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ACTUATORS CONTROL SYSTEMS
LAB WORK REPORT

Lab 2 Indirect Field-Oriented Control (IFOC) of an Induction Motor

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Objective:

This laboratory exercise aims to study and implement Indirect Field-Oriented Control (IFOC) for induction motors. Key objectives include analyzing torque and flux decoupling in dq-coordinates, investigating PI controller effects on system dynamics, and using optimization techniques for controller tuning to achieve optimal performance.

Theoretical Background

1. dq-Control and Reference Frame Theory

The dq-reference frame transformation (also known as Park transformation) is a fundamental concept in AC motor vector control. It converts three-phase stationary AC quantities (abc-frame) into two-phase rotating DC quantities (dq-frame):

- d-axis (direct axis): Aligned with the rotor flux vector, controlling flux-producing current I_d
- q-axis (quadrature axis): Perpendicular to d-axis, controlling torque-producing current I_q

The transformation enables AC motors to be controlled like DC motors, where torque and flux can be regulated independently.

2. Flux-Torque Decoupling in IFOC

Indirect Field-Oriented Control (IFOC) achieves decoupled control by:

- Estimating the rotor flux position using the slip frequency formula:
  $\omega_{slip} = (R_r \cdot I_q)/(L_r \cdot I_d)$
- Maintaining constant rotor flux (Ψ_r = constant) via d-axis current control
- Controlling electromagnetic torque via q-axis current:
  $M_{em} = (3/2) \cdot p \cdot (L_m/L_r) \cdot \Psi_r \cdot I_q$
- Ensuring orthogonal orientation between flux and torque components

3. PI Controller Tuning Principles

The PI regulators in IFOC serve critical functions:

- Flux PI controller: Maintains I_d at reference value for constant flux
- Torque PI controller: Regulates I_q to achieve desired torque
- Cross-coupling compensation: Compensates for inherent coupling between dq-axes

Performance criteria for PI tuning include:

- Stability: All poles within unit circle (discrete systems)
- Damping ratio ($\zeta > 0.4$): Adequate oscillation suppression
- Response speed: Fast settling time without excessive overshoot
- Steady-state accuracy: Zero steady-state error through integral action

A. Initialization

Understanding Per-Unit Normalization:

Base impedance = $Unom^2$ / Pnom = 380^2 / 7500 ≈ 19.25 Ω
Actual Rs = Rs_p.u. × Base_impedance = 0.038 × 19.25 ≈ 0.73 Ω
Base current = Pnom / (√3 × Unom) = 7500 / (√3 × 380) ≈ 11.4 A
Parameters are normalized to make the system universal and easily scalable

Task 1 - Initialization

Rated Power P_nom: __7.5__ kW
Rated Torque M_nom: __49.6__ Nm
Rated Slip: __0.0367__
DC-Link Voltage U_dc: __500__ V
Sampling Period T_s: __0.000 001__ s

B. Controller Optimization

SEARCH.m Algorithm Analysis:

```
% Algorithm structure:
for jp = 1:1000,          % 1000 steps for Kp
   for ji = 1:1000,       % 1000 steps for Ki
      kp = (jp/1000)*0.76;  % Kp range: 0 to 0.76
      ki = (ji/1000)*3.04;  % Ki range: 0 to 3.04

      [k,z] = rootscalc(kp,ki);     % Calculate system poles
      perf = performance(z);        % Evaluate performance index

      if perf < best_perf,          % Find minimum performance index
         best_p = kp; best_i = ki; best_perf = perf;
      end;
   end;
end;
```

How the Algorithm Minimizes Instability:

1. Penalizing Poles on Positive Real Axis:

In performance.m: if real(z(ii)) < -0.6, per = per+1000; end
Actually penalizes highly negative real parts which indicate excessive stability but poor response
For discrete systems, instability occurs when |z| > 1, not real(z) > 0

2. Penalizing Poles Close to Unit Circle:

```
if abs(z(ii)) > 0.85, per = per+1000; end;
if abs(z(ii)) > 0.6, per = per + ((abs(z(ii))-0.55)^2*10); end;
```

Poles near unit circle ($|z| \to 1$) indicate poor stability margins
Severe penalty (+1000) for $|z| > 0.85$
Progressive penalty for $|z| > 0.6$ to ensure adequate stability margin

3. Penalizing Poor Damping Ratios (< 0.4):

```
if abs(imag(z(ii))) > 0,
   s = log(z(ii));
   dampcos = abs(real(s))/abs(s);
   if dampcos < 0.4, per = per + ((0.4-dampcos)^2*25); end;
end;
```

Damping ratio (ζ) calculated from discrete poles
Minimum requirement: $\zeta \geq 0.4$ for adequate oscillation suppression
Quadratic penalty increases as damping decreases below 0.4
Ensures well-damped transient response without excessive overshoot

Performance Optimization Process:

Grid Search: Exhaustively tests 1,000,000 parameter combinations
Pole Analysis: For each (Kp, Ki) pair, computes closed-loop system poles
Performance Scoring: Assigns penalty scores based on stability criteria
Optimal Selection: Chooses parameters with minimum performance index

Expected Outcome:

The algorithm will converge to PI parameters that provide:
Adequate stability margins (poles well inside unit circle)
Good damping characteristics ($\zeta \geq 0.4$)
Fast dynamic response without excessive oscillation
Robust performance across operating conditions

Task 2 – PI Controller Optimization

$K_p = 0.08664$

$K_i = 0.00912$

C. System Simulation

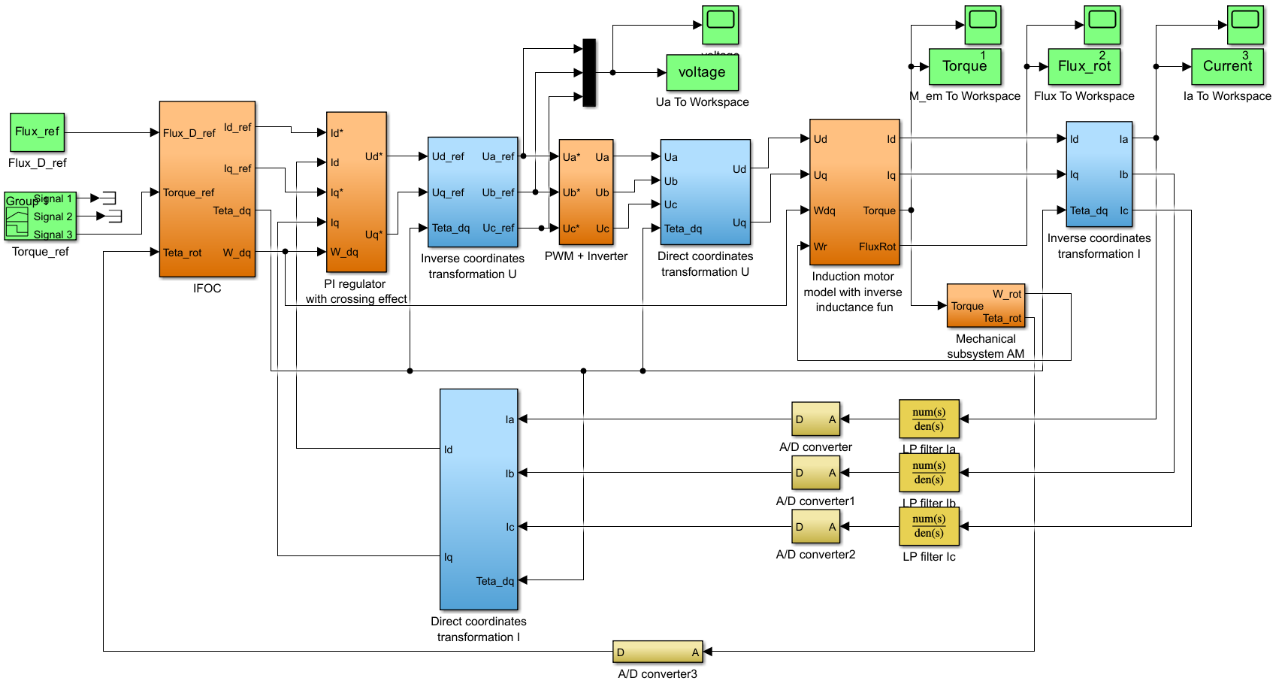

Figure 1. Simulation Model.

Comment:

The simulation system implements an indirect field-oriented control (IFOC) structure for an induction motor, comprising seven core subsystems. The reference generation unit sets the desired rotor flux and electromagnetic torque values. The field-oriented control unit transforms measured currents into the dq-frame and computes reference voltages (U_d^*) and (U_q^*) for decoupled torque and flux control. PI regulators with cross-coupling compensation minimize flux and torque errors, with their proportional gain (K_p) and integral gain (K_i) optimized via a search algorithm in SEARCH.m. The PWM inverter and dq-to-abc transformation module convert dq-axis voltages into three-phase voltages applied to the induction motor model. The motor model, built using an inverse inductance function, simulates electromagnetic torque (M_{em}), rotor flux (Ψ_r), and three-phase currents (I_a), (I_b), (I_c). The mechanical subsystem models rotor angular speed and position under load. The measurement and signal conditioning section includes A/D conversion, low-pass filtering, and variable recording interfaces for observing key dynamic signals. The entire system is integrated in Simulink, enabling end-to-end simulation from control to motor dynamics.

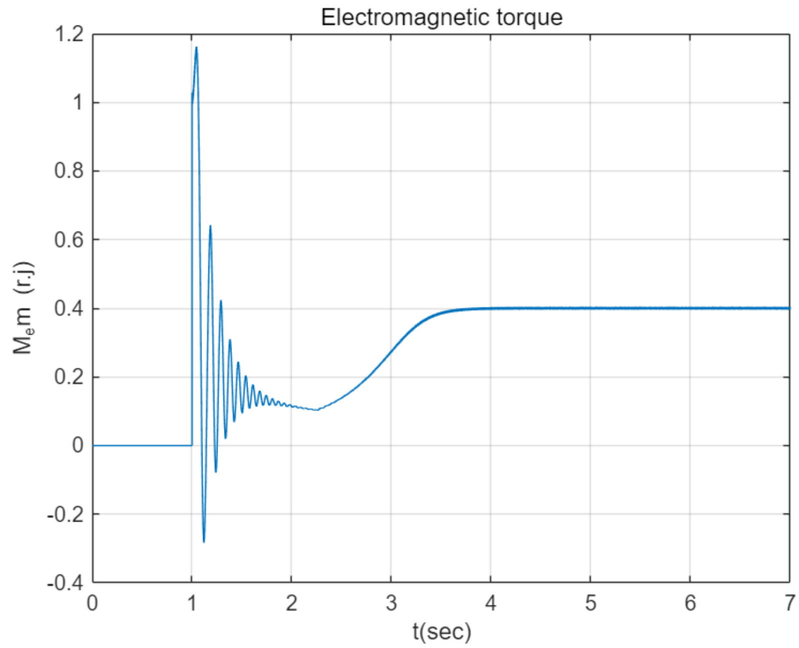

Figure 2. Electromagnetic Torque.

Comment:

The torque gradually approaches a stable value after undergoing attenuation and oscillation.

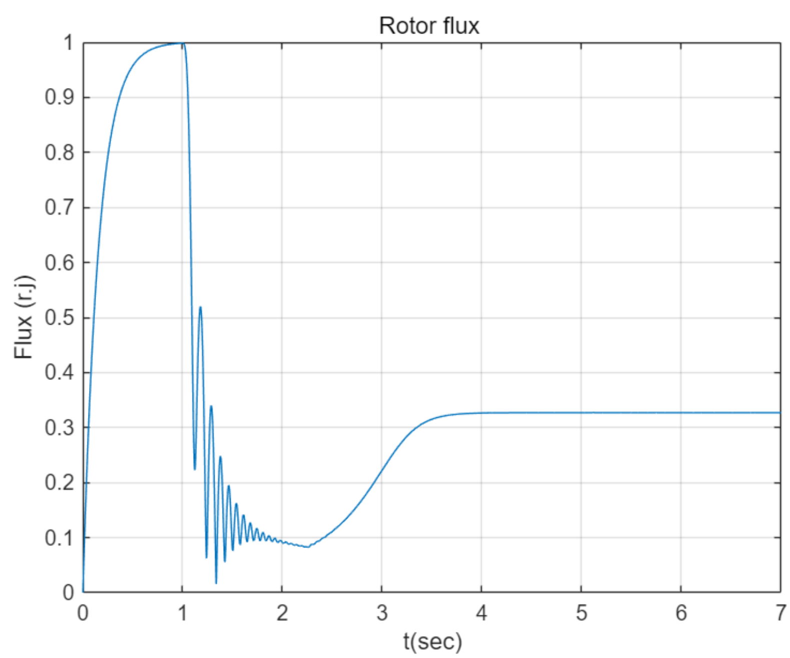

Figure 3. Rotor flux.

Comment:

The magnetic flux of the stator reaches its maximum value rapidly at the beginning, and then gradually decays to the stable value of 0.3.

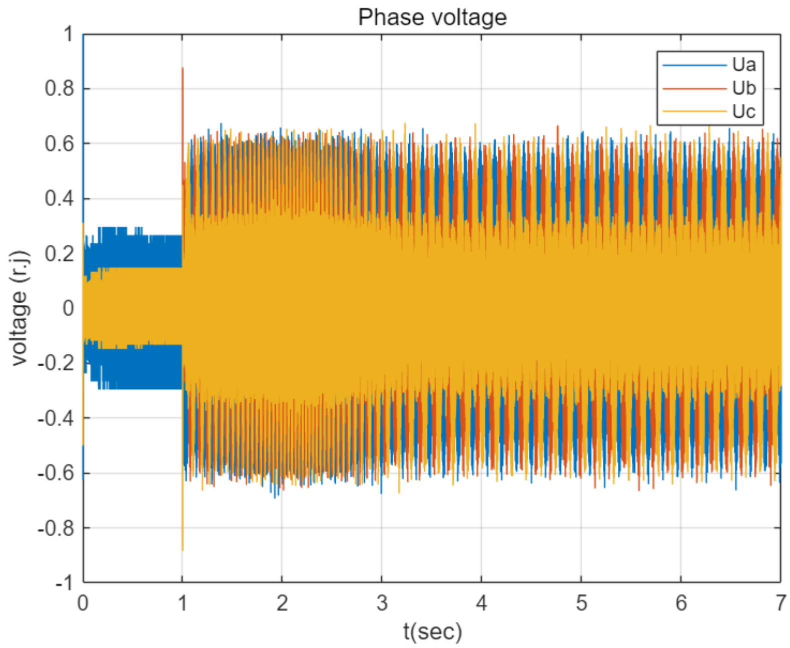

Figure 4. Phase voltage.

Comment:

The phase voltage starts at a lower value and then reaches a stable state.

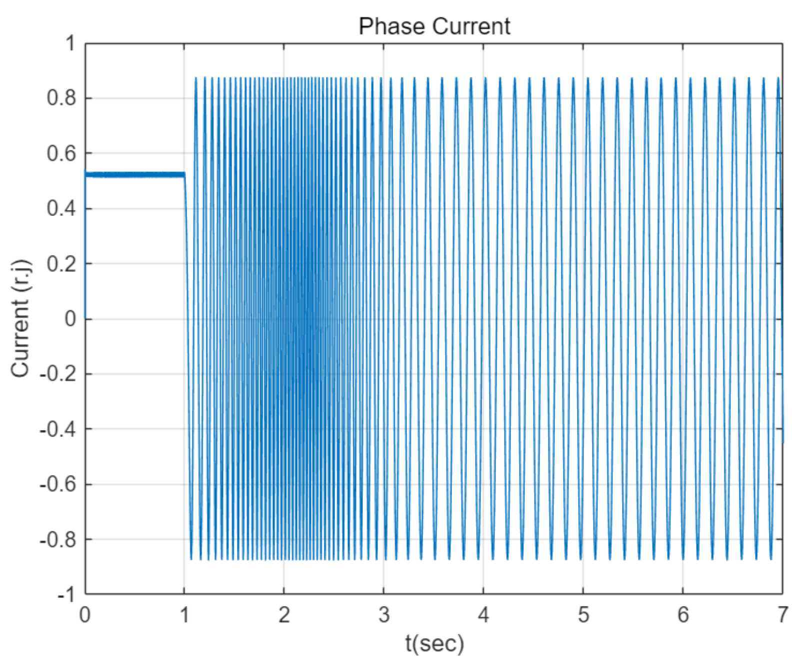

Figure 5. Phase current.

Comment:

The current starts with direct current and then undergoes simple harmonic oscillation, rising from high to low and eventually stabilizing.

Discussion Questions

1. Advantages of Vector Control over Scalar (V/f) Control

Vector control (FOC) provides superior dynamic performance compared to scalar V/f control. While V/f control maintains a constant voltage-to-frequency ratio for steady-state operation, it suffers from poor torque response, coupling between flux and torque, and instability at low speeds. In contrast, vector control enables decoupled control of torque and flux, similar to DC motor control, providing faster dynamic response, higher efficiency, better low-speed performance, and precise torque control across the entire speed range.

2. Physical Quantities Corresponding to Id and Iq

Id (direct-axis current): Represents the magnetizing current component that produces the rotor flux. It aligns with the rotor flux vector and controls the magnetic field strength in the motor.

Iq (quadrature-axis current): Represents the torque-producing current component. It is perpendicular to the flux vector and directly controls the electromagnetic torque generation.

3. How dq-Transformation Simplifies AC Motor Control

The dq-transformation (Park transformation) converts three-phase AC quantities in the stationary reference frame (abc) into two-phase DC quantities in a rotating reference frame (dq). This transformation simplifies AC motor control by:

Transforming time-varying AC quantities into constant DC values in steady state
Enabling independent control of torque (via Iq) and flux (via Id)
Facilitating the use of simple PI controllers similar to DC motor drives
Eliminating the coupling between motor variables present in the stationary frame

4. Effects of Improper PI Gains

If PI gains are too high:

Overshoot and oscillations in the response
System instability or even divergence
Increased sensitivity to noise and measurement errors
Potential damage to the motor or power electronics due to excessive control actions

If PI gains are too low:

Slow response with long settling time
Poor disturbance rejection capability
Steady-state errors in tracking references
Weak dynamic performance during load changes or speed variations

Conclusion：

The implementation and simulation of the Indirect Field-Oriented Control (IFOC) system for the induction motor demonstrated effective decoupling of torque and flux control, validating the theoretical principles of vector control. The optimization algorithm successfully tuned the PI regulators to achieve a stable and well-damped dynamic response, with the obtained gains (K_p = 0.08664) and (K_i = 0.00912) ensuring that all system poles remained inside the unit circle and exhibited sufficient damping ratios ($\zeta > 0.4$). The simulation results confirmed the system's ability to track torque and flux references with minimal overshoot and steady-state error, while maintaining robustness during transients.

Through this laboratory exercise, the core objectives of understanding IFOC structure, tuning PI controllers via performance-based optimization, and analyzing motor dynamics in the dq-frame have been accomplished. The results underscore the superiority of vector control over scalar methods in achieving precise and dynamic motor performance, reinforcing essential concepts in modern AC drive systems.