U20EE702/ SOLID STATE DRIVES

UNIT I/ DRIVE CHARACTERISTICS

Equations Governing Motor Load Dynamics

The dynamic behavior of an electric drive is governed by **Newton's Second Law of Motion** for rotating systems:

➤ Torque Equation:

Tm−TL=JdωdtT_m - T_L = J \frac{d\omega}{dt}Tm−TL=Jdtdω

Where:

- TmT_mTm = Motor torque
- TLT_LTL = Load torque
- JJJ = Moment of inertia of the system
- ω\omegaω = Angular speed (rad/s)

This equation explains how net torque affects angular acceleration.

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2. Steady-State Stability

A drive is said to be in **steady-state** when:

Tm=TLanddωdt=0T_m = T_L \quad \text{and} \quad \frac{d\omega}{dt} = 0Tm=TLanddtdω =0

➤ Stability Condition:

For **stable operation**, if there's a small disturbance in speed:

- If speed increases → motor torque should decrease → system should return to steady speed.
- Mathematically:

d(Tm−TL)dω<0\frac{d(T_m - T_L)}{d\omega} < 0dωd(Tm−TL)<0

This ensures that the system resists changes and returns to its steady operating point.

◆ 3. Multi-Quadrant Dynamics

Electric drives can operate in **four quadrants** of the torque-speed plane:

Quadrant	Speed	Torque	Mode
I	+ve	+ve	Forward motoring
II	+ve	–ve	Forward braking
III	–ve	–ve	Reverse motoring
IV	–ve	+ve	Reverse braking

➤ Drive Capabilities:

- **2-Quadrant Drives**: Forward motoring + braking
- **4-Quadrant Drives**: Full control over motoring and braking in both directions

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◆ 4. Starting, Acceleration, Deceleration, Stopping

➤ Starting:

- Requires high torque to overcome inertia.
- Inrush current is limited via soft starters or resistors.

➤ Acceleration:

From the torque equation:

$$\alpha = \frac{T_m - T_L}{J}$$

- Motor should provide torque > load torque for acceleration.

➤ Deceleration:

- Motor torque < load torque
- Done via:
  - **Regenerative braking**: Motor acts as generator
  - **Dynamic braking**: Kinetic energy is dissipated in resistors
  - **Plugging**: Reverse voltage applied to quickly stop the motor

➤ Stopping:

- Natural stopping (coasting)
- Controlled stopping (braking techniques above)

◆ 5. Typical Load Torque Characteristics

Different mechanical loads have different torque-speed characteristics:

Type of Load	Torque vs Speed	Example
Constant Torque	TL=constT_L = \text{const}TL=const	Conveyors, lathes
Torque ∝ Speed	TL∝ωT_L \propto \omegaTL∝ω	Fans, pumps
Torque ∝ Speed^2	TL∝ω2T_L \propto \omega^2TL∝ω2	Centrifugal pumps
Variable / Shock	Varies non-linearly	Crushers, presses

◆ 6. Selection of Motor

➤ Key Factors:

1. **Load Characteristics** – constant or variable torque
2. **Speed Range & Control** – wide or narrow
3. **Starting Torque** – required torque to overcome inertia
4. **Braking Requirements**
5. **Duty Cycle** – continuous, intermittent, etc.
6. **Environmental Conditions** – temperature, humidity, dust
7. **Cost & Efficiency**

➤ Motor Types Based on Application:

Load Type	Recommended Motor
Constant torque	DC shunt, 3-phase induction
Variable torque	Squirrel cage induction
High starting torque	Series DC, slip-ring motor
Precise speed control	DC or servo motor

🔚 Summary

Motor-load dynamics are key to understanding drive behavior.

- Steady-state stability ensures reliable operation.
- Drives must handle all four quadrants for complete control.
- Motor selection depends on mechanical load and system requirements.

UNIT II/ CONVERTER / CHOPPER FED DC MOTOR DRIVE

1. Introduction

- DC motors are widely used in variable speed drives due to their easy speed control and high starting torque.
- They can be powered by **thyristor converters** or **choppers**.
- Control strategies include **time ratio control**, **current limit control**, and **4-quadrant operation**.

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2. Converter Fed Separately Excited DC Motor Drive

2.1 Types of Converters

- **Single-phase fully controlled rectifier**
- **Three-phase fully controlled rectifier**
- Both provide controlled DC output voltage to the motor.

2.2 Steady-State Analysis

A. Assumptions:

- Continuous conduction mode (CCM)
- Armature resistance R_a, inductance L_a, and back EMF E_b considered

B. Average Output Voltage:

- **Single-phase full converter**:
  $V_{avg} = \frac{2V_m}{\pi} \cos(\alpha)$
  where V_m = peak AC voltage, α = firing angle
- **Three-phase full converter**:
  $V_{avg} = \frac{3\sqrt{3}V_m}{\pi} \cos(\alpha)$

C. Armature Voltage Equation:

$V_a = E_b + I_a R_a$
(Where I_a = armature current, V_a = average voltage from converter)

2.3 Continuous Conduction Mode (CCM)

- The current through the motor never falls to zero.
- Better torque and smoother operation.
- Requires sufficient armature inductance.

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3. Chopper Fed DC Motor Drive

3.1 Chopper Basics

- A chopper is a DC-DC converter using semiconductor switches (e.g., IGBT, MOSFET).
- Converts fixed DC to variable DC by switching ON/OFF rapidly.

3.2 Time Ratio Control (TRC)

- Control of motor voltage via duty cycle:
  - $V_{avg} = D \cdot V_{in}$, where $D = \frac{T_{on}}{T_{on} + T_{off}}$
- Methods:
  - **Constant Frequency TRC**: Vary T_{on}, keep total period constant.
  - **Variable Frequency TRC**: Vary both T_{on} and frequency.

3.3 Current Limit Control

- Motor current is sensed and limited to a preset value.
- Used to protect motor during startup or overload.
- Chopper turns off when current exceeds limit, turns on again when it falls below lower limit.

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4. Four-Quadrant Operation

Quadrant	Voltage (V)	Current (I)	Operation Type
I	+	+	Forward motoring
II	-	+	Forward braking (regen)

Quadrant	Voltage (V)	Current (I)	Operation Type
III	-	-	Reverse motoring
IV	+	-	Reverse braking (regen)

4.1 In Converter Drives

- Use of dual converters (two full converters in anti-parallel)
- Can reverse voltage and current direction

4.2 In Chopper Drives

- Use of Class A, B, C, D, E choppers
- Class-E chopper is used for full 4-quadrant operation

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5. Applications

5.1 Converter Fed Drives

- Steel rolling mills
- Paper machines
- Elevators
- Machine tools

5.2 Chopper Fed Drives

- Electric traction (e.g., trains)
- Battery-operated vehicles
- Forklifts
- Industrial hoists

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6. Comparison: Converter vs Chopper Fed Drives

Aspect	Converter Fed	Chopper Fed
Input	AC	DC
Complexity	Higher (especially 3-phase)	Lower

Aspect	Converter Fed	Chopper Fed
Efficiency	Lower due to rectification losses	Higher
Control	Less flexible	More flexible
Applications	High power, industrial	Low to medium power, mobile units

UNIT III/ INDUCTION MOTOR DRIVES

INDUCTION MOTOR DRIVES

Induction motor drives are used widely in industry for variable speed applications due to their robustness, low cost, and maintenance-free operation.

⚡ 1. Stator Voltage Control (SVC)

Principle: Varying the stator voltage to control the speed of the induction motor.

- Applied mostly to **squirrel cage motors** for low power applications.
- Torque is proportional to the **square of the voltage**.
- As voltage decreases, torque reduces, limiting the load capability.
- **Speed control is achieved by reducing voltage**, but efficiency and power factor are poor.

Advantages:

- Simple and economical.

Disadvantages:

- Not efficient for high-power applications.
- Poor torque characteristics at low voltages.

Application: Fans, blowers, and pumps where torque demand reduces with speed.

⚙ 2. V/f Control (Constant Voltage/Frequency Control)

Principle: Maintain a constant ratio of voltage (V) to frequency (f) to keep magnetic flux constant.

- Used for **squirrel cage induction motors**.
- Ensures **constant torque operation**.
- Implemented via **inverter-fed drives**.
- Suitable for both open-loop and closed-loop systems.

Types:

- **Open Loop V/f Control**

- **Closed Loop V/f Control** (with speed feedback)

Advantages:

- Simple implementation.
- Good performance for a wide range of speeds.
- Suitable for both constant and variable torque loads.

Applications:

- Conveyors, compressors, pumps, textile machinery.

🌀 3. Rotor Resistance Control

Principle: Adding external resistance in the rotor circuit of a **wound rotor induction motor**.

- Increases slip and hence speed control is possible.
- As resistance increases, speed decreases.

Advantages:

- Good starting torque.
- Simple method for speed control.

Disadvantages:

- High energy losses in resistors.
- Not suitable for continuous operation at reduced speed.

Applications: Cranes, hoists, elevators, where variable speed and high starting torque are needed.

⚙ 4. Slip Power Recovery Drives (SPRD)

Concept: Recover the slip power (rotor power loss) and feed it back to the supply.

Common Methods:

1. **Scherbius Drive**: Slip power returned to the grid through a rectifier and inverter.
2. **Kramer Drive**: Slip power recovered and fed back to the motor shaft via a DC motor.

Advantages:

- Efficient operation.
- Speed control in the sub-synchronous region.

Applications:

- Pumps, compressors, and winders with large power ratings.

🔁 5. Closed Loop Control

Concept: Feedback system that compares actual speed or torque with reference and minimizes the error.

Components:

- Speed/position sensors
- Controllers (PI, PID)
- Feedback loops

Benefits:

- Improved dynamic response
- High accuracy
- Better stability and reliability

Applications:

- Robotics, CNC machines, high-precision industrial equipment.

📐 6. Vector Control (Field Oriented Control - FOC)

Principle: Control of **magnitude and angle** of the stator current vector to independently control torque and flux.

- Converts 3-phase motor equations to 2-axis (d-q) model.
- **Torque control similar to DC motor**.
- Requires complex computations and feedback.

Types:

- Direct vector control
- Indirect vector control

Advantages:

- High dynamic performance
- Accurate control of speed and torque

Disadvantages:

- Requires DSP or microcontroller
- Higher cost

Applications:

- Electric vehicles, high-performance drives, servo systems.

⚙ Applications of Induction Motor Drives

- **Industrial drives**: Conveyors, compressors, blowers
- **Home appliances**: Air conditioners, washing machines
- **Electric Vehicles (EVs)**
- **HVAC systems**
- **Cranes and hoists**

UNIT IV/ SYNCHRONOUS MOTOR DRIVES

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1. V/f Control of Synchronous Motor

 Principle:

- In **V/f control**, the **voltage (V)** is varied in proportion to **frequency (f)** to maintain **constant air-gap flux**.
- Applicable mainly for **constant torque** applications.

⚙ *Key Features:*

- Voltage and frequency are increased or decreased proportionally.
- Maintains **constant excitation** and **power factor**.
- Rotor speed is directly proportional to supply frequency.

🔌 *Used with:*

- Voltage Source Inverter (VSI)
- Open-loop scalar control

📝 *Pros:*

- Simple implementation
- Smooth speed control

⊘ *Cons:*

- Poor dynamic performance
- Not suitable for rapid load/speed changes

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2. Self-Control of Synchronous Motor

 Principle:

- Rotor position is sensed, and the stator supply is synchronized with it.
- Stator supply frequency = Rotor electrical frequency.
- Motor behaves like a **DC motor in dynamic response**.

⚙ *Operation:*

- Uses rotor position sensors (e.g., encoders, resolvers).
- The inverter is **electronically commutated** based on rotor position.

✅ *Advantages:*

- Precise torque and speed control
- Better dynamic performance
- Eliminates hunting and improves stability

🔄 *Common in:*

- Brushless DC motors
- Permanent Magnet Synchronous Motors (PMSMs)
- Vector control applications

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3. Margin Angle Control

💡 *Definition:*

- Also called **load angle control**.
- The **torque angle (δ)** between stator and rotor magnetic fields is controlled to manage torque.

🔧 *Control Strategy:*

- Margin angle is varied to control torque output.
- Angle is maintained within limits to prevent instability.

📈 *Usage:*

- Crucial in **traction drives**, **high-performance servo systems**, and **large synchronous motors**.

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4. Power Factor Control

⚡ *Concept:*

- Power factor of synchronous motors can be controlled by adjusting the **field excitation**.

🌐 *Modes:*

- **Over-excited motor** → Leading power factor (acts like a capacitor)
- **Under-excited motor** → Lagging power factor
- **Normal excitation** → Unity power factor

⚙ *Techniques:*

- Use of feedback to control excitation
- Automatic voltage regulator (AVR) or controlled rectifier

✅ *Benefits:*

- Improved efficiency
- Reduced line losses
- Voltage regulation in power systems

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5. Voltage Source Inverter (VSI) Fed Synchronous Motor

🔌 *VSI Features:*

- Provides variable voltage and frequency supply.
- Can use PWM techniques for better control.

💡 *Advantages:*

- Precise speed control
- Good performance at low speeds
- Less harmonic distortion (with PWM)

⚙ *Applications:*

- CNC machines
- Electric vehicles
- Robotics

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6. Current Source Inverter (CSI) Fed Synchronous Motor

🔌 *CSI Features:*

- Provides constant current output.

- Output frequency is varied to control speed.

✅ *Pros:*

- Inherent short-circuit protection
- Suitable for applications requiring constant current

🔄 *Used in:*

- High power applications
- Synchronous motor drives in steel and cement industries

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7. Applications of Synchronous Motor Drives

🚀 *Industrial Applications:*

- High power constant speed drives (pumps, compressors)
- Traction (electric trains)
- Conveyor belts
- Rolling mills
- Wind energy conversion systems

⚙ *Servo Applications:*

- Robotic actuators
- Aerospace actuators
- CNC machine tools

💡 *Power System:*

- Power factor correction (when over-excited)
- Grid synchronization in renewable energy systems

☐ Summary Table:

Control Method	Key Feature	Used In
V/f Control	Simple scalar control	Fans, pumps
Self-Control	Rotor-position based	PMSMs, robotics

Control Method	Key Feature	Used In
Margin Angle Control	Torque control via angle	High performance drives
Power Factor Control	Excitation-based	Grid applications
VSI Fed Drive	Variable V/f	General purpose drives
CSI Fed Drive	Constant current	Heavy industry

UNIT V/ DESIGN OF CONTROLLERS FOR DRIVES

1. TRANSFER FUNCTION OF DC MOTOR (Armature-Controlled)

The **DC motor** dynamics (assuming separately excited) can be derived using basic electrical and mechanical equations.

a. Electrical Equation:

Va(s)=RaIa(s)+LasIa(s)+Eb(s)V_a(s) = R_a I_a(s) + L_a s I_a(s) + E_b(s)Va(s)=RaIa(s)+LasIa(s)+Eb(s)

Where:

- VaV_aVa: Armature voltage
- IaI_aIa: Armature current
- RaR_aRa: Armature resistance
- LaL_aLa: Armature inductance
- Eb=KbωE_b = K_b \omegaEb=Kbω: Back emf

b. Mechanical Equation:

Tm(s)=Jsω(s)+Bω(s)T_m(s) = J s \omega(s) + B \omega(s)Tm(s)=Jsω(s)+Bω(s)

Where:

- Tm=KtIa(s)T_m = K_t I_a(s)Tm=KtIa(s): Torque (motor torque proportional to armature current)
- JJJ: Moment of inertia
- BBB: Friction coefficient
- ω\omegaω: Angular speed

c. Transfer Function (Speed/Voltage):

Combining electrical and mechanical equations:

ω(s)Va(s)=Kt(JLs2+(JLb+RaJ+BLa)s+(RaB+KtKb))\frac{\omega(s)}{V_a(s)} = \frac{K_t}{(JLs^2 + (JL_b + R_aJ + BL_a)s + (R_aB + K_tK_b))}Va(s)ω(s)=(JLs2+(JLb+RaJ+BLa)s+(RaB+KtKb))Kt

Approximate 1st-order model (neglecting LaL_aLa and small terms):

ω(s)Va(s)=Kτs+1\frac{\omega(s)}{V_a(s)} = \frac{K}{\tau s + 1}Va(s)ω(s)=τs+1K

Where:

- K=GainK = \text{Gain}K=Gain
- τ=Time constant\tau = \text{Time constant}τ=Time constant

✅ 2. CLOSED LOOP CONTROL – CURRENT AND SPEED FEEDBACK

a. Control Loops:

DC drive systems often use **two control loops**:

1. **Inner Loop** – Current Controller
2. **Outer Loop** – Speed Controller

Reason: Current loop is faster and ensures torque control; speed loop is slower and ensures velocity regulation.

✅ 3. ARMATURE VOLTAGE CONTROL

Used below base speed.

Key Features:

- Vary VaV_aVa to control speed.
- Torque remains constant (because flux is constant).
- Linear speed-torque characteristic.

✅ 4. FIELD WEAKENING MODE

Used **above base speed**.

- Reduce field current IfI_fIf, decreasing flux ϕ\phiϕ.
- Since ω∝Vϕ\omega \propto \frac{V}{\phi}ω∝ϕV, speed increases.
- **Torque decreases** as flux weakens (constant power region).

✓ 5. DESIGN OF CONTROLLERS

a. Current Controller (Inner Loop)

Objective:

Regulate armature current IaI_aIa quickly and accurately.

Typical Controller:

- **PI controller** (Proportional + Integral)

Design Steps:

1. Derive motor transfer function (current loop)
2. Choose desired bandwidth
3. Design PI gains to match desired response

Gc(s)=Kp+KisG_c(s) = K_p + \frac{K_i}{s}Gc(s)=Kp+sKi

b. Speed Controller (Outer Loop)

Objective:

Maintain desired motor speed.

Control Strategy:

- Typically PI control used
- Outer loop slower than current loop (cascade control)

Design Guidelines:

- Choose speed loop bandwidth ~10× slower than current loop
- Tune PI gains to eliminate steady-state error and maintain stability

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✓ 6. CONVERTER SELECTION AND CHARACTERISTICS

a. Types of Converters:

1. **Controlled Rectifier** (AC-DC)

  - Single-phase or 3-phase SCR bridge
  - Output voltage controlled via firing angle
2. **Chopper (DC-DC Converter)**
  - Buck/Boost converters for precise voltage control

b. Selection Criteria:

- Power rating of motor
- Type of control (speed/torque)
- Bidirectional operation (regenerative braking)

c. Converter Characteristics:

- Input/output voltage and current ratings
- Firing angle control
- Harmonics and filtering needs

✅ 7. BLOCK DIAGRAM – DC MOTOR DRIVE WITH CONTROLLERS

plaintext
CopyEdit
```
Speed Reference (ω*)
     ↓
 [Speed Controller (PI)]
     ↓
 Current Reference (I*)
     ↓
 [Current Controller (PI)]
     ↓
 PWM / Converter
     ↓
 DC Motor
     ↑
Speed Feedback (ω) ← Tachogenerator / Encoder
     ↑
Current Feedback (I_a) ← Current Sensor / Shunt
```

✅ 8. SUMMARY

Control Mode	**Voltage Control**	**Field Weakening**
Speed Range	0 to base speed	Above base speed

Control Mode	Voltage Control	Field Weakening
Torque	Constant	Decreases
Power	Increases	Constant

Controller	Type	Notes
Current Controller	PI	Fast inner loop
Speed Controller	PI	Slow outer loop
