Control Block Diagram of Brushless PM Motors

- Similar to PM DC Motor Control
  - Except commutation requirement for AC circuit
- Electronic Commutation
  - 3 phase sinusoidal voltage (or current) based on rotor angle
  - Feedback information (sensor or sensorless) required
  - Possible phase delay at high speed
- 6-step (trapezoidal) or Sinusoidal
- Current Control for High Dynamic Performance
Current Controlled Drives

- AC Current Controller for
  - Higher dynamic performance (BW - Band Width)
  - Reduction of Current Phase Delay (performance at high speed)
  - Improved reliability
  - Multiple regulators

Flux Distribution from Polyphase Winding

- Poly-phase produces sinusoidally distributed rotating flux
  - Constant power flow, rotating mmf magnitude
  - Single phase cannot!
  - 2-ph 4 lines or 3-ph 3 lines possible
- Magnetic point of view, # of phase (>=2) does not matter
Rotating mmf in 3 phase system

- \( \text{mmf} = \frac{N_{se}}{2} \left[ I_a \cos \theta + I_b \cos (\theta - 120^\circ) + I_c \cos (\theta + 120^\circ) \right] \)
- \( \text{mmf} = 1.5 \left( \frac{N_{se}}{2} \right) \left[ I_s \cos (\omega t - \theta) \right] \)
- Constant magnitude, smooth rotation
- All poly-phase windings produces sin. distributed mmf!
- If synchronized to rotor mmf, with 90° offset, max torque results
- Rotating d-q axis transform

Trapezoidal vs Sinusoidal Control

- \( T \propto I_a \cos(\theta) + I_b \cos(\theta-120^\circ) + I_c \cos(\theta+120^\circ) \)
- Zero ripple condition
  \( \cos^2(\theta) + \cos^2(\theta-120^\circ) + \cos^2(\theta+120^\circ) = 1.5 \)
- All harmonics contributes to loss (ripple & noise)
- Trapezoidal commutation for low-cost, low-power motors
  - Wide angle conduction (> 120°)
  - Current control (magnitude only) may be applied
Various 6-Step Switching Schemes [1]

- All @20 kHz, 2Q(0) 4Q (1,2,3,4)
- Simultaneous (1,2) Split (3,4) with or without complementary

<table>
<thead>
<tr>
<th>Sch 0 (2Q)</th>
<th>Sch 1</th>
<th>Sch 2</th>
<th>Sch 3</th>
<th>Sch 4</th>
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<tbody>
<tr>
<td><img src="image1.png" alt="Waveform" /></td>
<td><img src="image2.png" alt="Waveform" /></td>
<td><img src="image3.png" alt="Waveform" /></td>
<td><img src="image4.png" alt="Waveform" /></td>
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Differences
- Ripple current magnitude
- Switching loss
- Sync Rectification
- Sensorless Control
- Detailed analysis req’d

FOC (Field oriented Control) for AC motors

- Synchronously rotating reference frame
  - Analogy: Geo-centric vs Helio-centric view
- AC motor current can be divided into two DC components
  - Torque producing current component (Iq)
  - Field flux current component (Id)
    - PM motor – Zero normally, Nonzero for IPM
    - Induction motor – Magnetization Current
- Independent control of two current components
- Operation is very similar to separately excited DC motors
Dynamic Equations of Brushless Motors

• Voltage Model in Synchronous Frame
  \[ V_q = (R_s + L_s \omega) I_q + \omega L_s I_d + \omega \lambda_m \]
  \[ V_d = (R_s + L_s \omega) I_d - \omega L_s I_q \]

• \( T = \left( \frac{3}{2} \right) P_p (\lambda_m I_q + (L_d - L_q) I_q I_d) \) 
  (reaction torque) + (reluctance torque)
  – if \( L_q = L_d \), similar to DC motor equation
  – Interior PM motor, \( L_q > L_d \)

Synchronous Current Regulator (SR)

– Aka Field Oriented Control (FOC)
– Zero steady-state phase error with PI control
  “Internal Model Principle”
– \( I_d^* \) is nonzero for phase angle advance
– Easy to add back emf & cross-coupling compensation
Low-cost Sensors & Sensorless Control

- Hall sensors (with linear interpolation)
- Magnetic Rotary Hall Position Sensors (AMS, Avago)

- Sensorless - Estimation of Flux Angle & Velocity
  - Popular technologies
    - Model-based Observer (Estimator)
    - Carrier injection (IPM, Audible noise)
  - Performance
    - BW limited, limited accuracy
    - Challenges at startup and near-zero speed, high torque application
    - Model of nonlinearities (Extra voltage drops)
    - Algorithm selection and tuning – key to success

Carrier Injection Method (IPM)

- For motors with significant inductance difference (Lq – Ld)
- Carrier Noise

![Diagram of Carrier Injection Method (IPM)]
Observer Methods

- Applied to 2-ph stationary quantities ($I_\alpha, I_\beta, E_\alpha, E_\beta$, etc.)
  - 2-ph Synchronous variables can also be used.
- Luenberger: Select $K$ so that observer bw is $>>10X$ motor model
- Sliding mode: Sliding gain $L > \max(E_\alpha, E_\beta)$, $K = \infty$
  - Chattering, heavy LPF
- Atan() or Phase Locked-Loop

Sensorless Start-up & Tuning Strategies

- Open-loop Forced start
  \[ K_t I_{qs} = J \frac{d\omega}{dt} + T_L \]
  - Set startup current $I_{qs}$ and acceleration rate should handle “worst case $J$ and $T_L$”
- Inductance-based angle detection for motors with high $\Delta L$
  - Voltage injection with Current rise-time measurement
  - Startup with no jump
- Carrier Injection Startup for motors with high $\Delta L$
- Harmonized tuning ($i$-loop, $\omega$-loop, observer-loop)
  - Software unit (Per unit) scaling
  - Spreadsheet computation, backed by simulation.
Limitations

• Limited dynamic performance
  – Good for steady-state or slowly changing load
  – Restarting sequence necessary
• Difficulty in low-speed, high torque operation
• Difficulty in Field weakening Operation
  – Close to 100% PWM
  – Voltage saturation
• Difficult to ensure optimal commutation.

General Application Examples

• Various Fans
  – Consistent, steady-state load, no low speed operation
  – Uni-directional
• Low speed motors (Ceiling Fans)
  – High pole counts, low speed operation
• Compressors, Pumps & Screws
  – Variations in start-up torque requirement
  – Electric boat
• Simple Power Tool (Garage tools)
  – Drills, Screw Drivers, Grinders, Sanders,
More Application Examples

- Premium Power Tools
  - High speed, Bidirectional startup
  - Sophisticated Applications – Quick stop
- Textile Machines, Vending machines
  - Varying Requirements including Servo
- Lawn and garden
  - Weed eater (Trimmer), Mower
- UAV
  - Propulsion, Starter-Generator
- And more….

Conclusion

- Many applications can be served by Sensorless PM motors for high efficiency, low-cost control
- To be successful,
  - Proper selection of control algorithm
  - Setup of operational and tuning parameters
  - Verification tests for operational variations
- Limitations
  - High torque, low speed, demanding dynamics
  - Wide variation on operating condition
About the Author

Dr. Dal Y. Ohm has spent most of his industrial and academic career in applied R & D and product development of diverse AC and DC motor drives, motion control, grid-connected inverters and power electronics. His research area also includes system analysis, modeling simulation of drive systems. He has successfully applied many advanced concepts and technologies into products for performance improvement and cost reduction.

He is now President and Principal Engineer of Drivetech, Inc. Prior to his current position, he was with Kollmorgen Motion Technologies Group as Technical Director and Program Manager. He was also with Baldor Electric Company, Electrocraft Corporation, and LG Industrial Systems. As an adjunct professor, he taught engineering courses at San Jose State University and NPU. He received his Ph.D. and M.S. degrees in Electrical Engineering from Texas A&M University.

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REFERENCES