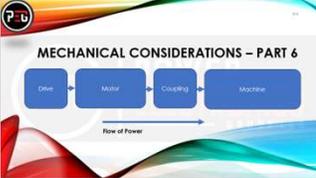




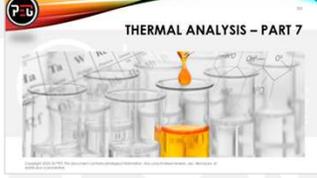
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**MECHANICAL CONSIDERATIONS – PART 6**

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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## MECHANICAL CONSIDERATIONS – PART 6

Drive

→

Motor

→

Coupling

→

Machine



**Flow of Power**

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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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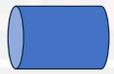
*022*



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## GENERAL LOAD REQUIREMENTS

- Motor Sizing *(performance)*
  - 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;



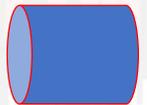
Motor

*T<sub>pk</sub> <math>\omega</math>*

*P = T<math>\omega</math>*



Inertia 10:1



Inertia 5:1



Inertia 1:1

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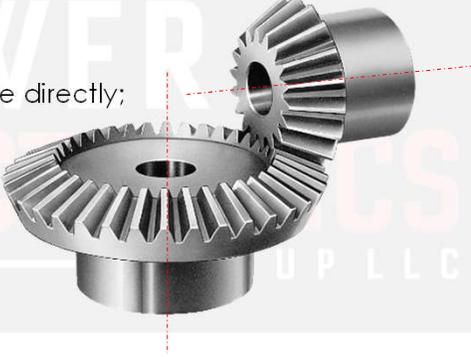
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## GENERAL LOAD REQUIREMENTS

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



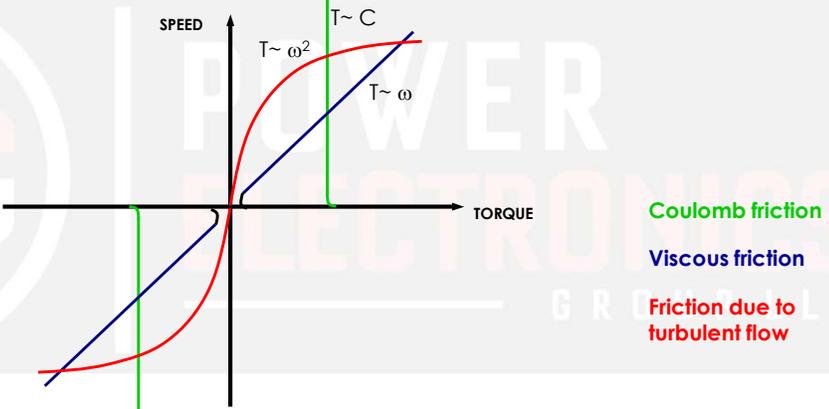
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## TORQUE-SPEED CHARACTERISTIC



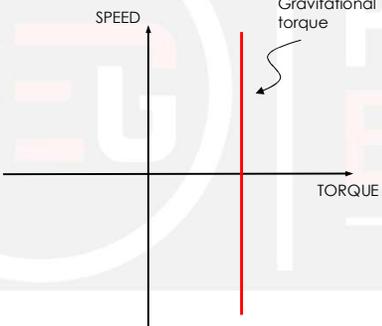
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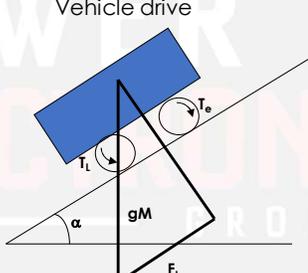
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## TORQUE-SPEED CHARACTERISTIC



Gravitational torque



Vehicle drive

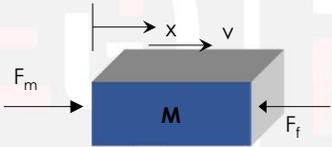
$T_L = rF_L = r g M \sin \alpha$

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## DYNAMICS OF MECHANICAL DRIVE SYSTEM



Newton's law

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

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

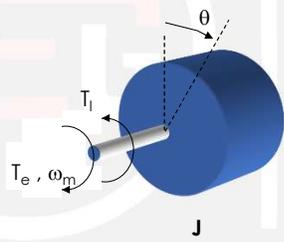
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## DYNAMICS OF MECHANICAL DRIVE SYSTEM

**Rotational motion**



**J**

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

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

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## DYNAMICS OF MECHANICAL DRIVE SYSTEM

For constant J,

$$J \frac{d(\omega_m)}{dt}$$

Torque dynamics – present during speed transient

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

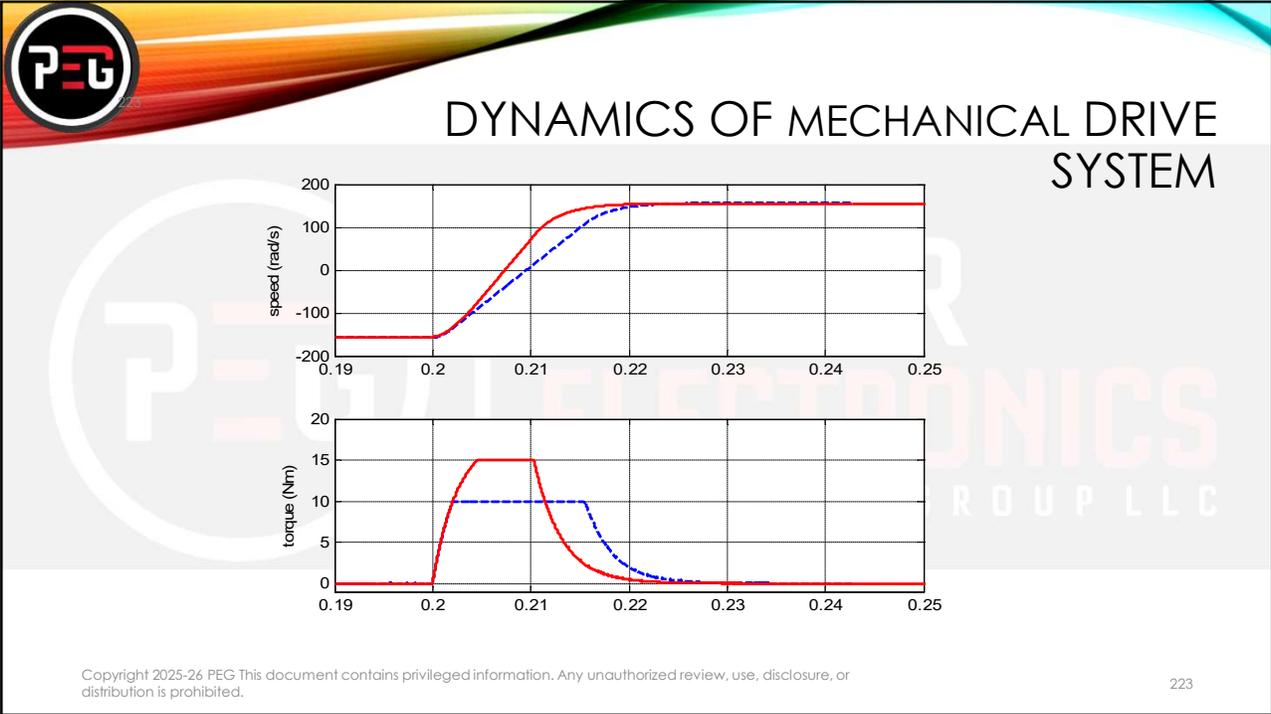
Angular acceleration

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

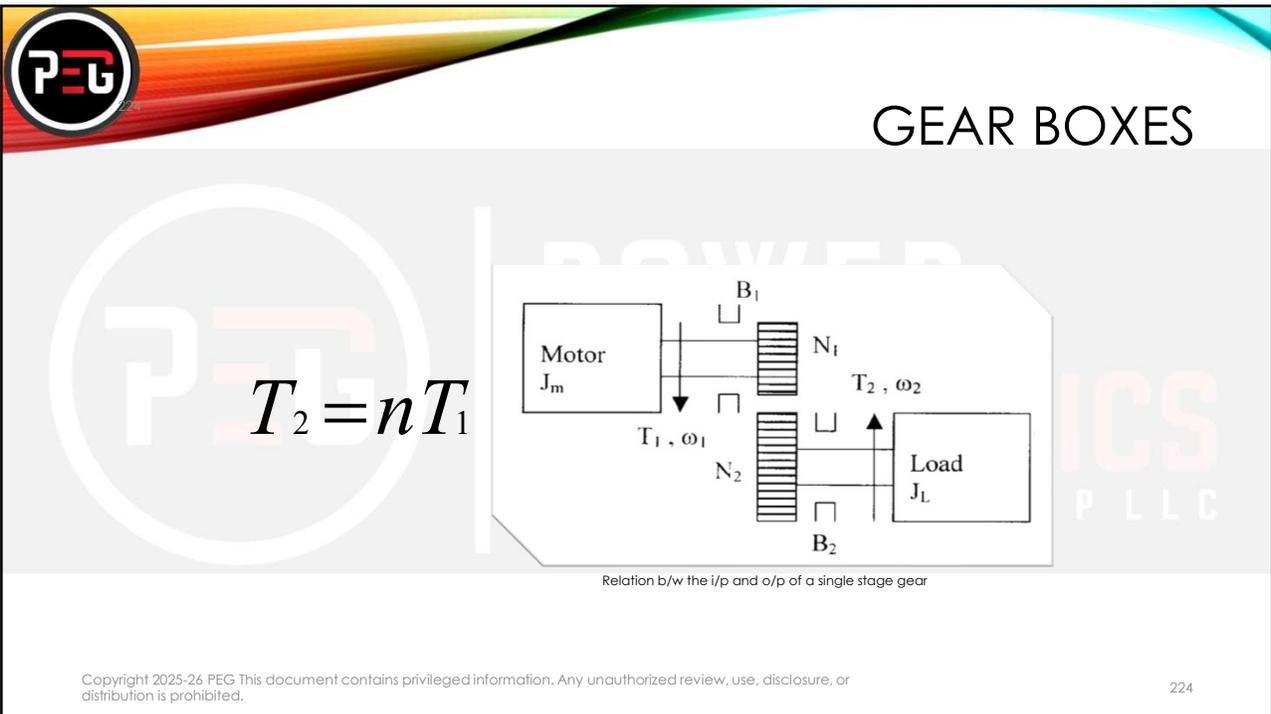
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## GEAR BOXES

Resultant mechanical constants at the shaft are,

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

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

**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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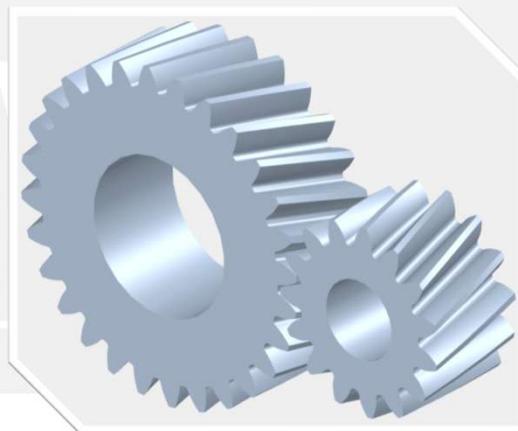
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# GEARS

- 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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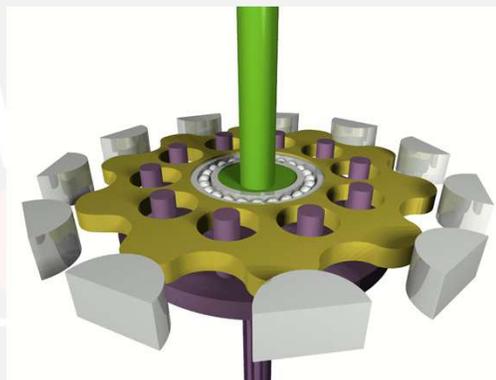
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## CYCLOID SPEED REDUCER

- Plain disc rolling around a stationary ring;
- Follows an eccentric path at speed  $n_1$ ;
- Rotation in the opposite direction with  $n_2$ .



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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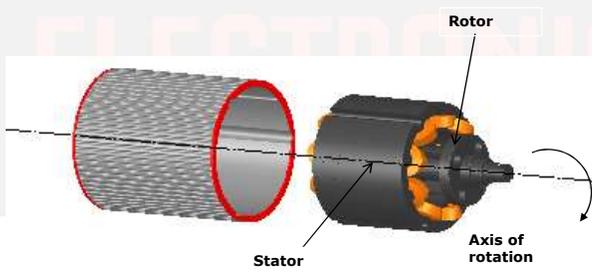
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## MOUNTING PRINCIPLE

- 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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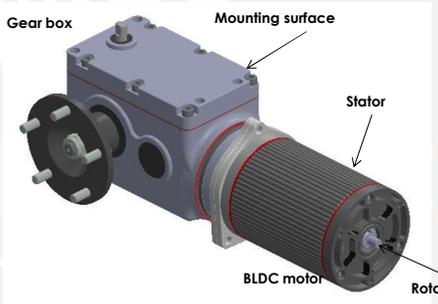


## WHEELCHAIR MOTOR MOUNTING

- Surface mounting.
- Inner runner motor.

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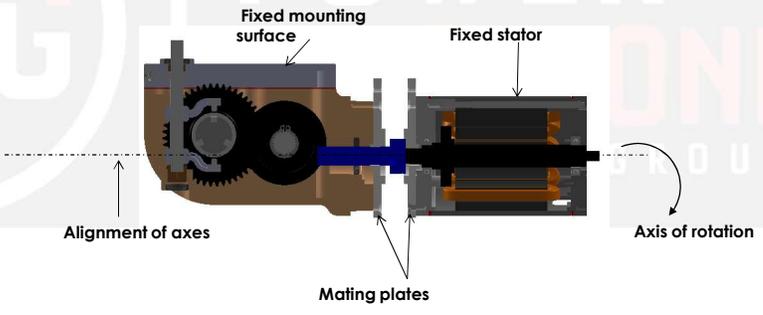
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## WHEELCHAIR MOTOR MOUNTING

- Critical mating plate;
- Fixed stator.



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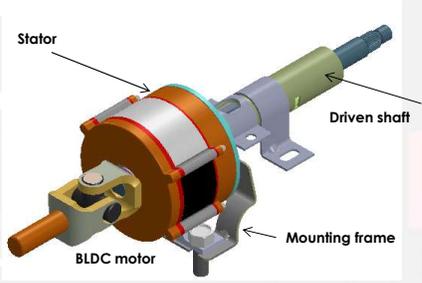
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## POWER STEERING MOTOR MOUNTING

- Mounting frame;
- Inner runner motor.



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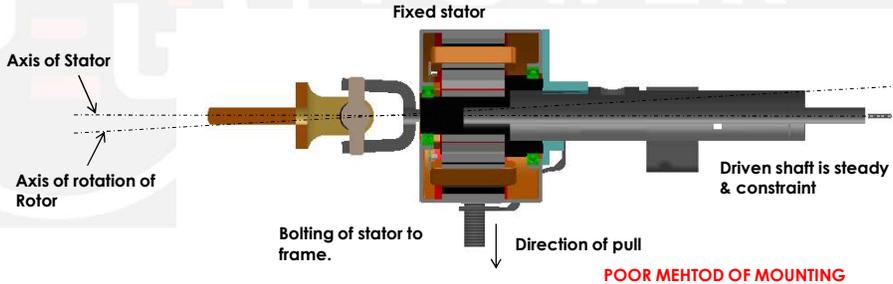
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## VIOLATION OF THE PRINCIPLE

- Pulling forces;
- Dynamics of Eccentricity.



**POOR MEHTOD OF MOUNTING**

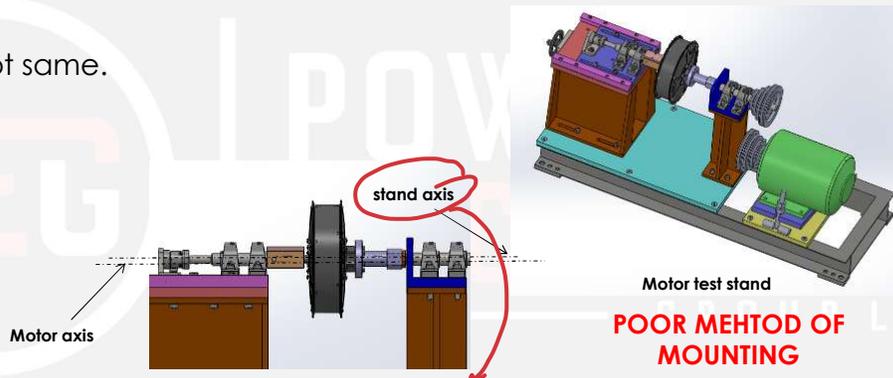
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## VIOLATION OF PRINCIPLE

- 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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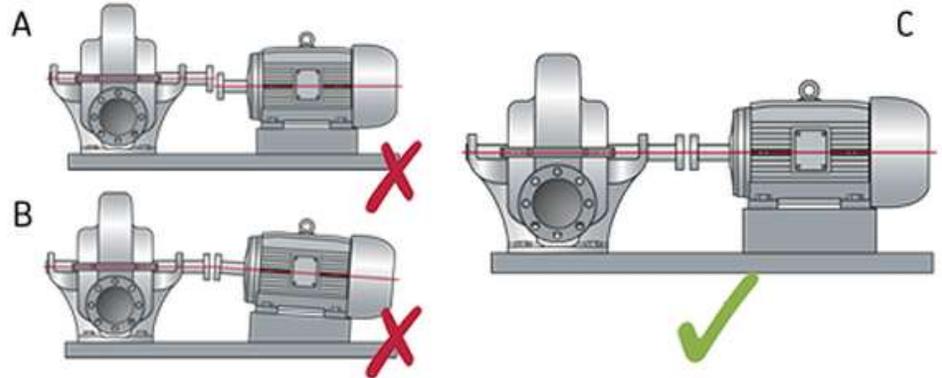
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*mounting 1/2 coupling?*

# ROLE OF COUPLINGS



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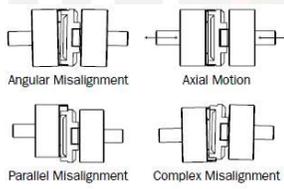
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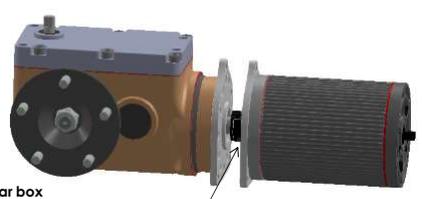
## FLEXIBLE COUPLINGS

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



Angular Misalignment    Axial Motion

Parallel Misalignment    Complex Misalignment



Gear box      Oldham's coupling      BLDC Motor

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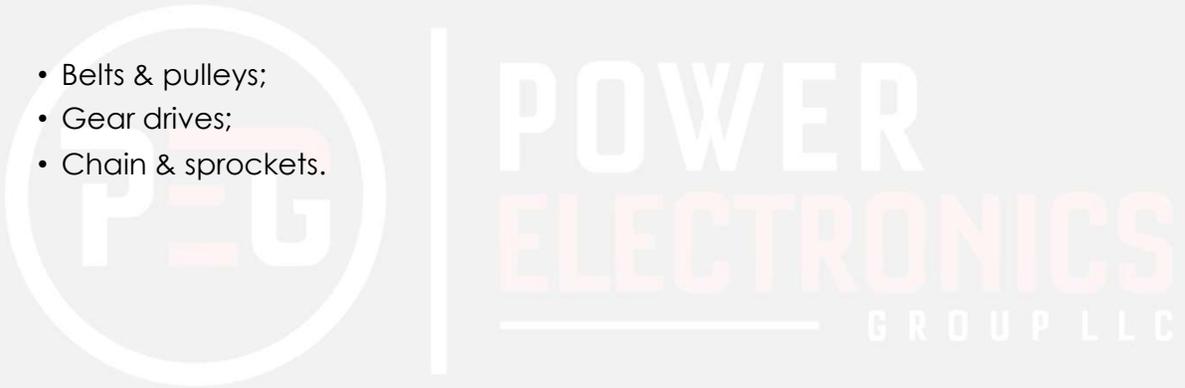
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## DRIVES

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



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## BELTS & PULLEY'S

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



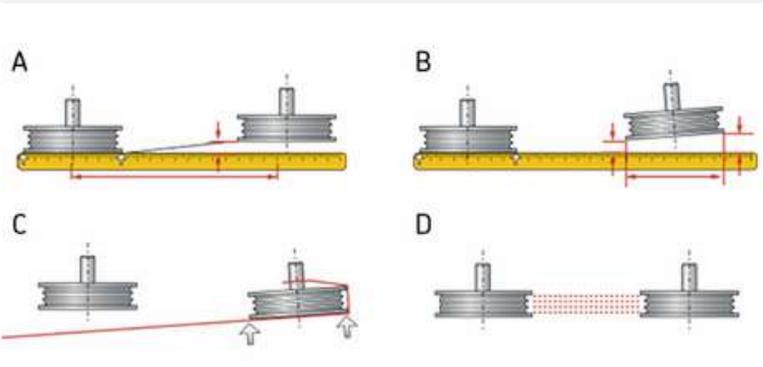
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## BELTS & PULLEYS



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## BELTS & PULLEYS

A



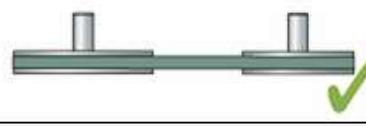
B



C



D



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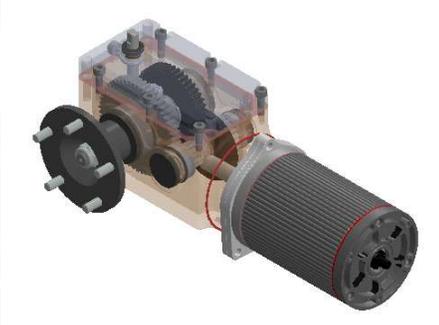
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## GEAR DRIVE MOUNTING

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



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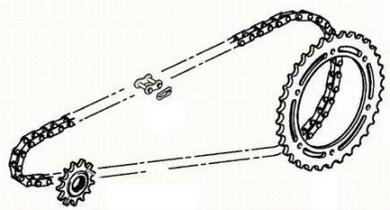
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## CHAIN & SPROCKETS

- 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**



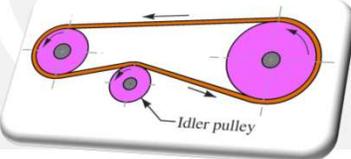
**Roller Chain Drive**



**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

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## 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

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## TYPES OF MECHANICAL DRIVES

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

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## 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,  
 $v_2 = \omega_2 D_2 / 2$

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## CONCEPT OF PERIPHERAL SPEED

or  $v_2 = \pi D_2 n_2 / 60$   
 Without slipping, the peripheral speeds  
 should be same  
 $v_1 = v_2$   
 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

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## EFFICIENCY OF POWER TRANSMISSION

- **Output Power**
  - $P_o = P_i \times \eta_i$
  - $M_t =$  torsional moment, Nm
  - $\omega =$  angular speed, radians/s
  - $M_t = kW \times 1000 / \omega$   
 $= kW \times 1000 / (2 \pi f)$   
 $= 9550 \times kW / \text{rev/min (Nm)}$

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## EFFICIENCY OF POWER TRANSMISSION

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

Hence

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

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

$Mt_2$  = torsional moment on the second shaft

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

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## EFFICIENCY OF POWER TRANSMISSION

- Total Speed Ratio,  
 $(VR)_{1,n} = (VR)_1 \times (VR)_2 \times (VR)_3 \dots \dots \dots (VR)_n$
- Total efficiency of the multistage drive,  
 $\eta_{1,n} = \eta_1 \cdot \eta_2 \cdot \eta_3 \dots \dots \dots \eta_n$

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# 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

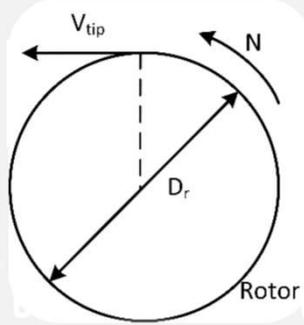
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## PERIPHERAL VELOCITY IMPACT

- 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=  $v_{\max} \leq 25$  m/s
- Belt (artificial fiber)=  $v_{\max} \sim 50$  m/s
- V belts=  $v_{\max} \sim 25$  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**

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## 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**)

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## 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

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# 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.

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# 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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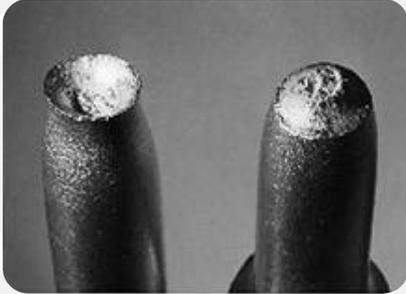
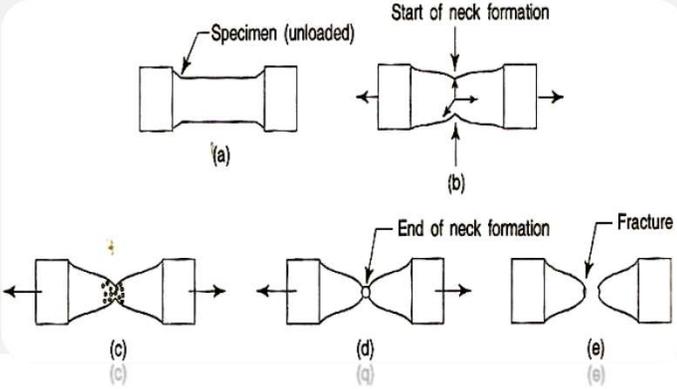
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## MODES OF MECHANICAL FAILURE

- Ductile fracture (High Energy Absorption)

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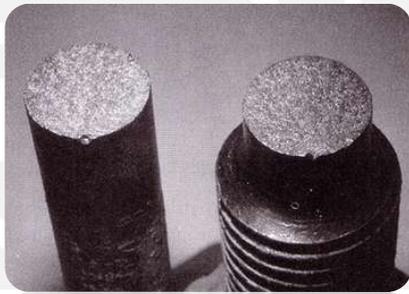
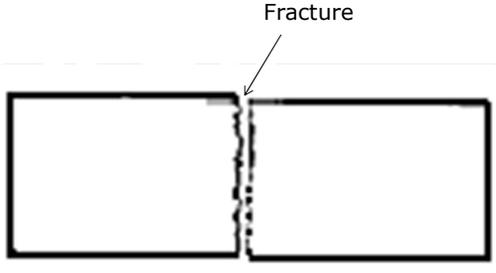
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## MODES OF MECHANICAL FAILURE

- Brittle fracture (Low Energy Absorption)

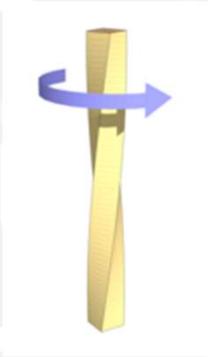
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## MECHANICAL FAILURE

- Torsion Failure
- Yielding Failure



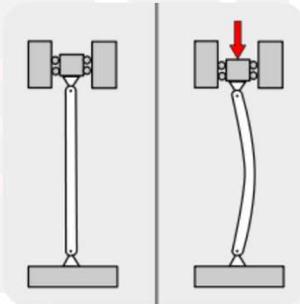
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## MECHANICAL FAILURE

- 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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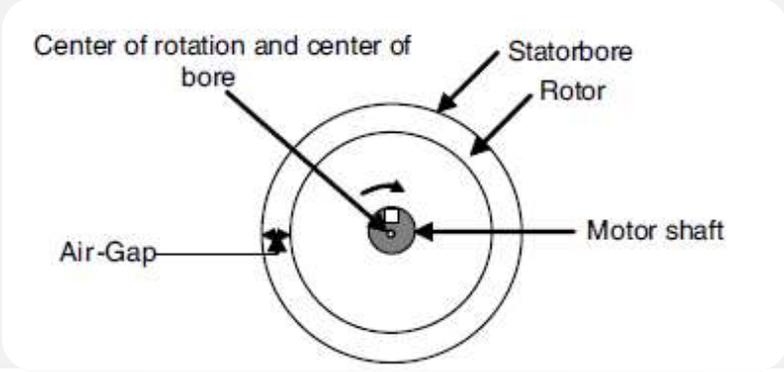
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## STATOR & ROTOR FAULTS

- Eccentricity



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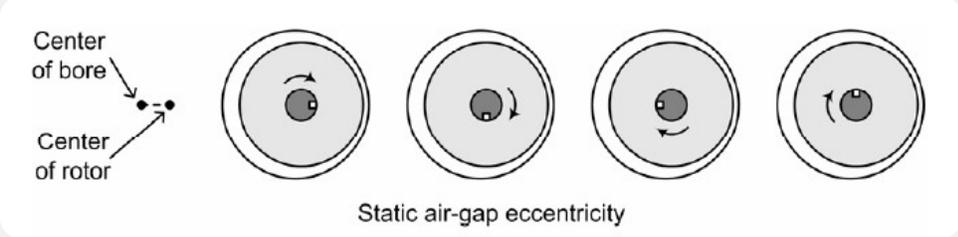
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## STATOR & ROTOR FAULTS

- Static Eccentricity



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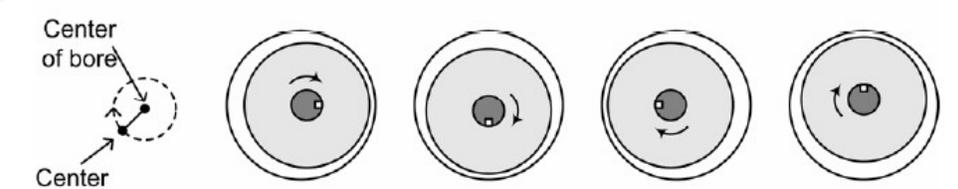
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## STATOR & ROTOR FAULTS

- Dynamic Eccentricity
  - Tolerances, Bent Shaft, Bearing Wear



Dynamic air-gap eccentricity

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## STATOR & ROTOR FAULTS

- Damaged rotor Magnets



Cracked magnet

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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

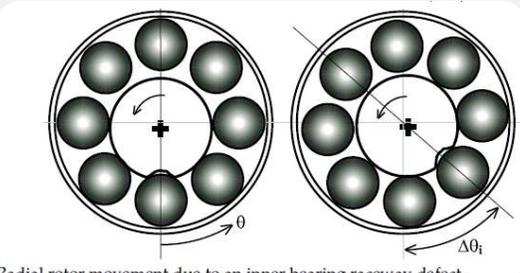
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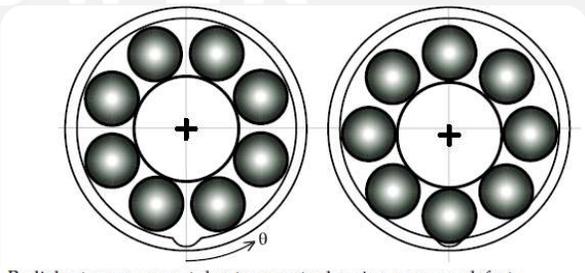


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## BEARING FAULTS



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
  - ✓ Reevaluate 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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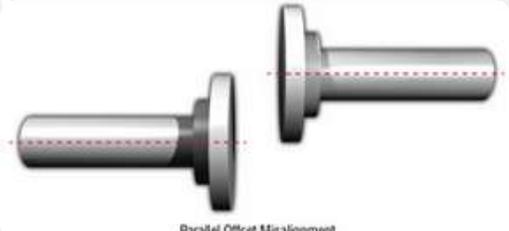


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## SHAFT MISALIGNMENT



**Angular Offset Misalignment**  
Angular offset alignment



**Parallel Offset Misalignment**  
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<sup>2</sup>;  
 $T_{ss}$  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

$$T_{ss} = 80.\left(\frac{A_s}{2.54^2 \cdot 10^2}\right)^{-0.7} .P_{loss}^{0.85}$$

$A_s$  is in mm<sup>2</sup>;  
 $T_{ss}$  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<sup>2</sup> 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<sup>2</sup> (20,680 mm<sup>2</sup>)

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## ESTIMATE LOSSES BASED ON MOTOR DIMENSIONS

- D = 90mm
- L = 100mm
  - Surface Area = 636,172 mm<sup>2</sup>
  - 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

Power Dissipation (Watts)	Temp Rise (A1) [°C]	Temp Rise (A2) [°C]	Temp Rise (A3) [°C]
0	0	0	0
100	~50	~30	~20
200	~100	~60	~40
300	~150	~90	~60

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

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## TRANSIENT BEHAVIOR

- Temp Rise of the Windings

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

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

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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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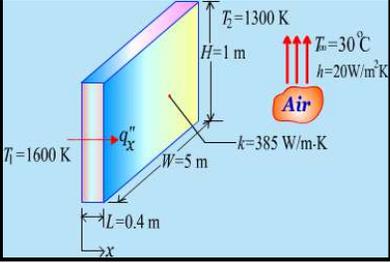

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## CONDUCTION

$$\frac{Q}{A} = k \cdot \frac{(T_1 - T_2)}{L} \quad \text{Heat Flux}$$

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

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



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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<sub>th</sub>=Thermal resistance in °K/W;

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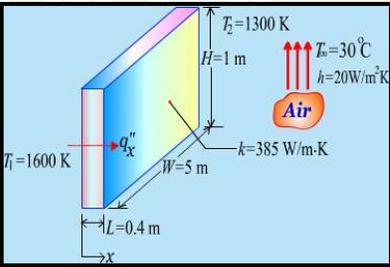

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## CONVECTION

$$\frac{Q}{A} = h \cdot (T_1 - T_2)$$

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

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



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## CONVECTION

- h = convective heat transfer coefficient
  - Forced Air Convection = 200W/m²K;
  - Free Convection with Water = 1000W/m²K;
  - Forced Convection with Water = 10,000W/m²K;

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## RADIATION

$$P = \epsilon \cdot \sigma \cdot A_s \cdot T^4$$

$\epsilon = \text{Emissivity}$

$\sigma = \text{Stefan - Boltzman}$

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## THERMAL ANALYSIS

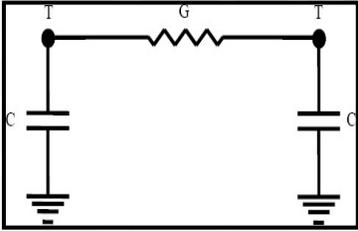
- The above three are sufficient to define the steady state heat transfer model.
- How do we build a time dependent model?

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## THERMAL NETWORK ELEMENTS



$$C = \rho \cdot V \cdot C_p$$

**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<sup>o</sup>K;

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# THERMAL NETWORK ELEMENTS

- $R_{th}$ =Thermal resistance in  $^{\circ}K/W$ ;
- $h$ =Convective heat transfer coefficient in  $W/m^2^{\circ}K$ ;
- $C$ =Specific heat capacity of the body in  $J/^{\circ}K$ ;
- $C_p$ =Specific heat constant in  $J/Kg^{\circ}K$ ;
- $\rho$ =Density of the material in  $Kg/m^3$ ;
- $V$ =Volume in  $m^3$ ;

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# THERMAL NETWORK ELEMENTS

Meaning	Material	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 coefficient	$h$ in $W/m^2K$	5 to 25								
Specific heat capacity	$C_p$ in $J/KgK$	287	900	510	490	460	482	383.1	502	
Density	$\rho$ in $Kg/m^3$	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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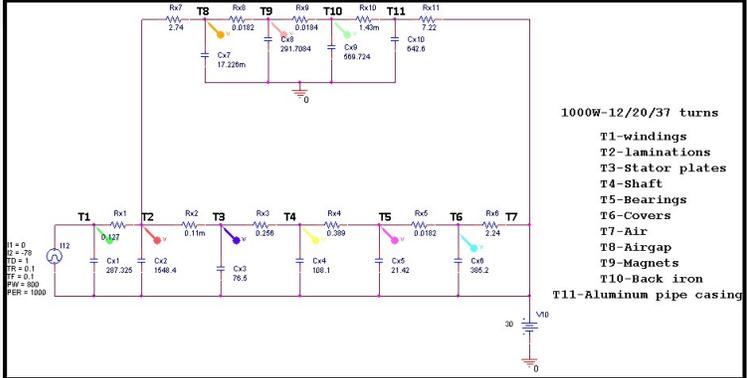
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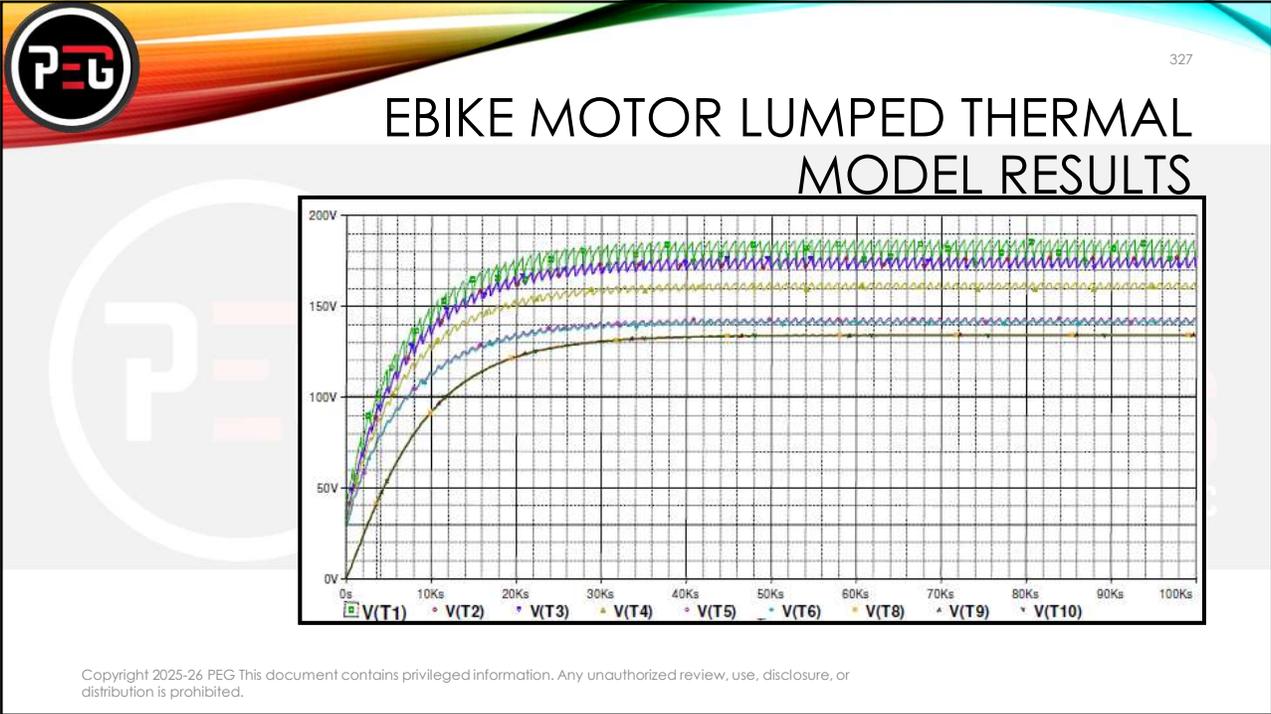
## EBIKE MOTOR THERMAL MODEL



**Rph=0.065 ohms, Turns=12, I<sub>rms</sub>/ph=14.14A/ph, P<sub>loss</sub>=65W+20%=80W;**

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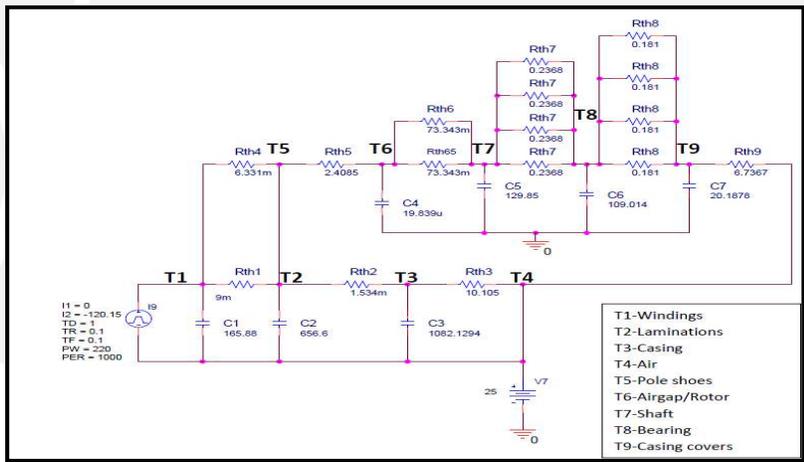
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- ### EBIKE MOTOR LUMPED THERMAL MODEL RESULTS
- Winding Temp=100 deg at 60min with 80W of Ploss considering h=5(worst case) & D=80%;
  - Winding Temp=100 deg at 90min with 80W of Ploss considering h=25(optimistic case) D=100%;
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# INNER ROTOR MOTOR THERMAL MODEL



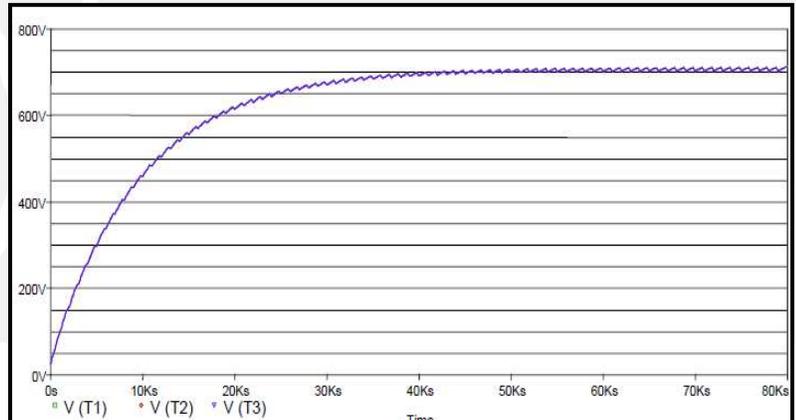
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# LUMPED THERMAL MODEL RESULTS



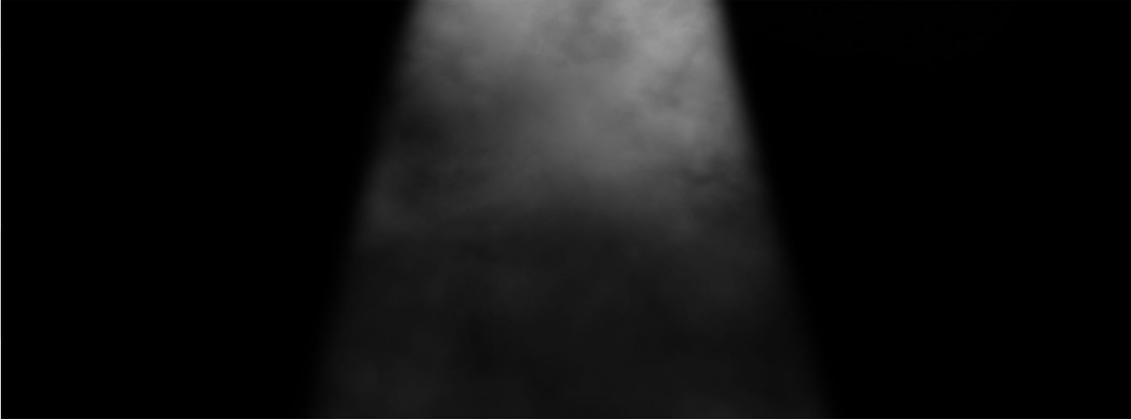
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# POWER STAGE DESIGN – PART 8



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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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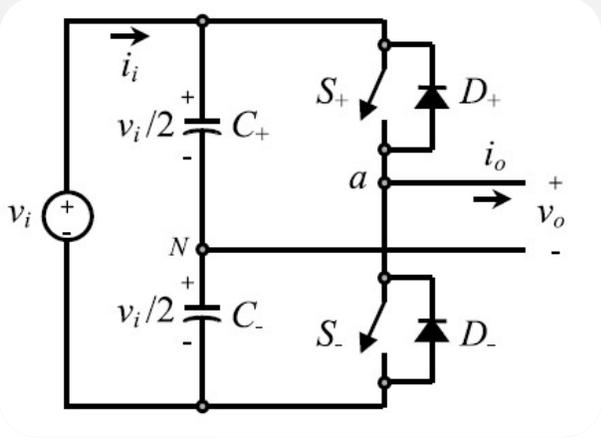
# MOTOR DRIVE TOPOLOGIES

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

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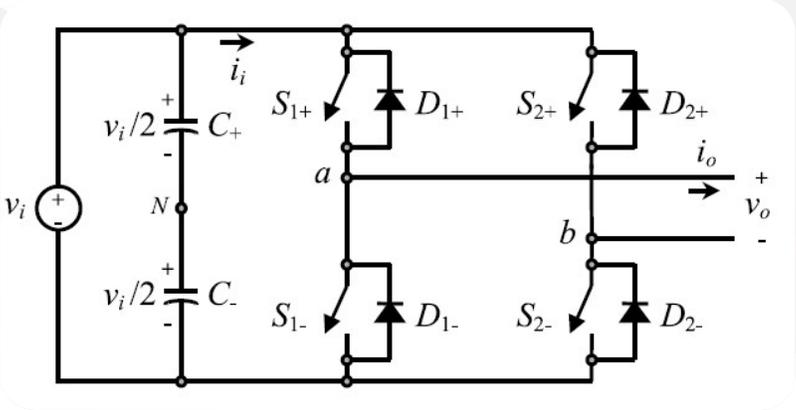
# TYPES OF BRIDGES – HALF BRIDGE



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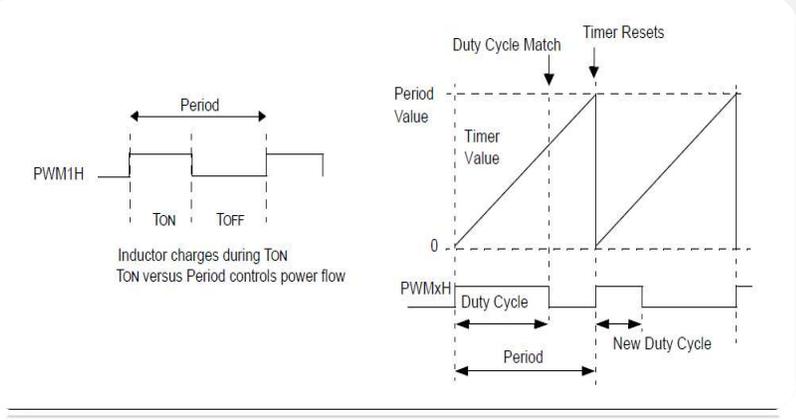
# TYPES OF BRIDGES – FULL BRIDGE



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# PWM TECHNIQUES – EDGE ALIGN PWM MODE (INDEPENDENT)

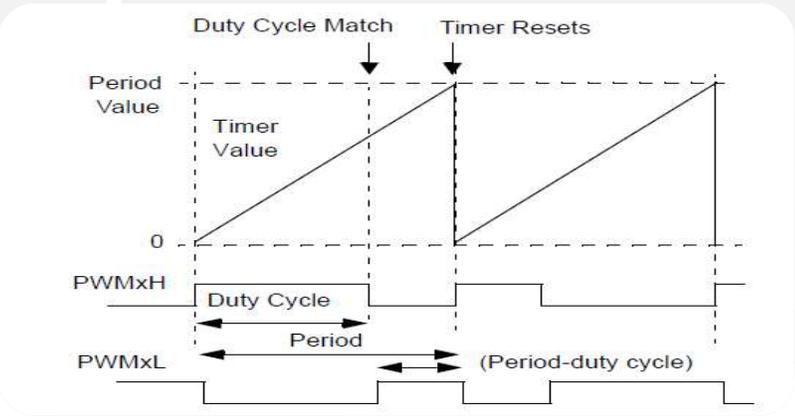


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# PWM TECHNIQUES – EDGE ALIGN PWM MODE (COMPLIMENTARY)



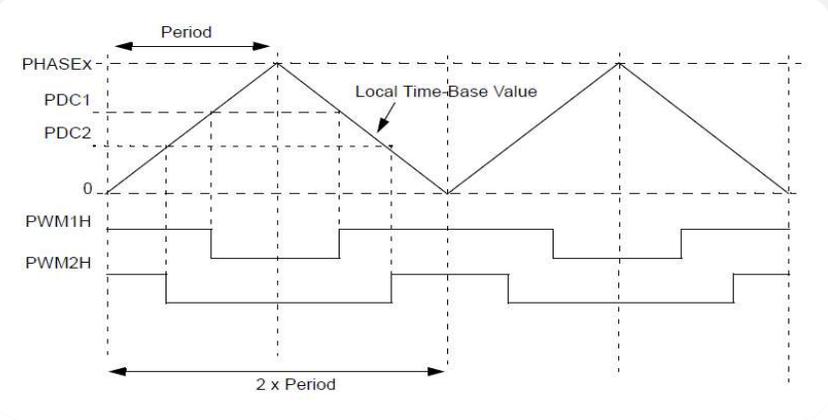
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# PWM TECHNIQUES – CENTER ALIGN PWM MODE (INDEPENDENT)



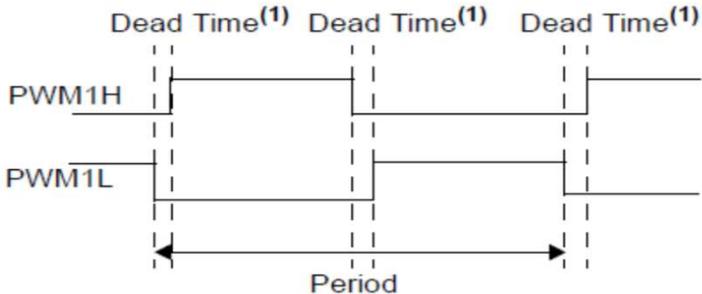
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## PWM TECHNIQUES – CENTER ALIGN PWM MODE (COMPLIMENTARY)



The diagram shows two complementary PWM signals, PWM1H and PWM1L, over one period. Each signal has a high state and a low state. There is a period where both signals are low, labeled as 'Dead Time(1)'. The total duration of one high and one low state is labeled as 'Period'.

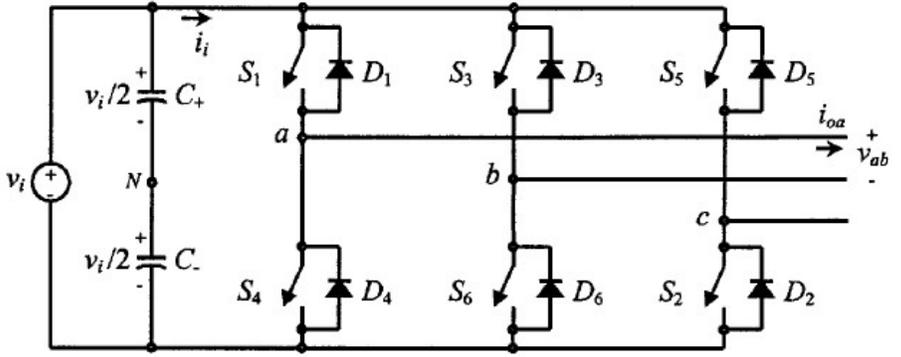
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## 3-PHASE INVERTER



The circuit diagram shows a three-phase inverter. It consists of a DC voltage source  $v_i$  connected to a neutral point  $N$ . Two capacitors,  $C_+$  and  $C_-$ , are connected to the positive and negative rails, respectively, with a voltage of  $v_i/2$  across each. The inverter has six transistors ( $S_1, S_2, S_3, S_4, S_5, S_6$ ) and six diodes ( $D_1, D_2, D_3, D_4, D_5, D_6$ ) arranged in three legs. The output terminals are labeled  $a, b, c$ . The output current is  $i_{oa}$  and the output voltage is  $v_{ab}$ . The input current is  $i_i$ .

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## 3 PHASE SINE INVERTER: GENERATING D

Inverter Output

Control Loop Output

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

$$D_{desired} = \left( \frac{2 \cdot V_{m\_desired}}{V_{dc}} + 1 \right) / 2$$

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## 3 PHASE SINE INVERTER: GENERATING D

Amplitude Modulation Ratio:

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

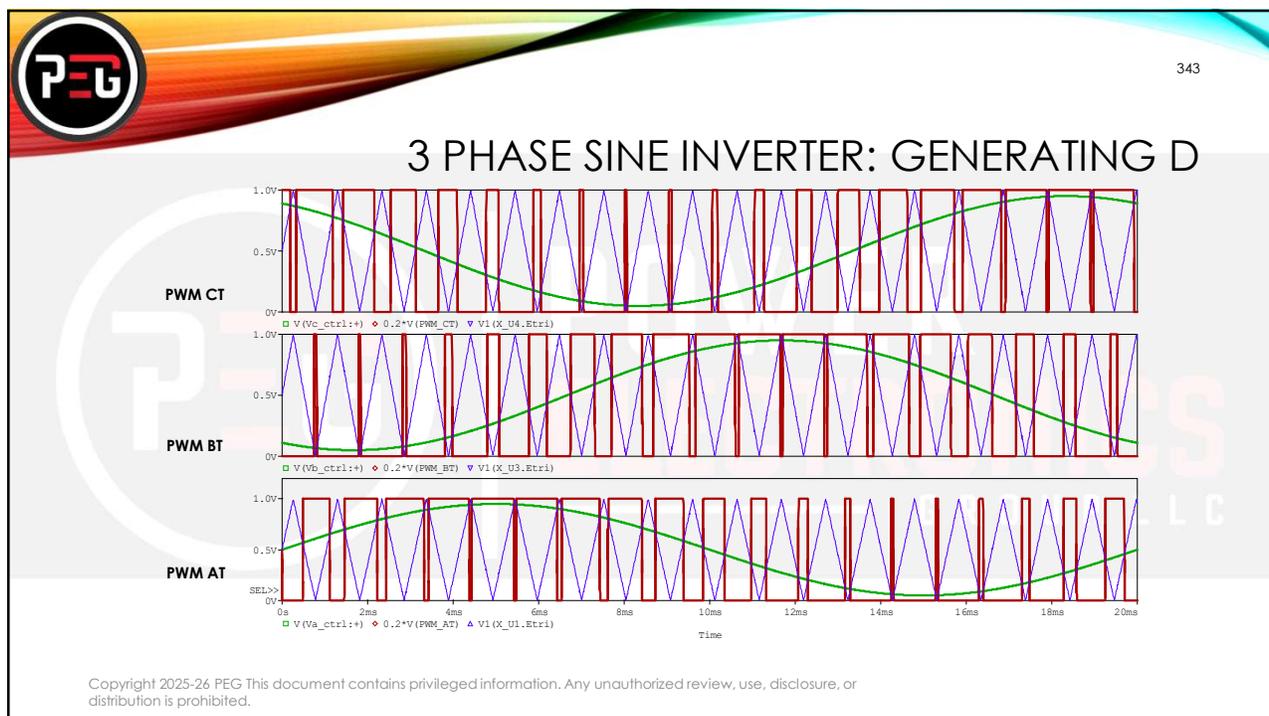
$$V_{a\_ctrl} = \frac{1}{2} \cdot \frac{V_m}{V_{dc}/2} \cdot \sin(\omega_e t) + \frac{1}{2}$$

$$V_{b\_ctrl} = \frac{1}{2} \cdot \frac{V_m}{V_{dc}/2} \cdot \sin(\omega_e t - 120^\circ) + \frac{1}{2}$$

$$V_{c\_ctrl} = \frac{1}{2} \cdot \frac{V_m}{V_{dc}/2} \cdot \sin(\omega_e t - 240^\circ) + \frac{1}{2}$$

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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

+V

Q1

R1  
0R - see text

Drive O/P

Q2

0V

Logic/PWM opto-coupler

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## MOSFET DRIVER

Up to 600V

V<sub>DD</sub>

LIN

HIN

V<sub>DD</sub>

COM

R<sub>BOOT</sub>

D<sub>BOOT</sub>

V<sub>B</sub>

HO

V<sub>S</sub>

LO

C<sub>BOOT</sub>

Load

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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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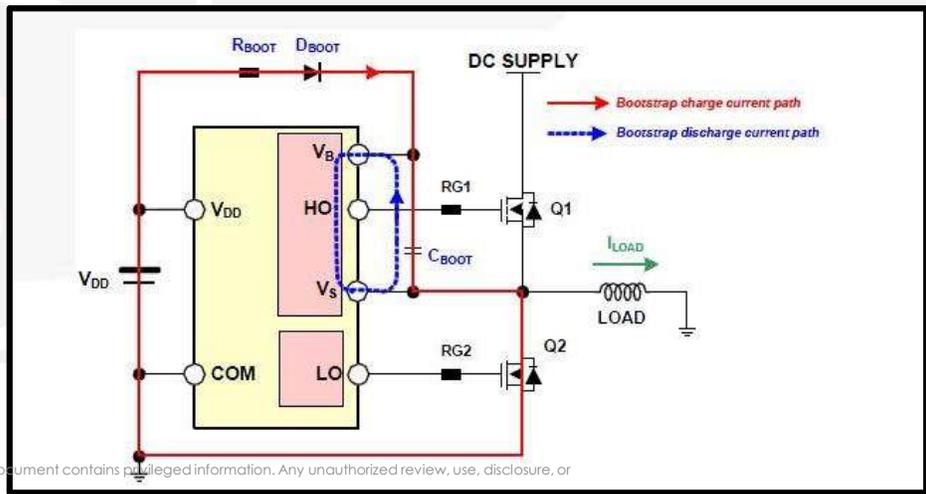
# BOOTSTRAP CAPACITOR

- 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,  $\Delta V_{BOOT}$  = 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;

$$Q_{TOTAL} = (I_{LKCAP} + I_{LKGS} + I_{QBS} + I_{LK} + I_{LKDIODE}) \cdot T_{ON} + Q_{LS}$$

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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

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

$$C_{boot} = 0.1\mu f$$

we have to choose 10 times of the calculated

$$C_{boot} = 0.1\mu f * 10 = 1\mu f.$$

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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.

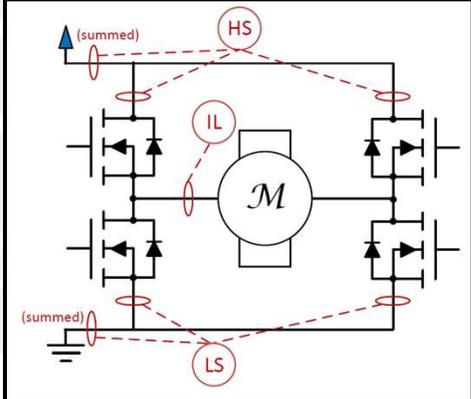


Image Source: <https://www.allegromicro.com/-/media/files/application-notes/an296276-current-sensing-in-motor-drives.pdf>

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## CURRENT FEEDBACK MEASUREMENT USING SHUNT RESISTOR

Methods of Measurement:

- High Side Current ;
- Low Side Current;
- Phase Current



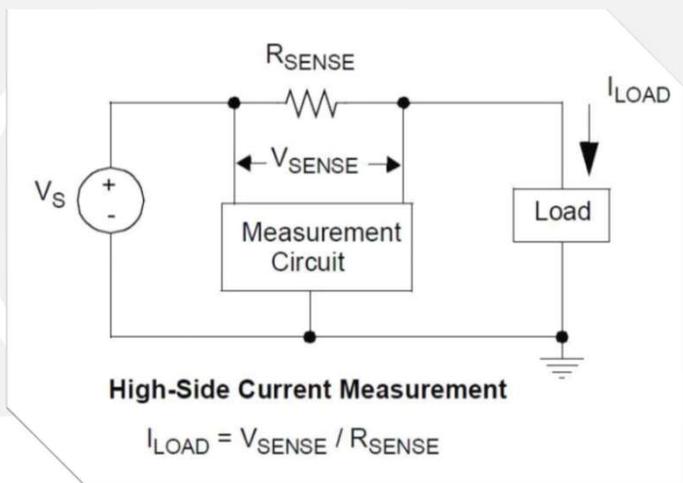
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# HIGH SIDE CURRENT MEASUREMENT



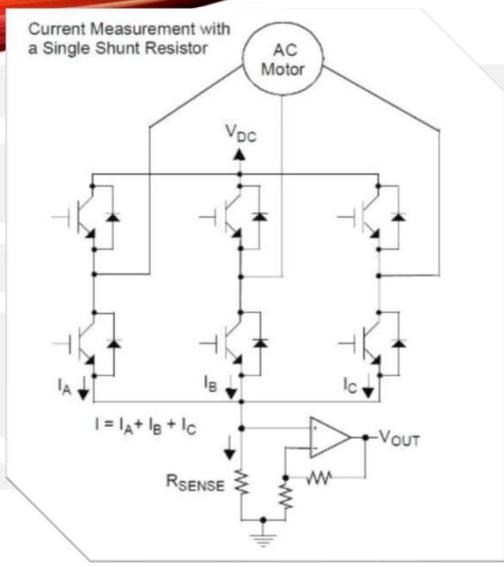
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# LOW SIDE CURRENT MEASUREMENT

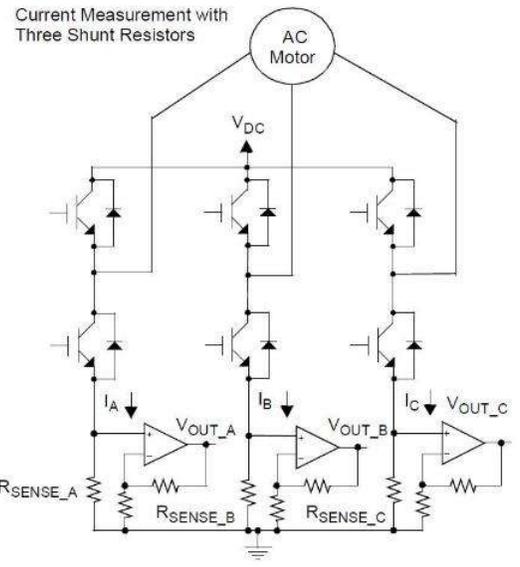


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# LOW SIDE CURRENT MEASUREMENT

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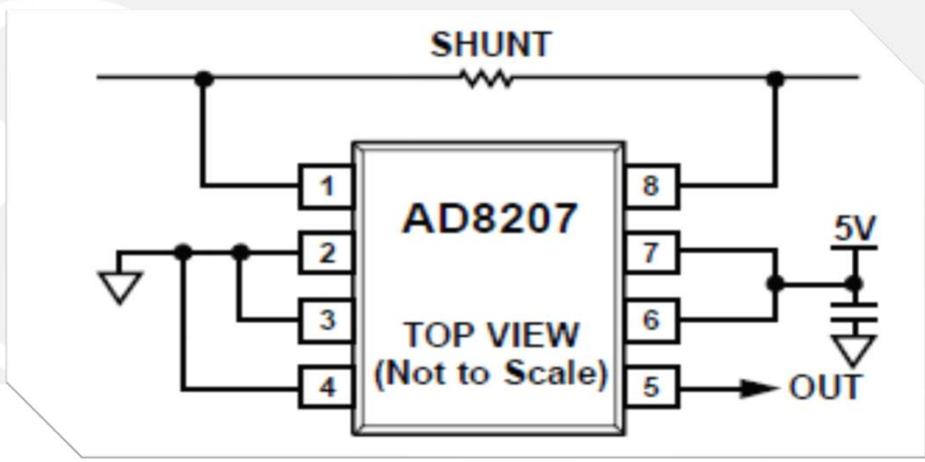
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# PHASE CURRENT MEASUREMENT

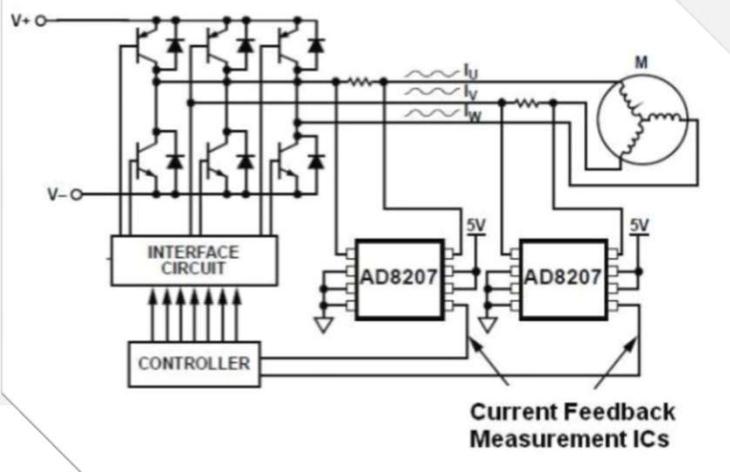


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## CURRENT FEEDBACK MEASUREMENT



**Current Feedback Measurement ICs**

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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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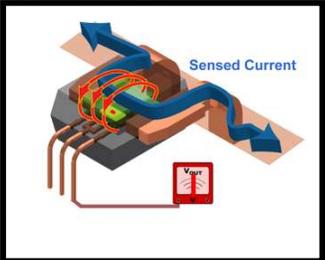
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## CURRENT FEEDBACK MEASUREMENT USING HALL EFFECT SENSOR

- 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.

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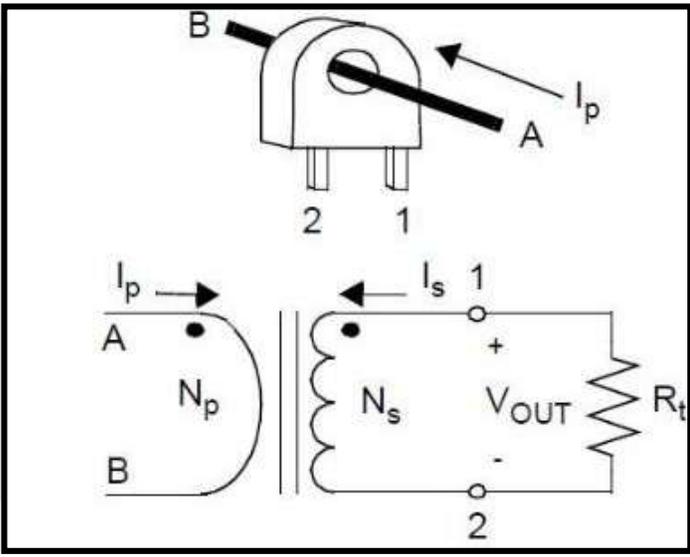
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### CURRENT FEEDBACK MEASUREMENT USING CURRENT TRANSFORMER

$I_s = I_p / N$  where,  $N =$  turns ratio;  
 $V_{OUT} = I_s \times R_t$



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### Current Sensing Options

Type	Low-side	High-side	In-line
Picture			
Detects short to GND	x	✓	✓
Detects short to supply	✓	x	✓
Asynch with PWM	x	x	✓
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	✓	x	✓
Measures HS brake	x	✓	✓
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

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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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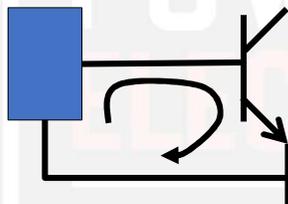
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# THE CARDINAL RULE

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



Gate Drive Loops should be well identified and keep short

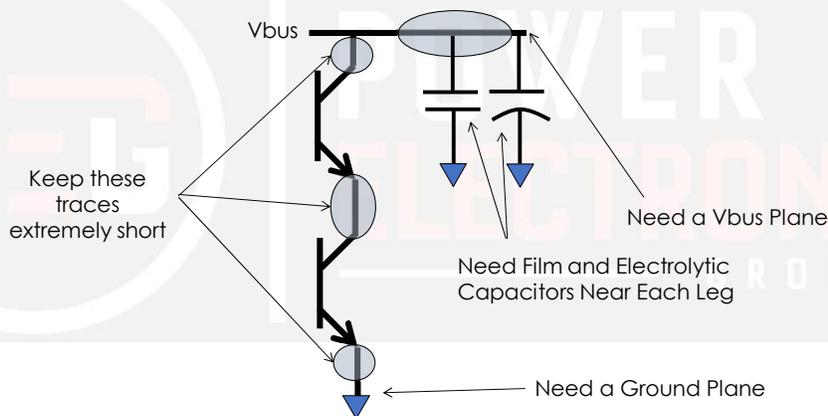
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# POWER SWITCHES



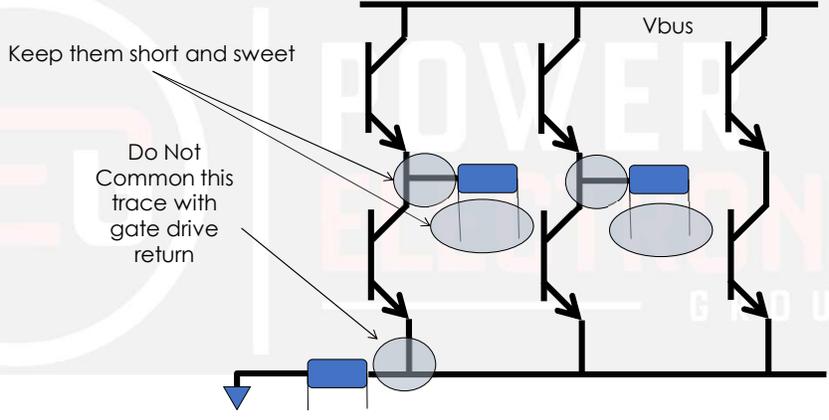
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## CURRENT SENSING



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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.

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## EMI FILTER DESIGN

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

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The diagram illustrates an EMI filter circuit. On the left, a blue arrow labeled "Source Side" points towards the circuit. Two capacitors, C10 and C11, are connected to the source side and are labeled "Y Caps". The circuit then passes through a "Common Mode Choke" consisting of two coupled inductors, L3 and L4. Following this, there is an "X Caps" section with capacitor C12. The circuit then passes through a "Differential Choke" consisting of two coupled inductors, L5 and L6, both labeled "10uH". Finally, capacitor C13 is connected to the "Load Side", indicated by a blue arrow pointing right.

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EMI FILTER

Source Side

Y Caps

X Caps

Common Mode Choke

Differential Choke

Load Side

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The slide is titled "EMI FILTER DESIGN – LAYOUT CONSIDERATIONS". It contains three bullet points:

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

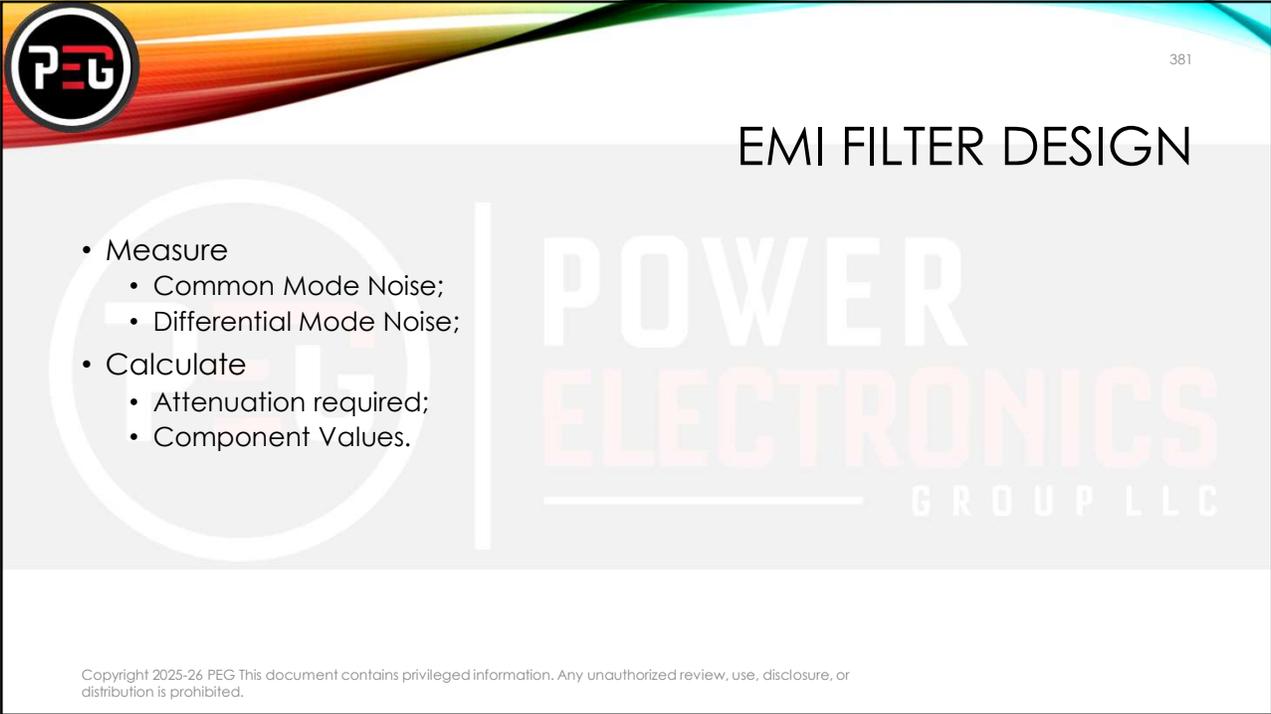
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EMI FILTER DESIGN – LAYOUT CONSIDERATIONS

- 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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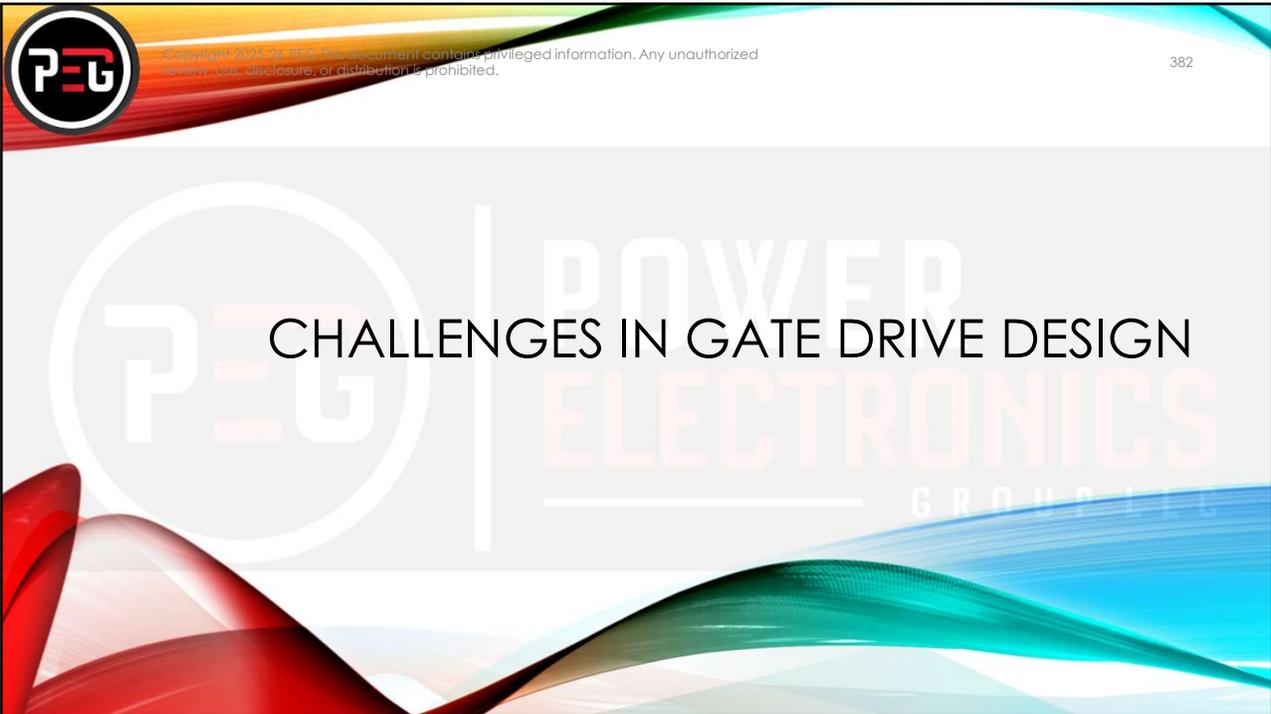
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# EMI FILTER DESIGN

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

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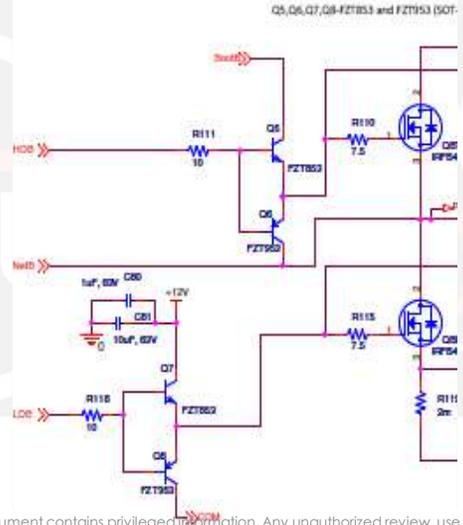
# CHALLENGES IN GATE DRIVE DESIGN

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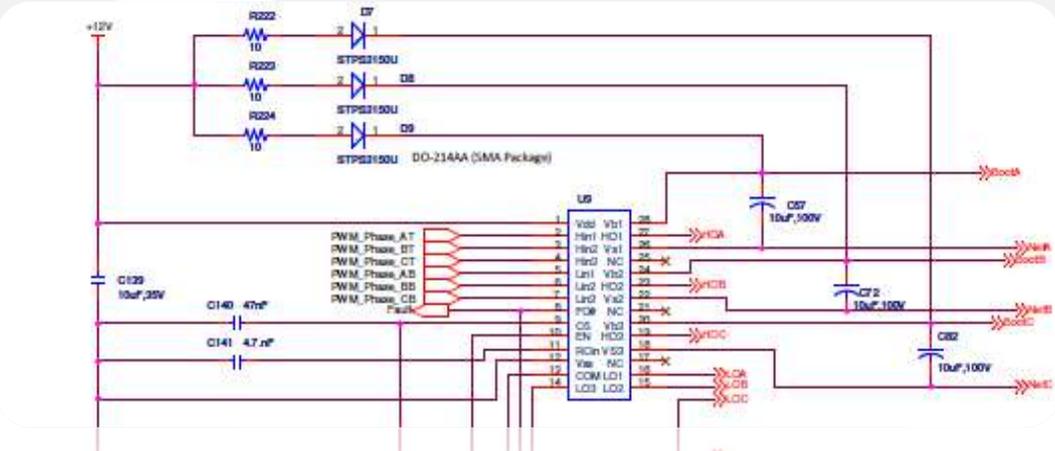
# INVERTER LEG



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# GATE DRIVER



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## DATASHEET

Symbol	Parameter	Min.	Typ.	Max.	Units	Conditions
$g_{fs}$	Forward Transconductance	160	—	—	S	$V_{GS} = 50V, I_D = 75A$
$Q_g$	Total Gate Charge	—	150	210	nC	$I_D = 75A$
$Q_{gs}$	Gate-to-Source Charge	—	35	—		$V_{DS} = 50V$
$Q_{gd}$	Gate-to-Drain ("Miller") Charge	—	43	—		$V_{GS} = 10V$ ①
$R_{DS}$	Gate Resistance	—	1.3	—	$\Omega$	
$t_{d(on)}$	Turn-On Delay Time	—	25	—	ns	$V_{DD} = 65V$
$t_r$	Rise Time	—	67	—		$I_D = 75A$
$t_{d(off)}$	Turn-Off Delay Time	—	78	—		$R_G = 2.6\Omega$
$t_f$	Fall Time	—	88	—		$V_{GS} = 10V$ ①
$C_{iss}$	Input Capacitance	—	9620	—	pF	$V_{GS} = 0V$
$C_{oss}$	Output Capacitance	—	670	—		$V_{DS} = 50V$
$C_{rss}$	Reverse Transfer Capacitance	—	250	—		$f = 1.0MHz$
$C_{oss\ eff. (ER)}$	Effective Output Capacitance (Energy Related) ②	—	820	—		$V_{GS} = 0V, V_{DS} = 0V \text{ to } 80V$ ③
$C_{oss\ eff. (TR)}$	Effective Output Capacitance (Time Related) ②	—	950	—		$V_{GS} = 0V, V_{DS} = 0V \text{ to } 80V$ ③

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## DATASHEET

### Diode Characteristics

Symbol	Parameter	Min.	Typ.	Max.	Units	Conditions
$I_S$	Continuous Source Current (Body Diode)	—	—	170 ①	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	$T_J = 25^\circ C, I_S = 75A, V_{GS} = 0V$ ③
$t_{rr}$	Reverse Recovery Time	—	50	75	ns	$T_J = 25^\circ C, V_R = 85V, I_F = 75A$
$Q_{rr}$	Reverse Recovery Charge	—	94	140		nC
		—	140	210		
$I_{RRM}$	Reverse Recovery Current	—	3.5	—	A	$T_J = 25^\circ C$
$t_{on}$	Forward Turn-On Time	Intrinsic turn-on time is negligible (turn-on is dominated by LS+LD)				

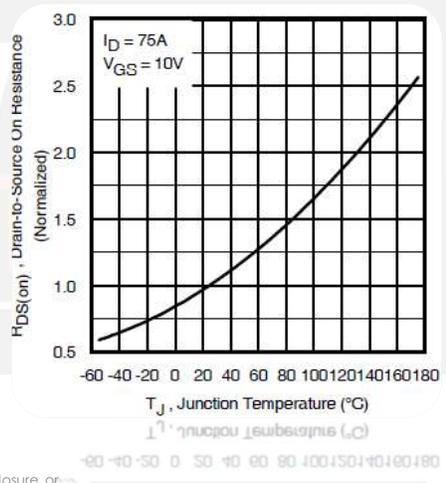
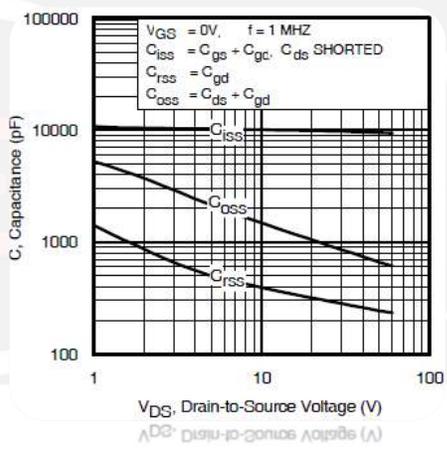
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# DATASHEET



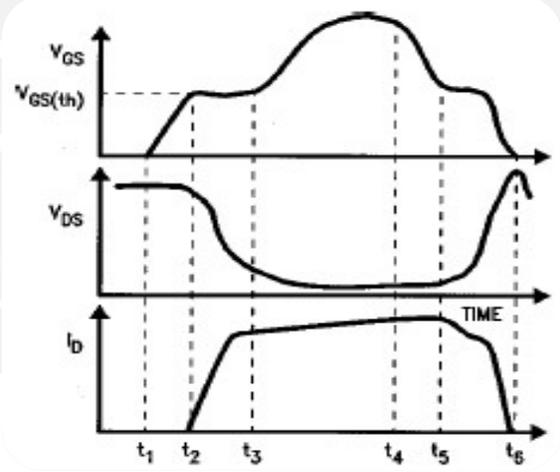
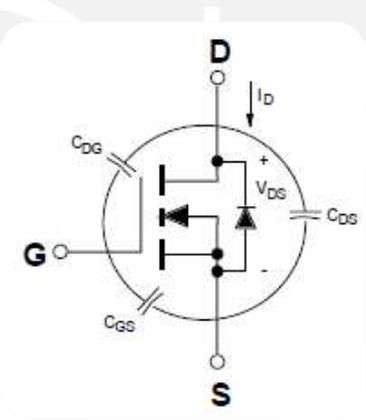
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# MOSFET FUNDAMENTALS



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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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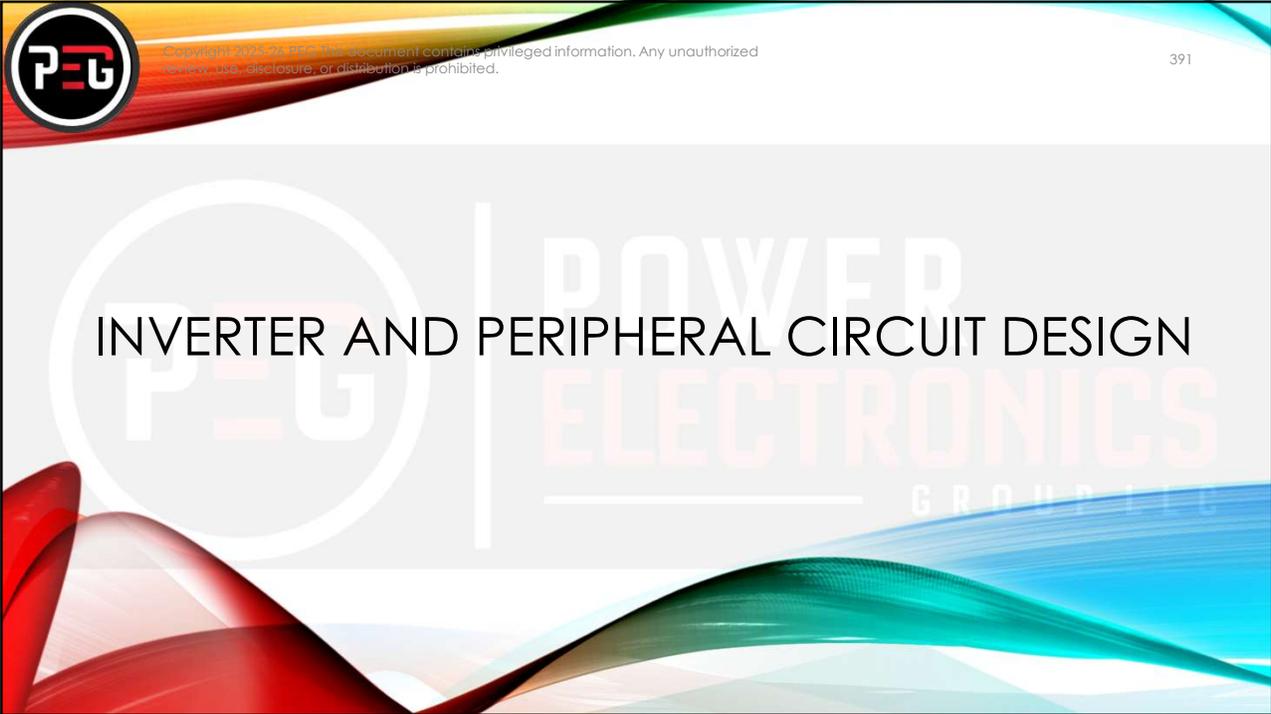
390

## SOLUTIONS

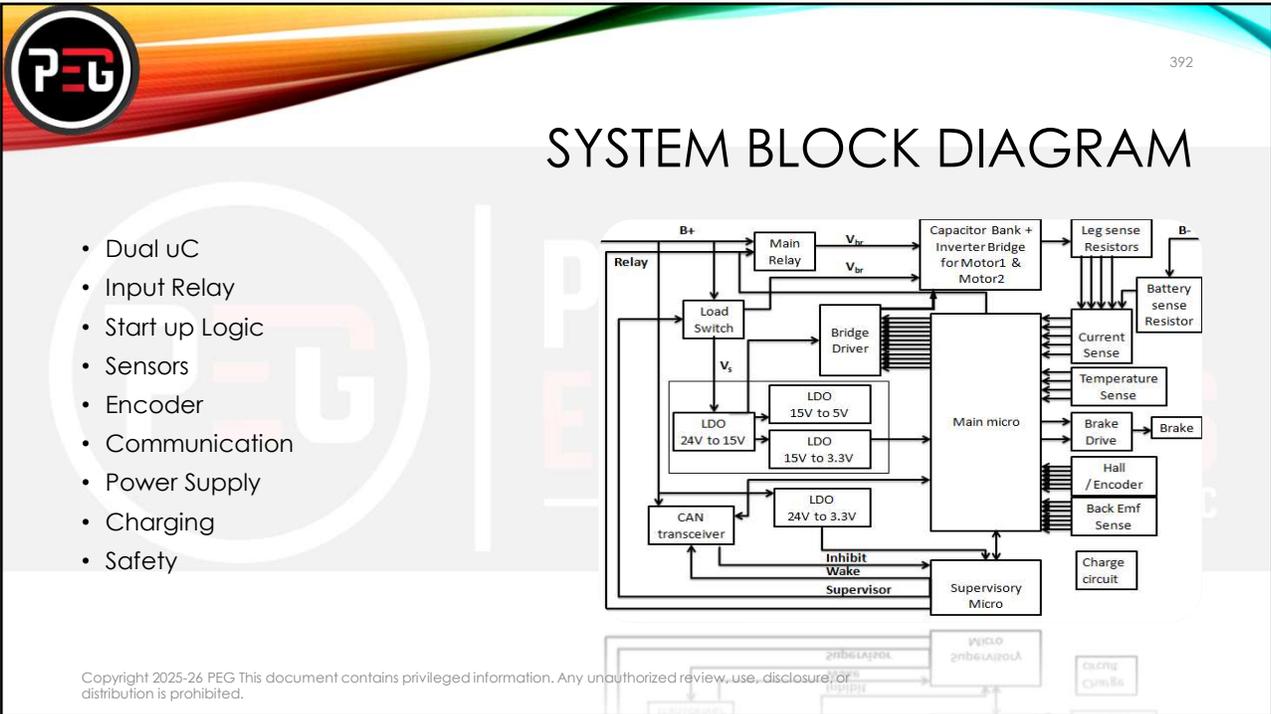
- Increased the top Rg;
- Reduced bottom Rg;
- Provided low impedance path;
- RC-snubber to damp unnecessary turn ON;
- Diodes included to turn OFF faster;

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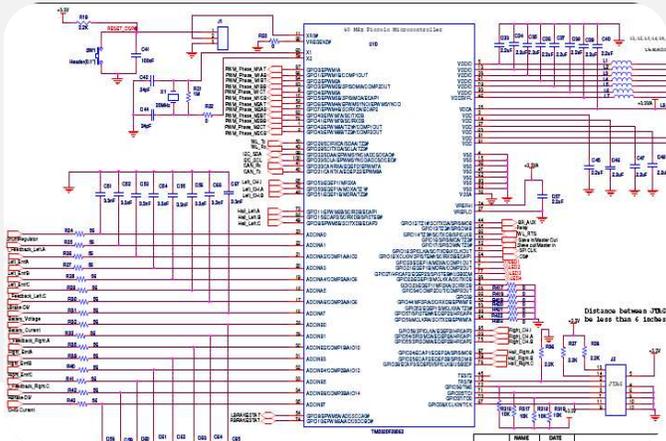




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## MCU WITH PERIPHERALS

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



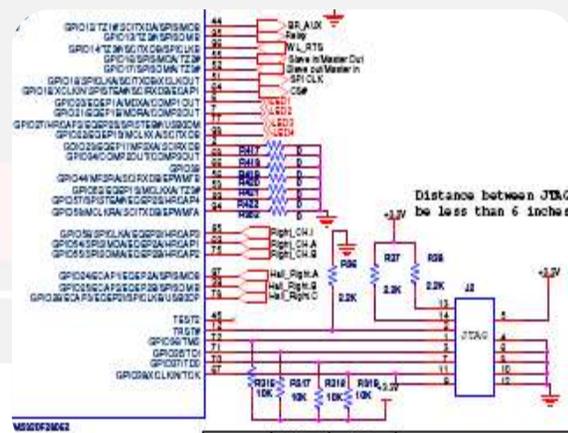
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## MCU WITH PERIPHERALS (DIGITAL I/OS + POSITION SENSING + JTAG)



Distance between JTAG be less than 6 inches.

NAME	DATE

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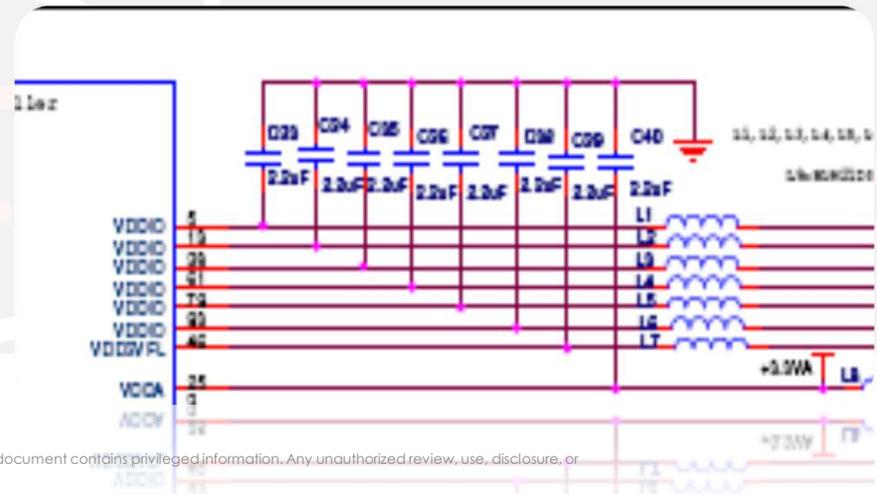
398





401

# MCU WITH PERIPHERALS (FILTERING FOR POWER SUPPLY PINS)



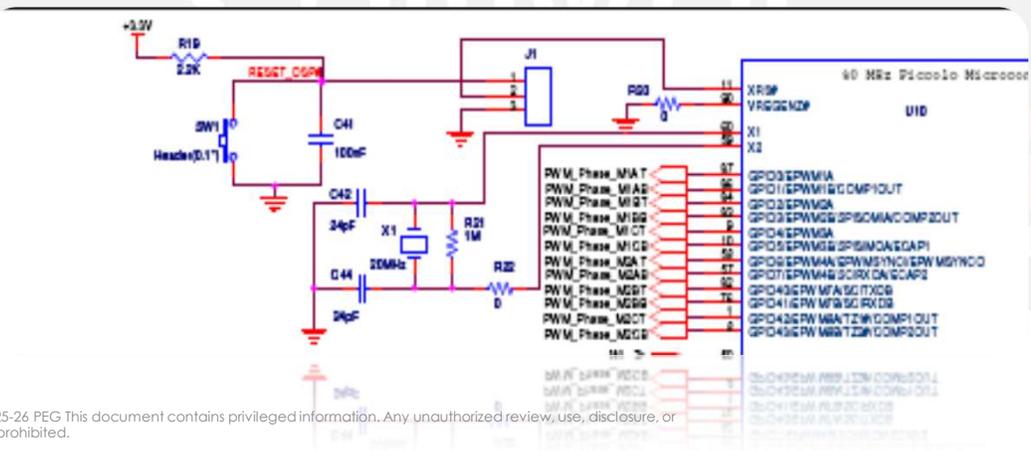
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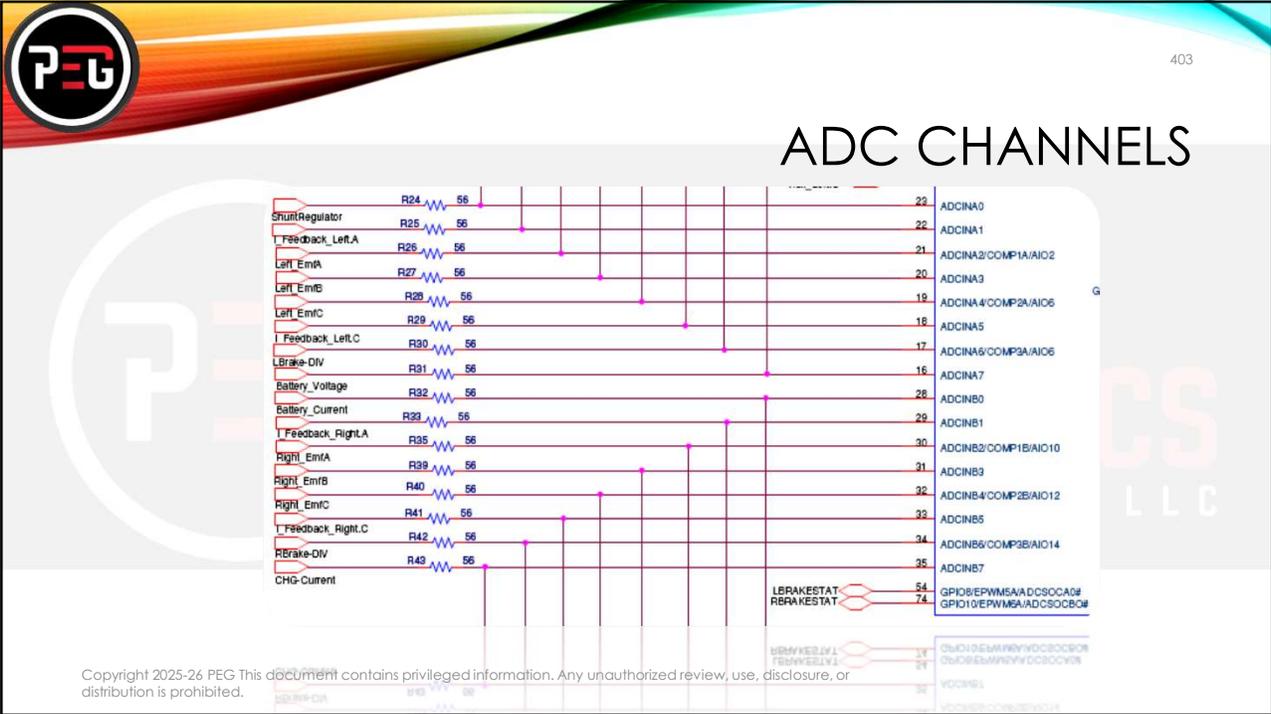
402

# MCU WITH PERIPHERALS (CRYSTAL + PWM CONFIG)



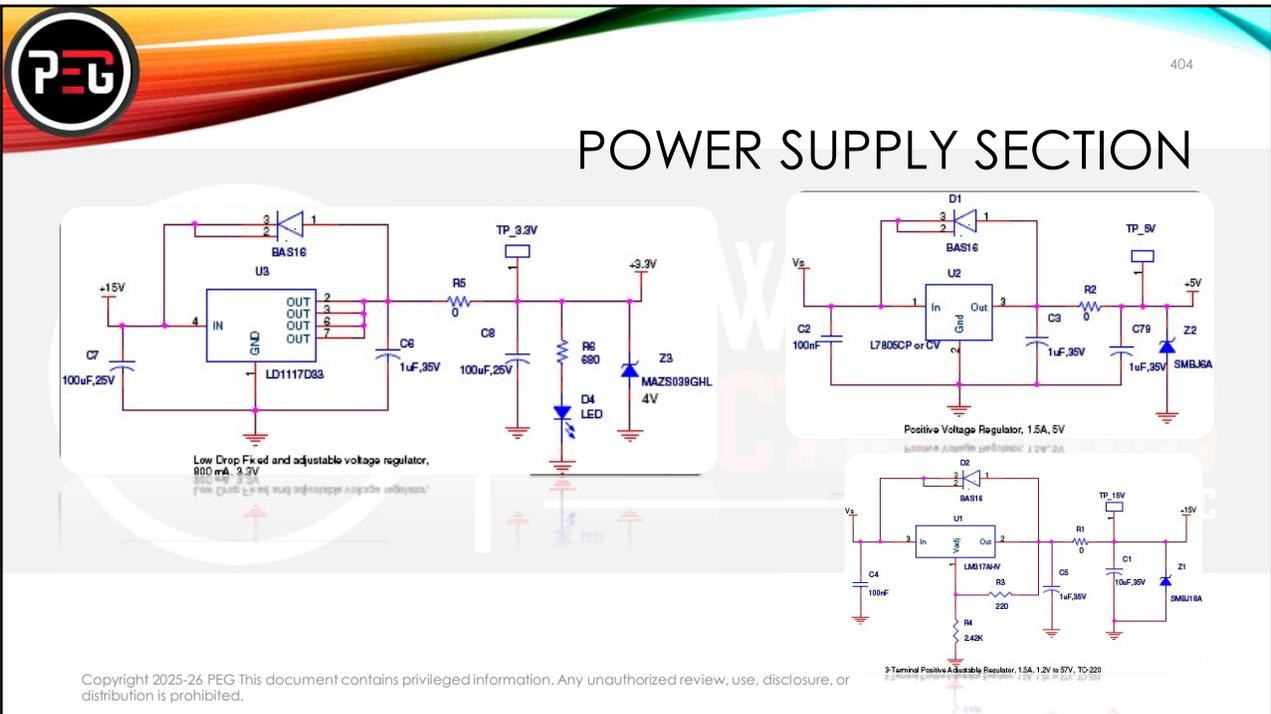
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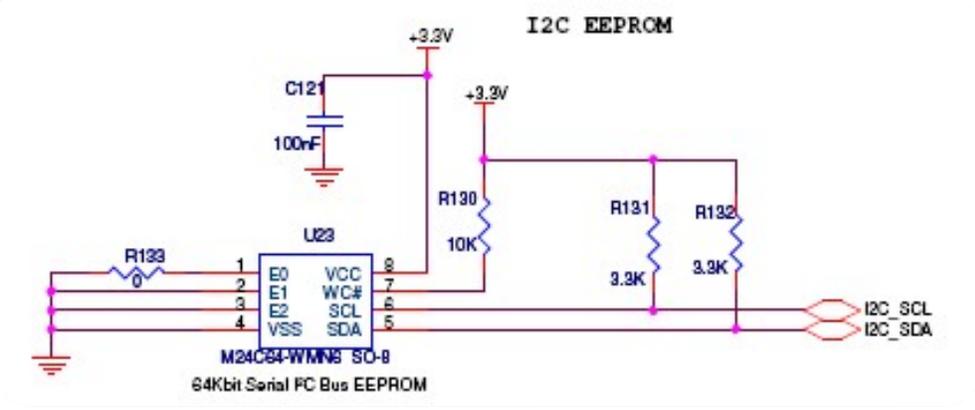


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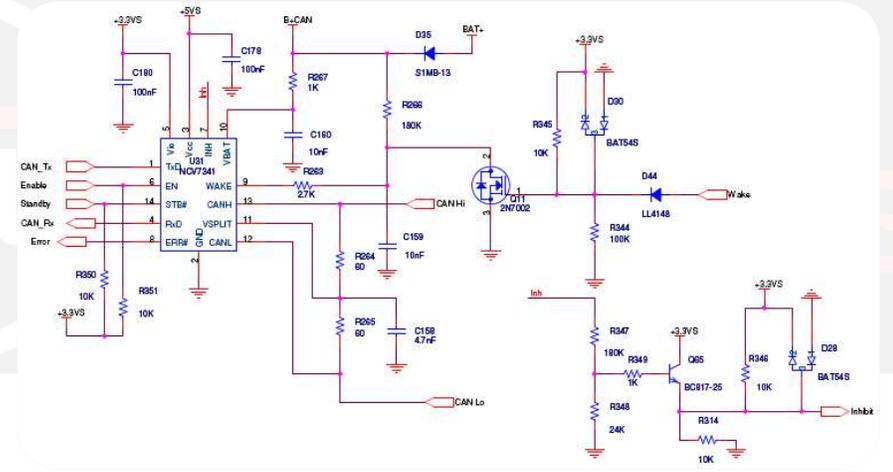
# EEPROM



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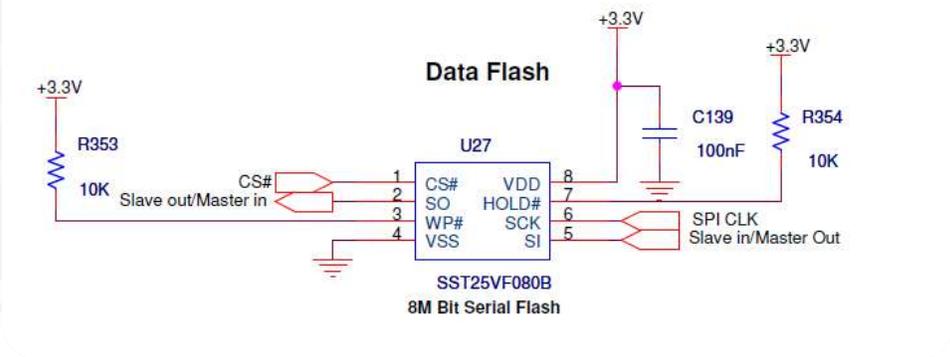
# CAN INTERFACE



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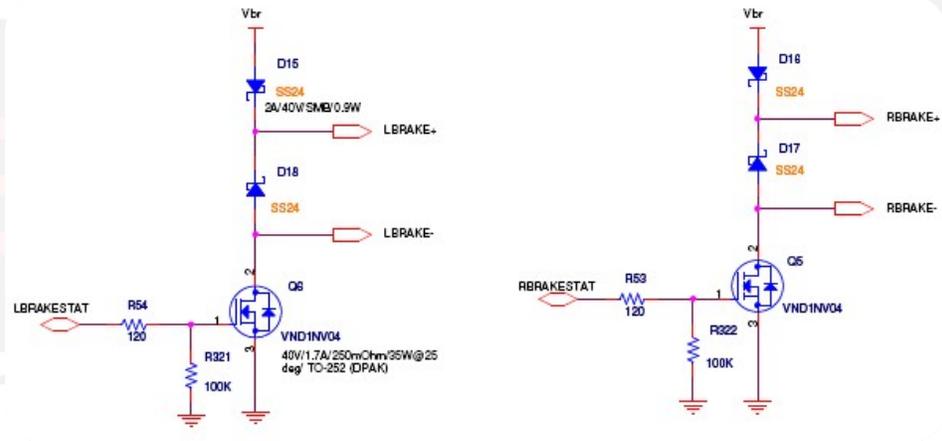
# SPI INTERFACE WITH FLASH



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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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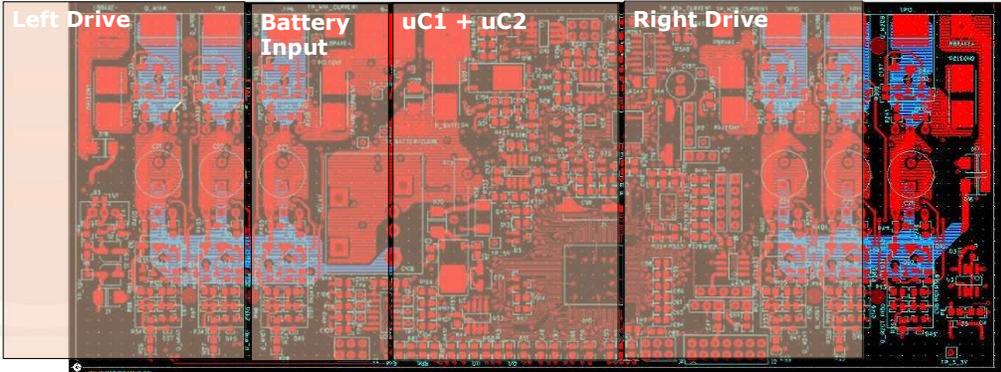
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## SECTIONS



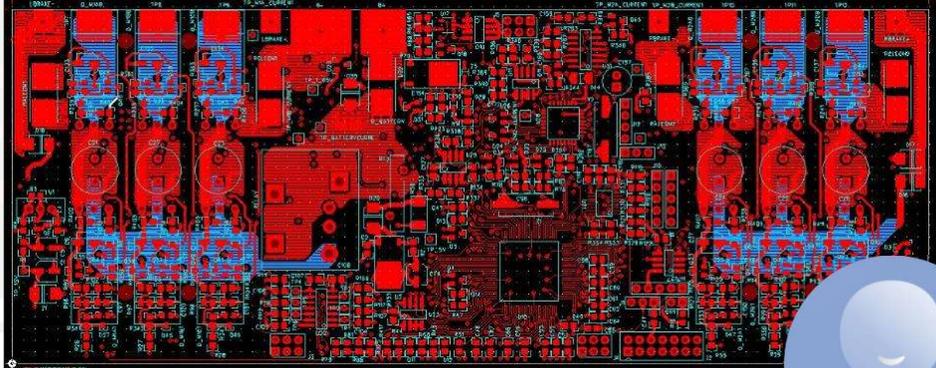
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# IDENTIFYING POWER TRACES (BRIDGE POWER FLOW)



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# CONTINUED.... (BRIDGE POWER FLOW)



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## CONTINUED.... (COPPER PLANE)



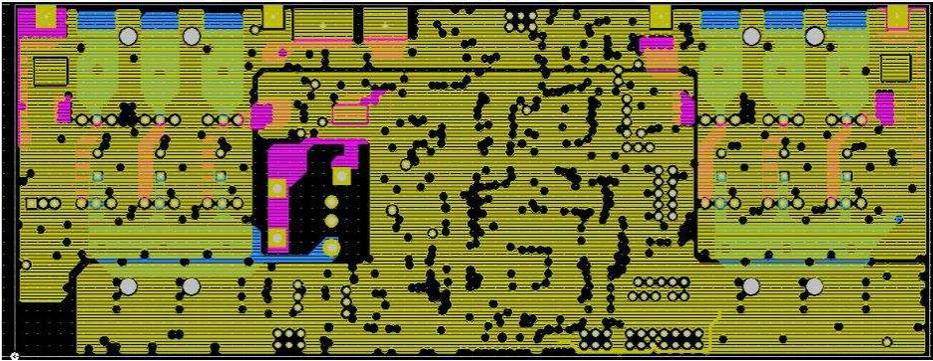

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## CONTINUED.... (SECTIONED POWER PLANES)



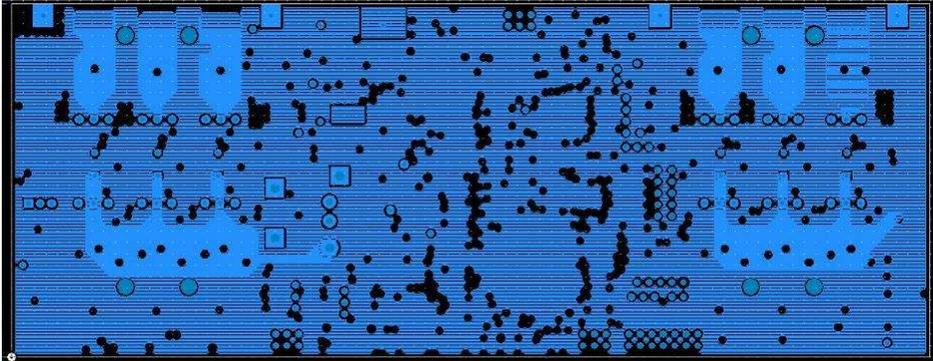
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PEG

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### CONTINUED... (COPPER PLANE)



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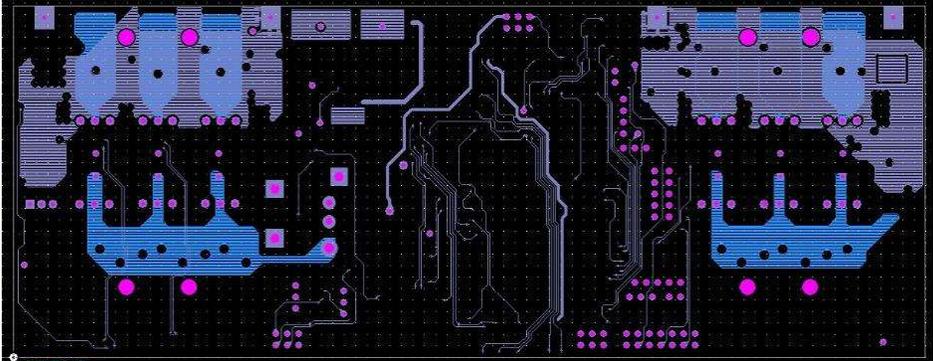
This slide displays a PCB layout for the copper plane. The layout features a black background with blue copper traces and planes. The traces form a complex network of lines and shapes, including several large, irregular shapes that appear to be pads or vias. The layout is centered on the slide, with a large, faint 'PEG' logo in the background.

417

PEG

418

### CONTINUED.... (COPPER POURS)



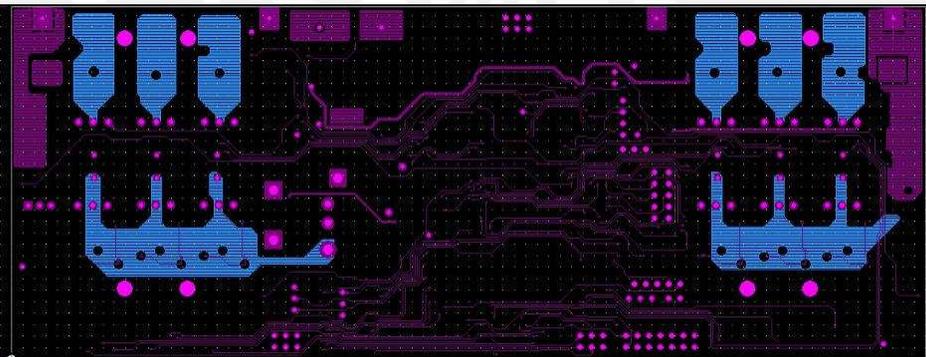
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This slide displays a PCB layout for copper pours. The layout features a black background with blue and pink copper pours. The pours are primarily in the form of large, irregular shapes that fill the space between traces and pads. The layout is centered on the slide, with a large, faint 'PEG' logo in the background.

418

PEG 419

## CONTINUED.... (COPPER POURS)



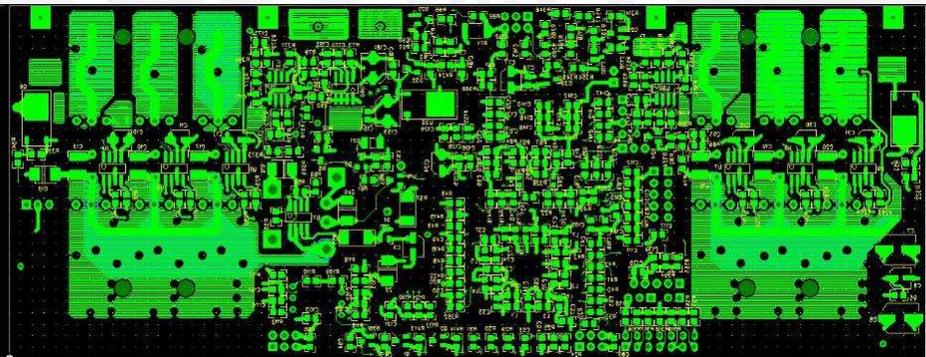
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This slide shows a top-down view of a PCB layout. The copper pour areas are highlighted in blue and purple. The layout includes several large rectangular pours on the left and right sides, and a complex network of traces and smaller pours in the center. The background is black with a grid of small white dots.

419

PEG 420

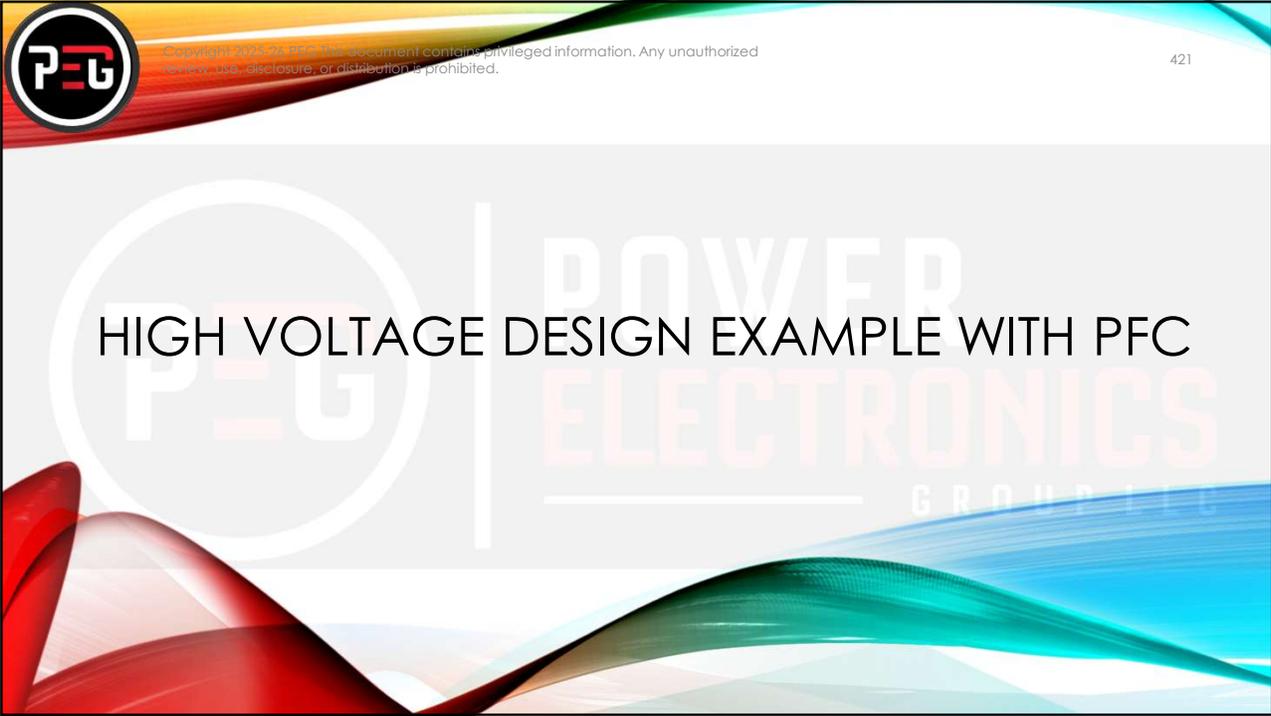
## CONTINUED.... (COPPER POURS)



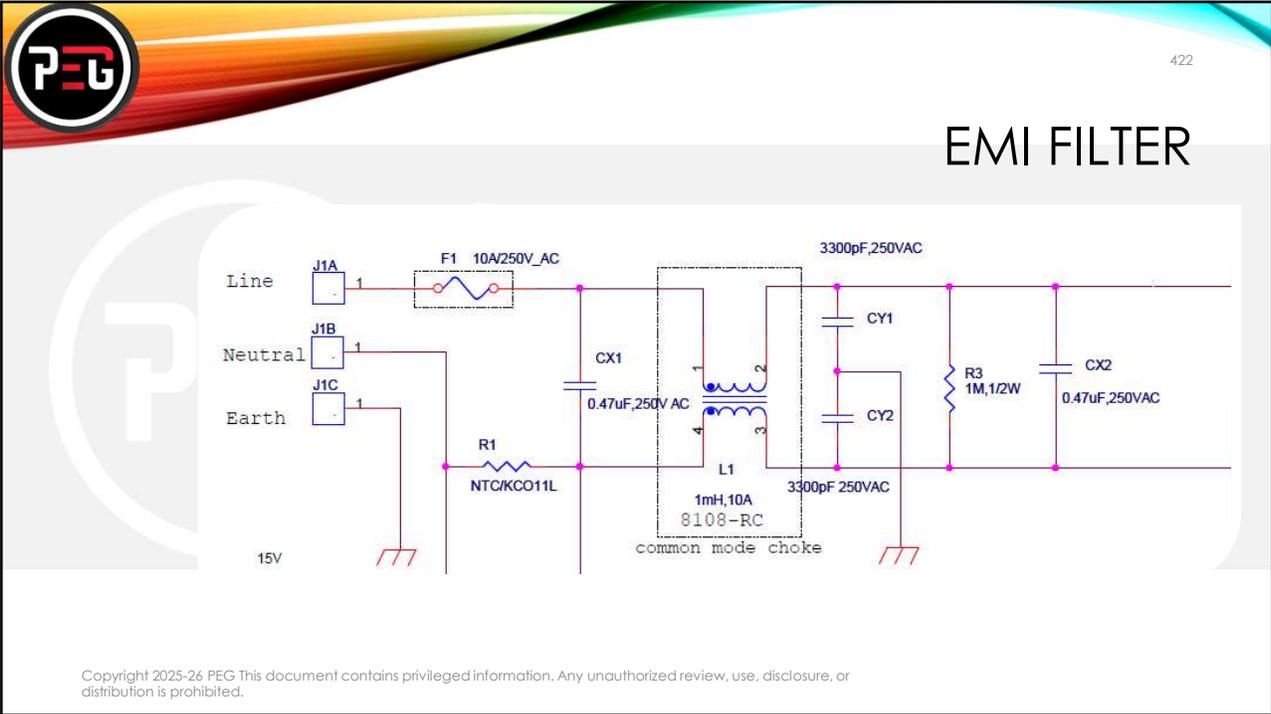
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This slide shows a top-down view of a PCB layout. The copper pour areas are highlighted in green. The layout is more densely packed than the previous slide, with many small components and traces. The copper pours are primarily in the left and right sections, with a central area containing many small components and traces. The background is black with a grid of small white dots.

420



421

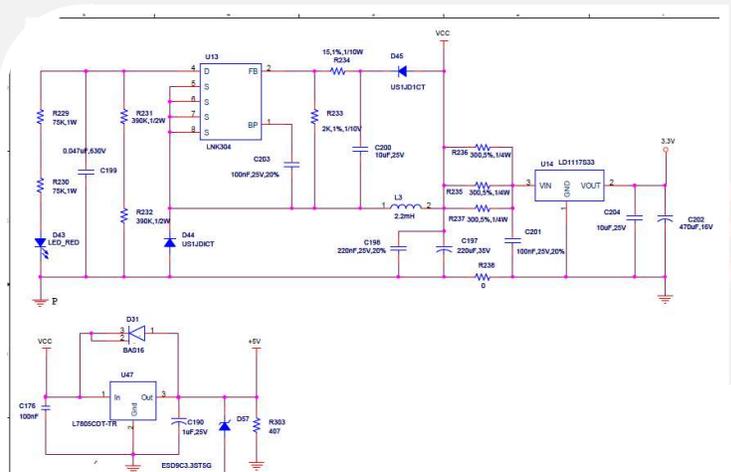


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423

# CONTROL POWER SUPPLY



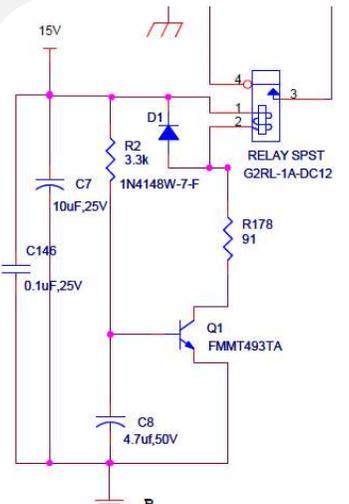
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# SLOW CHARGE CUT OFF



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## BRIDGE RECTIFIER

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## PFC CURRENT

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**AC VOLTAGE**

The diagram shows an AC voltage measurement circuit. It features two input channels, each starting with a 1.00M resistor (R193 and R195). The top channel includes a 1.00M resistor (R194) and a 4.87K, 1% resistor (R28). The bottom channel includes a 1.00M resistor (R196) and a 4.87K, 1% resistor (R27). Both channels are connected to a central node that branches into three output paths: VAC+ (OP1+), VAC- (OP1-), and VACO (OP1O). The circuit also includes several capacitors: C207 and C208 (4700pF, 50V, 10%), C240 (1000pF, 50V), and C243 (1000pF, 50V). A 4.87K, 1% resistor (R15) is connected to the VAC+ line. The circuit is powered by a source 'A'.

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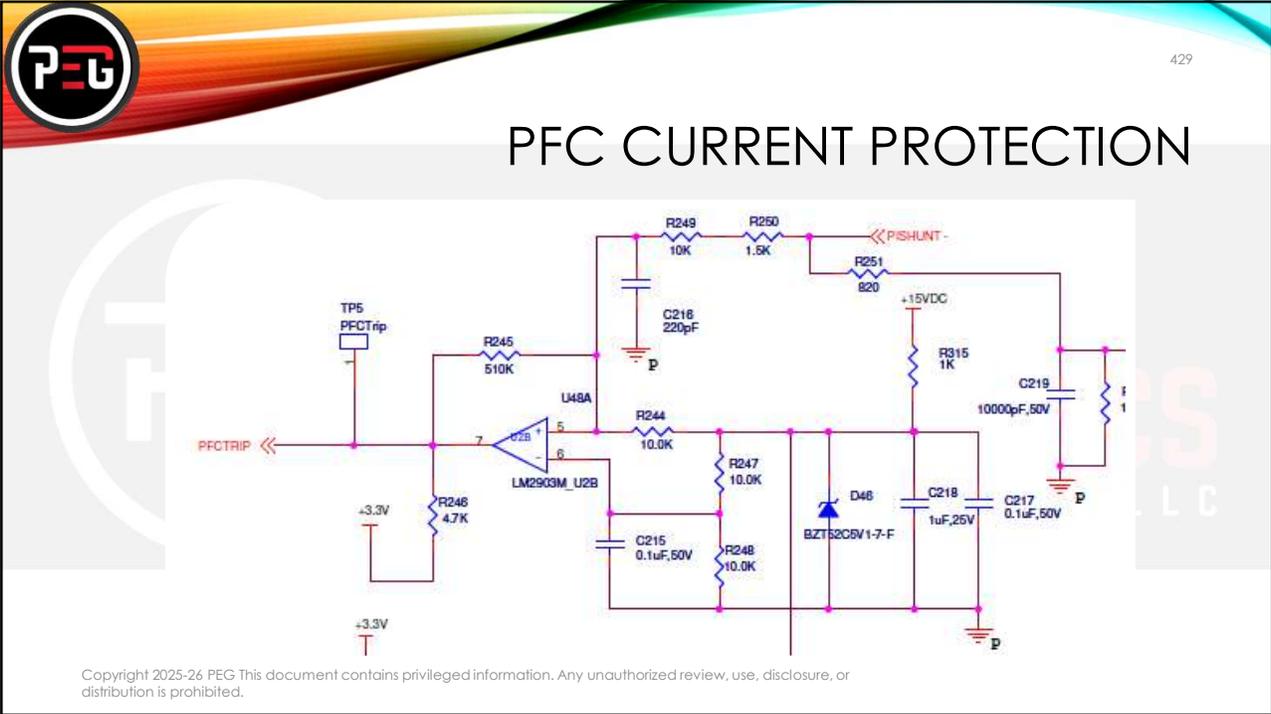
427

**PHASE CURRENT**

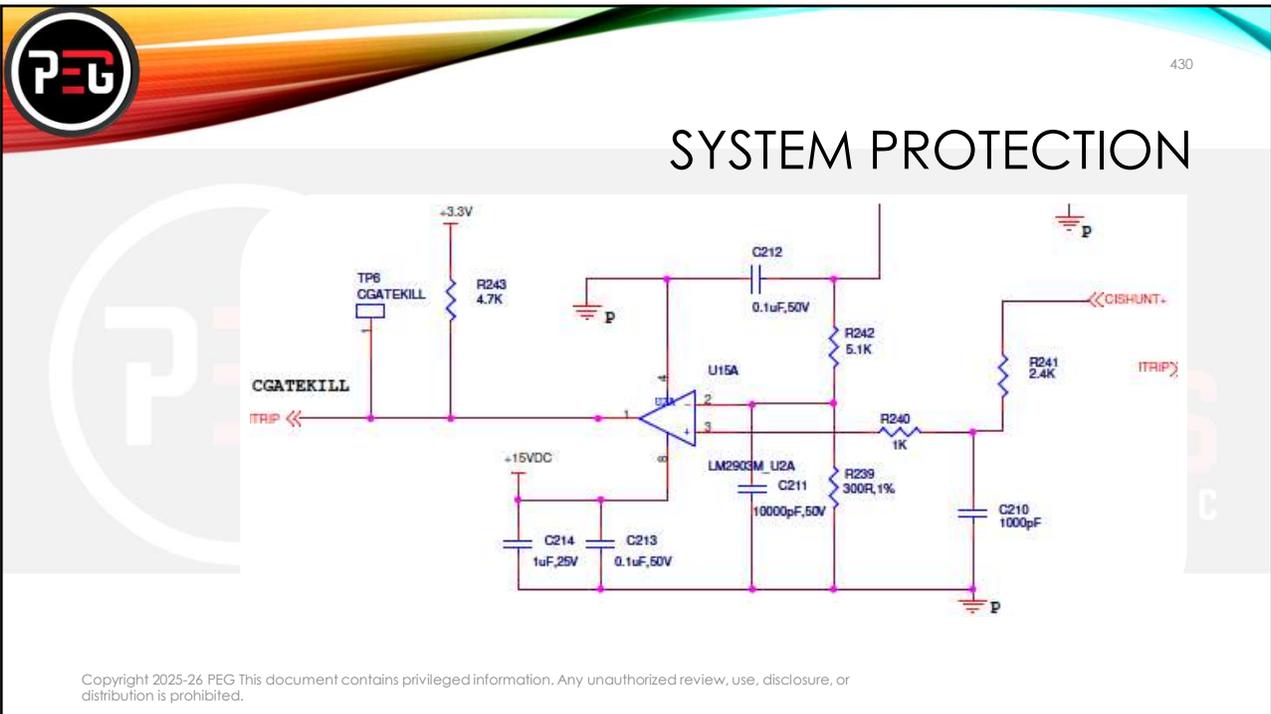
The diagram shows a phase current measurement circuit. It features two input channels: PGND and CISHUNT+. The PGND channel includes a 1.00K resistor (R254) and a 5.11K, 1% resistor (R256). The CISHUNT+ channel includes a 1.00K resistor (R255) and a 5.11K, 1% resistor (R257). Both channels are connected to a central node that branches into three output paths: IFBC+ (OP2+), IFBC- (OP2-), and IFBCO (OP2O). The circuit also includes several capacitors: C222 (47pF), C224 (33pF), and C258 (16.2K, 1%). A 16.2K, 1% resistor (R258) is connected to the IFBC+ line. The circuit is powered by a source 'G' with a value of 2.65.

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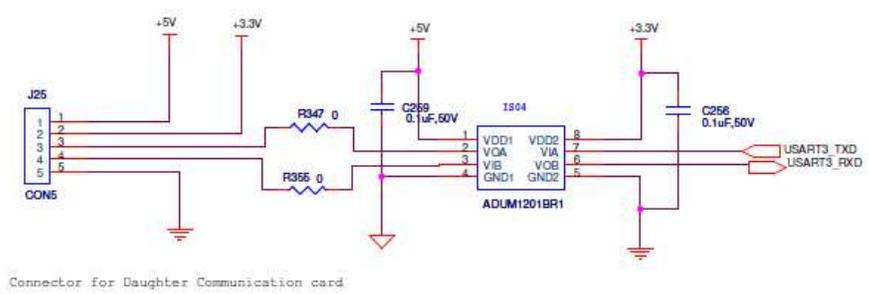


430



431

# DIGITAL ISOLATION



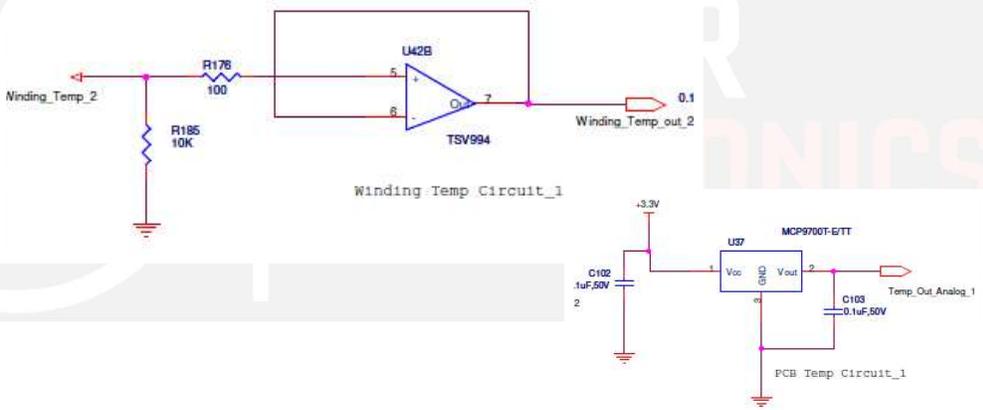
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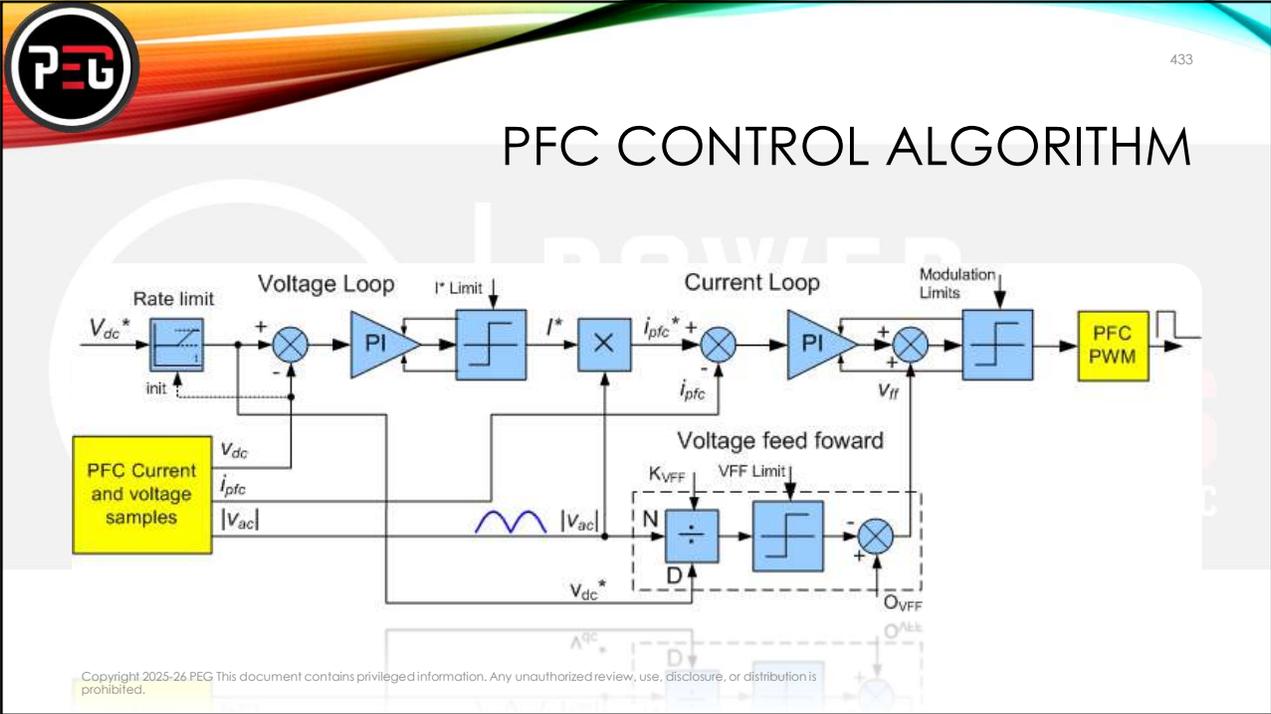
432

# TEMPERATURE

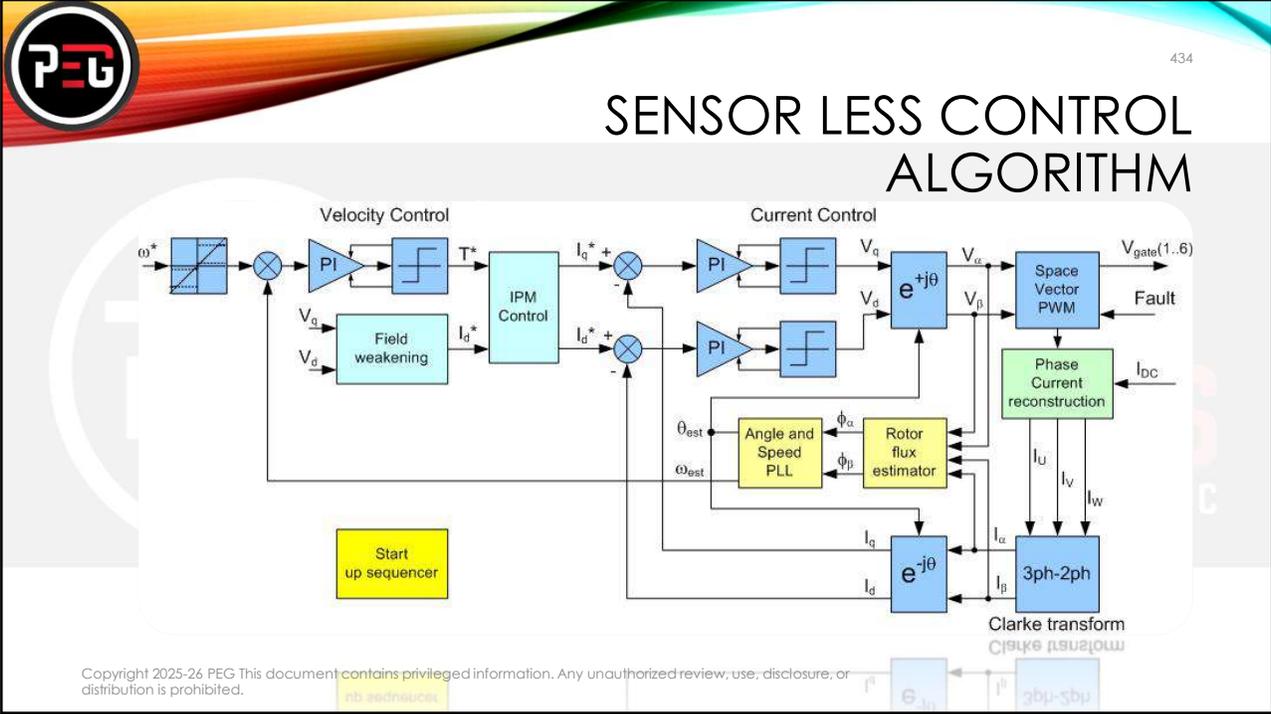


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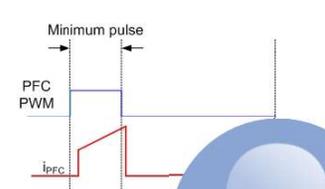
434



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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;



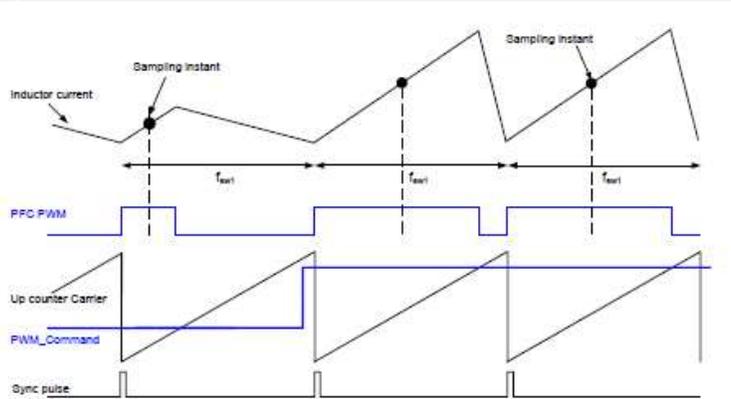
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## PFC SWITCHING CHARACTERISTICS



Note : Sync is interrupt generated

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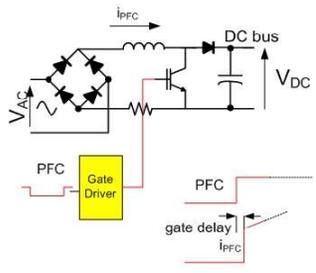
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## PFC GATING PROPAGATION DELAY

- 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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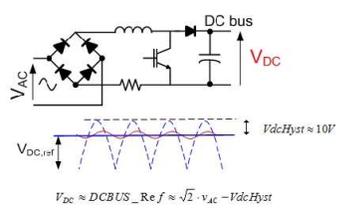
437



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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;



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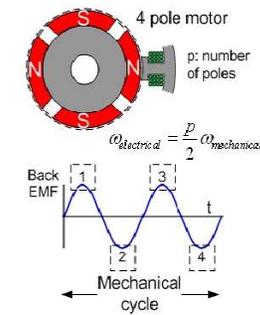
438


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## 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

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



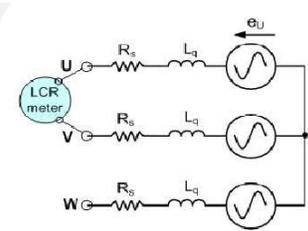
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## MOTOR STATOR RESISTANCE

- 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;

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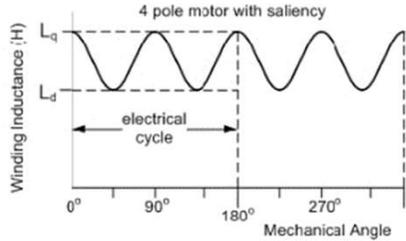


442

## MOTOR LD INDUCTANCE

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

4 pole motor with saliency



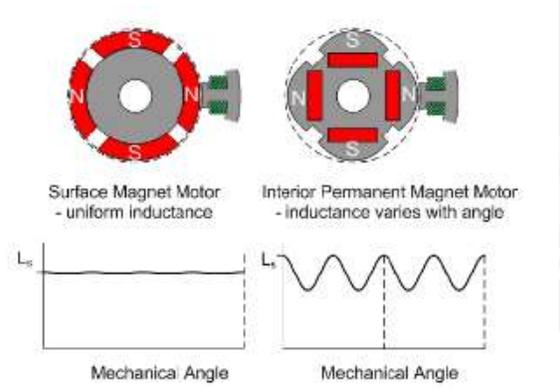
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# MOTOR LQ INDUCTANCE

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



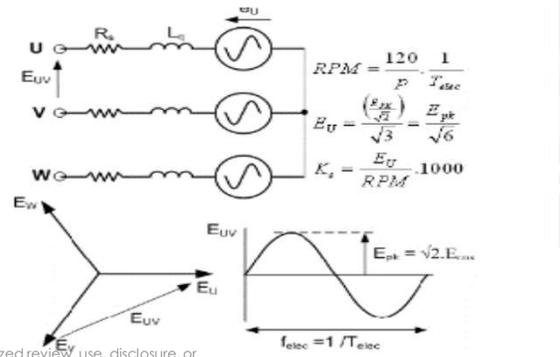
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# MOTOR BEMF CONSTANT KE

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

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



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## MOTOR TORQUE CONSTANT K<sub>T</sub>

- K<sub>t</sub> is current dependent parameter;
- Measured in Nm per amps rms of line current;
- If L<sub>d</sub> = = L<sub>q</sub>;

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

$T\omega = i_u e_u + i_v e_v + i_w e_w$

$\therefore$

$K_e = \frac{\text{volts}}{1000 \text{ RPM}} = \frac{\text{volts}}{\frac{100\pi}{3} \text{ rad s}^{-1}}$

$K_T = 3 \frac{\text{volts}}{\text{rad s}^{-1}} = \frac{9}{100\pi} K_e \cdot \text{Nm A}^{-1}$

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## MOTORS TOTAL SHAFT INERTIA

- Used for start acceleration and speed regulation;
- Expressed in Kg-m<sup>2</sup>;

Ring  
 $J = Mr^2$

Solid Cylinder  
 $J = \frac{1}{2} Mr^2$

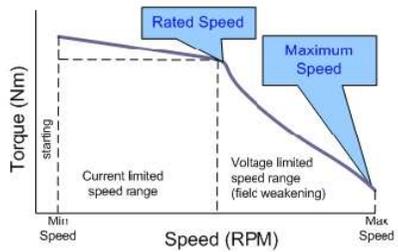
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# MOTOR MAX RPM;

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

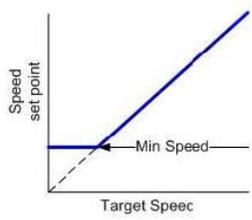


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# MINIMUM RUNNING SPEED

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

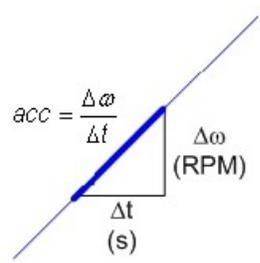


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# ACCELERATION RATE

- 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

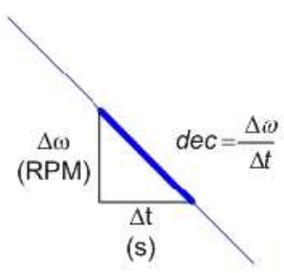


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# DECELERATION RATE

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



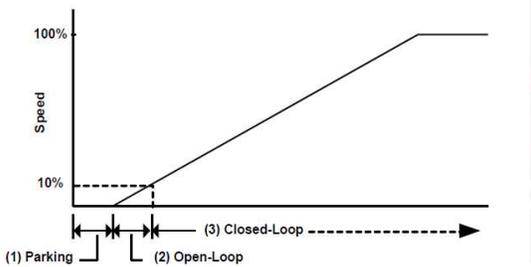
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## DRIVE START UP PROCESS

- Parking;
- Open loop speed & B<sub>emf</sub> 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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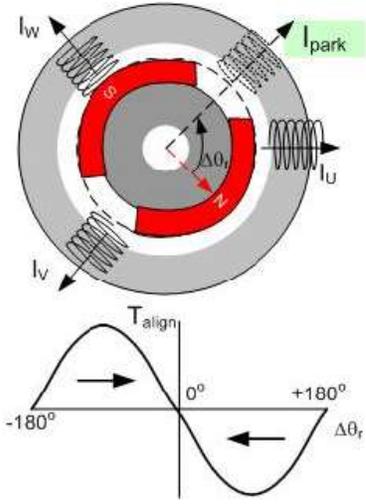
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## PARKING CONFIGURATION

Maximizes the torque at the start;  
 Parking current =  $0.25 \cdot I_{rated}$ ;



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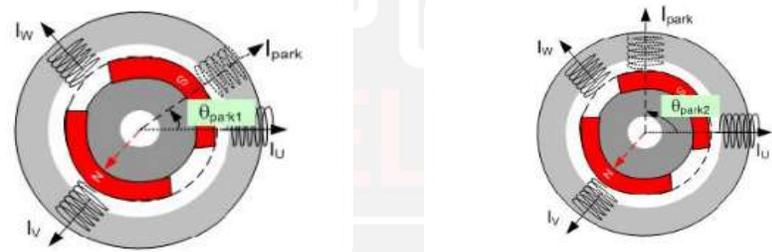
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## FIRST STAGE OF PARKING

- 2 angles are used to complete the parking process



First angle parking =  $120^\circ$

Second angle parking =  $90^\circ$

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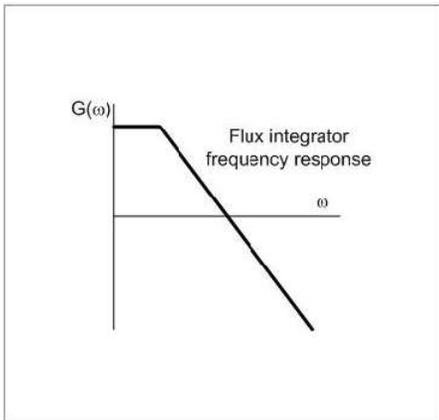
454



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## FLUX ESTIMATOR TIME CONSTANT

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



Flux integrator frequency response

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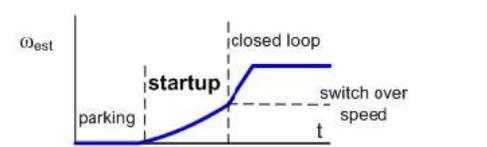
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456

## 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;



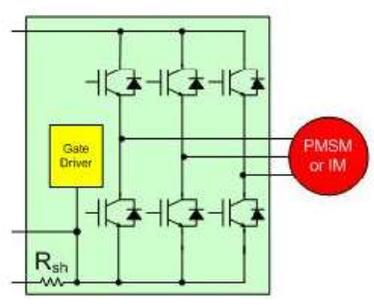
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# CURRENT FEED BACK SENSE

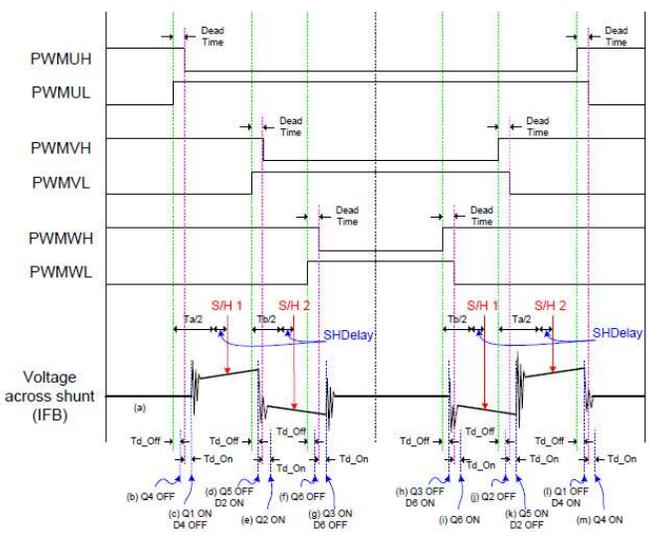
- Specify the value of the DC link current sense;
- Discrete component integrated into power module;



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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;

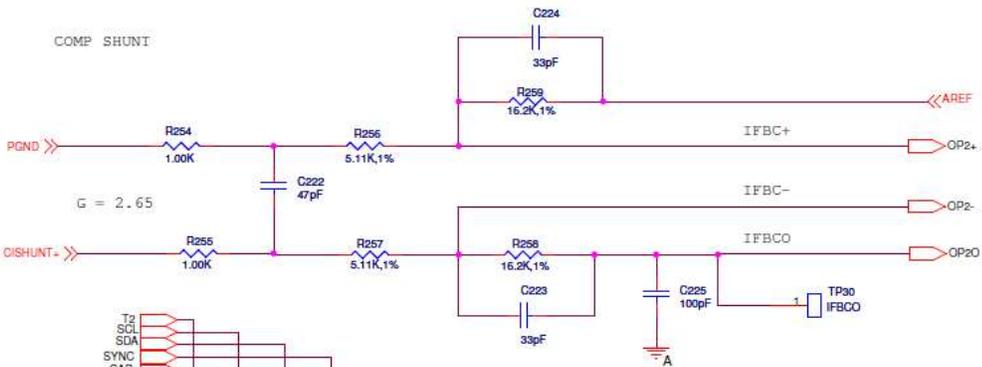
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## CALCULATION GAIN FOR MOTOR CURRENT F/B

- Motor current amplifier current feedback amplifier gain =  $\frac{162k}{1.00k + 5.1k} = 2.65$



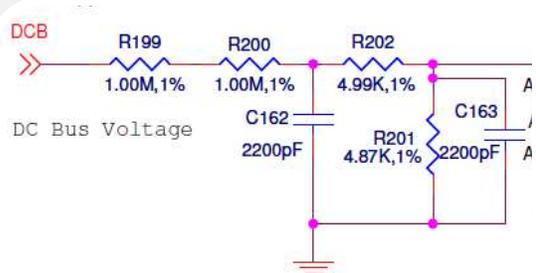
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## DC BUS FEEDBACK SCALING

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

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


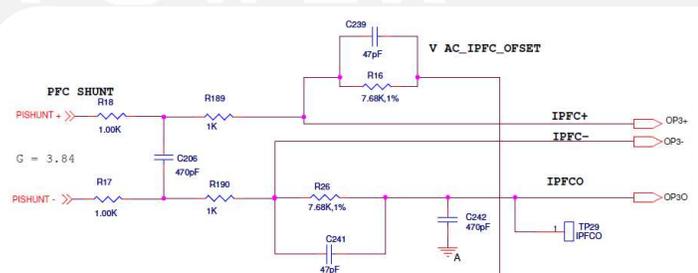
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## PFC CURRENT FEEDBACK AMPLIFIER GAIN

- Amplifier gain is determined from resistor network;
- Gain =  $\frac{3.847.68k}{1.00k + 1k}$



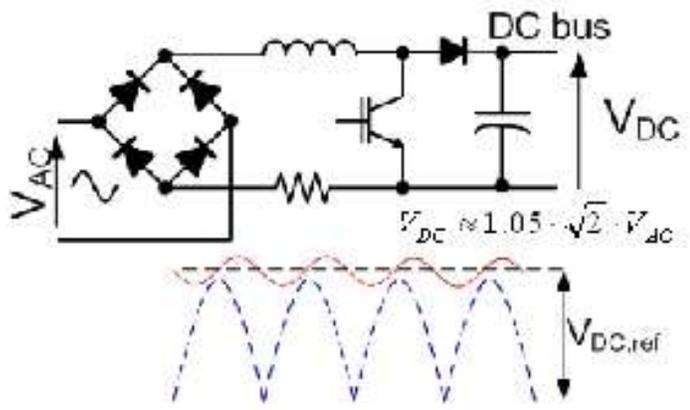
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### DC BUS VOLTAGE REFERENCE

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;

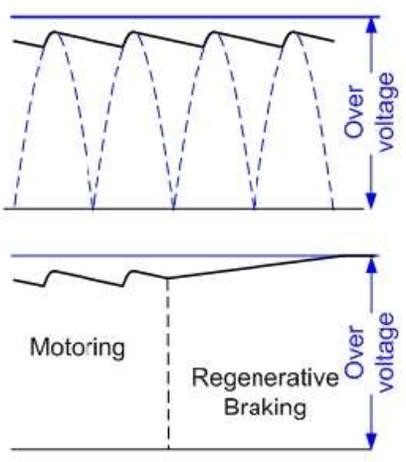


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### DC BUS OVER VOLTAGE LEVEL

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;

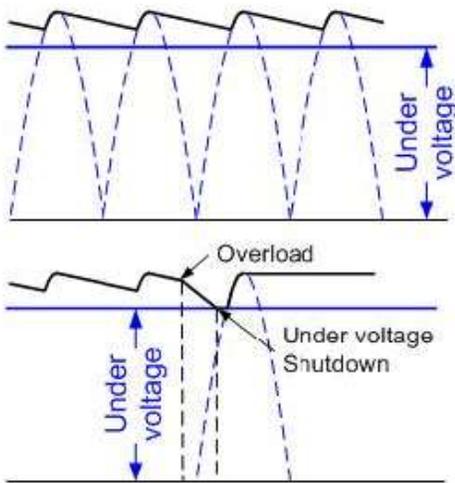


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### DC BUS UNDER VOLTAGE LEVEL

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;

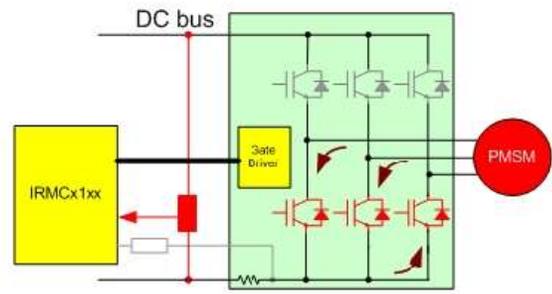


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### DC BUS CRITICAL VOLTAGE LEVEL

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;

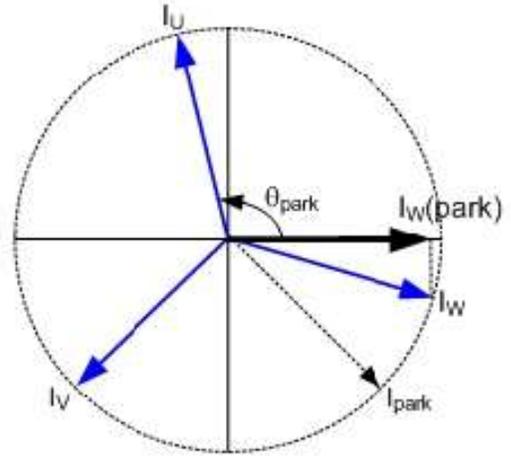


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### MOTOR PHASE LOSS DETECTION

Phase fault is detected during parking process;  
 If missing vector is identified, it generates fault;  
 Phase connection's fault is recorded;

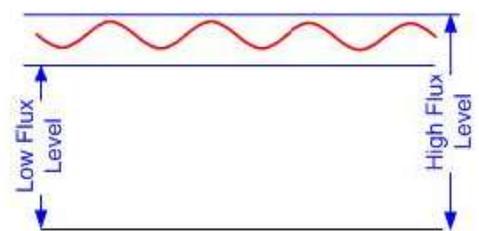


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### ENABLE START FAIL FAULT

- 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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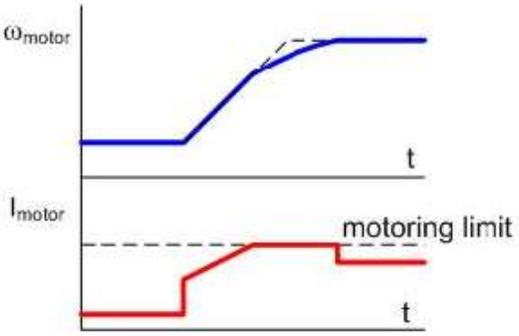
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## MOTOR CURRENT LIMIT

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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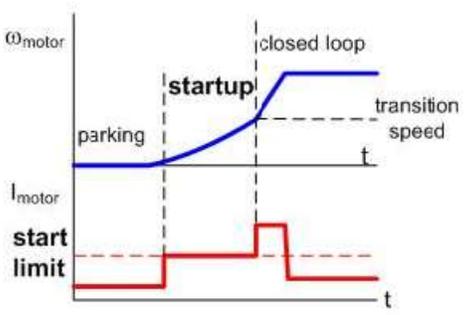
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## STARTING CURRENT LIMIT

- 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;



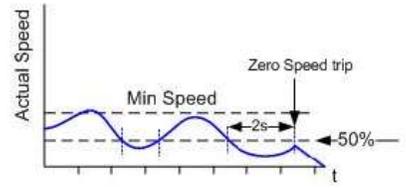
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# ZERO SPEED DETECTION

- 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
MtrCtr1Bits 80
MtrCtr1Bits_s 0
SysClk 800
PwmDeadTm 80
PwmPeriodConfig 6666
Pwm2HiThr 72
Pwm2LowThr 51
PwmGuardBand 0
ActivePol 32
TwoPhsctr1 0
GCChargePw 240
GCChargePd 40
GCChargeT 100
MotorLim 4095
RegenLim 0
StartLim 1229
KpIreg 4597
KpIregD 4597
KxIreg 8056
VdLim 722
VqLim 1324
VdCompScale 69
KpSreg 42
KxSreg 80
SpdSc1 768
SpdFltBW 195
SpdScale 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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**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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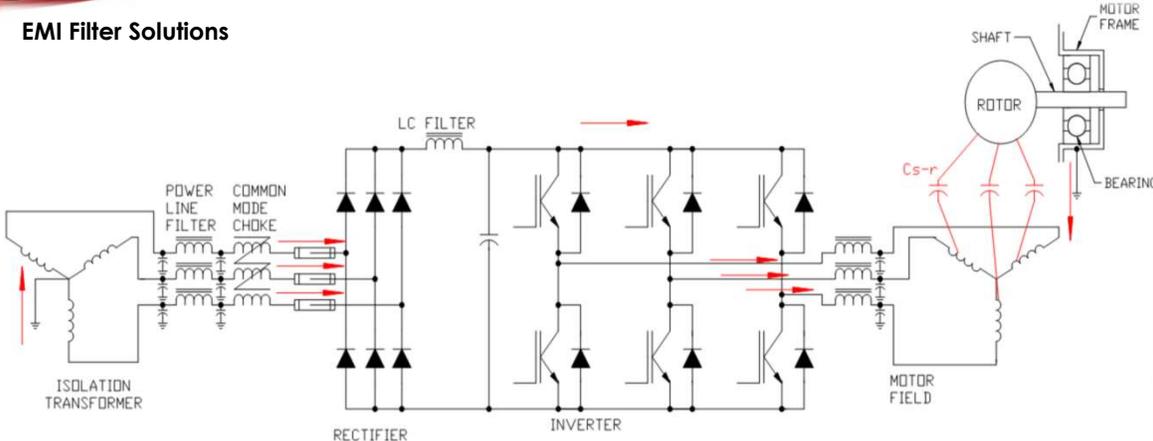
**EMI & EMC PROBLEMS**

Cabling between drivers and motors;

Long Cables;

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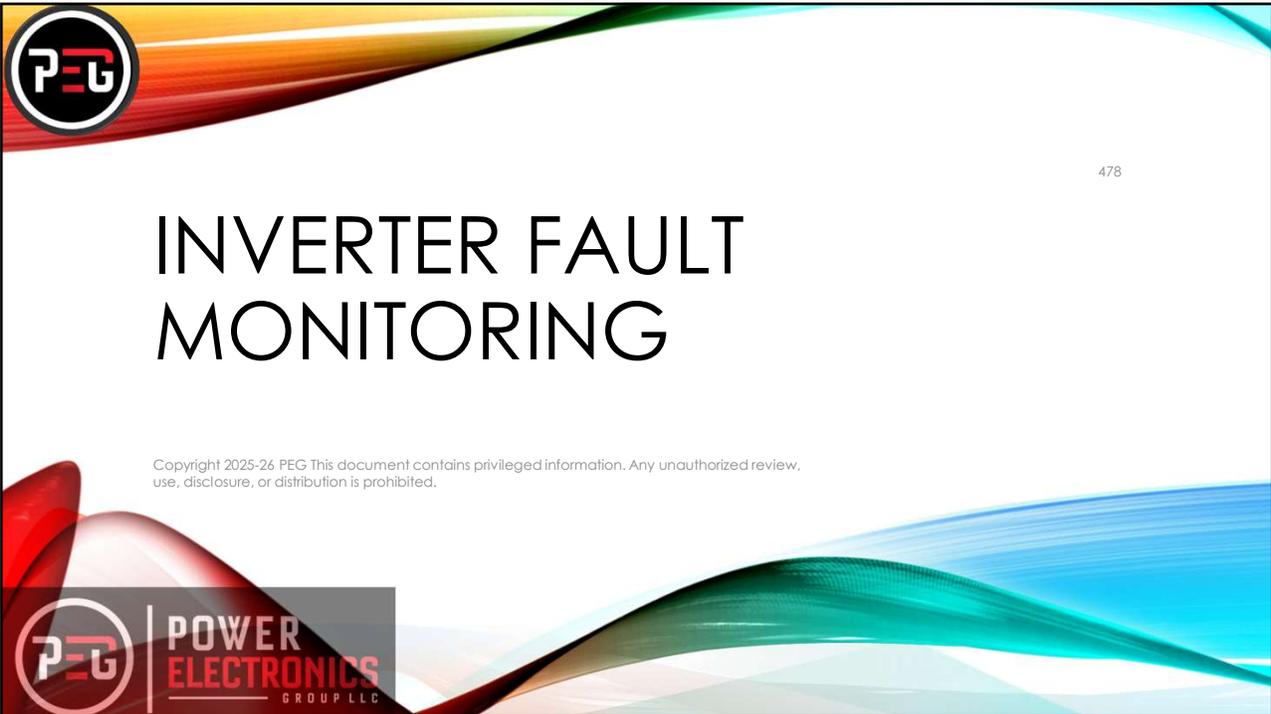
The diagram illustrates an EMI filter solution for a motor drive system. It starts with an ISOLATION TRANSFORMER, followed by a POWER LINE FILTER and a COMMON MODE CHOKE. The circuit then passes through an LC FILTER before entering a RECTIFIER stage. The output of the rectifier goes to an INVERTER stage, which drives the MOTOR FIELD. A cross-sectional view of the motor is shown on the right, highlighting the ROTOR, SHAFT, MOTOR FRAME, and BEARING. Red arrows indicate the flow of current and the placement of capacitors (Cs-r) for common mode filtering.

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**EMI Filter Solutions**

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The slide features a large title 'INVERTER FAULT MONITORING' in the center. At the bottom left, there is a logo for POWER ELECTRONICS GROUP LLC. The background has a colorful, wavy design.

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# INVERTER FAULT MONITORING

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# COGGING TORQUE SOLUTIONS

## TIMING TECHNIQUE

- Dead Zone
- Tooth notching

## SMOOTHING TECHNIQUE

- Sinusoidal magnetization

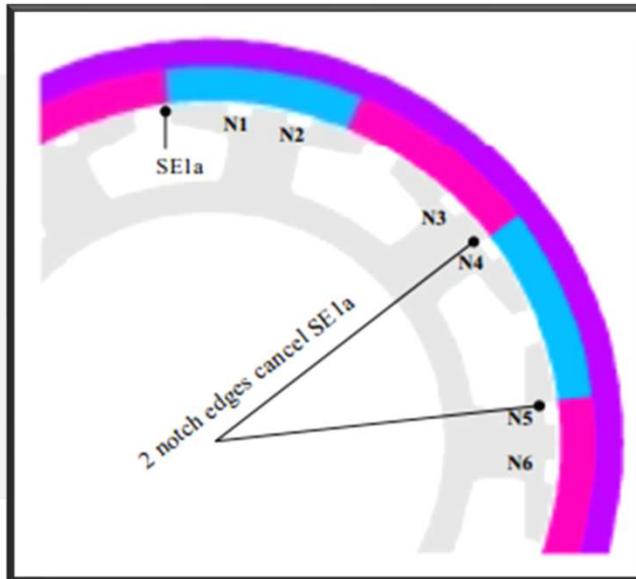
## GEOMETRIC TECHNIQUE

- Tooth crowning
- Slot skewing

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# COGGING REDUCTION BY NOTCHES



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 Torque  
Ripple

Causes  
Solutions

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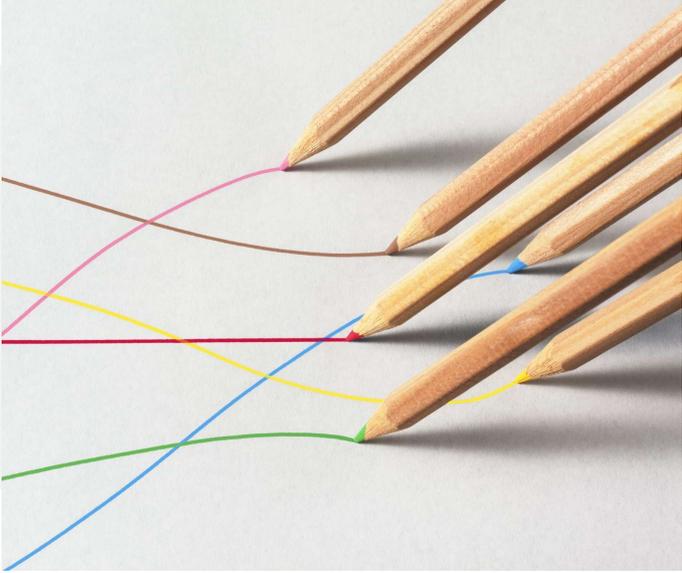
481

482

**PEG**

**IMPROVED MOTOR DESIGN TECHNIQUES**

- Skewing;
- Fractional slot winding;
- Short pitch winding;
- Increased number of phases;
- Air-gap windings;



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## 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);

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## CONTROL SYSTEM FAULTS/DIAGNOSIS



Short circuit conditions at motor terminals;

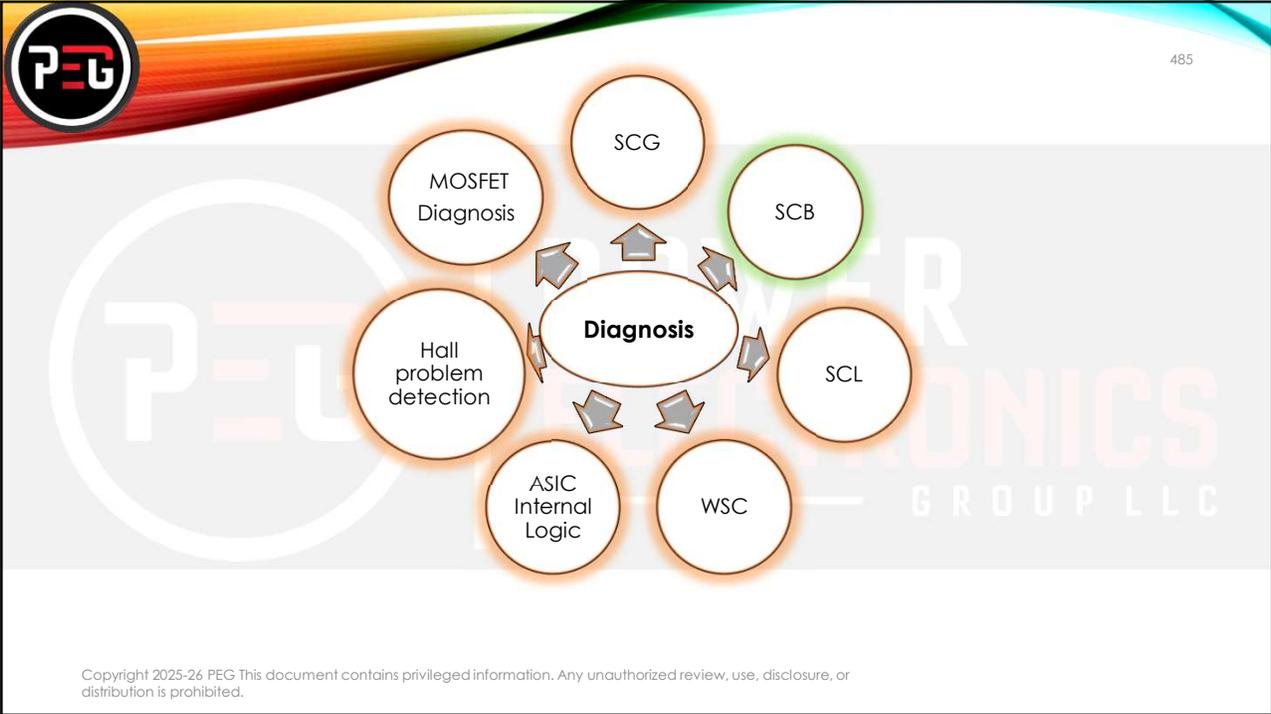


Internal, external power supply voltages and over-temperature failure Conditions;

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BLDC MOTOR  
DIAGNOSIS  
CONCEPTS

ONSM (ON State Monitoring)

OFSM (OFF State Monitoring)

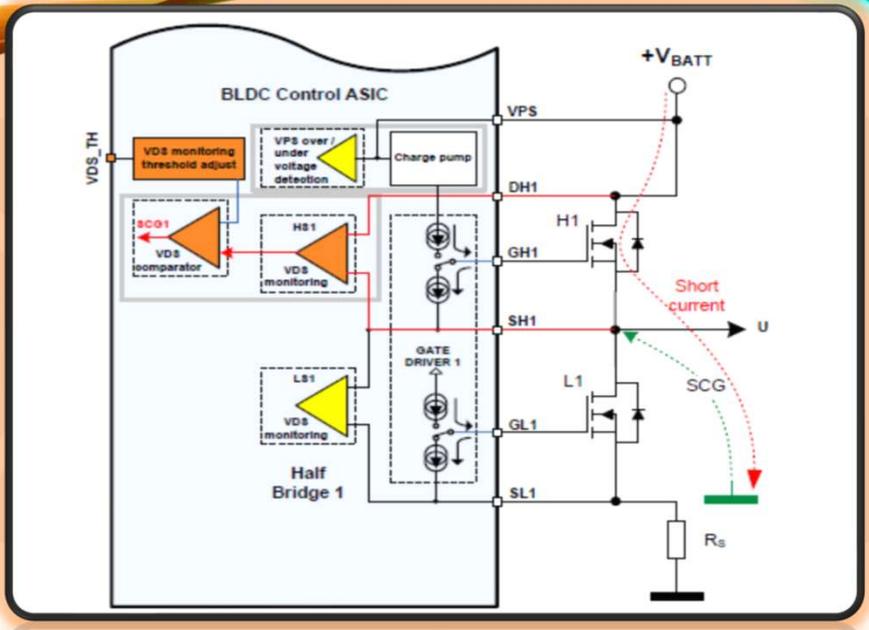
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# SCG

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

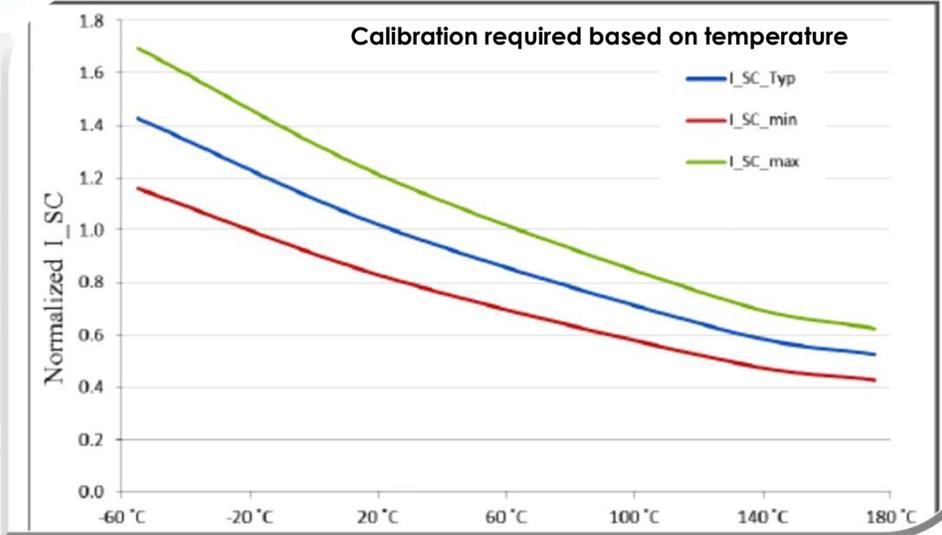


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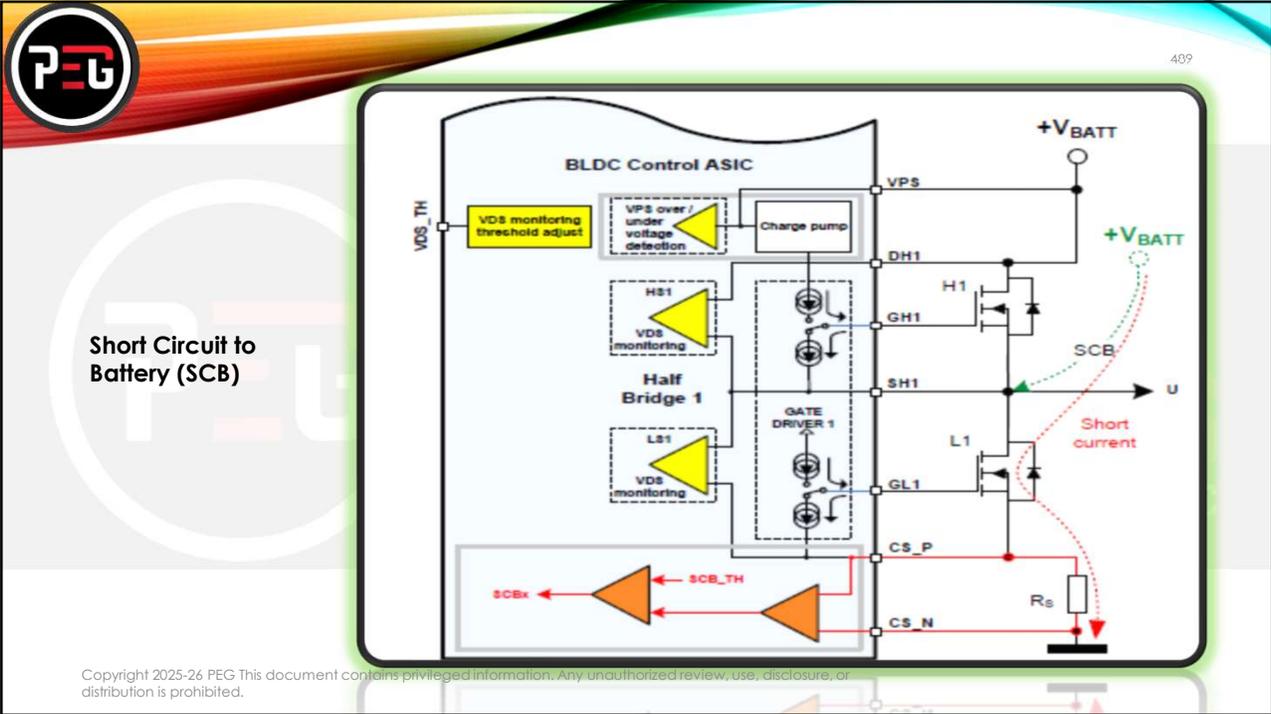


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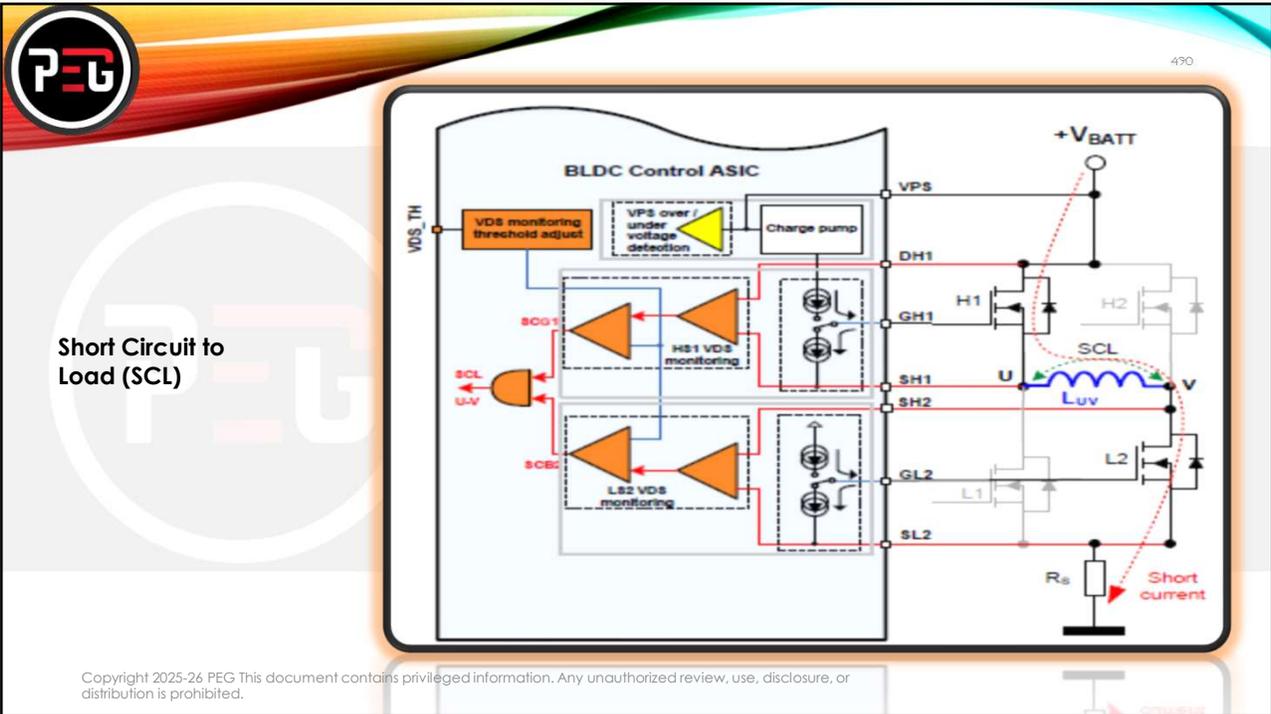


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$$I_{WSC} \geq \frac{W_{SC\_TH}}{R_s}$$

**Weak Short Circuit (WSC)**

(a) PWM ON phase      (b) PWM OFF phase

(c) WSC current

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Vint (from charge pump)

$I_{OSM}$

sw1

SCB\_V\_OSM ←  $V_{REF\_SCB}$

SCG\_V\_OSM ←  $V_{REF\_SCG}$

U

SW2

R\_OSM

V

SW3

R\_OSM

W

SCB\_U\_OSM ←  $V_{REF\_SCB}$

SCG\_U\_OSM ←  $V_{REF\_SCG}$

SCB\_W\_OSM ←  $V_{REF\_SCB}$

SCG\_W\_OSM ←  $V_{REF\_SCG}$

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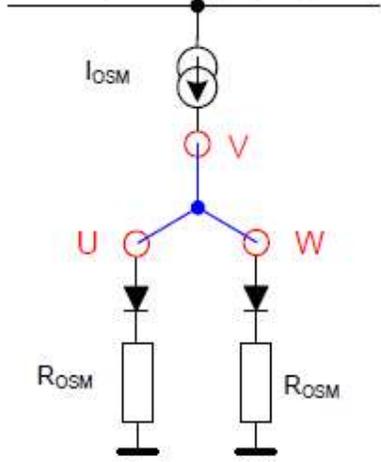
493

### 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**

Vint (from charge pump)



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Supply voltage monitoring unit

↓

1. Battery voltage
2. logic supply

Hall sensor monitoring unit

↓

1. Hall pattern error detection
2. Hall sequence error detection

Logic clock monitoring unit

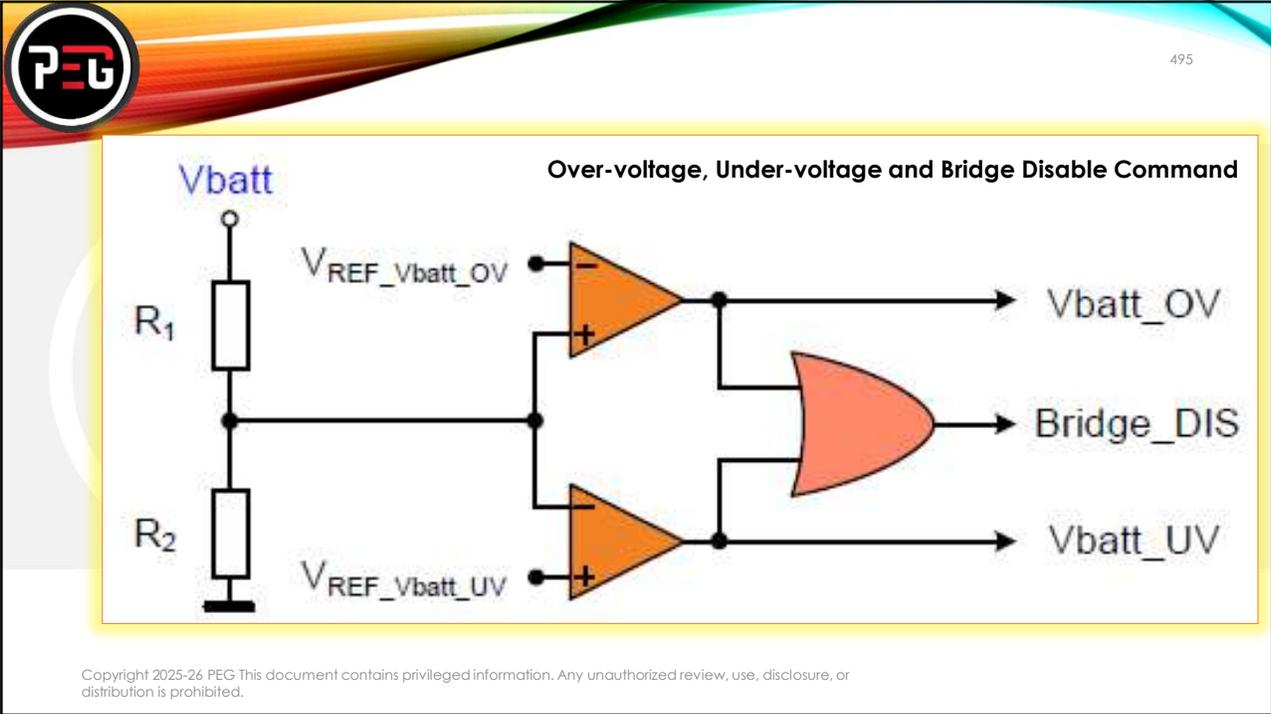
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Bridge over current sensing

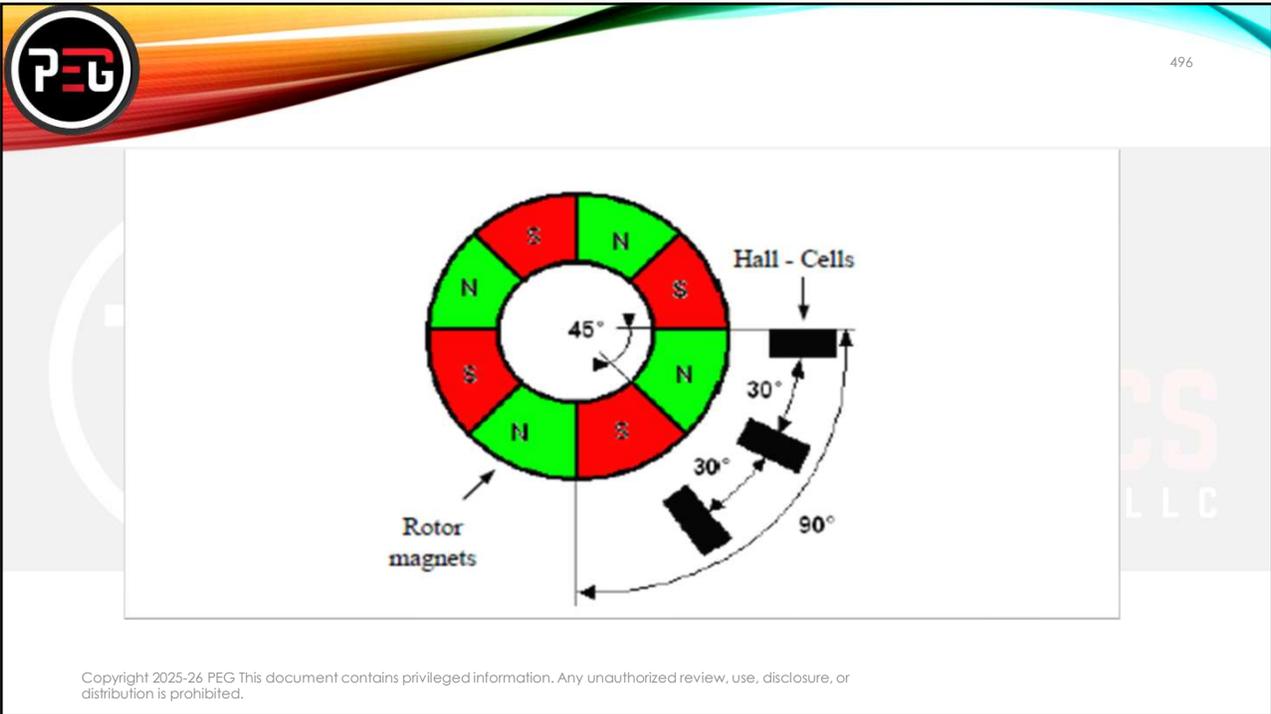
Over Temperature sensing

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A circular diagram divided into six sectors with binary numbers: 100 (top), 110 (top-left), 101 (top-right), 010 (bottom-left), 001 (bottom-right), and 011 (bottom). Two curved arrows on the left and right sides indicate a clockwise flow. To the right, a tree diagram shows '100' at the top with three arrows pointing down to 'HALL1', 'HALL2', and 'HALL3'.

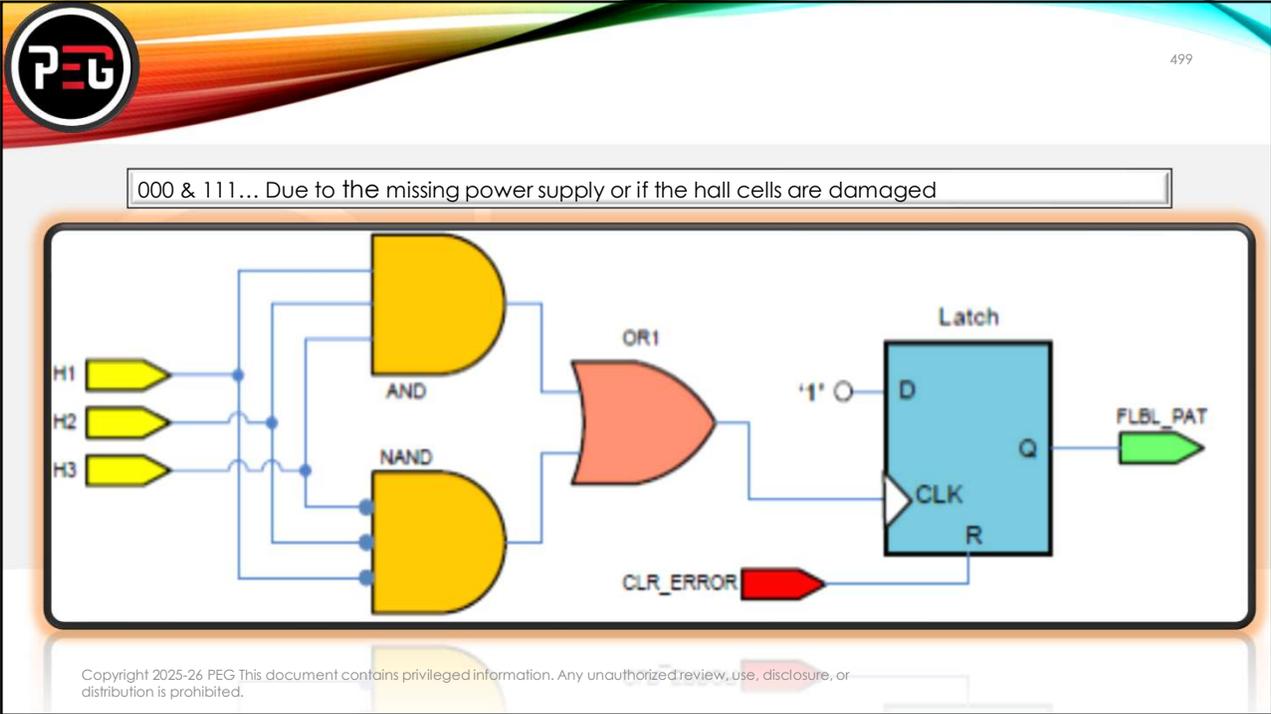
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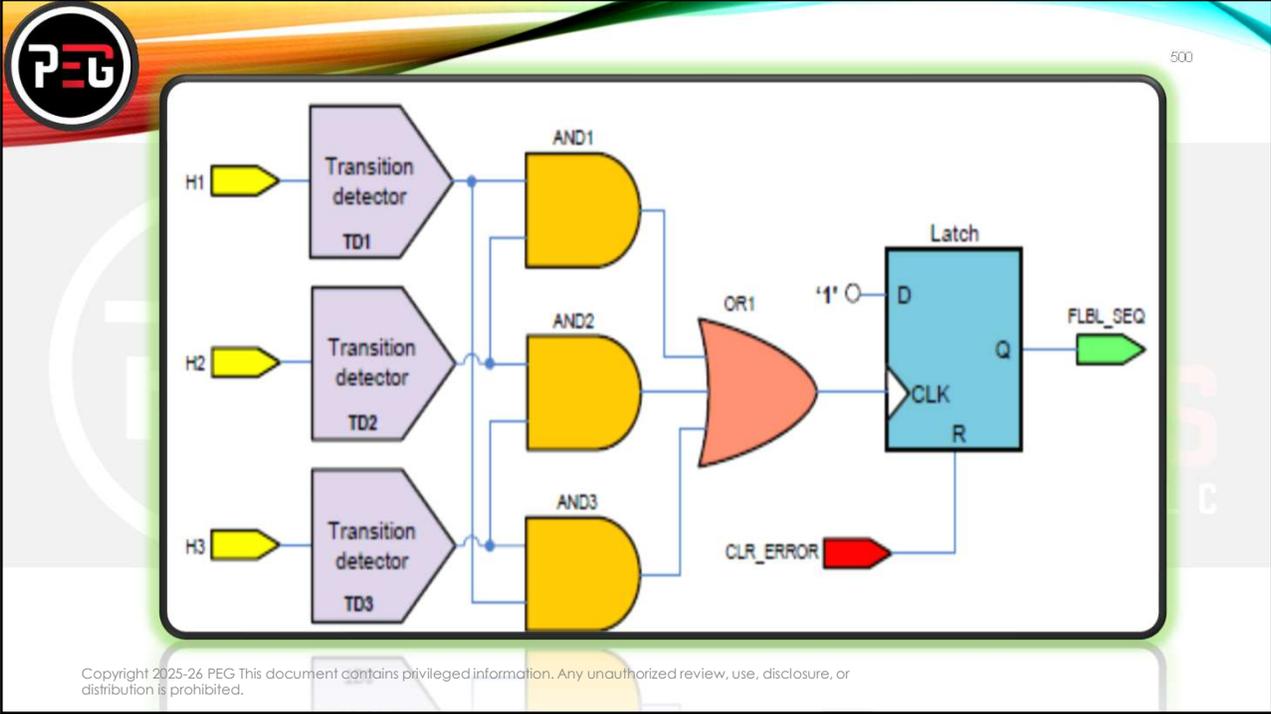
HALL1	HALL2	HALL3	
0	0	0	<b>Invalid!</b>
1	0	0	Sequence 1
1	0	1	Sequence 2
0	0	1	Sequence 3
0	1	1	Sequence 4
0	1	0	Sequence 5
1	1	0	Sequence 6
1	1	1	<b>Invalid!</b>

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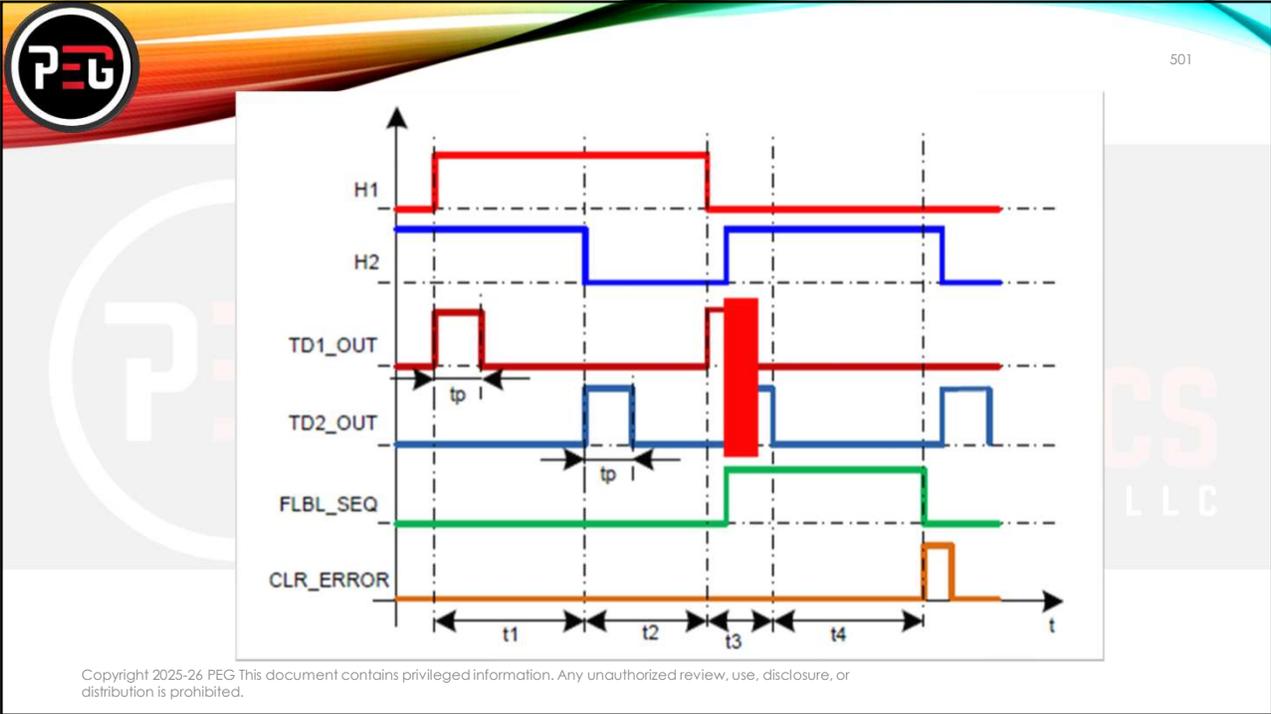
498



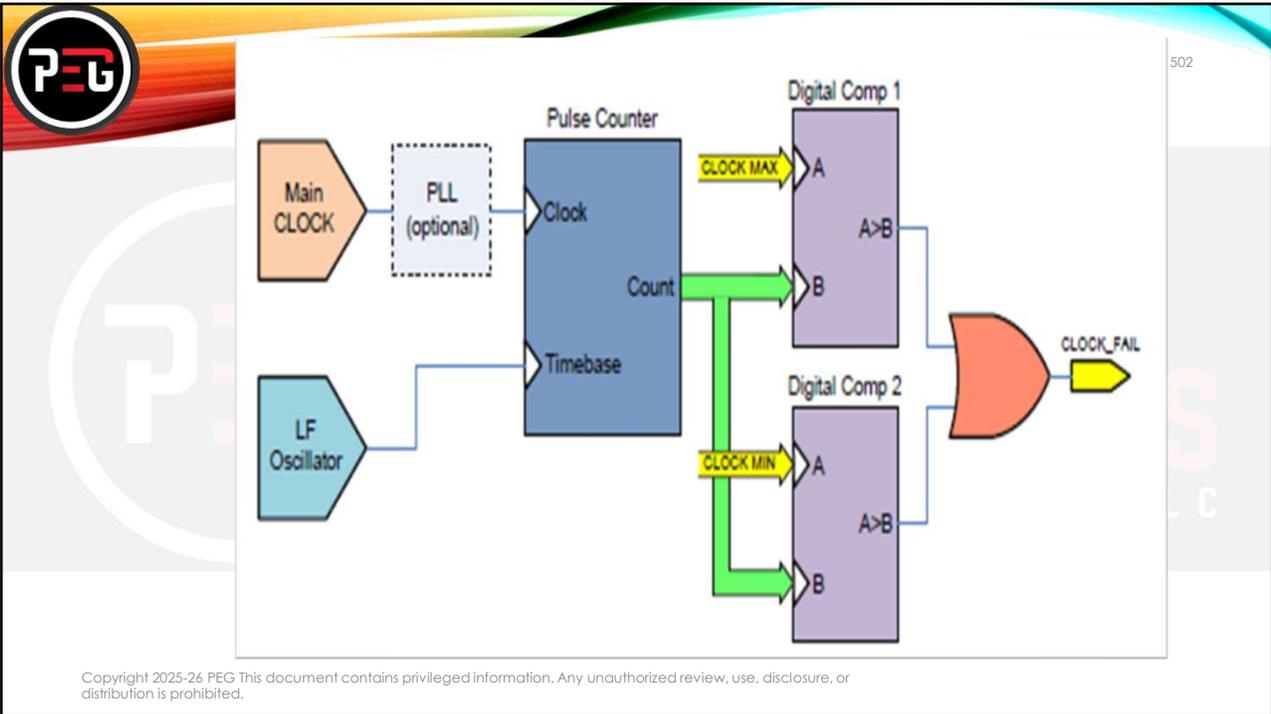
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**OVER TEMPERATURE SENSING**

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

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## 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 Modelling	Power Electronics	Code Generation	HIL Support	Real-Time Sim	Domain Focus	Supported Processors
Allair Activate	✓	✓	✓				Multi-Domain	Depends on Modelica backend
Allair 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
Typoon HIL			✓		✓	✓	Real-Time HIL	No direct target code gen, HIL-focused
VisSim (Allair 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

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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.

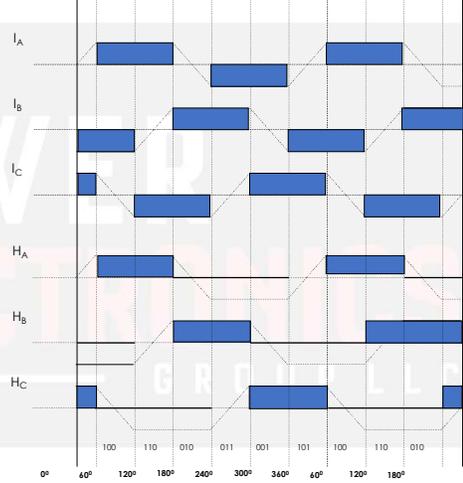
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## THE SYSTEM WAVEFORMS

	100	110	010	011	001	101
A <sub>T</sub>	1	1				
B <sub>T</sub>			1	1		
C <sub>T</sub>					1	1
A <sub>B</sub>				1	1	
B <sub>B</sub>	1					1
C <sub>B</sub>		1	1			



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# POWER ELECTRONICS GROUP

## 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

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

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

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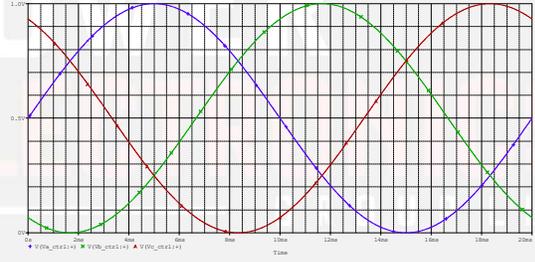
### 3 PHASE SINE INVERTER: GENERATING D

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

$$V_{a\_ctrl} = \frac{1}{2} \cdot \frac{V_m}{V_{dc}/2} \cdot \sin(\omega_e t) + \frac{1}{2}$$

$$V_{b\_ctrl} = \frac{1}{2} \cdot \frac{V_m}{V_{dc}/2} \cdot \sin(\omega_e t - 120^\circ) + \frac{1}{2}$$

$$V_{c\_ctrl} = \frac{1}{2} \cdot \frac{V_m}{V_{dc}/2} \cdot \sin(\omega_e t - 240^\circ) + \frac{1}{2}$$



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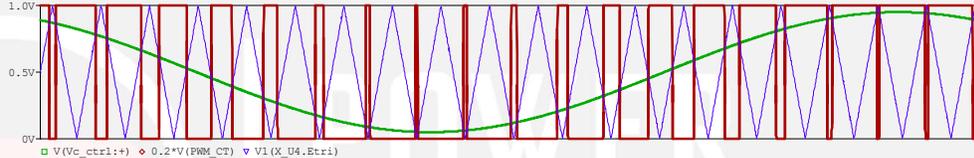
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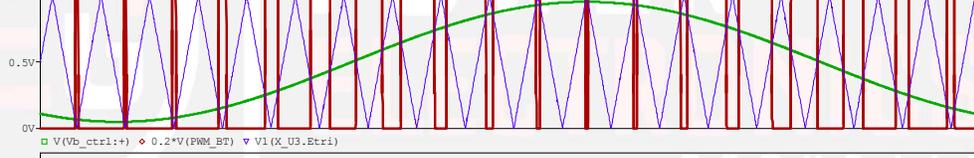
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### 3 PHASE SINE INVERTER: GENERATING D

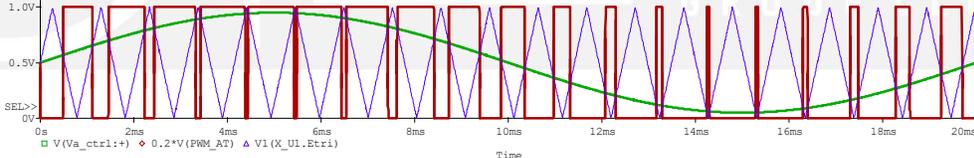
**PWM CT**



**PWM BT**



**PWM AT**



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# FIELD ORIENTED CONTROL

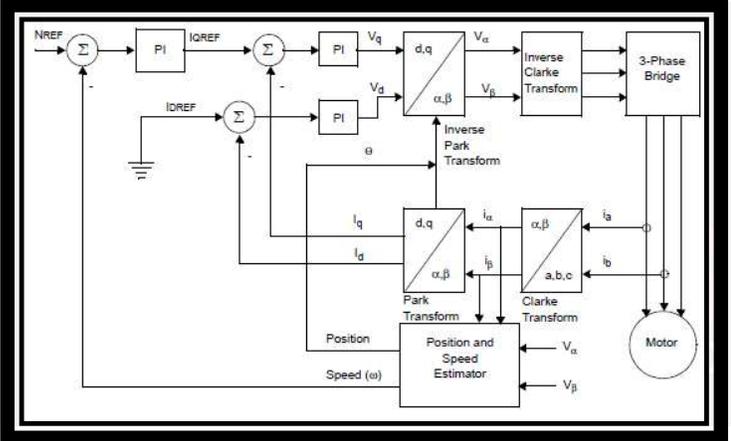
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# BLOCK DIAGRAM FOC CONTROL



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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.

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## 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);

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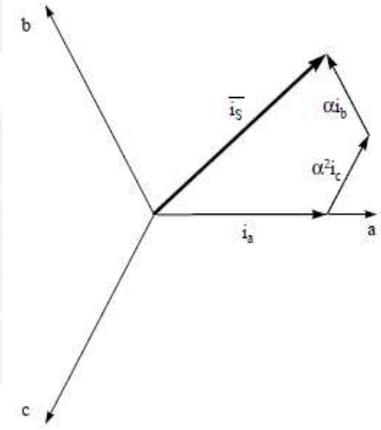

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## FOC FUNDAMENTALS

- 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

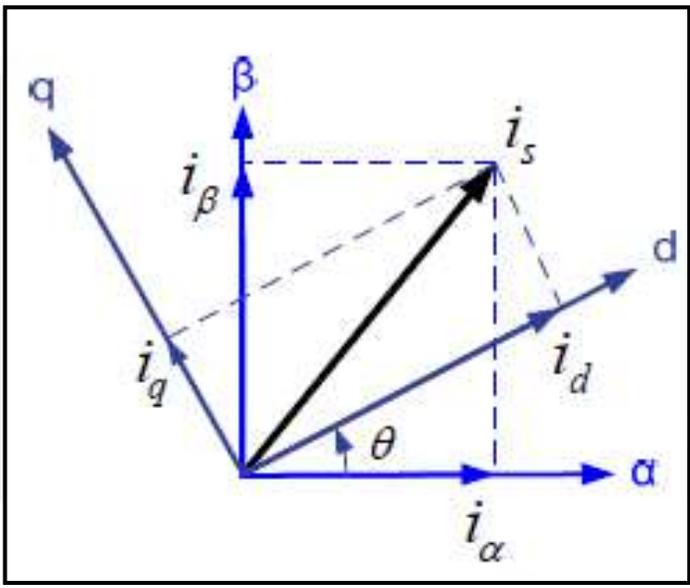
- The complex stator current vector is represented by:
 
$$\bar{i}_s = i_a + \alpha i_b + \alpha^2 i_c$$
- Where  $\alpha = e^{j2\pi/3}$  and  $\alpha^2 = e^{j4\pi/3}$  are the spatial operators.

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## TRANSFORMATIONS



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## TRANSFORMATIONS

Clarke's transformation

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

Park's transformation

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

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.

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## BLDC MOTOR: FOC MODEL

- Electrical equations:
 

$V_{as} = V \cos(\omega t)$ $V_{bs} = V \cos(\omega t - 2\pi/3)$ $V_{cs} = V \cos(\omega t - 4\pi/3)$ $\theta_e = \theta_m \cdot p$ $\omega_e = \omega_m \cdot p$	$I_{as} = I \cos(\omega t)$ $I_{bs} = I \cos(\omega t - 2\pi/3)$ $I_{cs} = I \cos(\omega t - 4\pi/3)$ $v = Ri + \frac{d\lambda}{dt} = Ri + \frac{d}{dt}(Li + \lambda_m(\theta))$
--	---

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## BLDC MOTOR: FOC MODEL

- The BEMF is given by:

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

- Magnetic flux of permanent magnet.

$\lambda_m$

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## BLDC MOTOR: FOC MODEL

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

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

$$\lambda_d = \lambda_m$$

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

- Mechanical equations:

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

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## BLDC MOTOR: FOC MODEL

Clarke's transformation

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

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

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

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

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

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

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## BLDC MOTOR: FOC MODEL

Park's transformation

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

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

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

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

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

$$\lambda_q = L_s i_q$$

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

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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

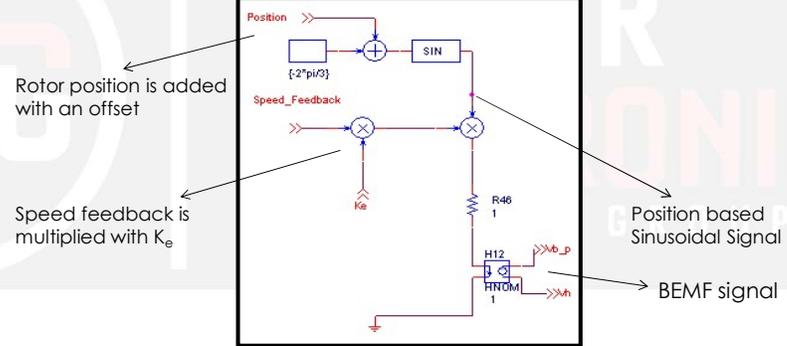
Where 'f' can be either Voltage or Current.

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### P-SPICE IMPLEMENTATION

- Sinusoidal BEMF modeling

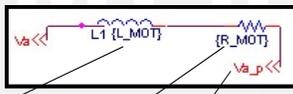


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### P-SPICE IMPLEMENTATION

- Developing a per phase Motor model



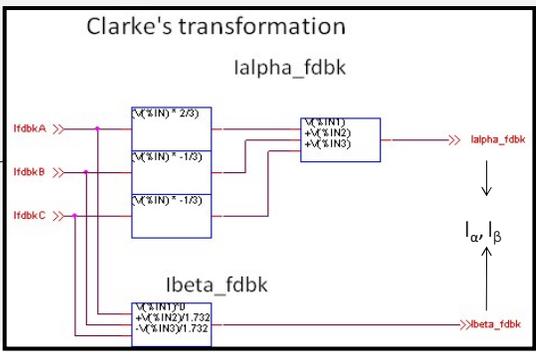
Motor Inductance per phase  
 Motor Resistance per phase  
 BEMF signal

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### P-SPICE IMPLEMENTATION

- Clarke's Transformation.



3-Phase feedback currents

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### P-SPICE IMPLEMENTATION

- Park's Transformation

Park's transformation

$I_d, I_q$

$I_\alpha, I_\beta$

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### P-SPICE IMPLEMENTATION

- Generating Position Ramp

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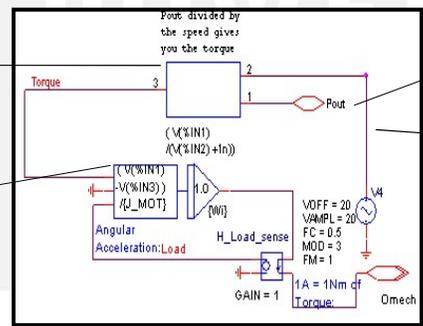


### P-SPICE IMPLEMENTATION

- Generating Torque

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

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



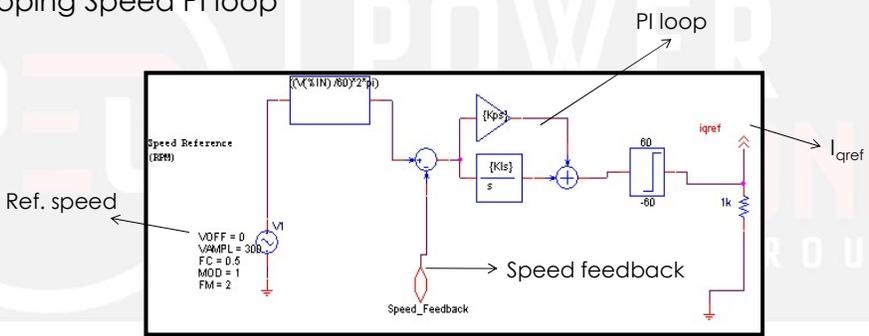
Output power  
Speed

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### P-SPICE IMPLEMENTATION

- Developing Speed PI loop



Ref. speed

PI loop

iqref

Speed feedback

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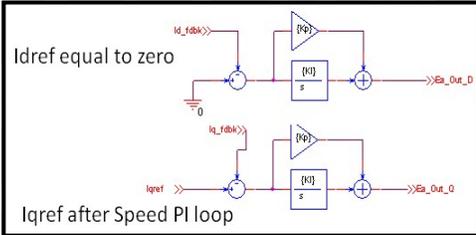


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## P-SPICE IMPLEMENTATION

- PI loop implementation

Idref equal to zero



Iqref after Speed PI loop

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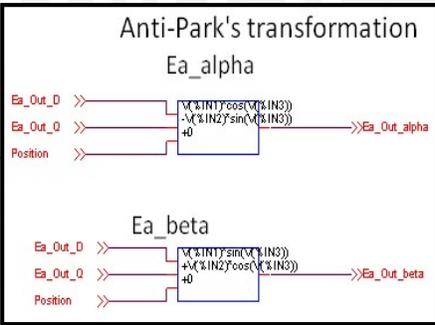
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## P-SPICE IMPLEMENTATION

- Anti-Park's transformation

### Anti-Park's transformation

Ea\_alpha



Ea\_beta

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### Anti-Clarke's transformation

## P-SPICE IMPLEMENTATION

Anti Clarke's transformation

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## P-SPICE IMPLEMENTATION

- Generating Duty Cycle

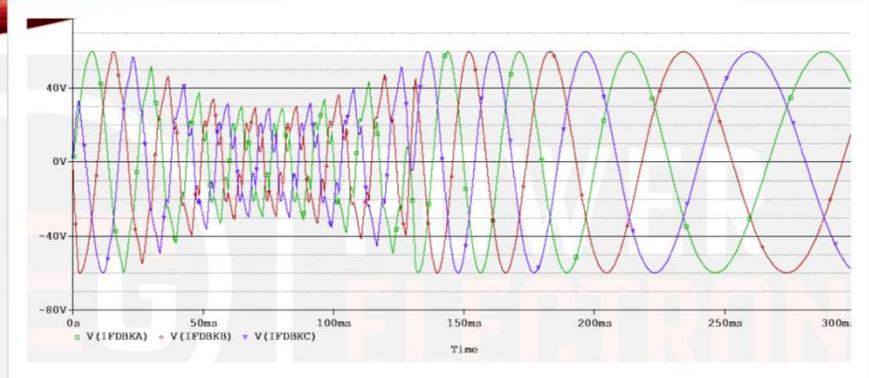
Duty Cycle  $\rightarrow V_m = \frac{V_{dc}}{2} [2 \cdot D - 1]$

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### SIMULATION RESULTS

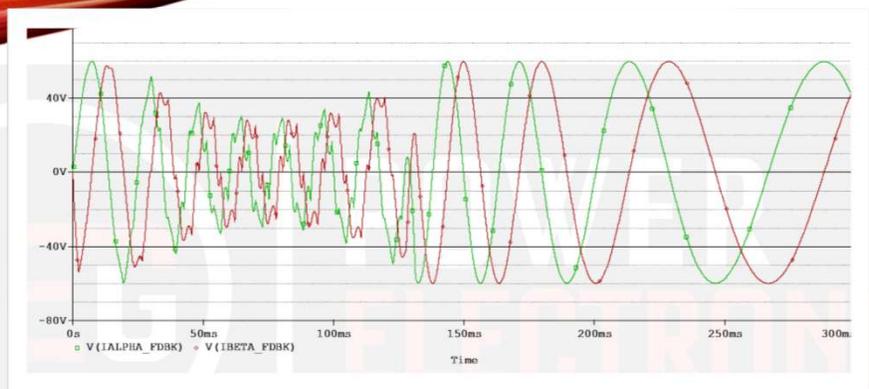
Feedback phase currents  $I_a, I_b, I_c$

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### SIMULATION RESULTS

Clarke's transformation

$I_\alpha, I_\beta$

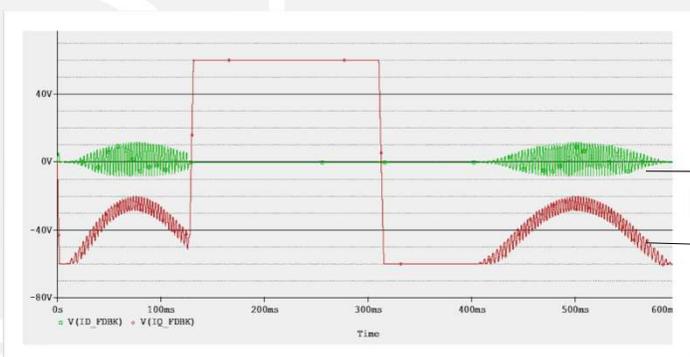
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### SIMULATION RESULTS



Park's transformation

$I_d, I_q$

$I_d$

$I_q$

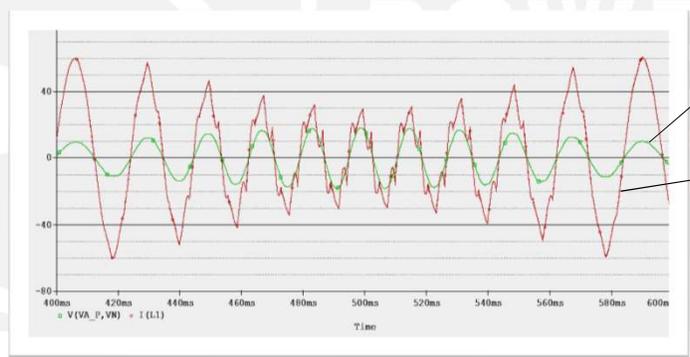
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### SIMULATION RESULTS



BEMF of phase-A

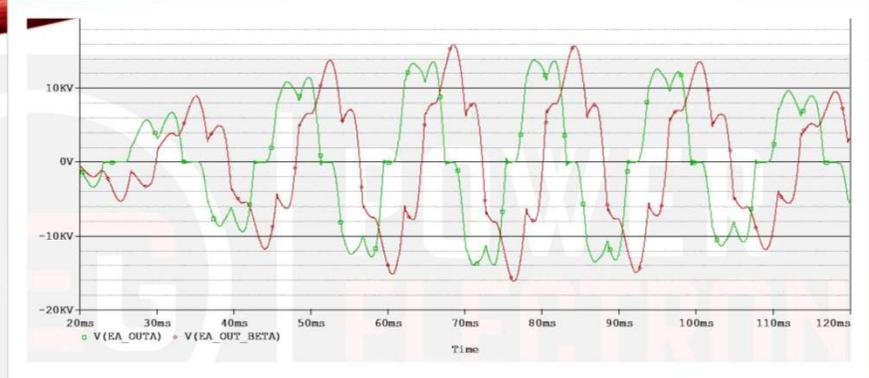
Phase-A current

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### SIMULATION RESULTS

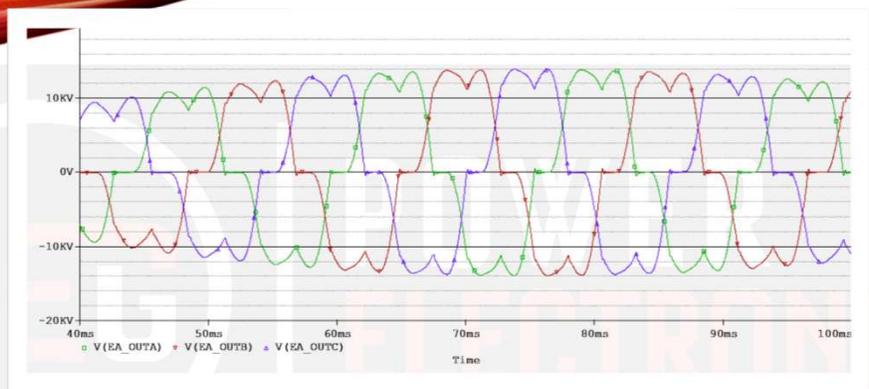
Anti-Park's transformation

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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

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April 22 - 25, 2025

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## SPACE VECTOR REPRESENTATION

$$V_a = V_m \sin(\omega t)$$

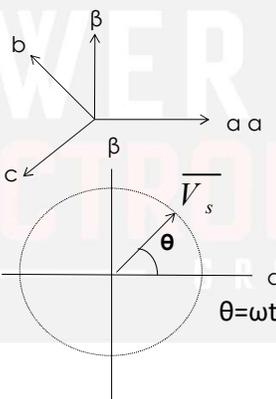
$$V_b = V_m \sin(\omega t - 120)$$

$$V_c = V_m \sin(\omega t + 120)$$

$$V_a + V_b + V_c = 0$$

$$V_s = V_a + V_b e^{j\frac{2\pi}{3}} + V_c e^{j\frac{-2\pi}{3}}$$

$$\overline{V}_s = \frac{3}{2} V_m (\sin \omega t - j \cos \omega t)$$



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## SVM FUNDAMENTALS

$$\overline{V}_s = V_\alpha + jV_\beta = |V_s| e^{j\omega t} \begin{bmatrix} f_\alpha \\ f_\beta \end{bmatrix} = \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} f_a \\ f_b \\ f_c \end{bmatrix}$$

- 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.

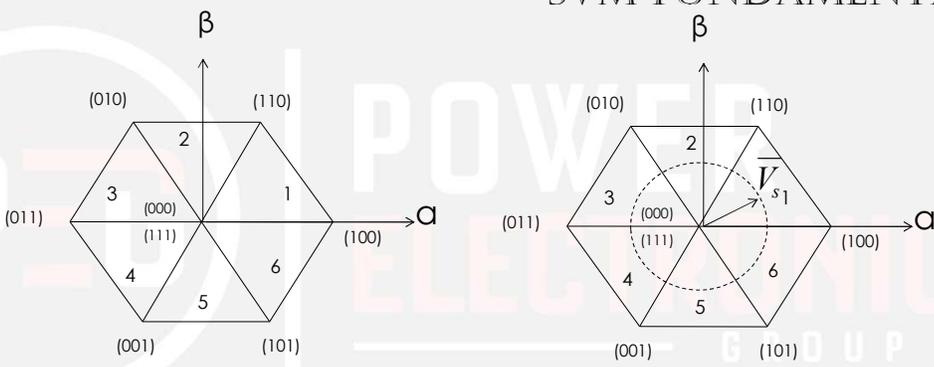
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## SVM FUNDAMENTALS



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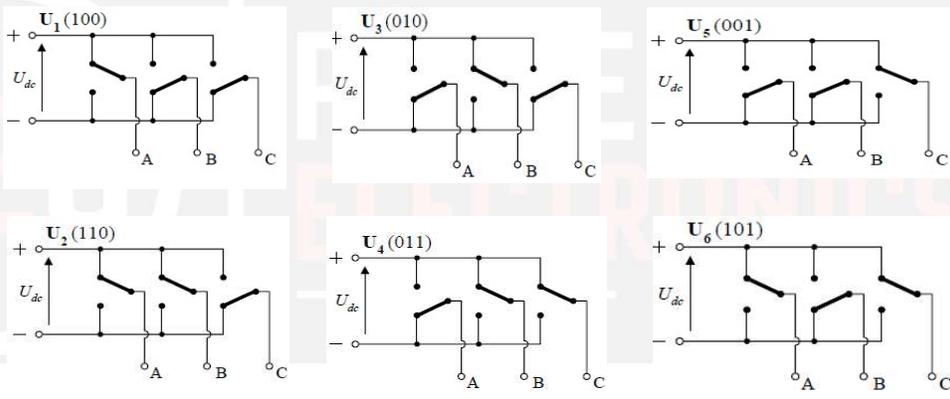
### SVM FUNDAMENTALS

- 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 =  $V_{dc}$ .

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### SVM FUNDAMENTALS



1 to 6 Active states.

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**SVM FUNDAMENTALS**

**Null states**

$U_0(000)$

$U_7(111)$

$U_{dc}$

A B C

V B C

V B C

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**SVM FUNDAMENTALS**

$V_3(010)$

$V_2(110)$

$V_{ref}$

$(t_2/T_s)V_2$

$V_{ref\_MAX}$

$\alpha$

$V_0(000)$

$V_7(111)$

$(t_1/T_s)V_1$

$V_1(100)$

$V_5(001)$

$\Lambda^2(001)$

$V_8(101)$

$\Lambda^2(101)$

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## SVM FUNDAMENTALS

Volt second balance equation along  **$\alpha$ -axis**

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

Volt second balance equation along  **$\beta$ -axis**

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

Solving for  $T_1, T_2$  &  $T_0$

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

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## SVM FUNDAMENTALS

Where  $\alpha$  varies from 0 to 60 Degrees.

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

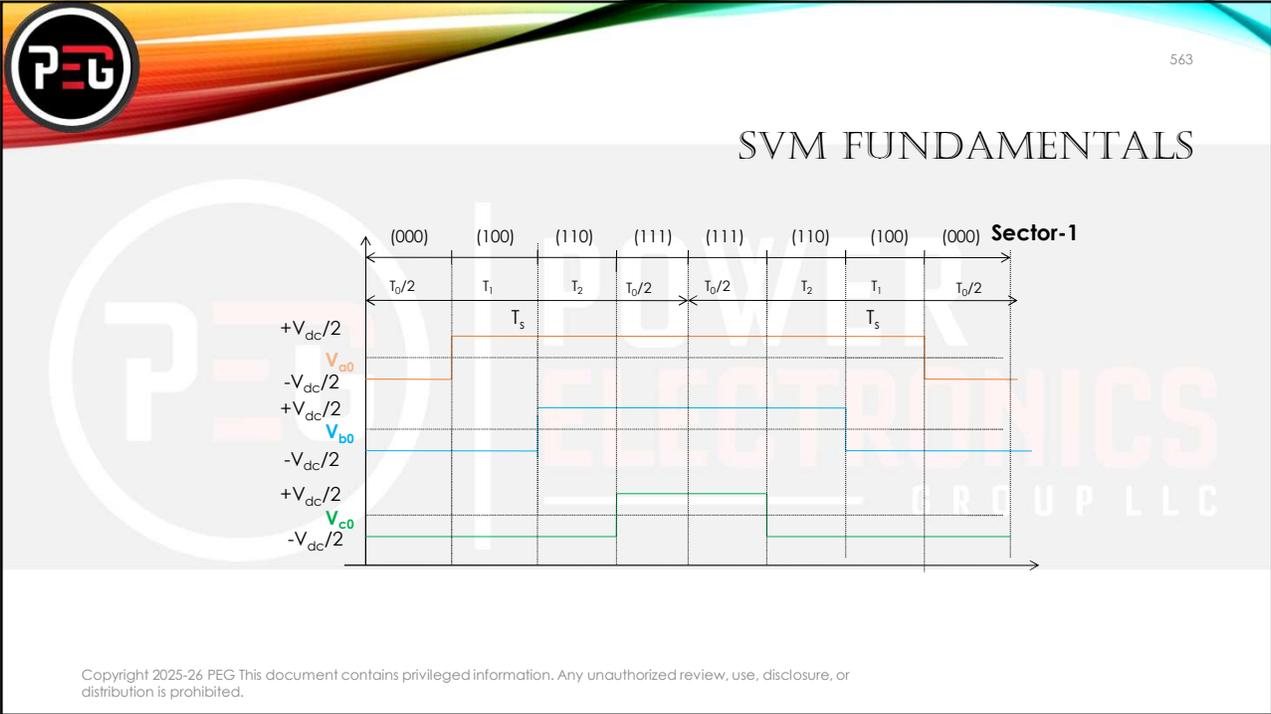
$$T_0 = T_s - (T_1 + T_2)$$

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

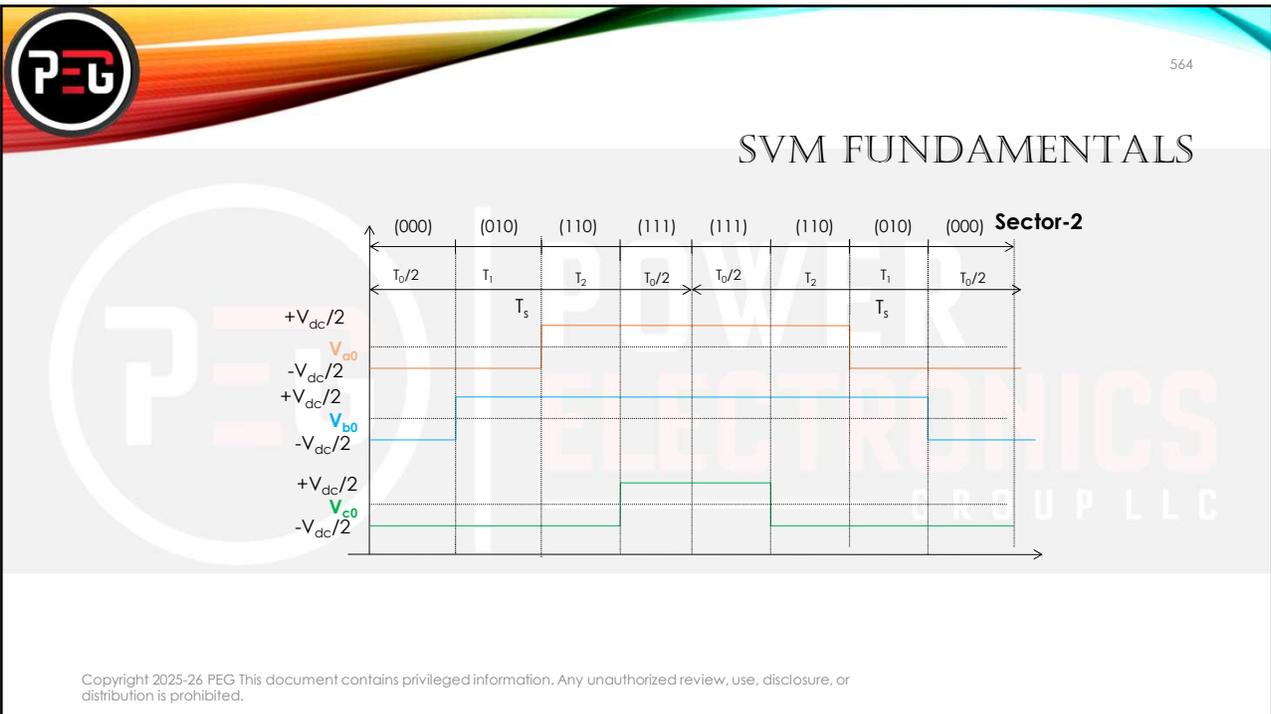
$$dy = \frac{\sin(\alpha)}{\sin(\frac{\pi}{3})}$$

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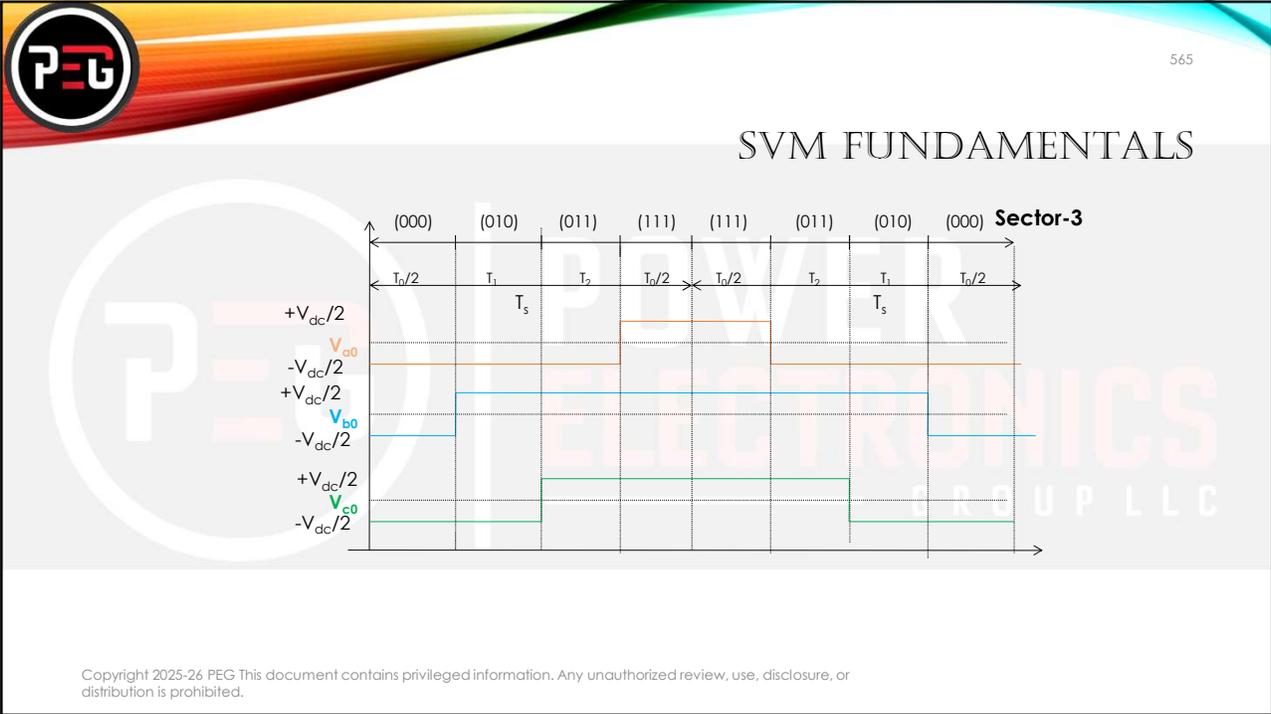
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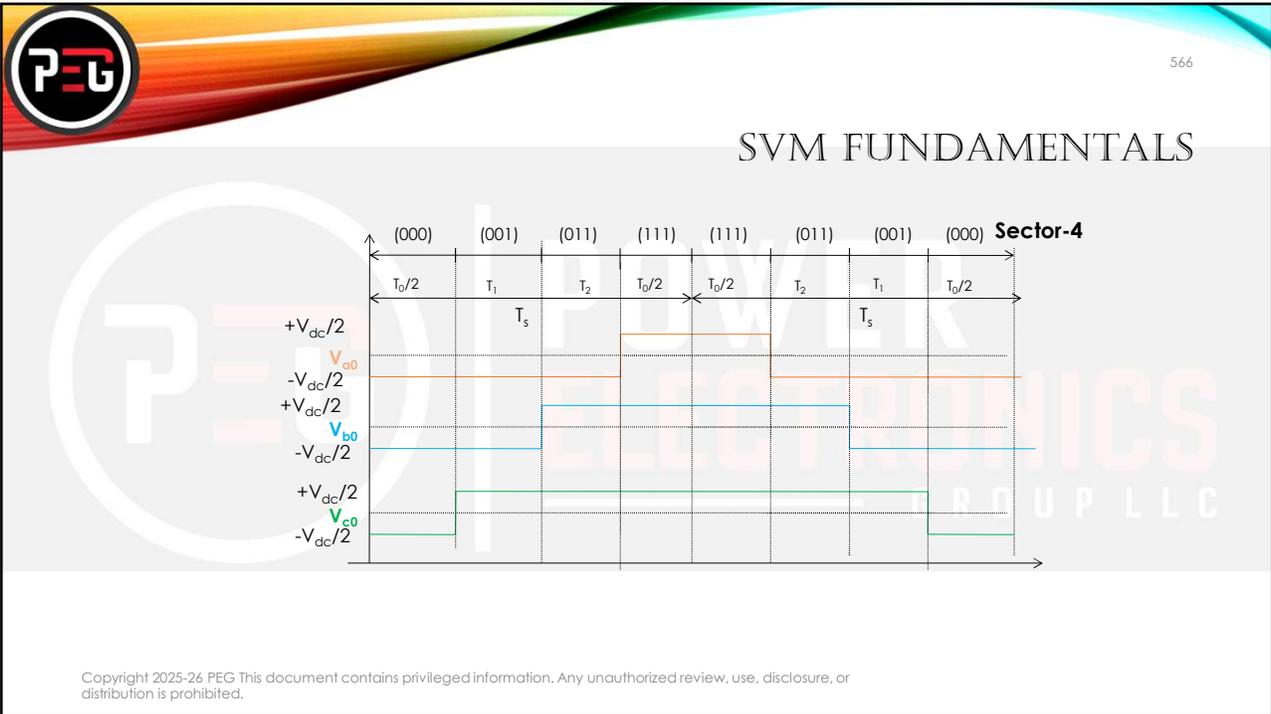
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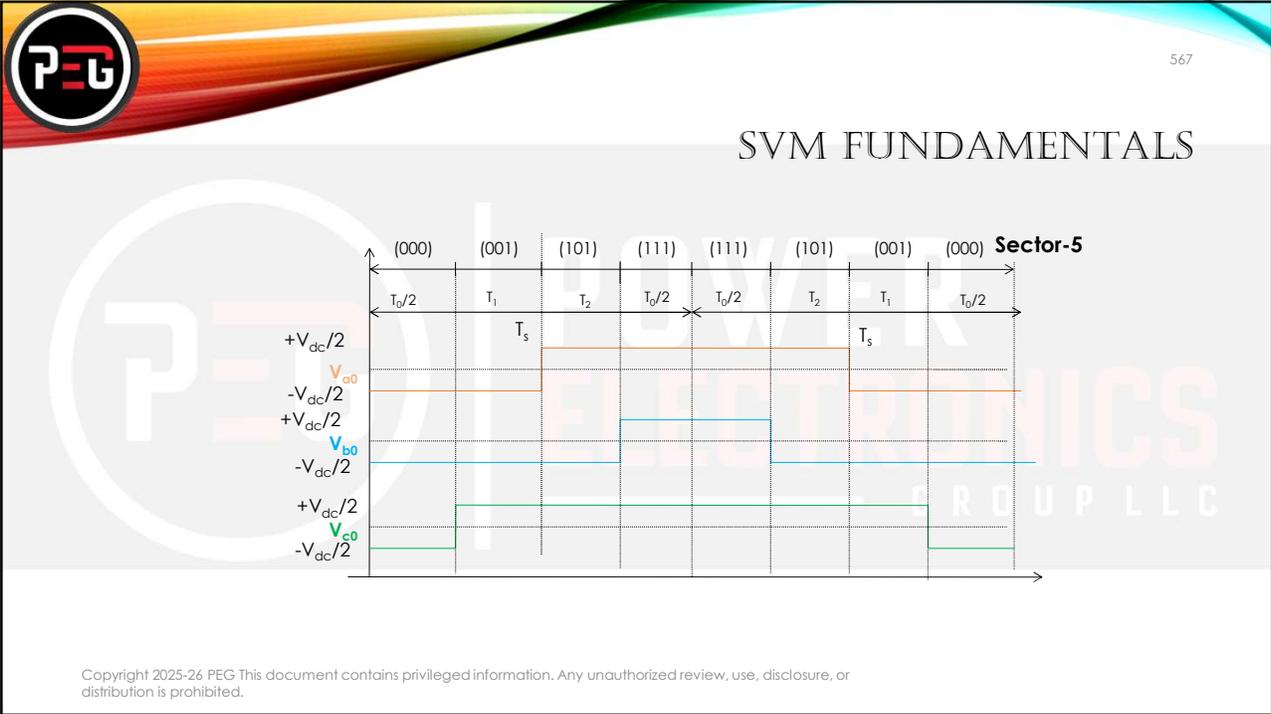
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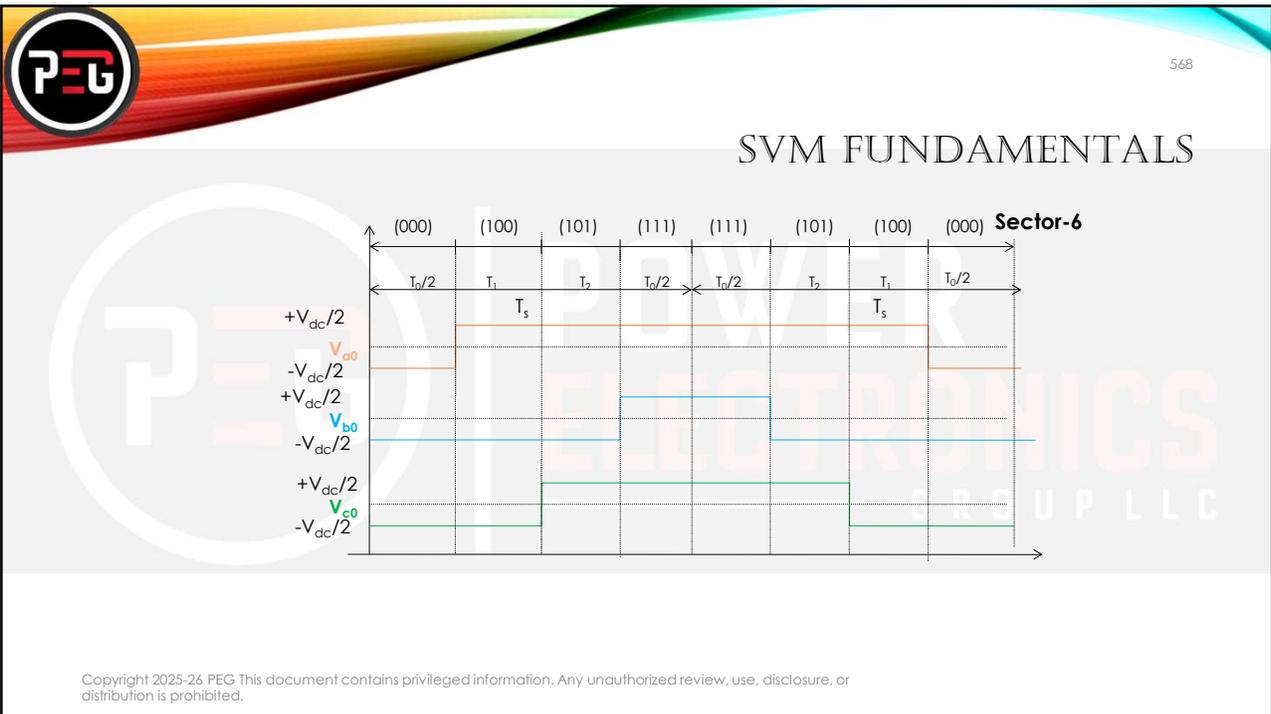
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### SVM FUNDAMENTALS

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

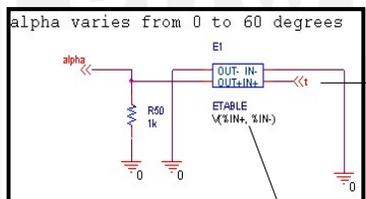
4	A	$(1+dx+dy)/2$
	B	$(1-dx+dy)/2$
	C	$(1-dx-dy)/2$
5	A	$(1+dx-dy)/2$
	B	$(1+dx+dy)/2$
	C	$(1-dx-dy)/2$
6	A	$(1-dx-dy)/2$
	B	$(1+dx+dy)/2$
	C	$(1-dx+dy)/2$

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### P-SPICE IMPLEMENTATION

- Angle  $\alpha$  generation.



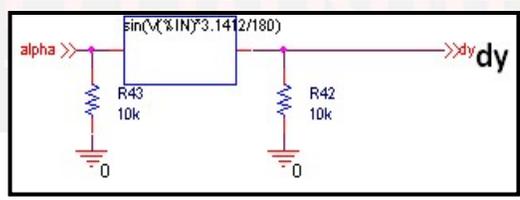
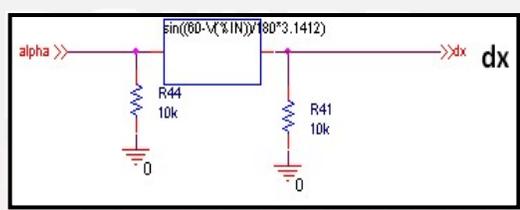
(0,0) (60,60) (60,1.0) (120,60) (120,1.0) (180,60) (180,1.0) (240,60) (240,1.0) (300,60) (300,1.0) (359.9,60) (360,0)

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### P-SPICE IMPLEMENTATION

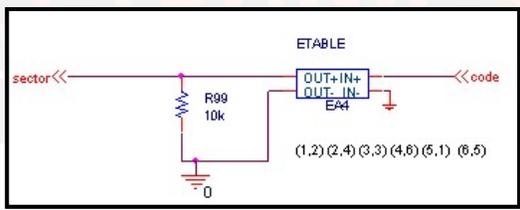
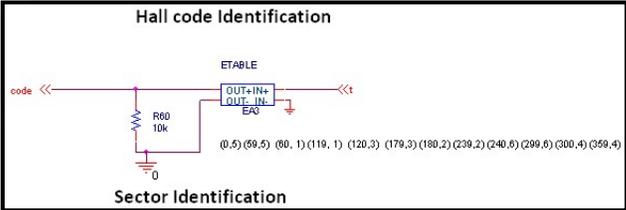
- Duty cycle  $dx$  &  $dy$  generation.



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### P-SPICE IMPLEMENTATION

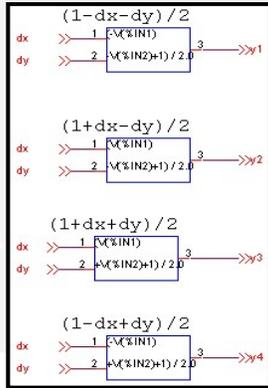


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### P-SPICE IMPLEMENTATION

- Duty cycle generating formulae.

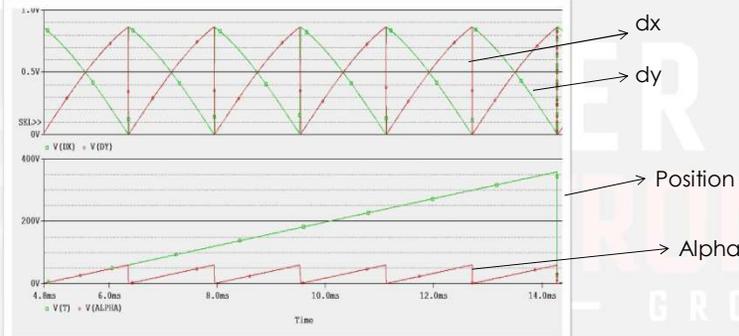


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### SIMULATION RESULTS



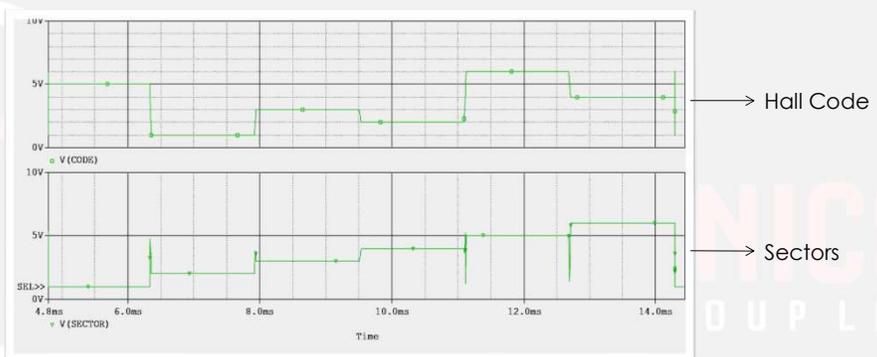
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### SIMULATION RESULTS

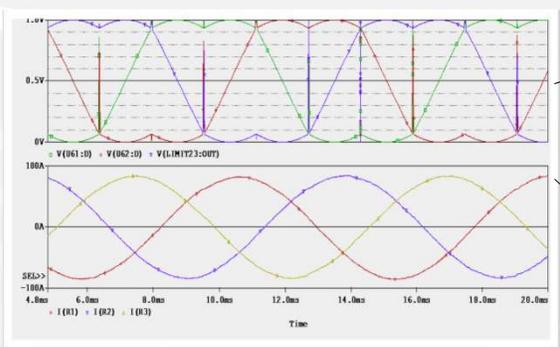


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### SIMULATION RESULTS



PWM-A,PWM-B,PWM-C

Phase Currents- $I_a, I_b, I_c$

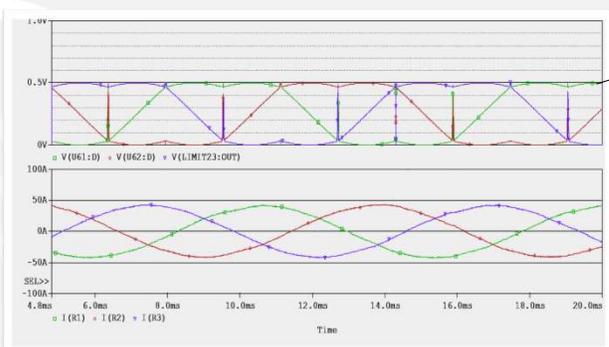
$$\text{For } \frac{|V_s|}{V_{dc}} = 1$$

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

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### SIMULATION RESULTS



PWM-A,PWM-B,PWM-C

Phase Currents- $I_a, I_b, I_c$

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

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

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## SCALAR VS. VECTOR CONTROL



**5-Phase Drive  
(Scalar Control)**



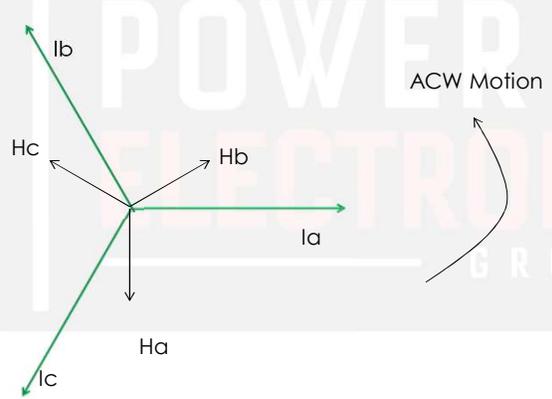
**3-Phase Dual Drive  
(Vector Control)**

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## VECTOR DIAGRAM - ACW



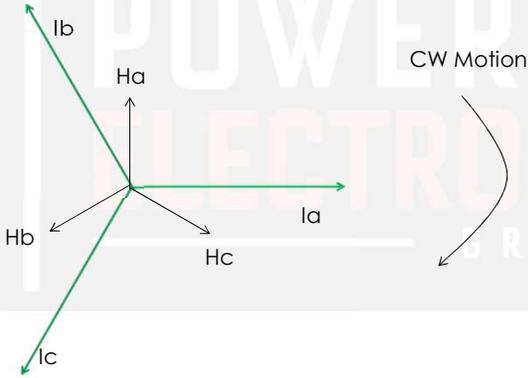
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## VECTOR DIAGRAM - CW



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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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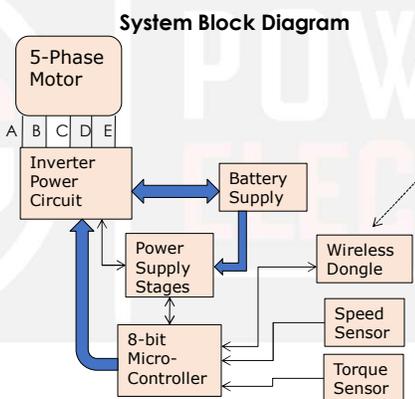
# 5-PHASE MOTOR DRIVE

- 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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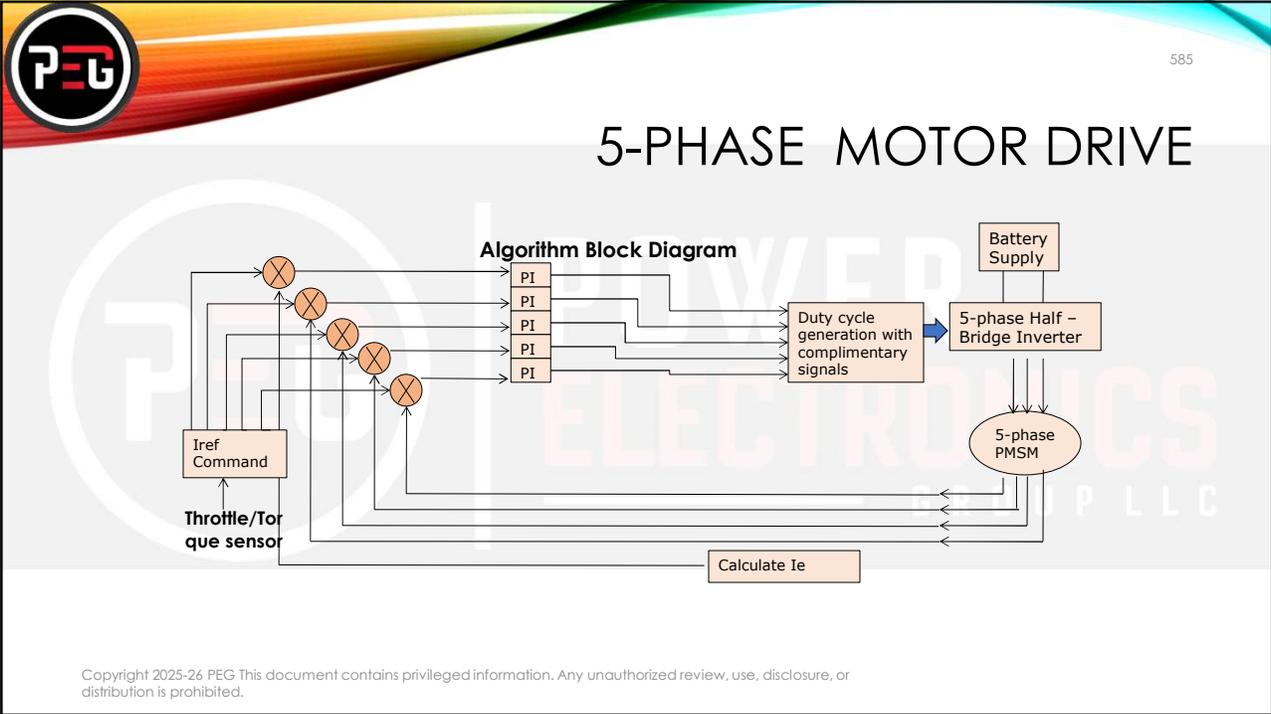


# 5-PHASE MOTOR DRIVE



Wireless Display or App

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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**

The diagram illustrates the system architecture. At the top, two motor blocks labeled 'Motor-1' and 'Motor-2' are shown, each with three phase outputs (A, B, C). Below each motor is an 'Inverter Power Circuit-1' and 'Inverter Power Circuit-2' respectively. A 'Battery Supply' is connected to both inverters. 'Power Supply Stages' provide power to the DSP Controller. The DSP Controller is connected to both inverters and receives input from a 'Joystick'. 'Hall Signals' are shown as feedback loops from the motor outputs back to their respective inverter circuits.

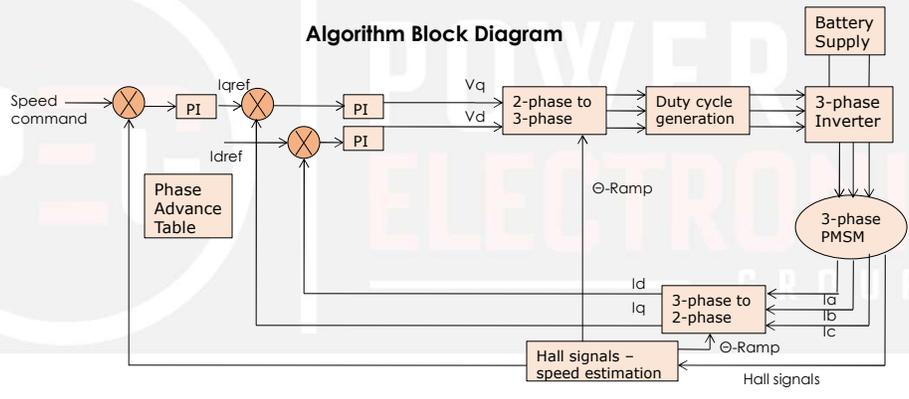
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# 3-PHASE DUAL MOTOR DRIVE



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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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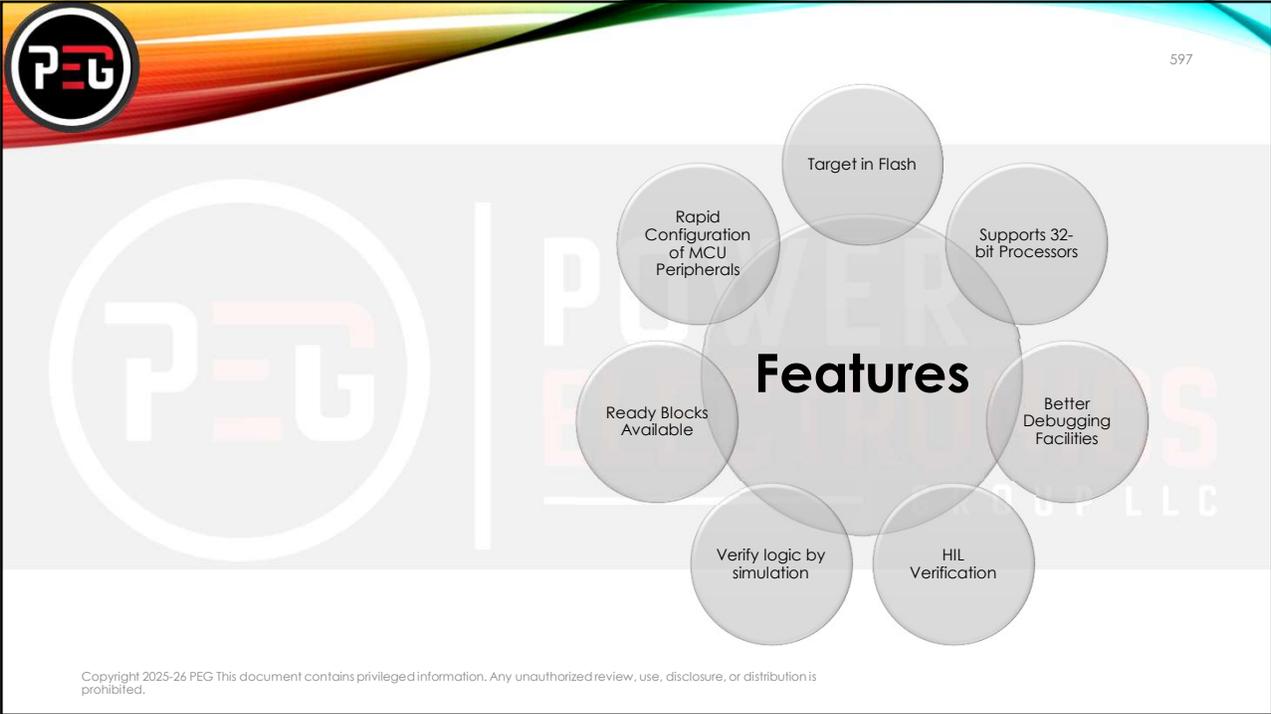
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**WHY ALTAIR EMBED?**

- 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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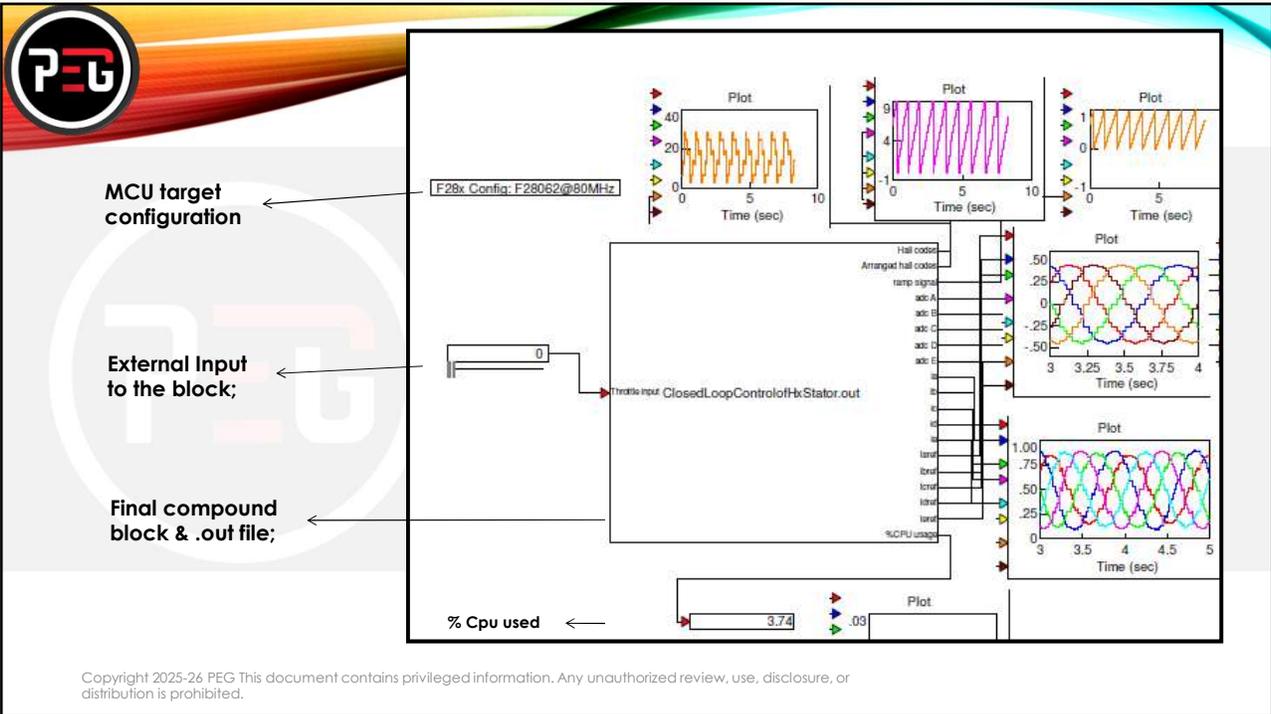


**Features**

- Target in Flash
- Supports 32-bit Processors
- Better Debugging Facilities
- HIL Verification
- Verify logic by simulation
- Ready Blocks Available
- Rapid Configuration of MCU Peripherals

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**MCU target configuration** ← F28x Config: F28062@80MHz

**External Input to the block;** ← 0

**Final compound block & .out file;** ← TheatixInput\_ClosedLoopControlofStator.out

**% Cpu used** ← 3.74

Plots showing:

- Plot 1: Amplitude vs Time (sec)
- Plot 2: Amplitude vs Time (sec)
- Plot 3: Amplitude vs Time (sec)
- Plot 4: Hall codes, Arranged hall codes, ramp signals, and ADCs (A-E) vs Time (sec)
- Plot 5: %CPU usage vs Time (sec)

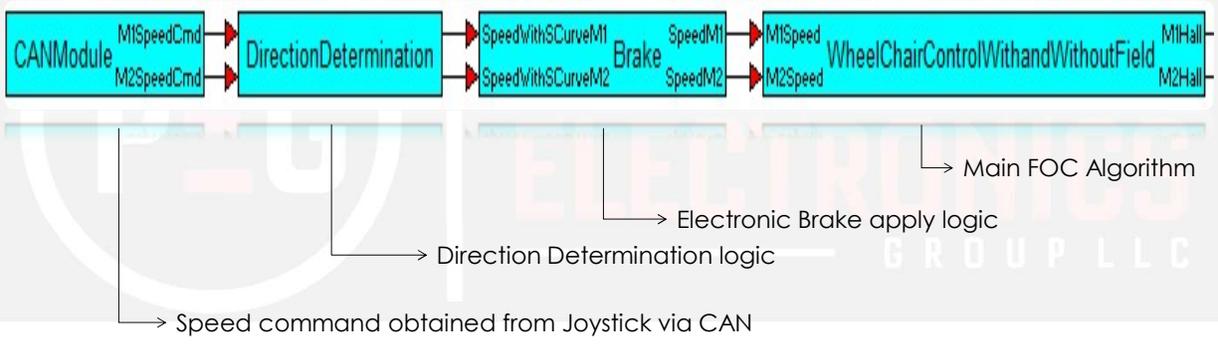
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# EXAMPLE OF DUAL BLDC MOTOR DRIVE USING FOC



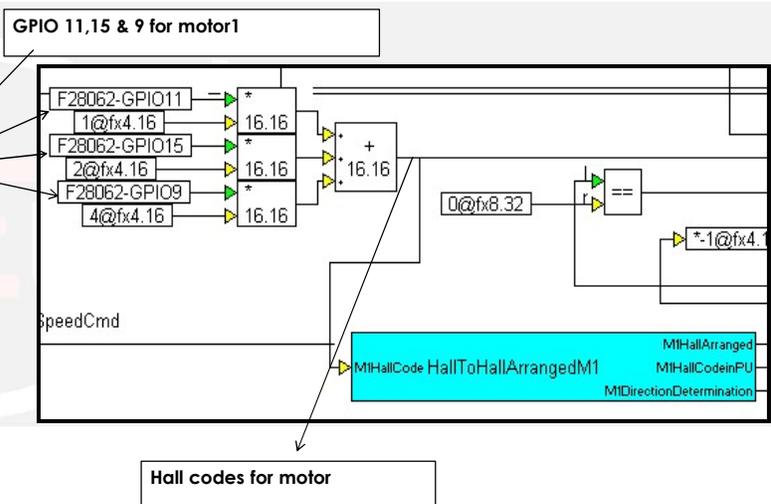
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# HALL CODE GENERATION



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## HALL CODE ARRANGEMENT

**Arranged hall Codes(0 to 5) or (5 to 0)**

**Gain of 0.166667 is needed to get PU values for ramp to vary from (0 to 1)**

**Direction determination**

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## MOTOR DIRECTION DETERMINATION

**Interp Pos & speedM1**

**Arranged hall code is delayed (unit delay) to get previous hall code value;**

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

M1theta M1w

M1pos

negM1@327

edgeM1@327

M1isNeg

sigM1

0@tr16.16

0x1

1/Z

+

S&H

edgeM1@327

0

b

x

1,0,0

.32.32

0x1

0x3

0x5

0x4

0x1

0x2

0x6

case

M1HallCode

0.166667@tr@32

+

0x1

-16.16

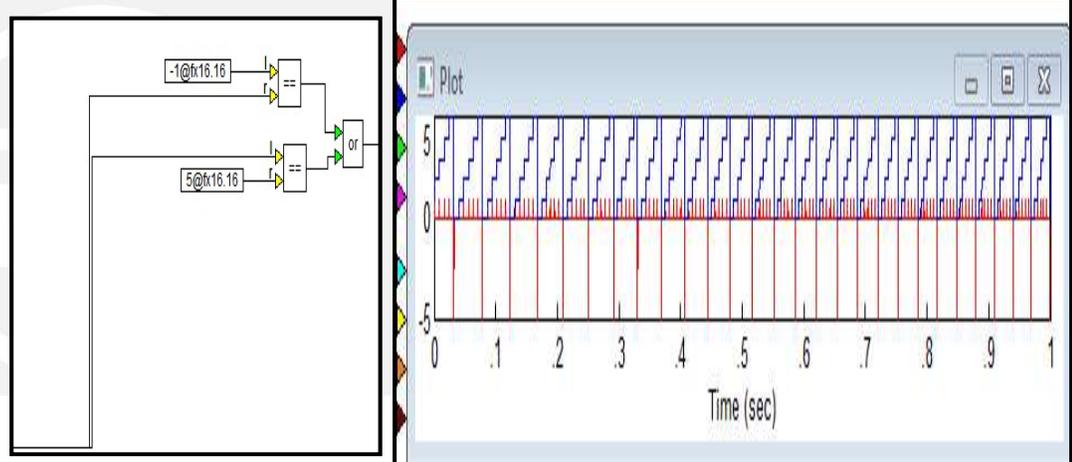
M1DirectionDetermination

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# MOTOR DIRECTION DETERMINATION



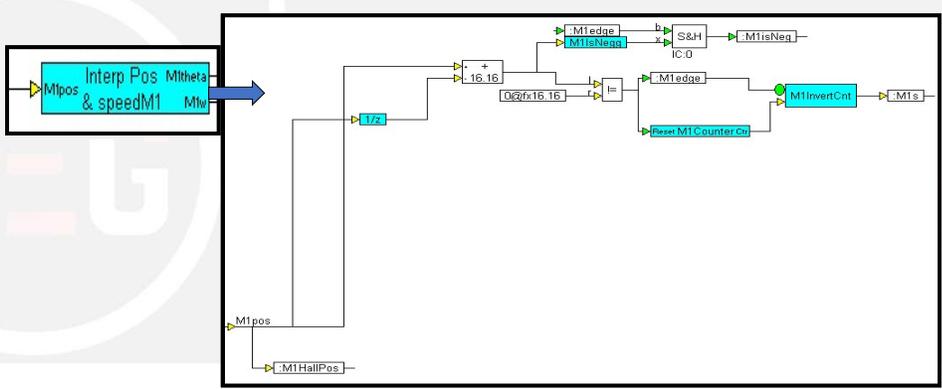
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# SPEED CALCULATION



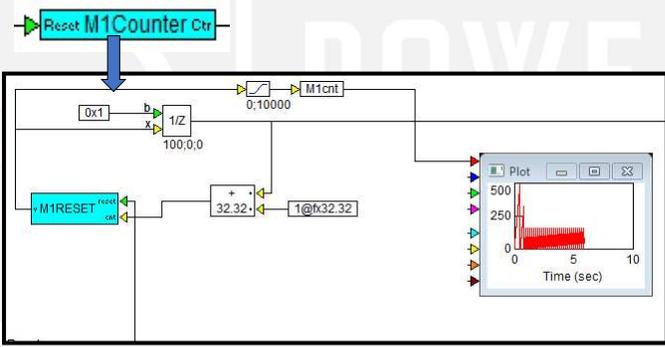
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# SPEED CALCULATION



> Shows number of counts between the hall codes;

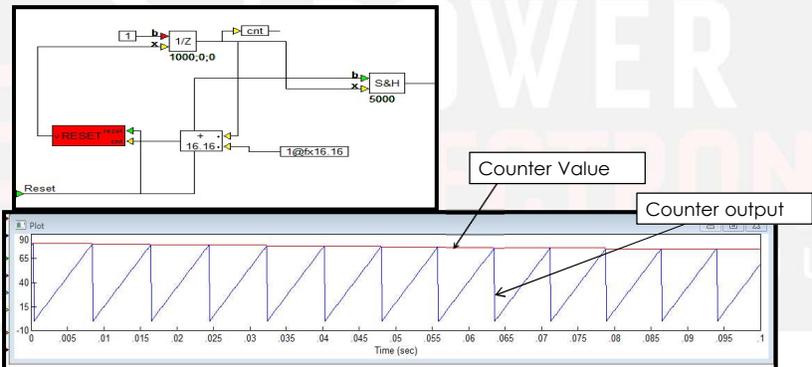
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# SPEED CALCULATION



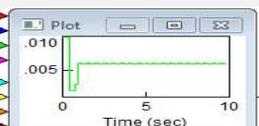
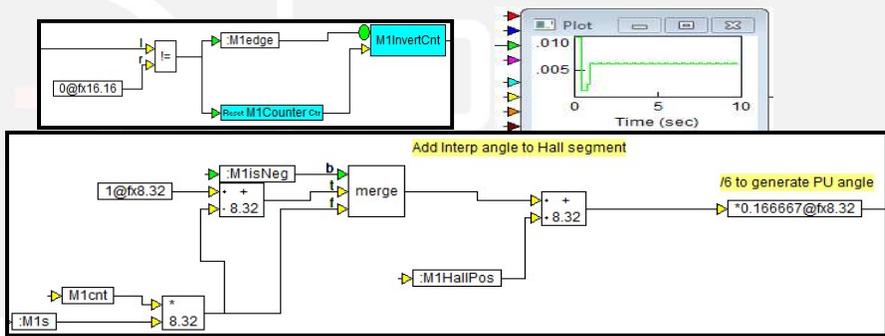
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# THETA CALCULATION



Theta is required for vector transformations;

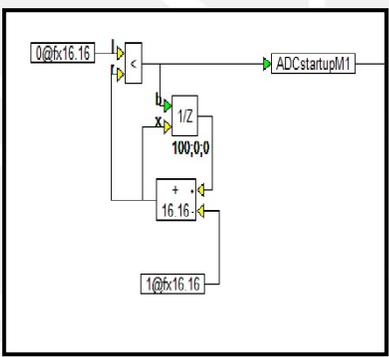
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# ADC SAMPLING



- > 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.

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The diagram illustrates the ADC offset calculation process. It starts with the ADC startup signal (ADCstartupM1) which is delayed by 1/Z. This signal is then multiplied by 0.5@fx1.16. The result is added to the ADC result (F28062-ADCRESULT1) which has been multiplied by -0.5@fx4.16. The sum is then multiplied by 0.5@fx1.16. Finally, the result is added to the offsetM1A value (multiplied by 1.16) to produce the final output M1laa.

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The flowchart outlines the steps for ADC offset calculation:

- Read ADC register
- Subtract 0.5
- Multiply gain of -0.5
- Add with a delayed read value multiplied by 0.5
- Generate Offset value
- Subtract the Offset value from value of 3<sup>rd</sup> step.

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### 3-PHASE TO 2-PHASE TRANSFORMATION

Currents read from ADC → M1Iaaa, M1Ibbb, M1Iccc  
 Theta Calculated → M1ThetainRad

ABC To DQM1

M1D Id feedback  
 M1Q Iq feedback

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

Theta is used from the calculation seen before;

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612

### SPEED PI LOOP

Speed Ref → convert → M1Cmd

Speed Fdbk → convert → M1Fbk

M1SpeedPID M1Errorspeed

MotorId.map Id Reference  
 MotorIq.map Iq Reference

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

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**CURRENT PI LOOP**

Id Reference → M1cmd PIDM1 M1errorD  
 Id feedback → M1PV  
 Iq Reference → M1Ccmd M1PIDwithFeedForward errorQM1  
 Iq feedback → M1PV

D correction  
 Q correction

**PIDM1 Properties**

Upper Bound (-128..127.999):	1
Lower Bound (-128..127.999):	-1
P (-128..127.999):	1
I (-128..127.999):	0
D (-128..127.999):	0

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**2-PHASE TO 3-PHASE TRANSFORMATION**

D correction → M1errorD  
 Q correction → M1errorQ  
 Theta Calculated → M1 ThetainRad

M1 Ia → Va  
 M1 Ib → Vb  
 M1 Ic → Vc

Scale & apply to ePWM blocks;

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

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## DUTY CYCLE CALCULATION

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## HIL

- Hardware In Loop for BLDC Motor control using FOC;

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**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:DS100v2 USB

Control Clk. Src: 32 bit timer 2

EPWM Interrupt Event: CTR = 0

Control Clk. Prescale: 1

Ctrl Clk. Count Mode:

DLLEXD Version: VisSim/ECD for F280K 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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**618**

## ePWM CONFIGURATION

**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 SYNC pulse TBPHS (phase): 0

Change Phase Dynamically EPWMSYNCO pin: GPIO6

EPWMSYNCO: EPWMSYNCO EPWMSYNCO pin: Unused

CMPA Load On: CTR = Zero CMPB Load On: CTR = Zero

Action Qualifier:

	CMPA		CMPB			
	up	down	up	down	P	GPIO Pin
EPWMA:	X	X	X	X	X	GPIO0
EPWMB:	X	X	X	X	X	GPIO1

Deadband:

Delay Mode: Disabled

Polarity: No Inversion

Input Select: D1A in = PwMA, D1B 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  Digital Compare...

EPWMB output on fault: High impedance

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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# EPWM CONFIGURATION

- Switching Frequency settings
- $F_s=20\text{kHz}$ :
- $T_{pwm}=2 \cdot T_{bprd} \cdot T_{bclk}$ ;
- $1/20\text{k}=2 \cdot 1/80\text{M} \cdot T_{bprd}$ ;
- $T_{bprd}=2000$ ;
- Count Mode: up/down;



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# ADC CONFIGURATION

Interrupt settings for SOC  
 Sampling Period settings  
 Start Of Conversion trigger settings  
 Samplings for two different sequences  
 Different ADC Result Registers

ADC F28062 Properties

SYSCLK: 80 Mhz

ADCLK: SYSCLK / 6 13.33 Mhz

Interrupt on Conversion Start

ADC Result Register	Src	Trigger	Sample Clks	Dual Sample
ADCRESULT0	A0	Timer 2	7	<input type="checkbox"/>
ADCRESULT1	A1	Timer 2	7	<input type="checkbox"/>
ADCRESULT2	A2	Timer 2	7	<input type="checkbox"/>
ADCRESULT3	A3	Timer 2	7	<input type="checkbox"/>
ADCRESULT4	A4	Timer 2	7	<input type="checkbox"/>
ADCRESULT5	A5	Timer 2	7	<input type="checkbox"/>
ADCRESULT6	A6	Timer 2	7	<input type="checkbox"/>
ADCRESULT7	A7	Timer 2	7	<input type="checkbox"/>
ADCRESULT8	B0	Timer 2	7	<input type="checkbox"/>
ADCRESULT9	B1	Timer 2	7	<input type="checkbox"/>
ADCRESULT10	B2	Timer 2	7	<input type="checkbox"/>
ADCRESULT11	B3	Timer 2	7	<input type="checkbox"/>
ADCRESULT12	B4	Timer 2	7	<input type="checkbox"/>
ADCRESULT13	B5	Timer 2	7	<input type="checkbox"/>
ADCRESULT14	B6	Timer 2	7	<input type="checkbox"/>
ADCRESULT15	B7	Timer 2	7	<input type="checkbox"/>

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**CAN CONFIGURATION**

**CAN Receive Properties**

- CAN Device: A
- Data Pins: 2
- Mailbox Number: 3
- Message ID(11 bits): 0x7F9
- Masking Register (enter zero for no masking): 0x00
- Mux Pin: GPIO30
- Receive extended frames
- Set address dynamically
- Data Pin Configuration:
  - Pin: 1 Type: signed 2-byte
  - Radix Point: 4 Word Size: 16
  - Byte offset into CAN packet: 0

**Controller Area Network Configuration**

- Unit: A
- Bus Rate (BPS in Mbits): 6.666667
- Baud Rate Prescale (1-255): 1
- TSeg1: 3 TSeg2: 2
- Sample Point: 1 Point Sync Jump Width: 1
- Synchronization: Falling Byte Order: Big Endian

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**I2C CONFIGURATION**

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

**I2C Port Properties**

- Port: A
- Prescale (I2CPSC): 0 0..255
- High Time (I2CCLKH): 100 1..65535
- Low Time (I2CCLKL): 100 1..65535
- Data Bits: 1
- Address Mode: 7
- Own Address: 0
- Mux Pin: GPIO28/GPIO29
- Tx Queue Length: 16
- Rx Queue Length: 16
- Use Freeform Mode (no addressing):

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## 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;

**SPI Configuration Properties**

Unit: SPIA Transmitted Bits: 16

Clk Src: LSPCLK

Bit Rate: LSPCLK/4 5 MHz

Sync Data: on clk edge

CLK Polarity: send on rise/latch on fall

Network Mode: Slave

STE mode: Active Low

Use FIFO FIFO Tx Xfer Delay: 0

Use TX Soft Queue Length: 16

Interrupt on TX FIFO Queue Level: 1

Use RX Soft Queue Length: 16

Interrupt on RX FIFO Queue Level:

**Mux Pin Assignment**

SPISIMO: GPIO5 SPISOMI: GPIO3

SPICLK: GPIO18 SPISITE: GPIO19

OK Cancel Help

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## UART CONFIGURATION

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

**Serial Port Config**

Port: A Parity: None

Baud Rate: 300 Data Bits: 7

Stop Bits: 1

Tx Queue Length: 16

Rx Queue Length: 16

**Mux Pin Assignment**

SCIRX: GPIO7 SCITX: GPIO12

OK Cancel Help

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**eCAP CONFIGURATION**

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**eCAP Configuration**  
Pre-scaling option of the input

Mux GPIO pin which is to be used as eCAP;

Maximum of 4 events can be captured for the same signal.

Pre-scaling option of the input

**280x eCap Properties**

Capture Unit: 1 Input Prescale: None  
 Max Events: 1 Mux Pin: GPIO5

Event 1: trigger on rising edge  Reset Counter on Capture  
 Event 2: trigger on rising edge  Reset Counter on Capture  
 Event 3: trigger on rising edge  Reset Counter on Capture  
 Event 4: trigger on rising edge  Reset Counter on Capture

OK Cancel Help

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**BUFFERS**

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- 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;

**F28062-Monitor Buffer Read/Write**

Trig Buffer

trig(16..16) F28062-Monitor Buffer Write  
 signal 0

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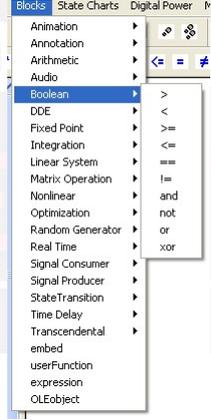
626


627

## OTHER EMBEDDED BLOCKS



**Used for conversion of the variables to different data types**



**Different Blocks set used in Embedded:**

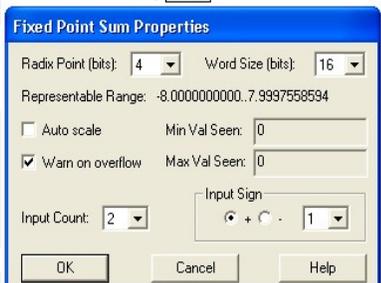
- Arithmetic;
- Boolean;
- Fixed Point;
- Matrix operations (2D/3D Tables);
- Time Delay;
- Non-Linear Block sets:
- If Else;
- Case switch;
- Gain;
- etc;
- Fixed point block sets:
- Atan;
- Cos, Sin;
- Multiply, Divide;
- PI, PID Regulators;
- Summation;
- Signed / Unsigned integers;
- Abs;
- Sample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

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## 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

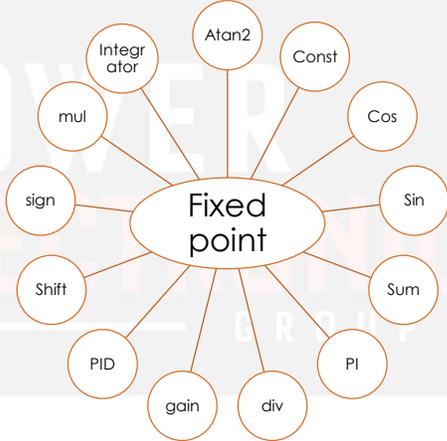
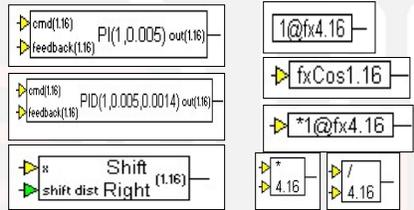
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# Other Embedded Blocks



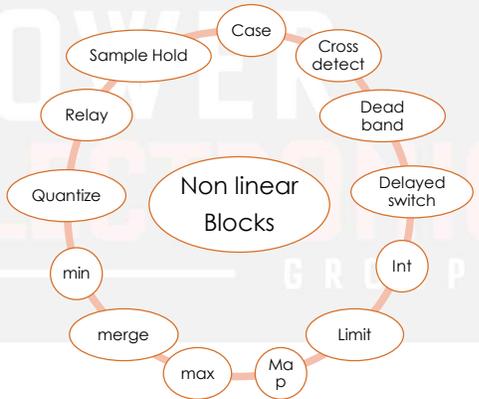
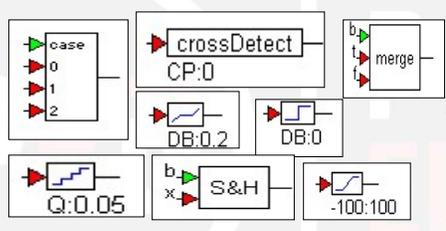
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# Other Embedded Blocks



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# CODE GENERATION

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

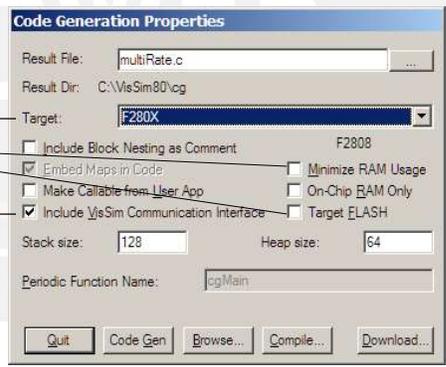
Option to minimize the RAM usage;

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;

MCU target selection

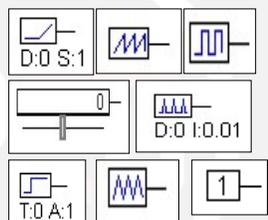
Flashing the code directly



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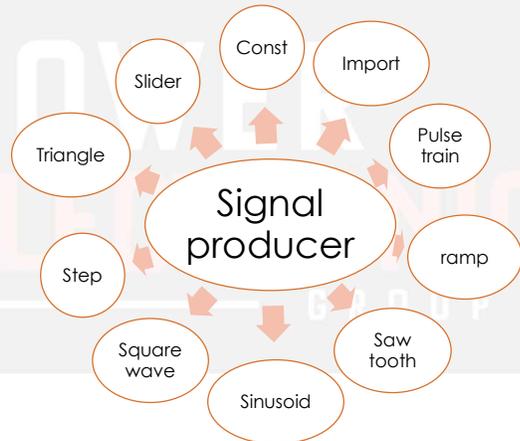


# SIMULATION BLOCKS



Different types of Sources

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



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## EX:1 MATRIX & COMPLEX NUMBERS

**Matrix Examples**

ones(3,4) → 

1	1	1	1
1	1	1	1
1	1	1	1

zeros(3,4) → 

0	0	0	0
0	0	0	0
0	0	0	0

diag([1:3]) → 

1	0	0
0	2	0
0	0	3

diag([1:5:3]) → 

1	0	0	0	0
0	1.5	0	0	0
0	0	2	0	0
0	0	0	2.5	0
0	0	0	0	3

eye(5) → 

1	0	0	0	0
0	1	0	0	0
0	0	1	0	0
0	0	0	1	0
0	0	0	0	1

**Complex Numbers Examples**

(5,6) → complexToReIm → real: 5, imag: 6

(5,6) → magPhase → mag: 7.81025, phase: 876058

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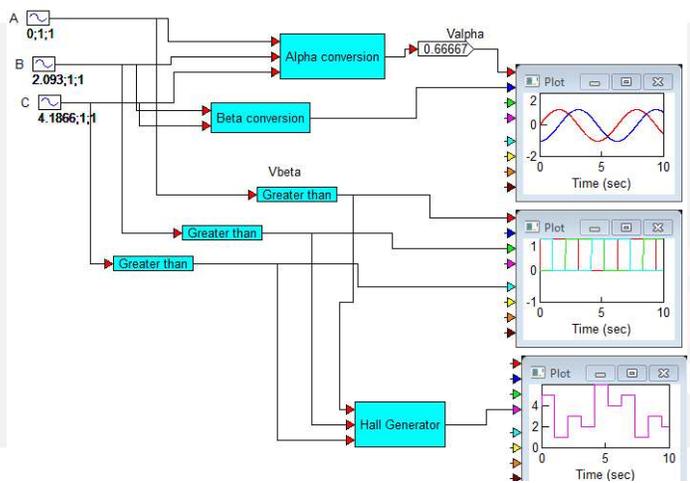
## 3-PHASE TO 2-PHASE CONVERSION & HALL CODE GENERATION

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

A 0,1,1

B 2.093,1,1

C 4.1866,1,1



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**DUTY CYCLE GENERATION USING SVM METHOD**

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**FOC FOR ACIM**

Rate Estimator Poles (Hertz):	120
Processor Clock (Hertz):	10000
Resolution (lines):	4000

Number of Motor Poles:	2
Stator Inductance (per phase) (H):	.165
Stator Resistance (per phase) (Ohms):	4.495
Stator Leakage Inductance (H):	.016
Rotor Resistance (Ohms):	5.365
Rotor Leakage Inductance (H):	.013
Rotor Moment of Inertia (Kg-m <sup>2</sup> ):	.001
Rotor Shaft Coulomb Friction Magnitude (N-m):	0
Rotor Shaft Stiction Factor (N-m):	0
Rotor Shaft Viscous Damping Factor (Kg-m <sup>2</sup> /s):	.001

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**Field Orientated Controller (FOC) Properties**

Number of Poles:	2	Direct Axis Current Control Upper Sat limit (Amp):	220
Sampling Rate (Hertz):	10000	Direct Axis Current Control Lower Sat Limit (Amp):	-220
Inverter DC Bus Voltage (volts):	310	Quadrature Axis Current Control Integral Gain:	0.00625
Stator Inductance (per phase) (H):	.165	Quadrature Axis Current Control Proportional Gain:	.8
Stator Leakage Inductance (H):	.016	Quadrature Axis Current Control Upper Sat limit (Amp):	220
Rotor Leakage Inductance (H):	.013	Quadrature Axis Current Control Lower Sat Limit (Amp):	-220
Rotor Resistance (Ohms):	5.365	Speed Control Integral Gain (Amp/rad):	5e-5
Direct Axis Current Control Integral Gain:	.00625	Speed Control Proportional Gain (Amp-s/rad):	45.1
Direct Axis Current Control Proportional Gain:	.8	Speed Control Upper Sat limit (Amp):	50
		Speed Control Lower Sat Limit (Amp):	-50

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**Speed Control of 3 Phase AC Induction Motor**

Graph showing Actual Measured Motor Speed (red line) and Commanded Motor Speed (blue line) over Time (sec). The speed steps up from 0 to 100 rad/sec at 0.5s, 150 rad/sec at 1.5s, and 200 rad/sec at 3.0s.

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**REFERENCE FRAMES IN VECTOR CONTROL**

The diagram illustrates the process of converting a 3-phase AC source into a rotating reference frame. It includes the following components and plots:

- 3 Phase AC Source:** Provides three-phase voltage signals (a-phase, b-phase, c-phase).
- Clarke Transform:** Converts the three-phase signals into a 2-axis stationary reference frame (alpha and beta axes).
- Park Transform:** Converts the 2-axis stationary signals into a rotating reference frame (D and Q components).
- Angle Shift (rad):** A constant value of 0.502656 is used for the Park Transform.
- Plots:**
  - 3 phase:** Shows three sinusoidal waveforms over 10 seconds.
  - 2 axis Stationary ...:** Shows the alpha and beta components of the stationary frame.
  - Rotating Frame:** Shows the D component (DC) and Q component (AC) in the rotating frame.
  - Angle:** Shows a sawtooth wave representing the reference angle in radians over 10 seconds.

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**SYSTEM PROPERTIES**

The image shows two screenshots of the 'System Properties' dialog box, highlighting different configuration options:

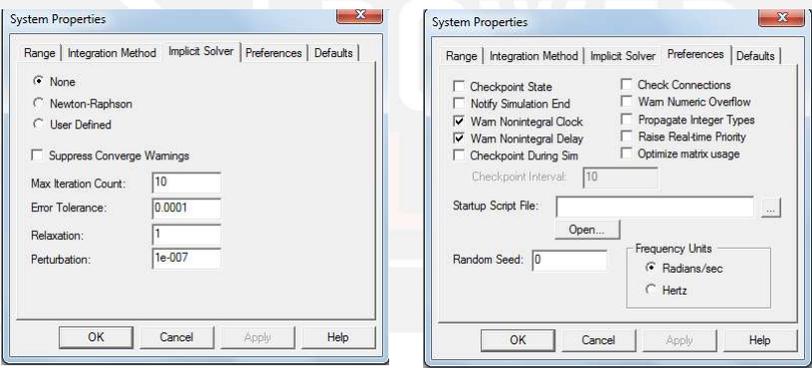
- Left Screenshot:** Shows the 'Range' tab with the following settings:
  - Start (sec): 0
  - Time Step: 0.001
  - End (sec): 1
  - Units: Seconds
  - Run in Real Time:
  - Auto Restart:
  - RT Scale Factor: 1
  - Retain State:
- Right Screenshot:** Shows the 'Integration Method' tab with the following settings:
  - Integration Method: Runge Kutta 2nd order
  - Nonlinear Solver: Functional iteration
  - Min Step Size: 1e-006
  - Max Truncation Error: 1e-005
  - Max Iteration Count: 250

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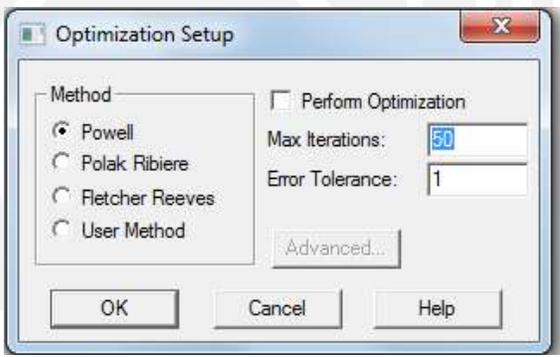
# SYSTEM PROPERTIES



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# SYSTEM PROPERTIES

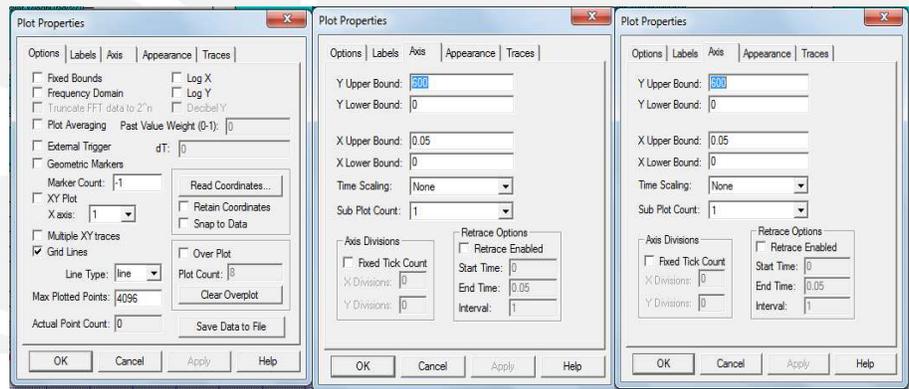


- Optimize the simulation;
- Minimize convergence problems;
- Set the error tolerance;
- Change the step size;
- Various methods of optimization are available;
- Various ready-made blocks available;
- Various Examples of different concepts readily available;

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# PLOT PROPERTIES

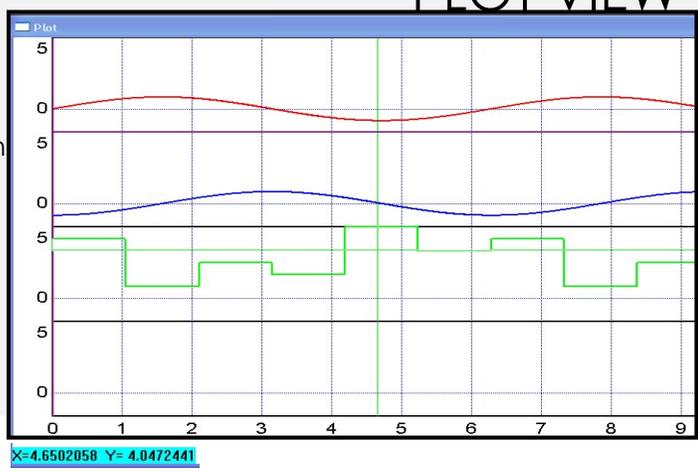


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# PLOT VIEW

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



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