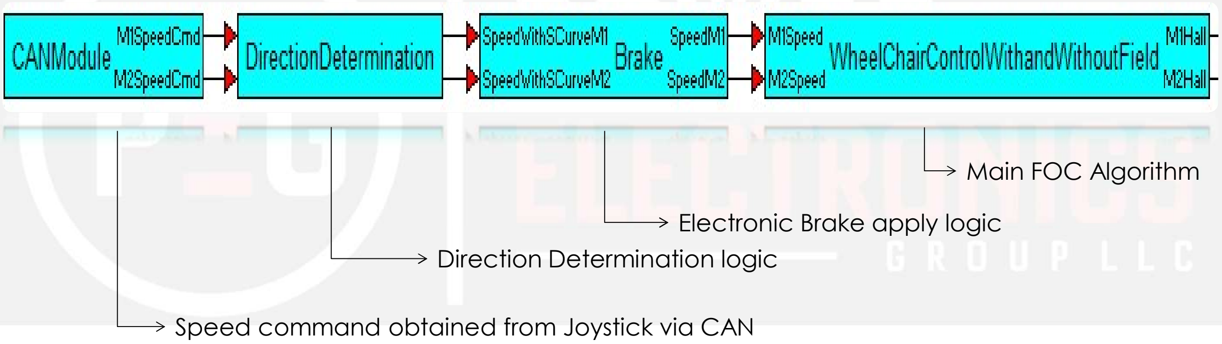
EXAMPLE OF DUAL BLDC MOTOR DRIVE USING FOC



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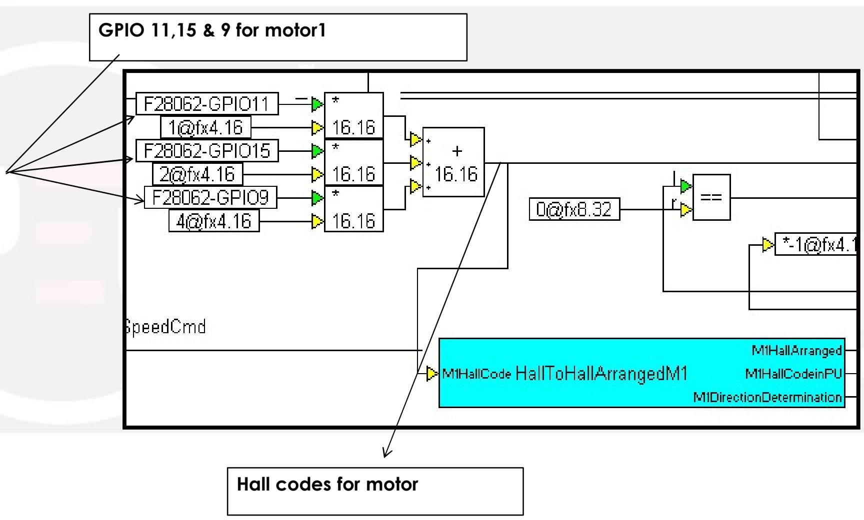
HALL CODE GENERATION



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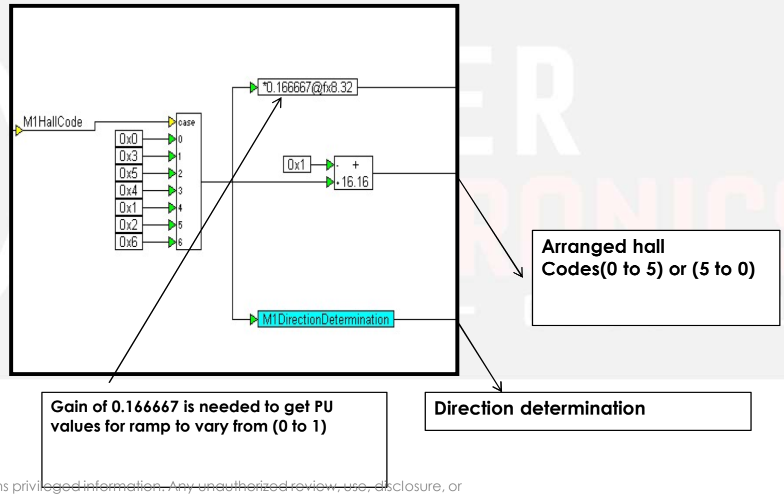
HALL CODE ARRANGEMENT



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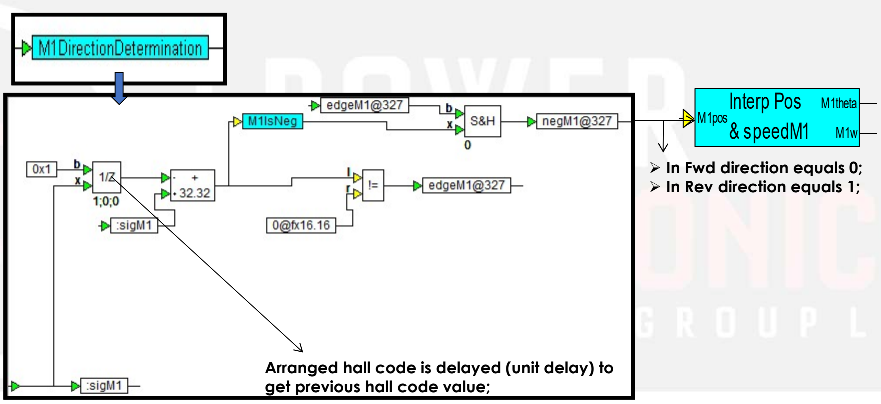
MOTOR DIRECTION DETERMINATION

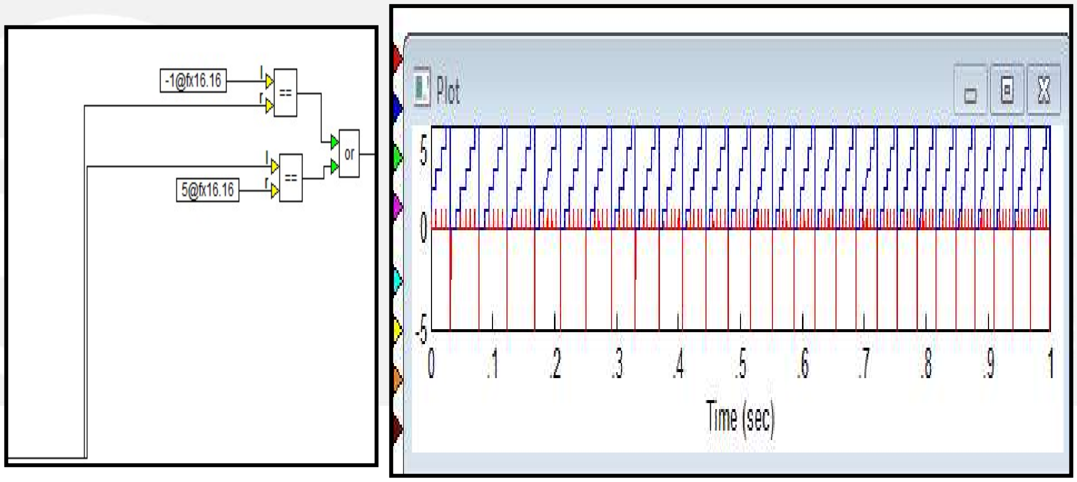


- In Fwd direction equals 0;
- In Rev direction equals 1;

602

603

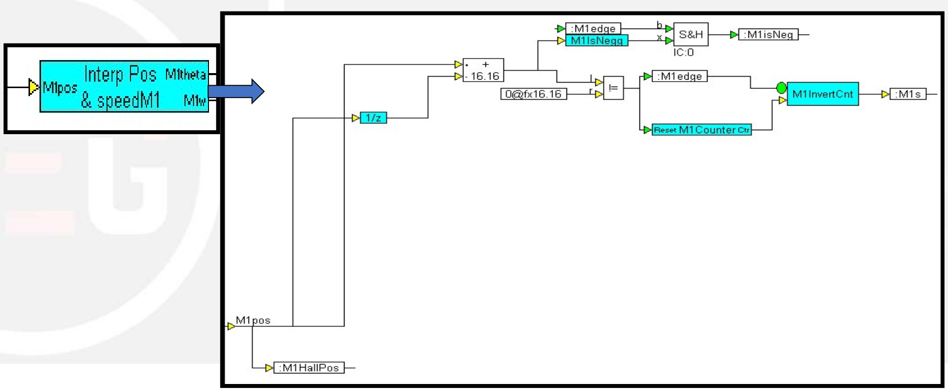
MOTOR DIRECTION DETERMINATION



603

604

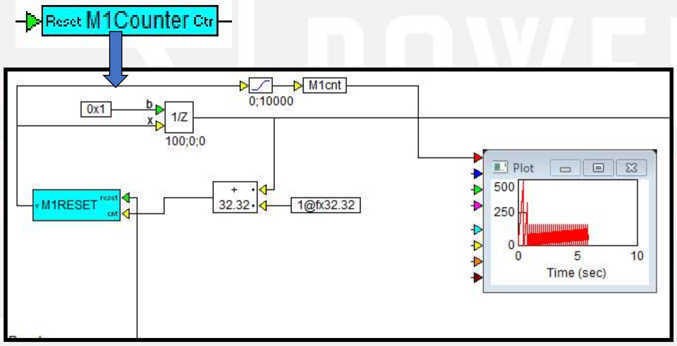
SPEED CALCULATION



604

605

SPEED CALCULATION

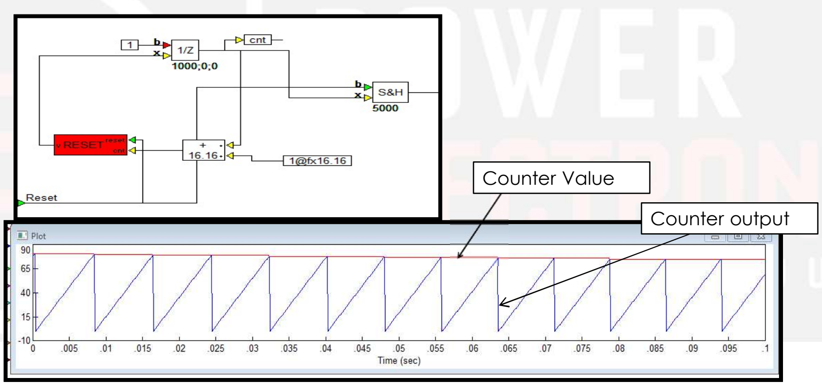


➢ **Shows number of counts between the hall codes;**

605

606

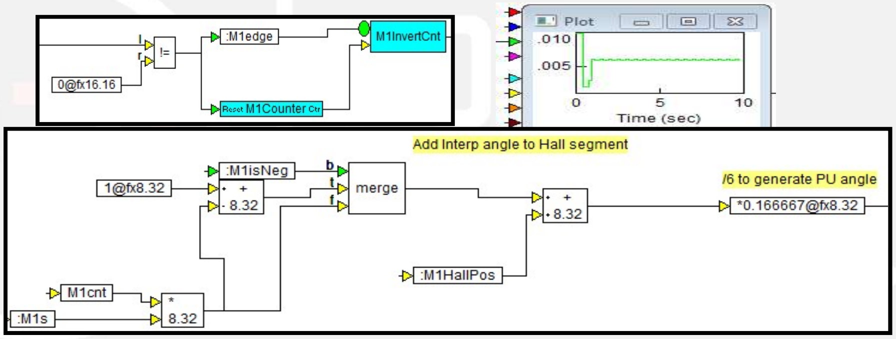
SPEED CALCULATION



606

607

THETA CALCULATION

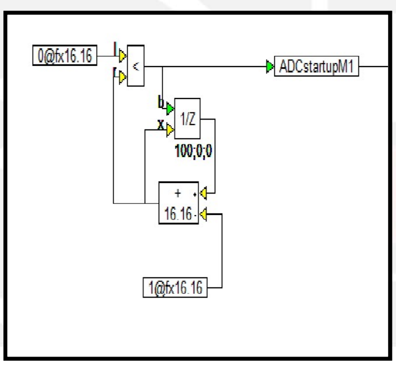


Theta is required for vector transformations;

607

608

ADC SAMPLING

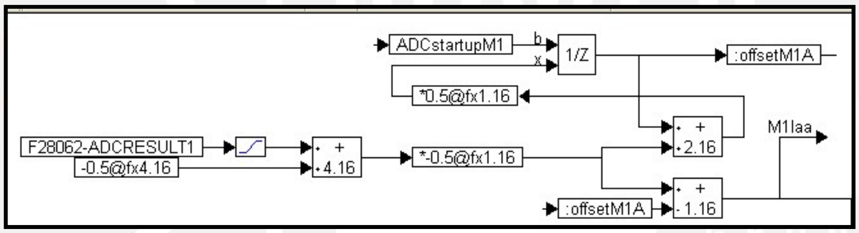


- ADC reading is delayed by 100 clock cycles @ 80 MHz =1.25us;
- It is done to allow the values to settle (read offset values);
- The moment o/p is 1, ADC sampling starts.

608

609

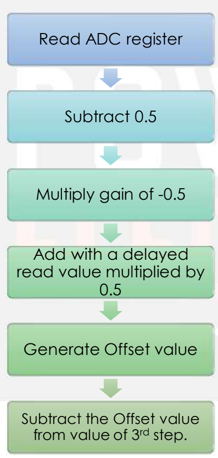
ADC OFFSET CALCULATION



609

610

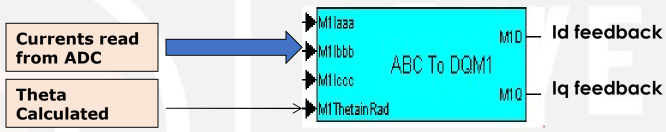
ADC OFFSET CALCULATION



610

611

3-PHASE TO 2-PHASE TRANSFORMATION



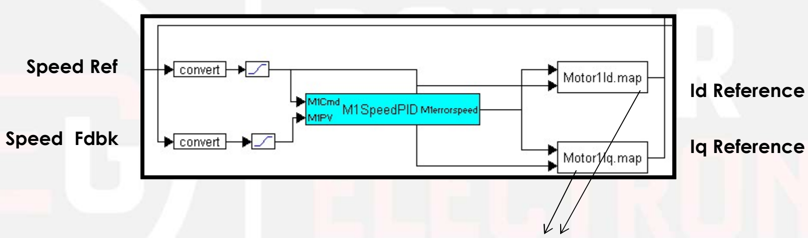
$$\begin{bmatrix} I_q \\ I_d \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \sin(\theta) & \sin(\theta - 120) & \sin(\theta - 240) \\ \cos(\theta) & \cos(\theta - 120) & \cos(\theta - 240) \\ 1/2 & 1/2 & 1/2 \end{bmatrix} . \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix}$$

Theta is used from the calculation seen before;

611

612

SPEED PI LOOP

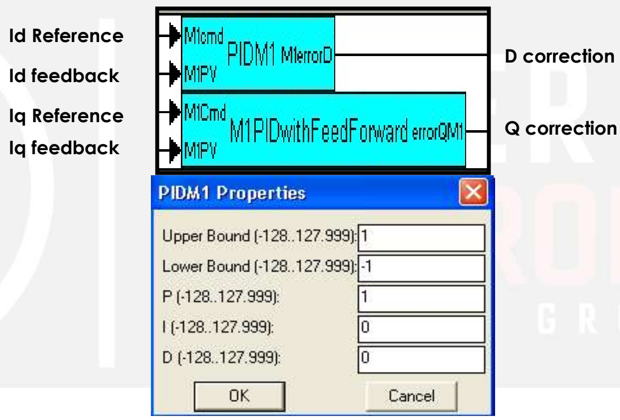


Id & Iq reference values from Phase advance tables based on speed;

612

613

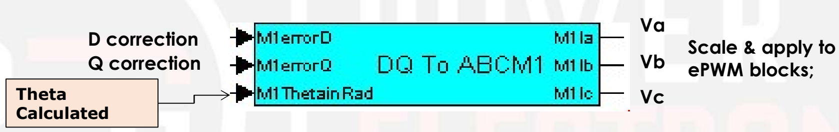
CURRENT PI LOOP



613

614

2-PHASE TO 3-PHASE TRANSFORMATION

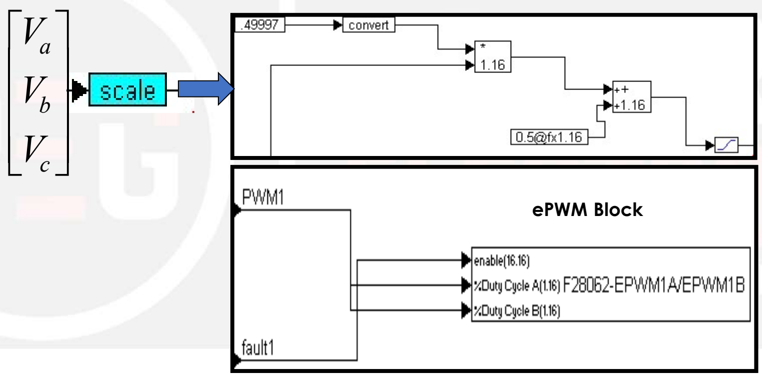


$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} \cos(\theta) & \sin(\theta) \\ \cos(\theta - 120) & \sin(\theta - 120) \\ \cos(\theta - 240) & \sin(\theta - 240) \end{bmatrix} \cdot \begin{bmatrix} V_d \\ V_q \end{bmatrix}$$

614

615

DUTY CYCLE CALCULATION

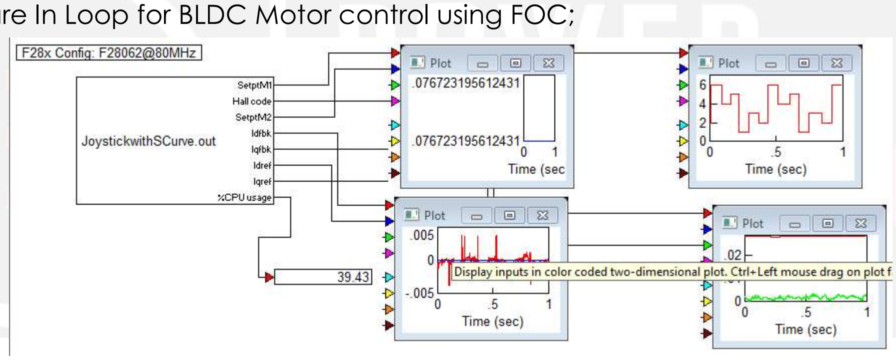


615

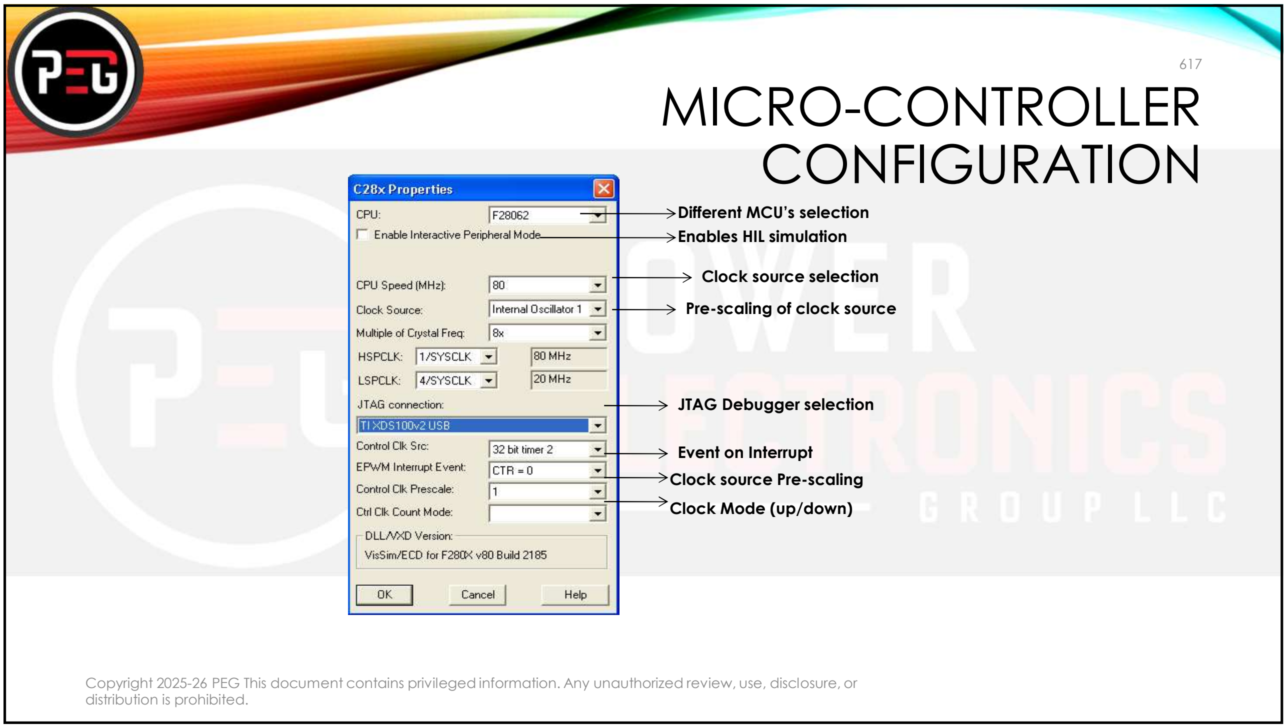
616

HIL

- Hardware In Loop for BLDC Motor control using FOC;



616


617
MICRO-CONTROLLER CONFIGURATION
C28x Properties
CPU: F28062
Enable Interactive Peripheral Mode
CPU Speed (MHz): 80
Clock Source: Internal Oscillator 1
Multiple of Crystal Freq: 8x
HSPCLK: 1/SYSCLK 80 MHz
LSPCLK: 4/SYSCLK 20 MHz
JTAG connection:
TI XDS100v2 USB
Control Clk Src: 32 bit timer 2
EPWM Interrupt Event: CTR = 0
Control Clk Prescale: 1
Ctrl Clk Count Mode:
DLL/VXD Version:
VisSim/ECD for F280X v80 Build 2185
OK
Cancel
Help
Different MCU's selection
Enables HIL simulation
Clock source selection
Pre-scaling of clock source
JTAG Debugger selection
Event on Interrupt
Clock source Pre-scaling
Clock Mode (up/down)
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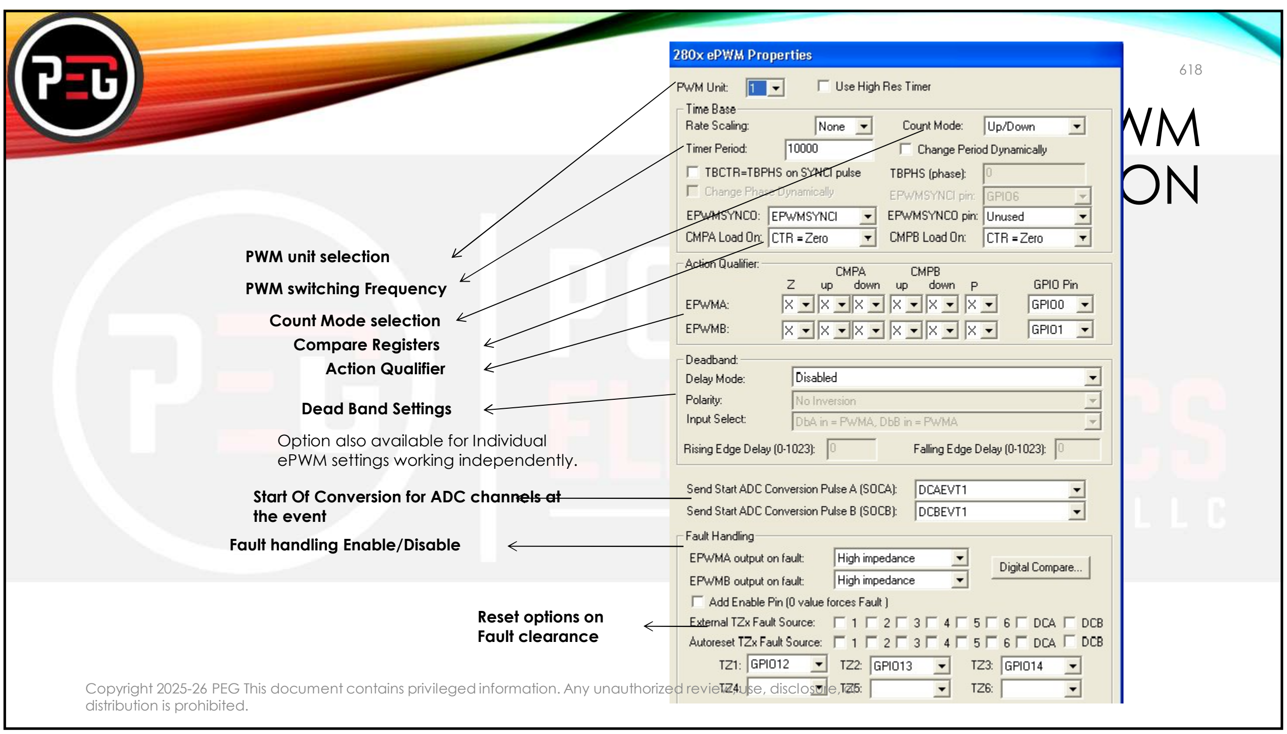
617


618
280x ePWM Properties
PWM Unit: 1
Use High Res Timer
Time Base
Rate Scaling: None
Count Mode: Up/Down
Timer Period: 10000
Change Period Dynamically
TBCTR=TBPHS on SYNCI pulse
TBPHS (phase): 0
Change Phase Dynamically
EPWMSYNCI pin: GPIO6
EPWMSYNCO: EPWMSYNCI
EPWMSYNCO pin: Unused
CMPA Load On: CTR = Zero
CMPB Load On: CTR = Zero
Action Qualifier
CMPA
CMPB
Z up down up down P
GPIO Pin
EPWMA: GPIO0
EPWMB: GPIO1
Deadband
Delay Mode: Disabled
Polarity: No Inversion
Input Select: DbA in = PWMA, DbB in = PWMA
Rising Edge Delay (0-1023): 0
Falling Edge Delay (0-1023): 0
Send Start ADC Conversion Pulse A (SOCA): DCAEVT1
Send Start ADC Conversion Pulse B (SOCB): DCBEVT1
Fault Handling
EPWMA output on fault: High impedance
EPWMB output on fault: High impedance
Digital Compare...
Add Enable Pin (0 value forces Fault)
External TZx Fault Source: 1 2 3 4 5 6 DCA DCB
Autoreset TZx Fault Source: 1 2 3 4 5 6 DCA DCB
TZ1: GPIO12 TZ2: GPIO13 TZ3: GPIO14
TZ4: TZ5: TZ6:
PWM unit selection
PWM switching Frequency
Count Mode selection
Compare Registers
Action Qualifier
Dead Band Settings
Option also available for Individual ePWM settings working independently.
Start Of Conversion for ADC channels at the event
Fault handling Enable/Disable
Reset options on Fault clearance
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618

619

EPWM CONFIGURATION

- Switching Frequency settings
- Fs=20kHz:
- Tpwm=2*Tbprd*Tbclk;
- 1/20k=2*1/80M*Tbprd;
- Tbprd=2000;
- Count Mode: up/down;

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620

ADC CONFIGURATION

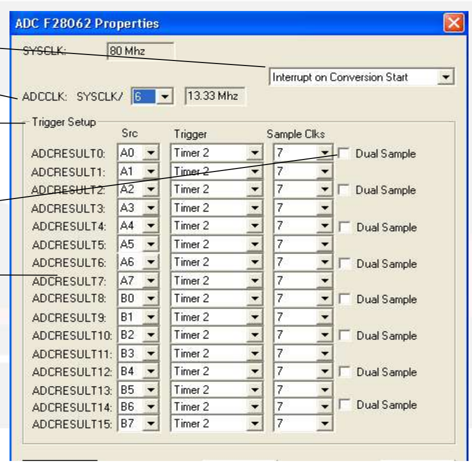
Interrupt settings for SOC

Sampling Period settings

Start Of Conversion trigger settings

Samplings for two different sequences

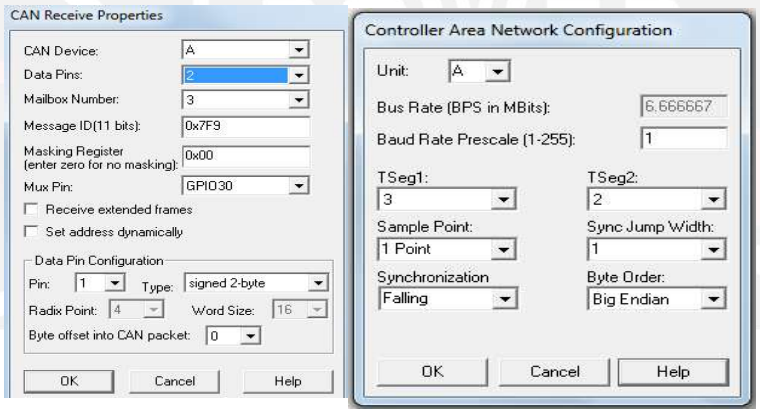
Different ADC Result Registers



620

621

CAN CONFIGURATION

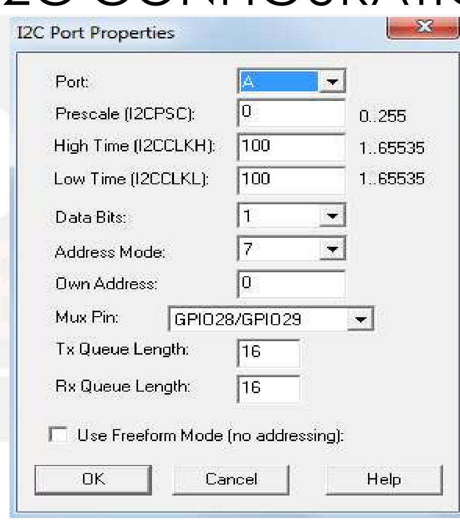


621

622

I2C CONFIGURATION

- Port Specification;
- Selection of GPIO to Mux;
- Tx/Rx Queue length selection;

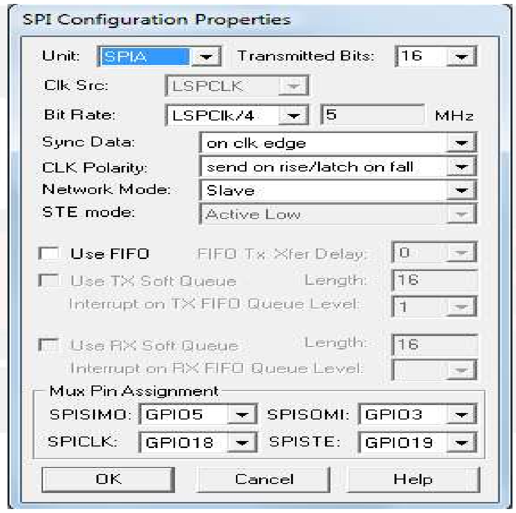


622

623

SPI CONFIGURATION

- Bit Rate settings;
- Clock polarity settings;
- Network Mode settings;
- Mux pin assignments;
- FIFO option;
- TX/RX soft Queue option;
- Interrupts for TX/RX settings;

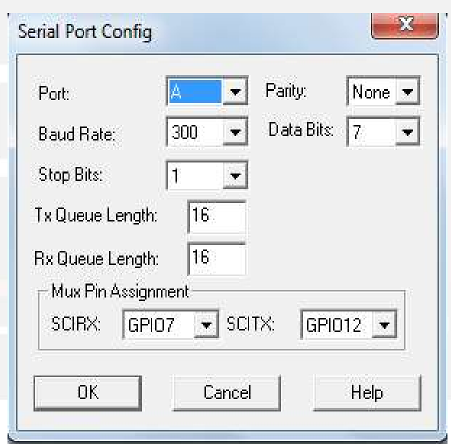


623

624

UART CONFIGURATION

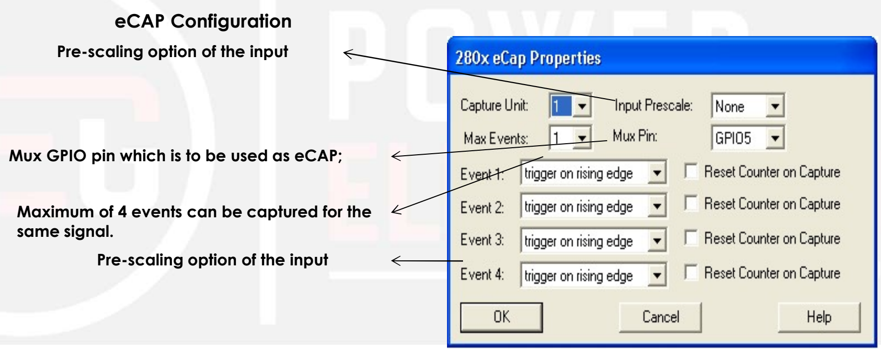
- Baud rate settings;
- Data bits, stop bits;
- Tx/Rx Queue length;
- Mux pin assignments;
- Parity settings;



624

625

ECAP CONFIGURATION

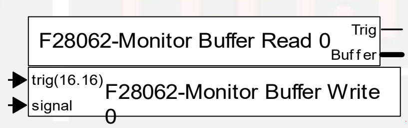


625

626

BUFFERS

- Can assign a variable or a Buffer, which is to be monitored for every trigger signal;
- Can read the Buffer for every trigger signal;
- Triggering can be given by number of different ways;



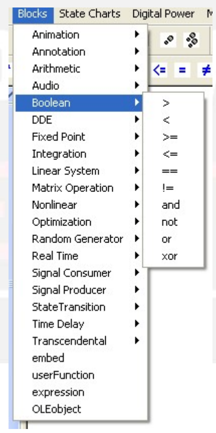
Monitor Buffers Read/Write

626

627

OTHER EMBEDDED BLOCKS

Used for conversion of the variables to different data types

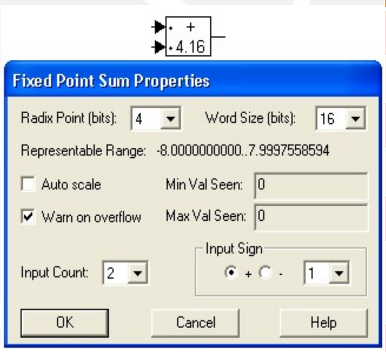


Different Blocks set used in *Embedded:*
- **Arithmetic;**
- **Boolean;**
- **Fixed Point;**
- **Matrix operations (2D/3D Tables);**
- **Time Delay;**
- *Non–Linear Block sets:*
- **If Else;**
- **Case switch;**
- **Gain;**
- **etc;**
- *Fixed point block sets:*
- **Atan;**
- **Cos, Sin;**
- **Multiply, Divide;**
- **PI, PID Regulators;**
- **Summation;**
- **Signed / Unsigned integers;**
- **Abs;**
- **Sample & Hold;**
- **etc;**

627

628

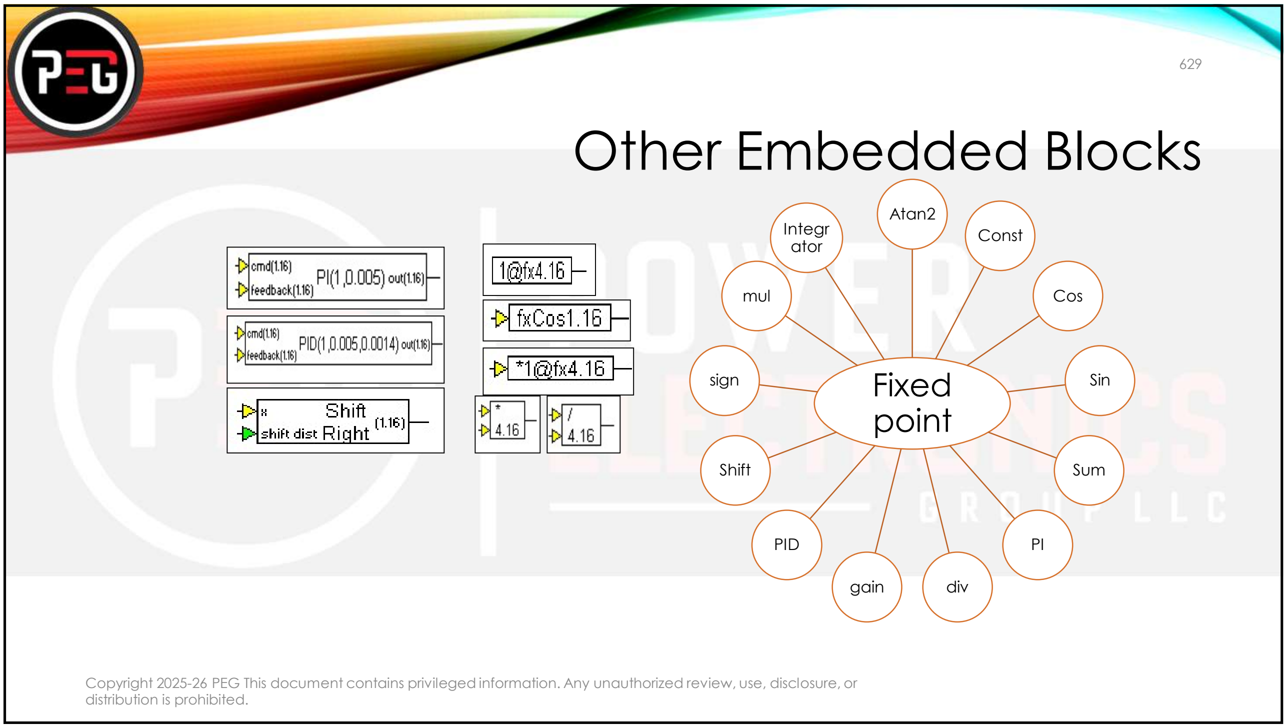
OTHER EMBEDDED BLOCKS



$$-2^{b-1}/2^f \ to \ +(2^{b-1}-1)/2^f$$

Radix point (bits)	Word size (bits)	Representable range
4	4	-8 to 7
4	5	-8.0 to 7.5
4	6	-8.00 to 7.75
4	8	-8.0000 to 7.9375
4	12	-8.00000000 to 7.99609375
4	16	-8.0000000000 to 7.9997558594
4	32	-8.0000000000 to 7.9999999963

628


629
Other Embedded Blocks
cmd(1.16)
feedback(1.16)
PI(1,0.005) out(1.16)
PID(1,0.005,0.0014) out(1.16)
x
shift dist
Shift Right (1.16)
1@fx4.16
fxCos1.16
*1@fx4.16
4.16
4.16
Fixed point
Atan2
Integr ator
Const
mul
Cos
sign
Sin
Shift
Sum
PID
PI
gain
div
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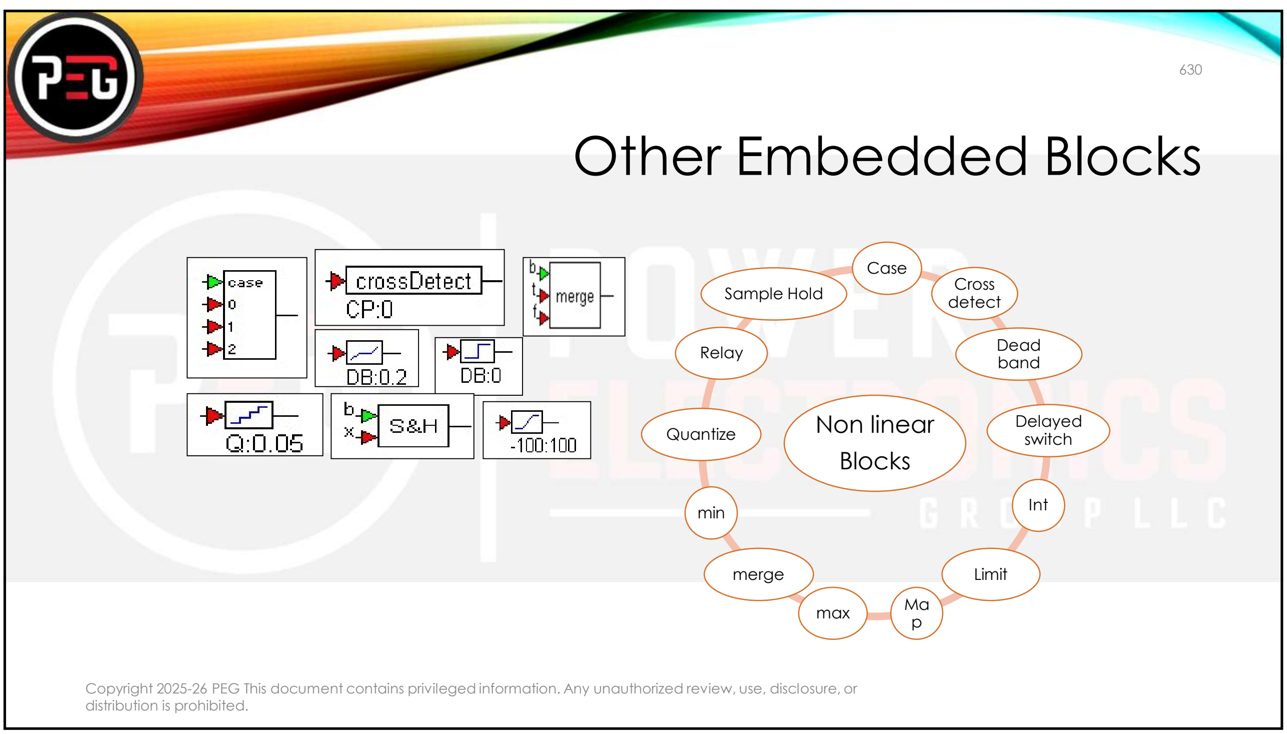
629


630
Other Embedded Blocks
case
0
1
2
crossDetect
CP:0
merge
DB:0.2
DB:0
Q:0.05
S&H
-100:100
Non linear Blocks
Case
Sample Hold
Cross detect
Relay
Dead band
Quantize
Delayed switch
min
Int
merge
Limit
max
Ma p
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631

CODE GENERATION

Can Compile & check for the errors & download the code into MCU using JTAG;

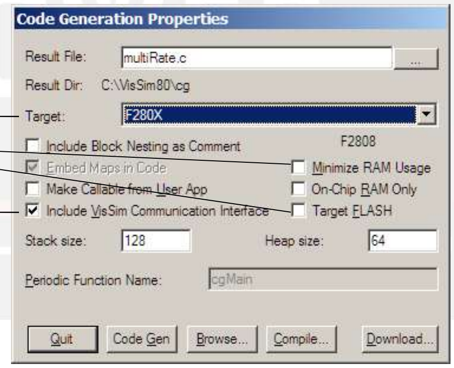
MCU target selection

Option to minimize the RAM usage;

Flashing the code directly

Observe the variables behavior during run & can give inputs to the block in run mode.

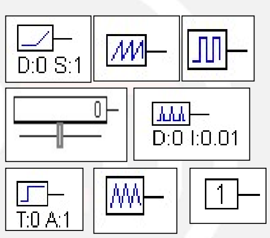
- **Stack size depends on no. of functions, interrupts, variables etc.,**
- **Heap size used only when JTAG debugging;**



631

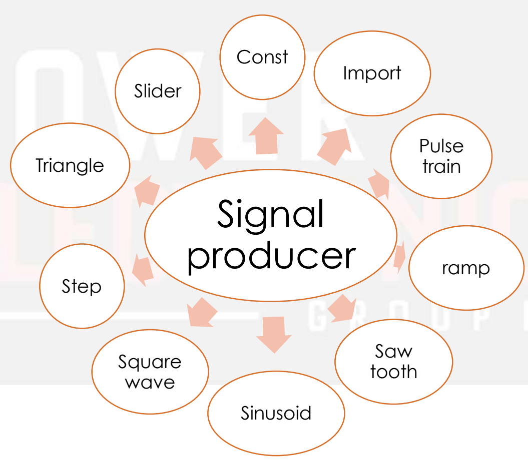
632

SIMULATION BLOCKS



Different types of Sources

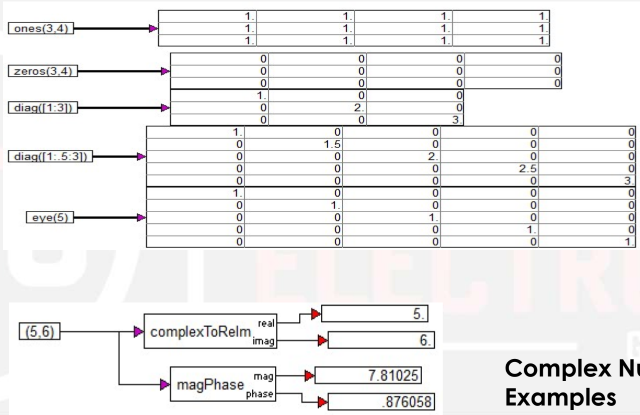
Note: These block sets can also be used as Embedded blocks;



632

633

EX:1 MATRIX & COMPLEX NUMBERS



Matrix Examples

Complex Numbers Examples

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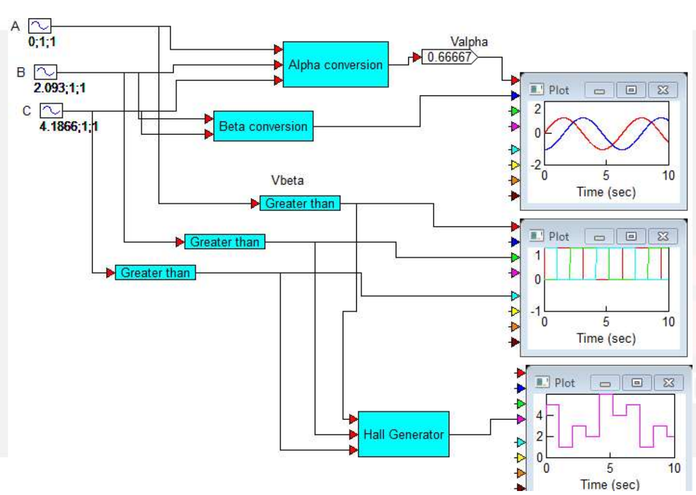
634

3-PHASE TO 2-PHASE CONVERSION & HALL CODE GENERATION

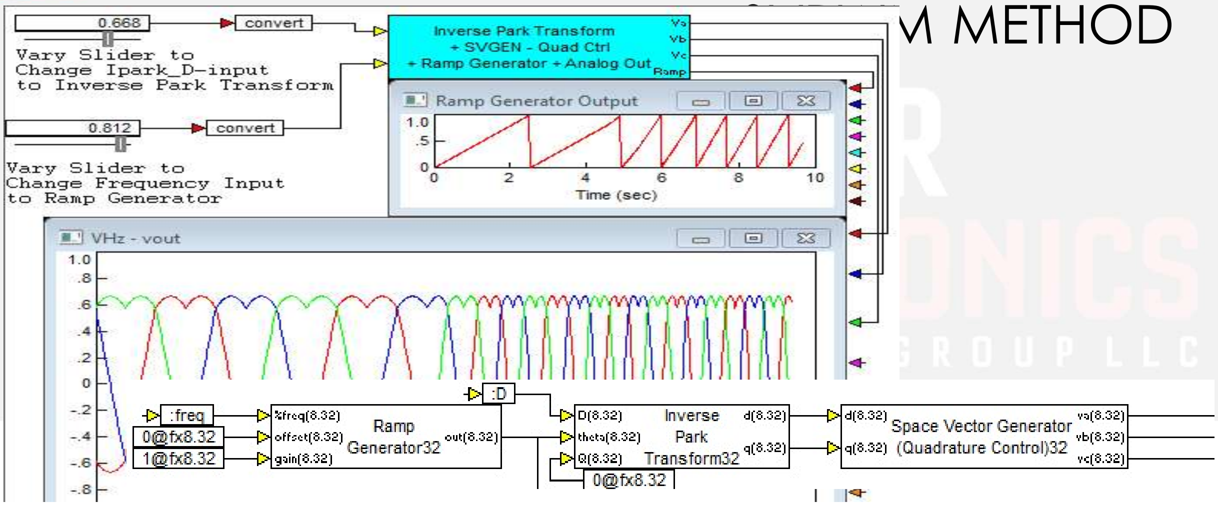
3-Phase to 2-Phase conversion & generation of Hall code;



634

635

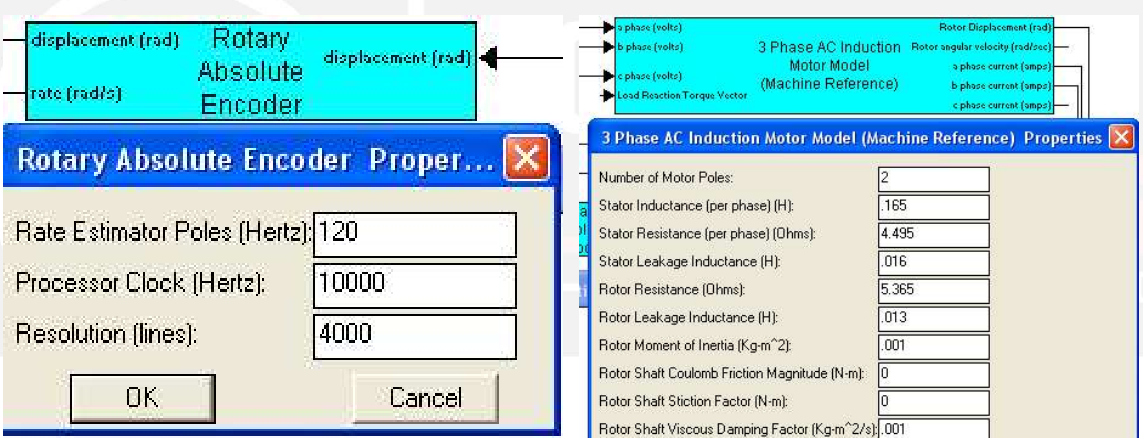
DUTY CYCLE GENERATION USING ... M METHOD



635

636

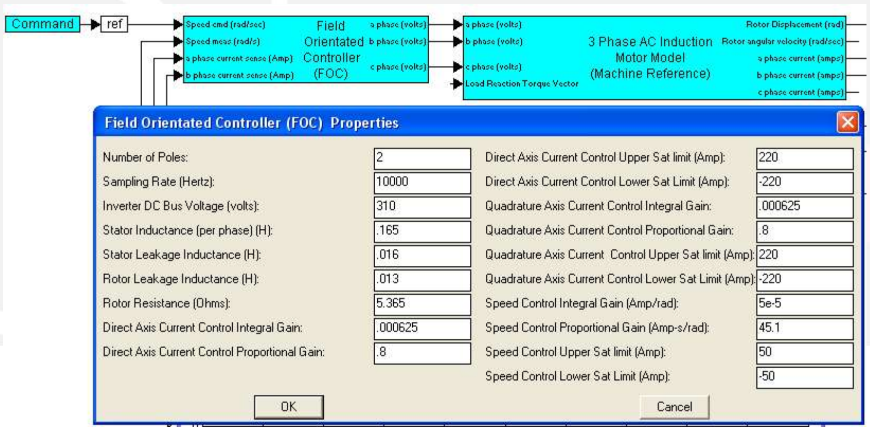
FOC FOR ACIM



636

637

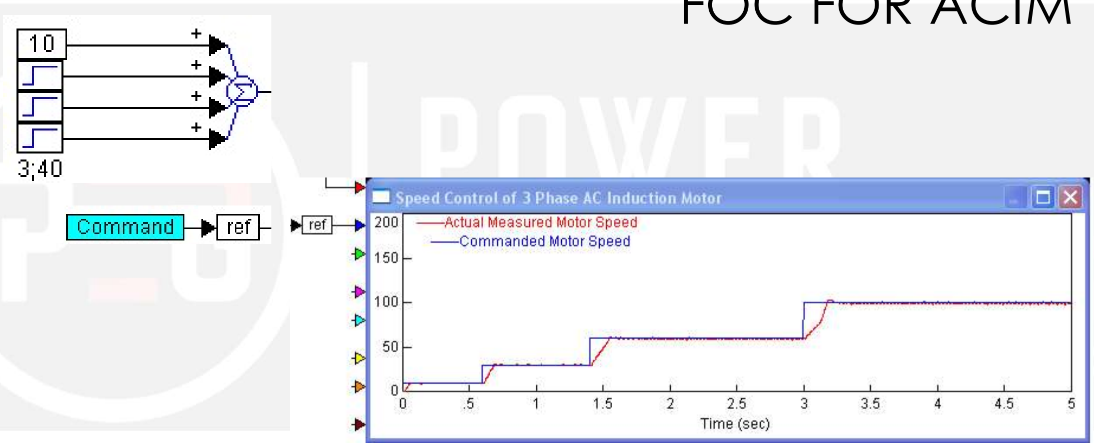
FOC FOR ACIM



637

638

FOC FOR ACIM



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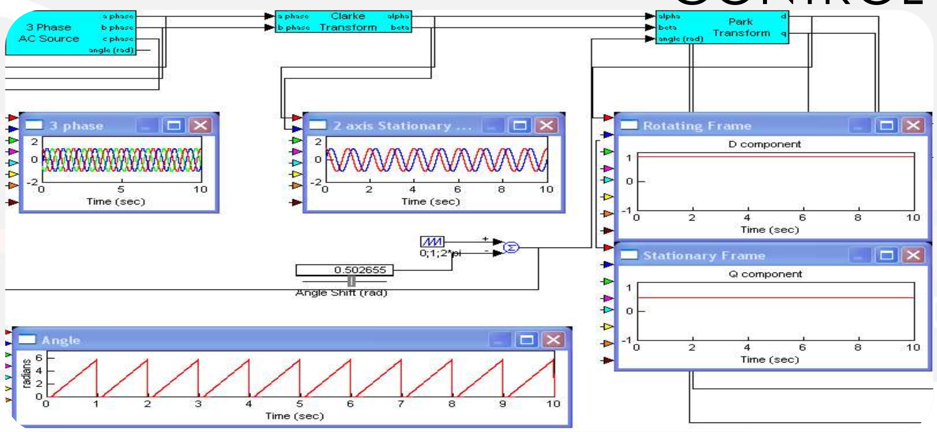
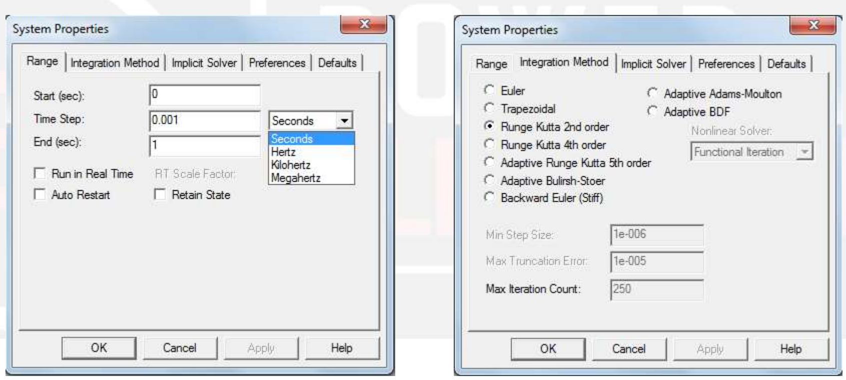
REFERENCE FRAMES IN VECTOR CONTROL



639

640

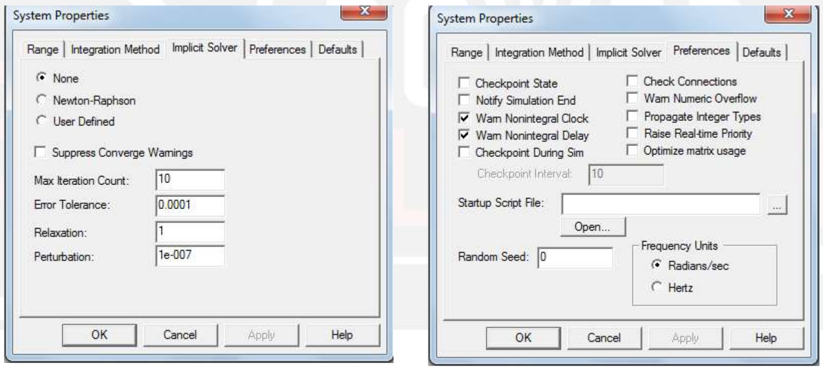
SYSTEM PROPERTIES



640

641

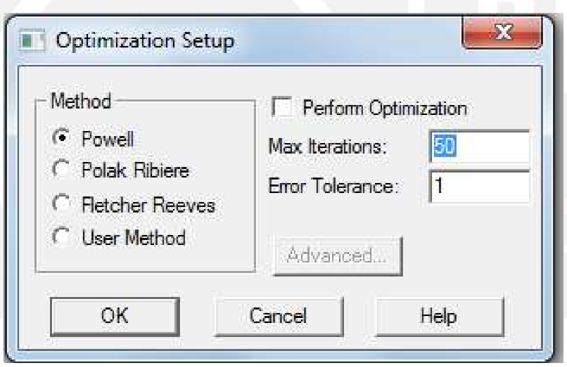
SYSTEM PROPERTIES



641

642

SYSTEM PROPERTIES



- Optimize the simulation;
- Minimize convergence problems;
- Set the error tolerance;
- Change the step size;
- Various methods of optimization are available;
- Various ready-made blocks available;
- Various Examples of different concepts readily available;

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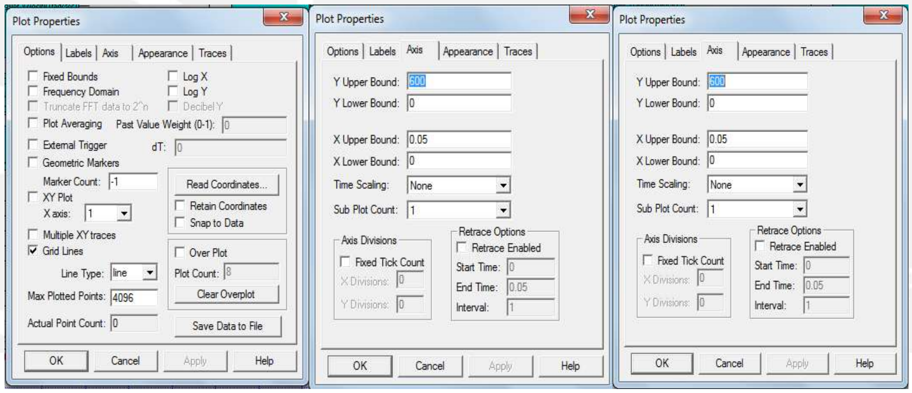
PLOT PROPERTIES



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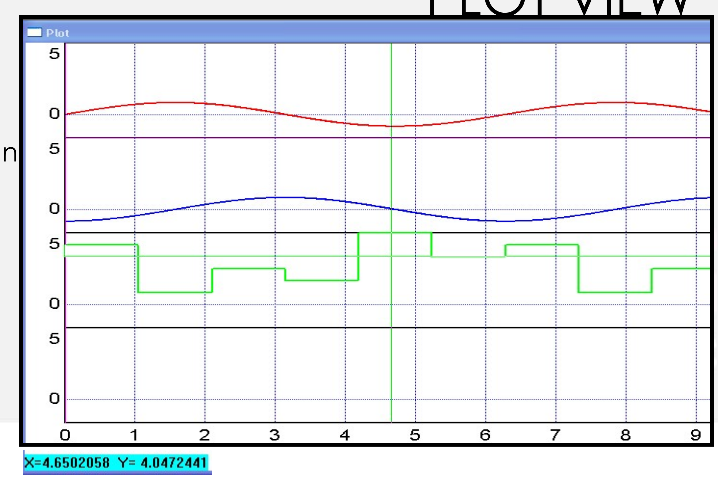
PLOT VIEW

- ➢ Features:
- ➢ Maximum of 8 plots can be plotted;
- ➢ Grid lines;
- ➢ Co-ordinates reading;
- ➢Save data to file;



644