Modified Synchronous Current Regulator

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Coverage

- Field-Oriented Control Objective

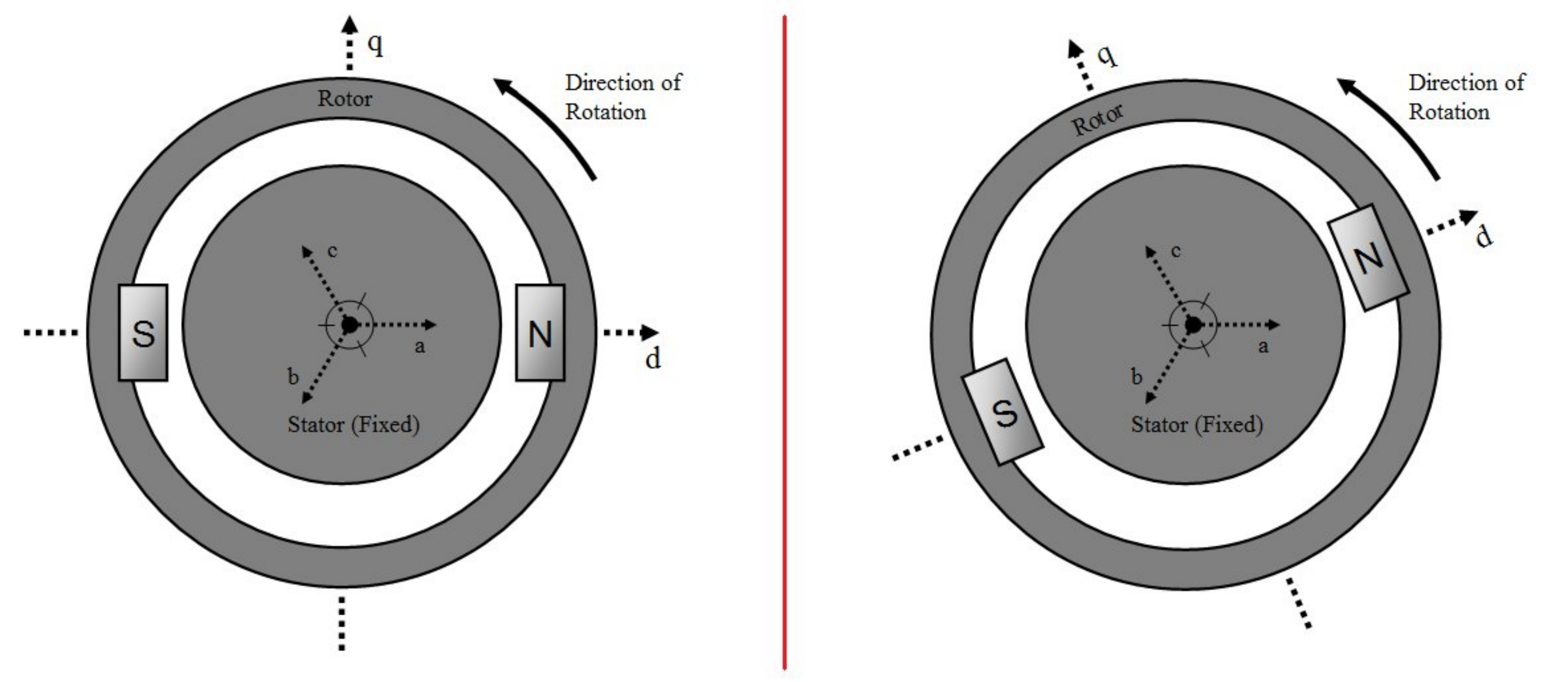
- Synchronous Current Regulator

- Modified Synchronous Current Regulator
  - Theoretical Advantages
  - Simulation
  - Practical Advantages

- Real-World Implementations

Field-Oriented Control Objective

…as applied to permanent magnet synchronous motors (PMSM):

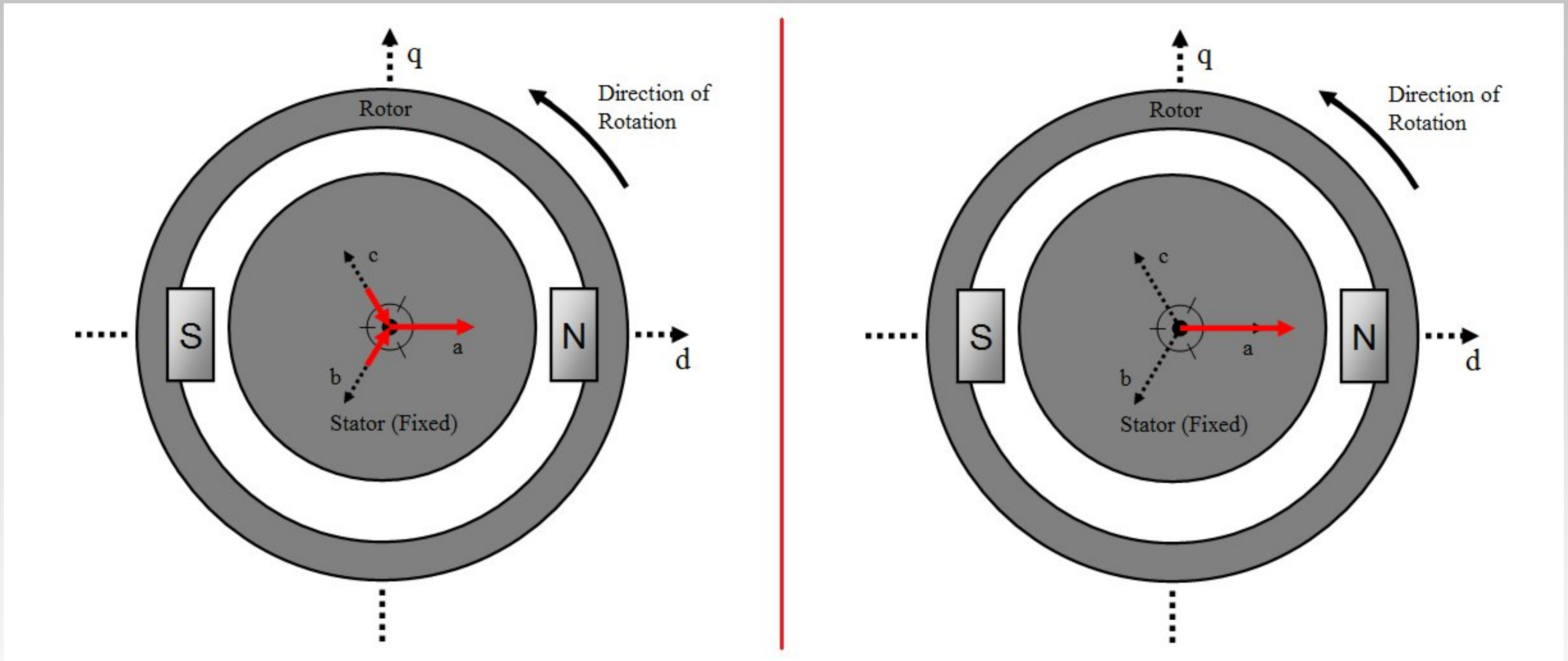


Start with a rotating frame of reference that is fixed to the *rotor*.
(The illustration shows an "outrunner" or outer-rotor PMSM.)

- "Direct" d-axis: Aligned with the magnetic axis of the rotor.
- "Quadrature" q-axis: Leading the magnetic axis by 90º *electrical*.

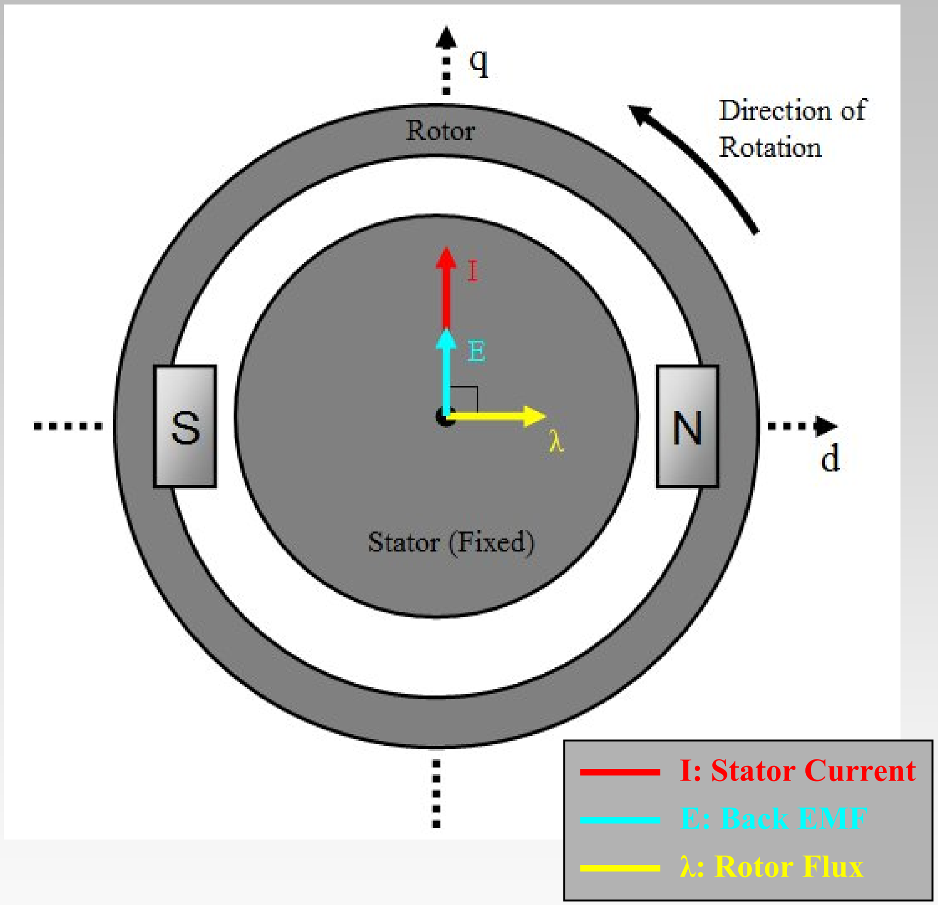
Field-Oriented Control Objective

Stator currents (and flux) can be projected from three phase axes to d- and q-axis using simple trigonometry. (See: Park Transform.)



In this case, I_d is positive, I_q is zero.
No torque will be generated, since the stator and rotor flux are already aligned.

Field-Oriented Control Objective



To optimize torque:

- Stator current (flux) should lead rotor flux by 90º *electrical*.

⇕

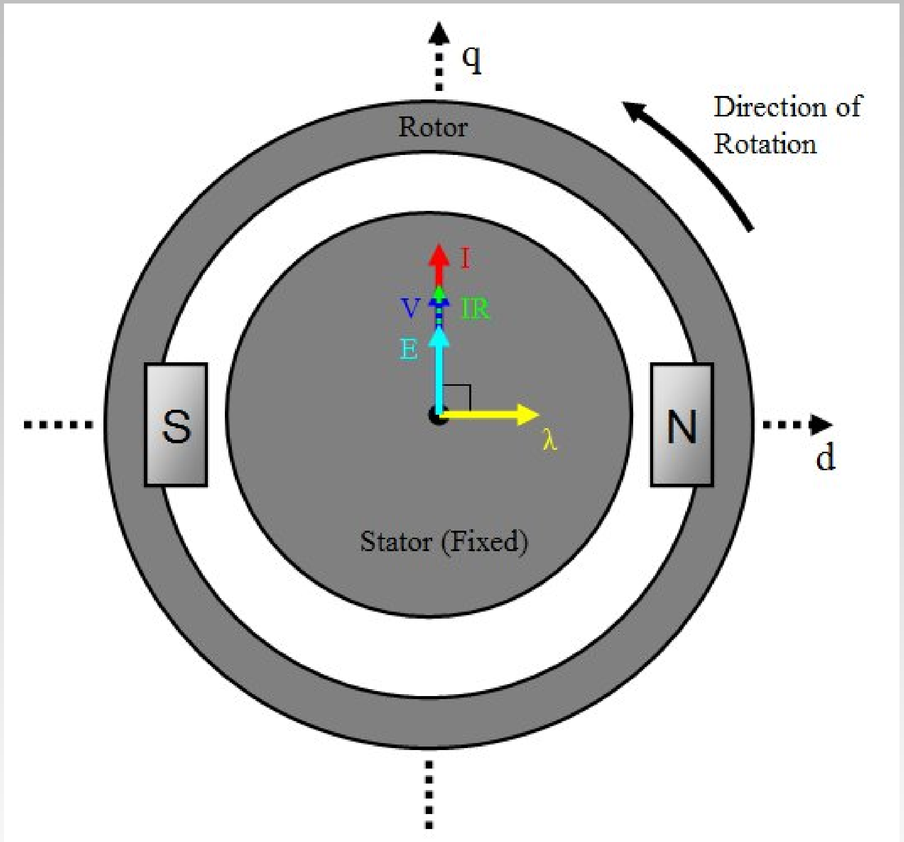
- Stator current should be in phase with back EMF (max power converted).

⇕

- I_q should be positive. I_d should be zero.

These three statements are equivalent. For a PMSM, back EMF is always on the q-axis. (It leads rotor flux by 90º *electrical*.)

Field-Oriented Control Objective

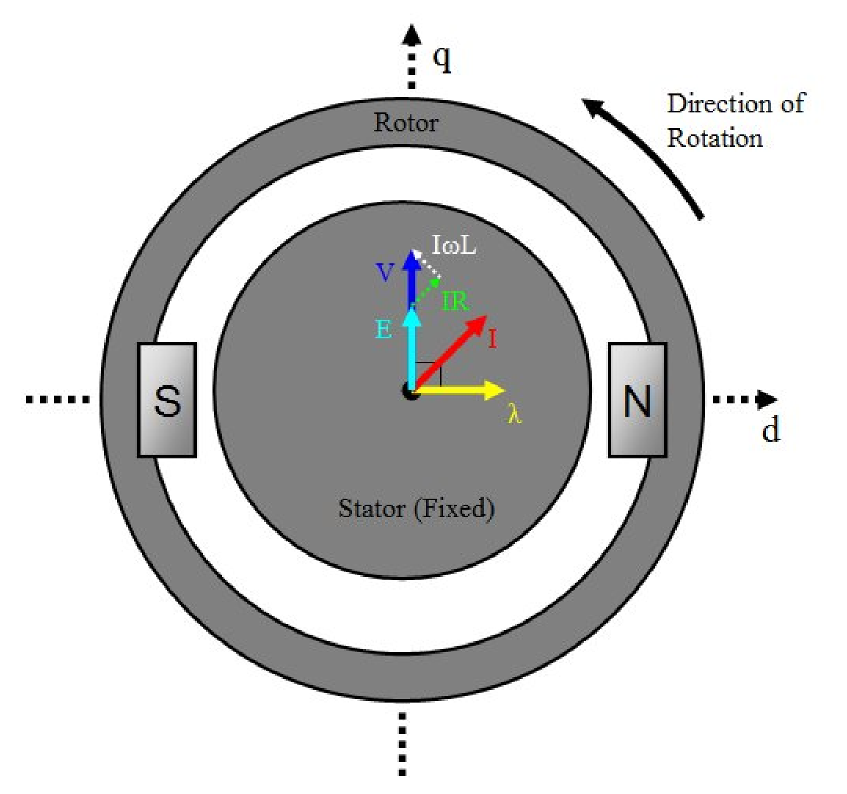


With negligible inductance, or at low speed (i.e. $\omega L << R$):

- Motor windings can be modeled as resistors.
- V and I always align.
- $(V - E) = IR$, based on KVL.
- Torque is optimized by setting voltage on the q-axis. This can be done open-loop.

Surface PM motors have relatively low inductance due to the large effective air gap. So, open-loop commutation is often a good option.

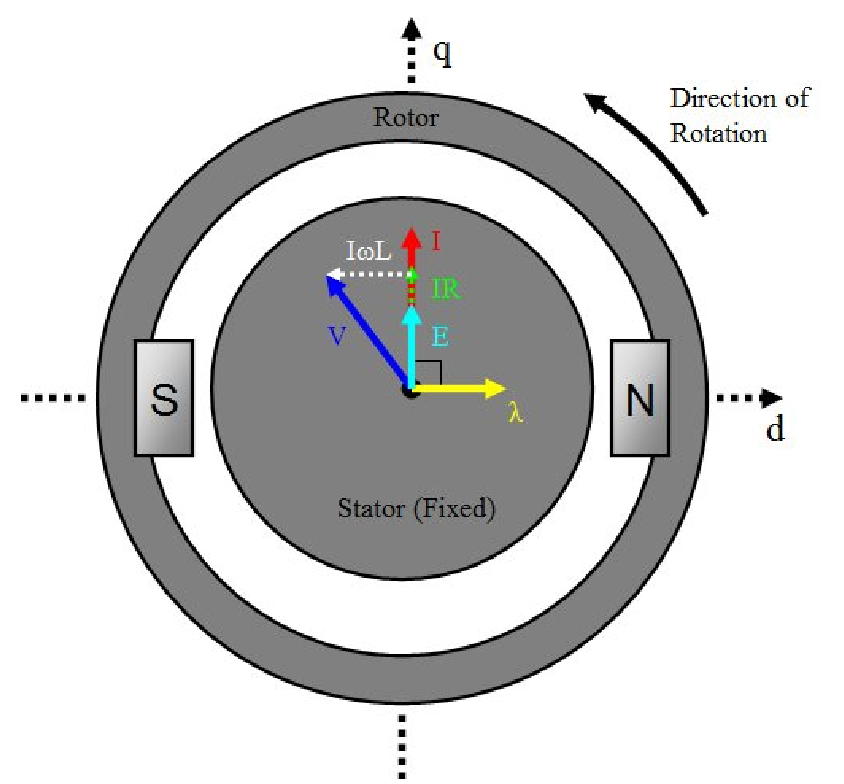
Field-Oriented Control Objective



With non-negligible inductance, or at high speed (i.e. $\omega L \approx R$ or $\omega L > R$):

- Current lags voltage under load.
- Two components to (V - E), one resistive and one reactive. KVL still holds in the vector sense.
- If voltage is placed on the q-axis, current and back EMF are out of phase.
- Torque per unit current will be sub-optimal.

Field-Oriented Control Objective



Field-Oriented Control Objective:

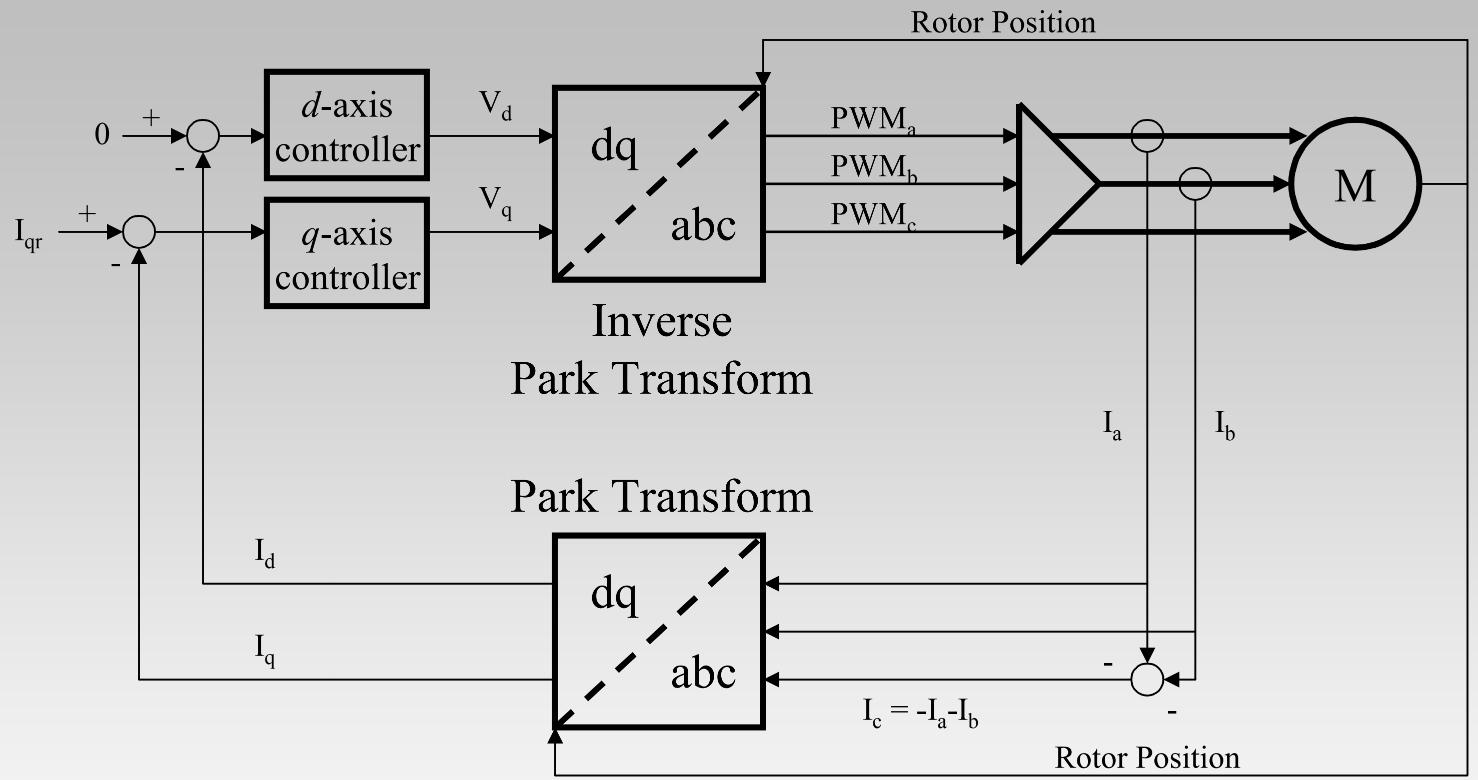
- Dynamically adjust the voltage lead so that current vector falls on the q-axis to optimize torque.

OR

- Place the current vector anywhere on the d-q plane. This gives more flexibility for extending speed range (field weakening).

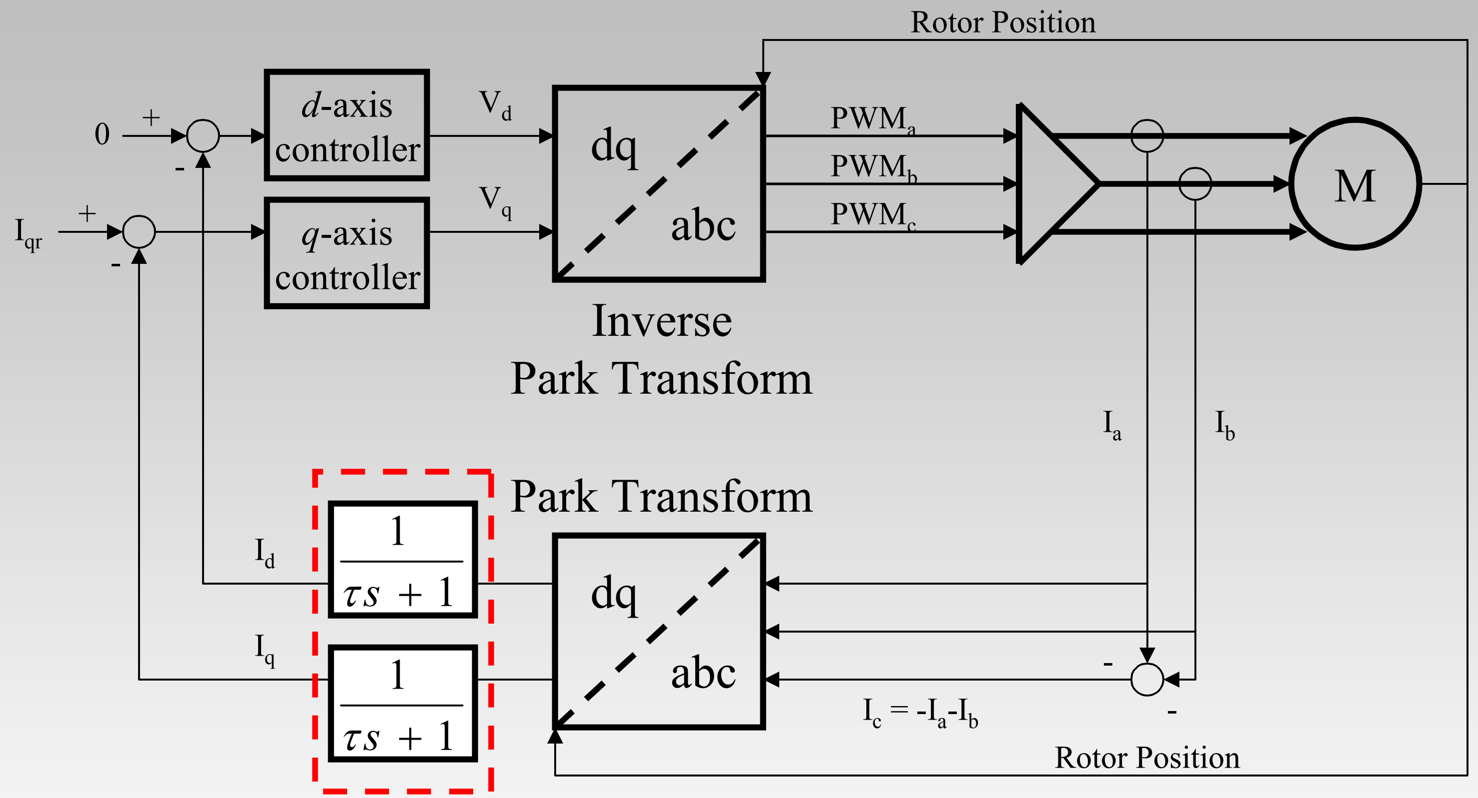
This is a closed-loop process, based on current measurement, although some controllers simply feed-forward a phase advance angle.

Synchronous Current Regulator



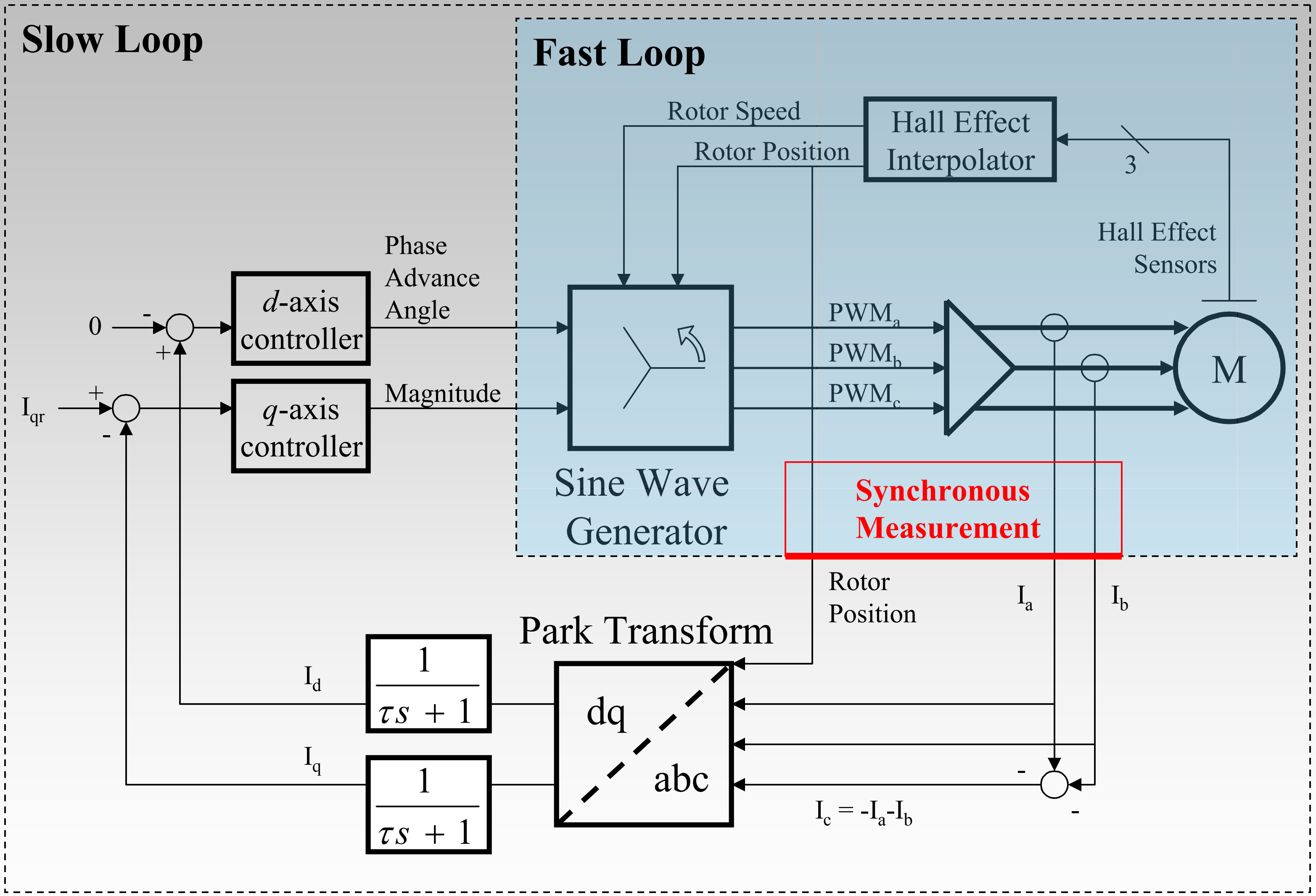
- Uses Park and Inverse Park Transform to project from stator (abc) to rotor (dq) frame. This is done in software and requires knowledge of the rotor position.
- All control is in the rotor frame. (Controllers can be simple P.I.)
- Controller outputs are V_d and V_q, which define the voltage vector to be sent to the power stage and eventually to the motor as PWM.

Synchronous Current Regulator



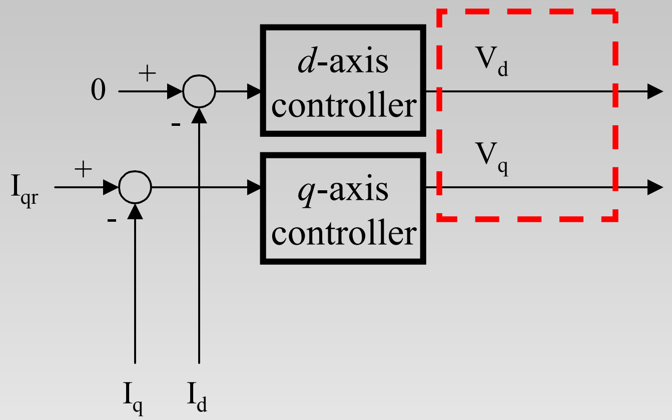
- I_q and I_d can be low-pass filtered at longer time constants than the commutation period of the motor. (I_a, I_b, and I_c cannot because they are AC quantities.)
- This is one of the major benefits of the synchronous current regulator.
- Commutation noise in the current measurement can be greatly reduced.

Modified Synchronous Current Regulator



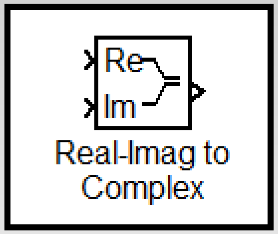
Modified Synchronous Current Regulator

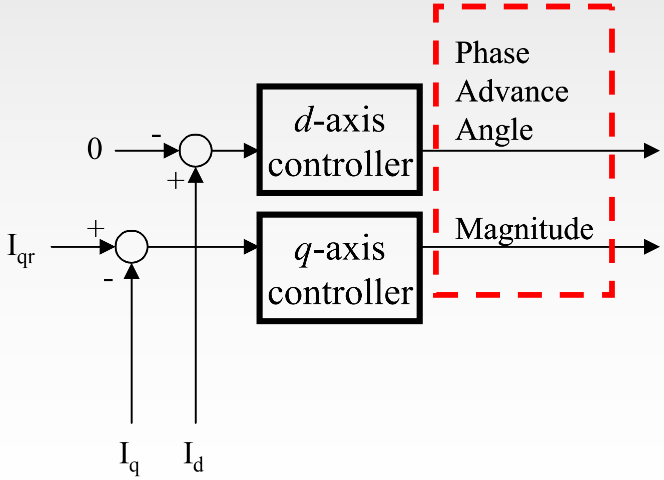
The primary theoretical difference is at the controller outputs.



Standard S.C.R.

- V_d and V_q fully-define a voltage vector.
- d-axis gain: V/A
- q-axis gain: V/A
- Simulate with:

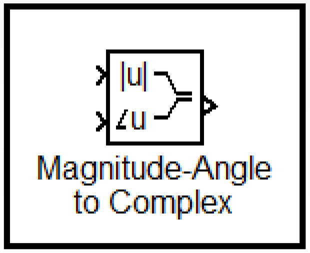




Modified S.C.R.

- $|V|$ and $\angle V$ fully-define a voltage vector.
- d-axis gain: rad/A

  q-axis gain: V/A
- Simulate with:



Modified Synchronous Current Regulator

Because of the controller outputs, the modified synchronous current regulator takes a more direct path between operating points. For example, a simulated step increase in the torque command (through I_{qr}) with speed held constant:

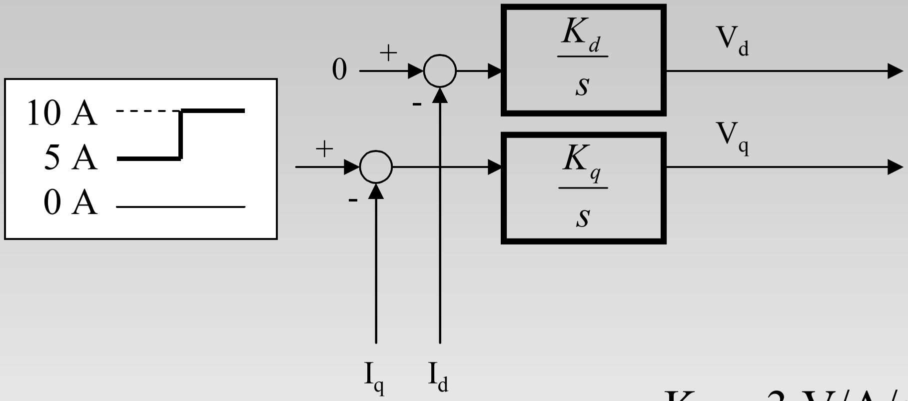
Common Simulation Parameters

Symbol	**Description**	**Quantity**	**Units**
K_t	Per-Phase Torque Constant Per-Phase Back-EMF Constant	33 24 33 47	$\mathrm{mNm/A_{rms}}$ $\mathrm{mNm/A_{peak}}$ $\mathrm{mV_{rms}/(rad/s)}$ $\mathrm{mV_{peak}/(rad/s)}$
R_a	Phase Resistance	0.89	Ω
L_s	Synchronous Inductance	4.2	mH
p	Number of Pole Pairs	4	-
τ	Low-Pass Filter Time Constant	0.1	s
Ω	Mechanical Speed (held constant)	1500 157	rpm rad/s
I_{qr1} I_{qr2}	Initial Operating Point Final Operating Point	5 10	$\mathrm{A_{peak}}$ $\mathrm{A_{peak}}$

Motor parameters are similar to Applied Motion Products V0250-214-B-000.
http://www.applied-motion.com/V/index.php

Simulations

Simulation #1: Standard Synchronous Current Regulator

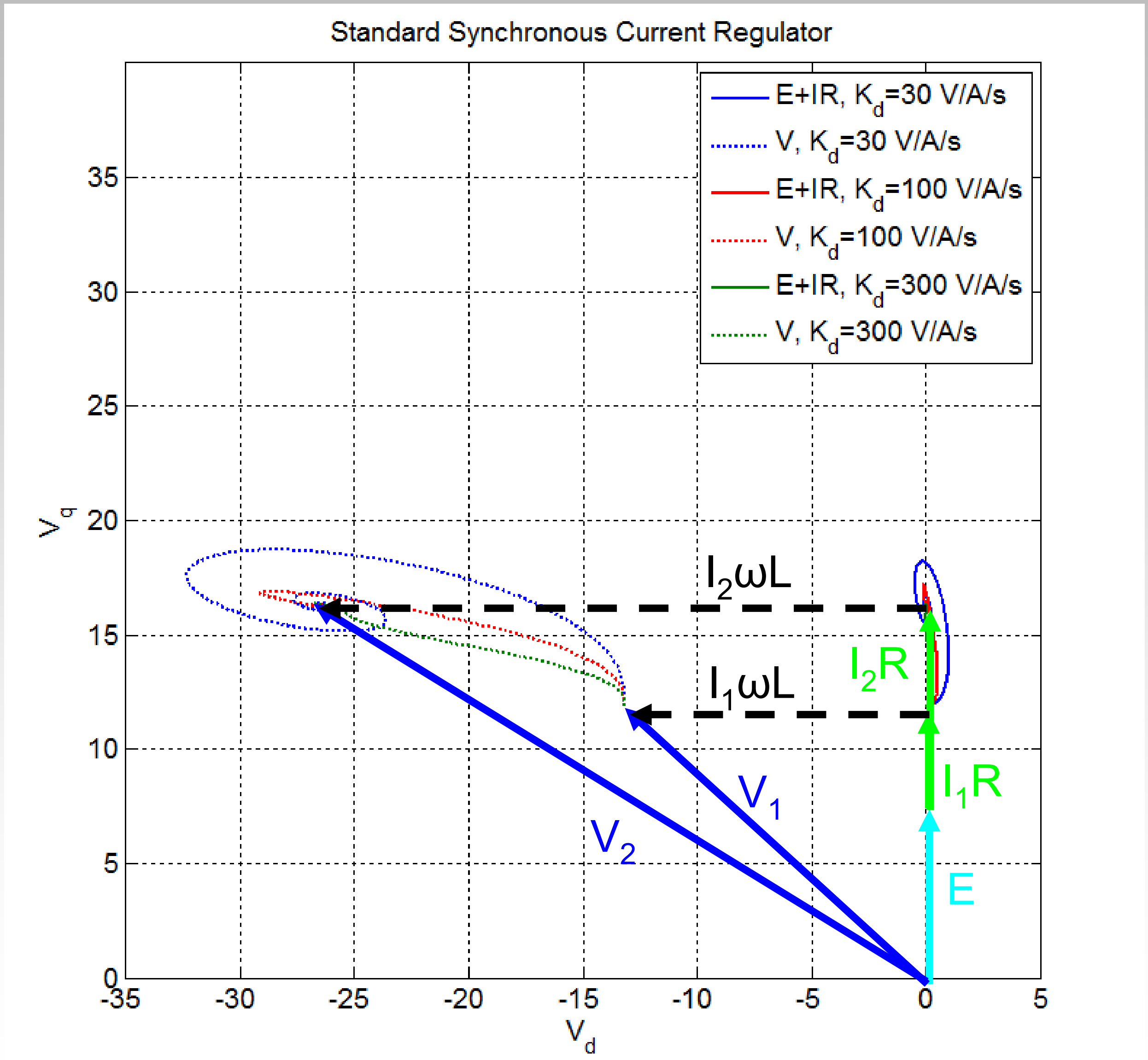


$K_q = 3$ V/A/s
$K_d = \{30, 100, 300\}$ V/A/s

Initial response to I_q error of 5A:

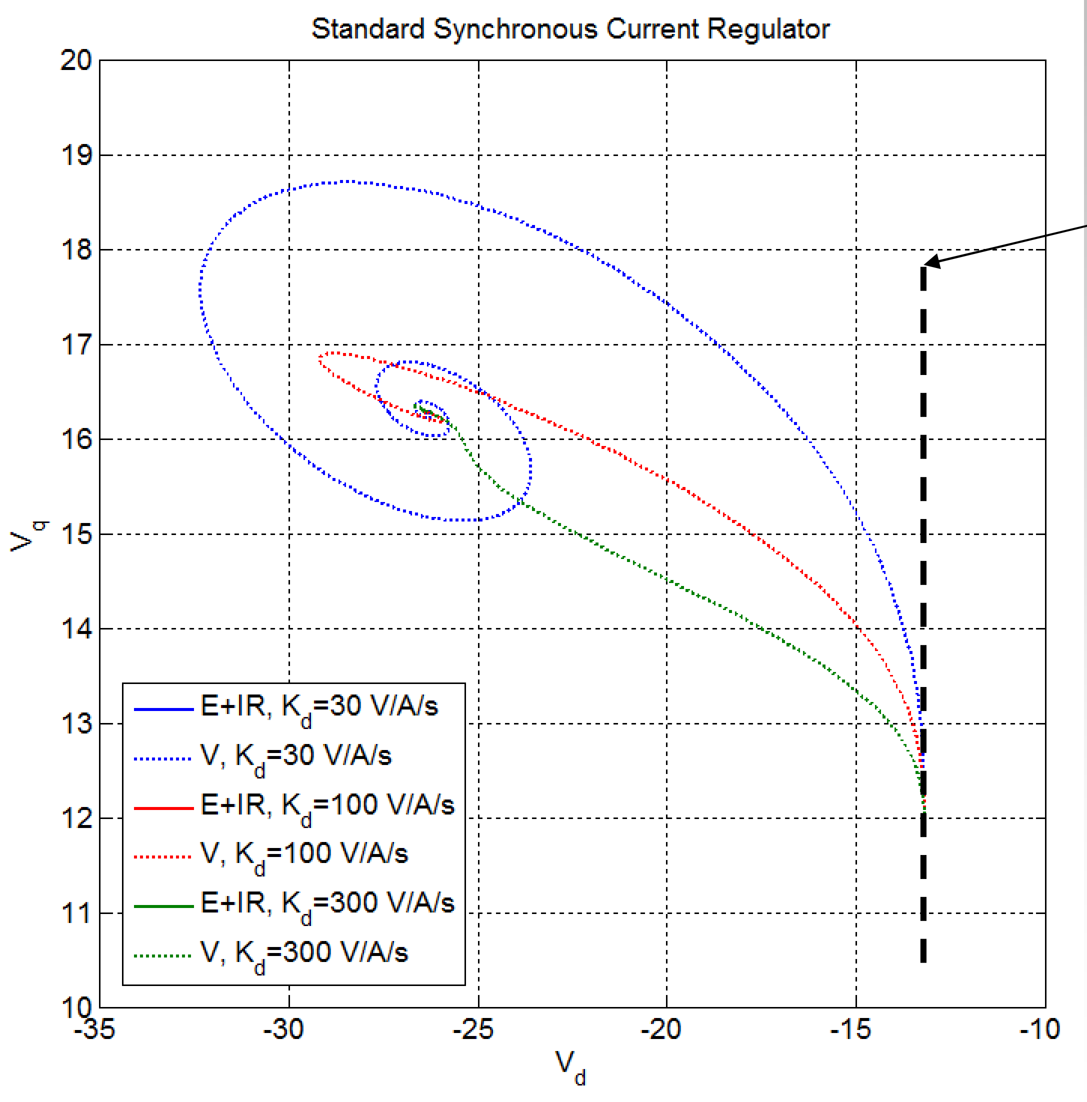
- V_q slew rate of 15 V/s.
- V_d slew rate of 0 V/s (since there is no intial d-axis error).
- Voltage vector trajectory leaves parallel to the q-axis, regardless of K_d.

Simulations



Simulations

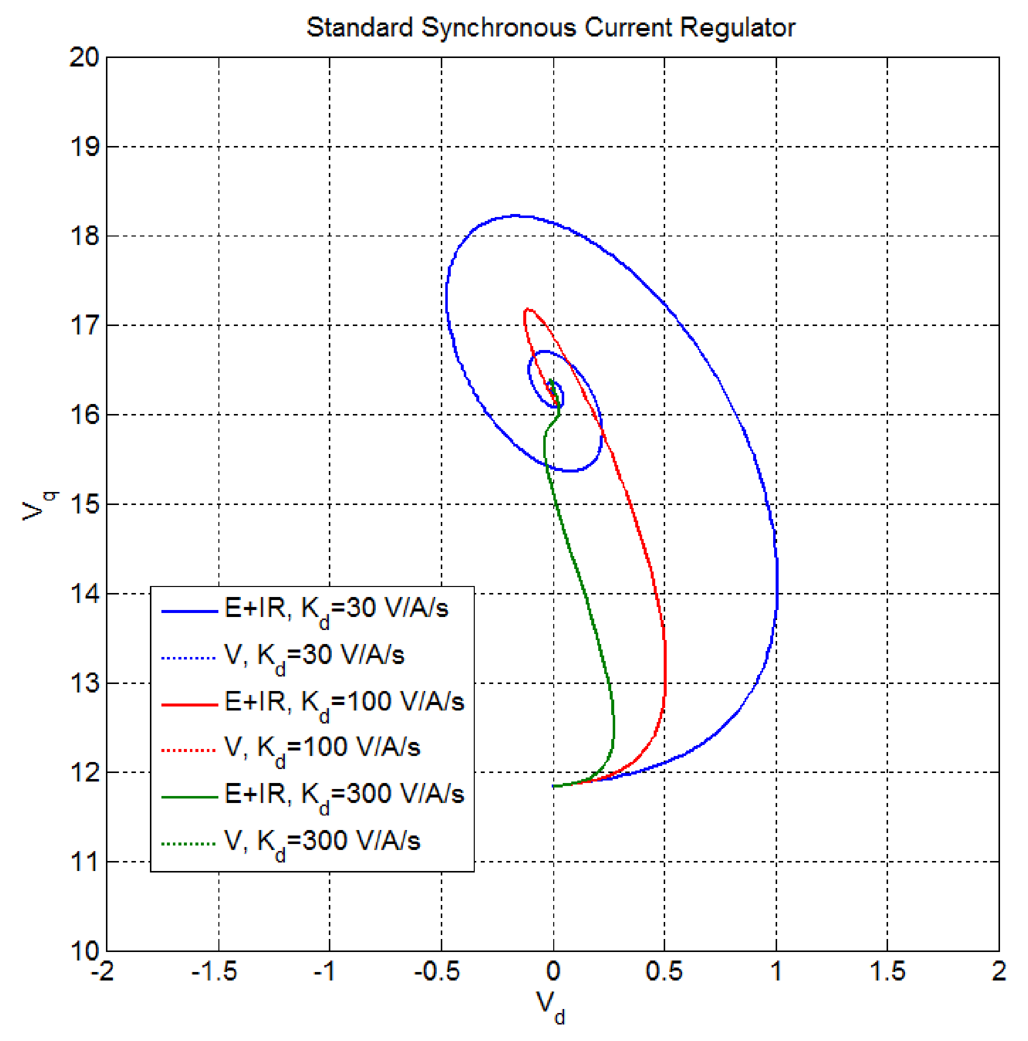
Scaled to show detailed voltage trajectories:



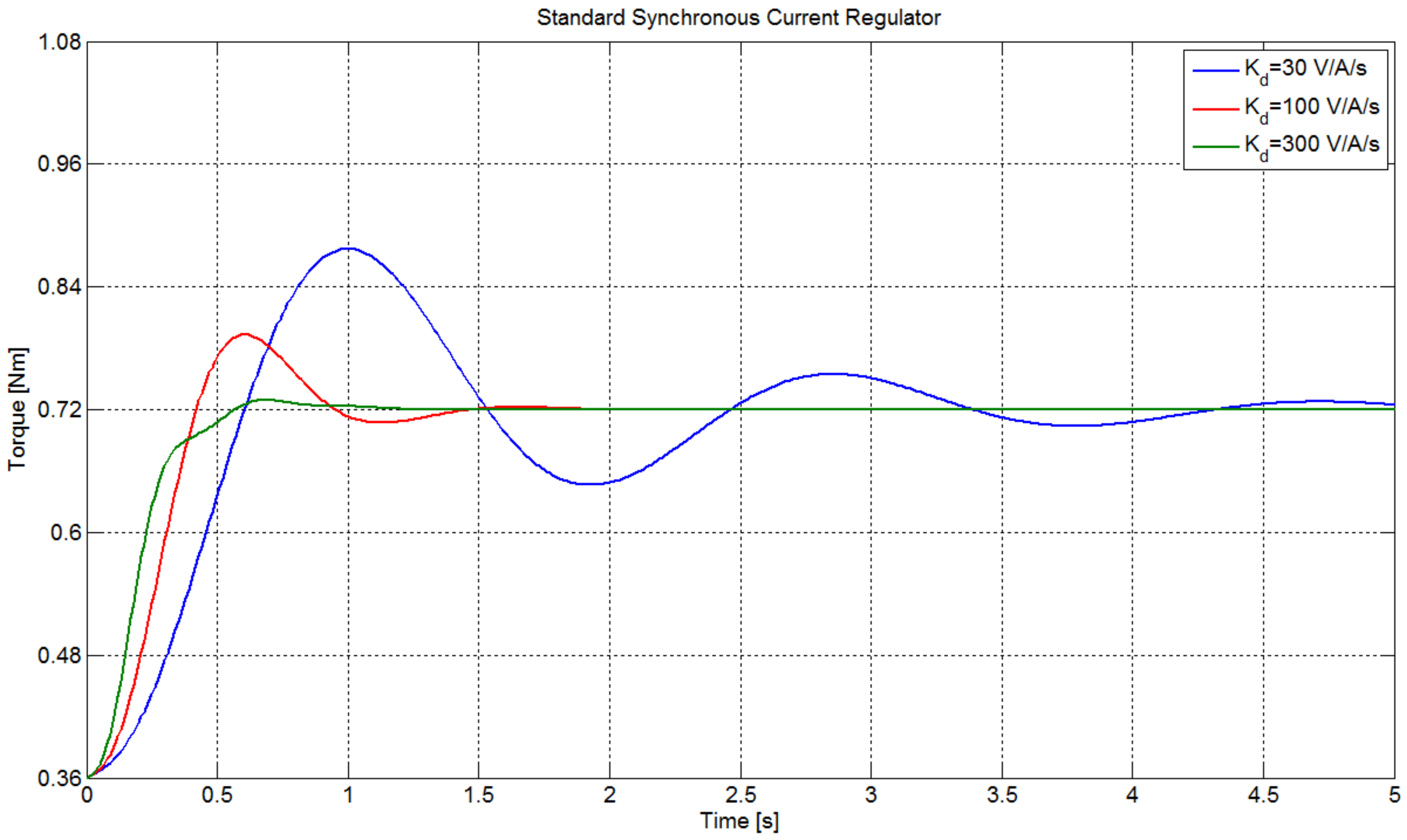
All trajectories leave parallel to the q-axis.

Simulations

Scaled to show detailed current trajectories:

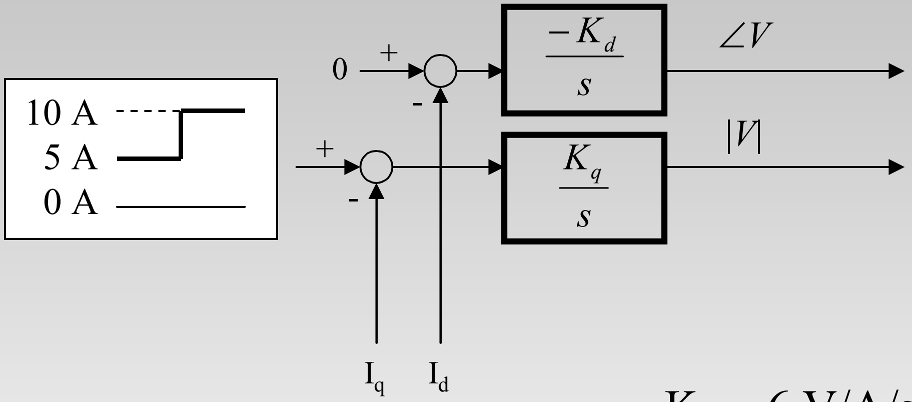


Simulations



Simulations

Simulation #2: Modified Synchronous Current Regulator

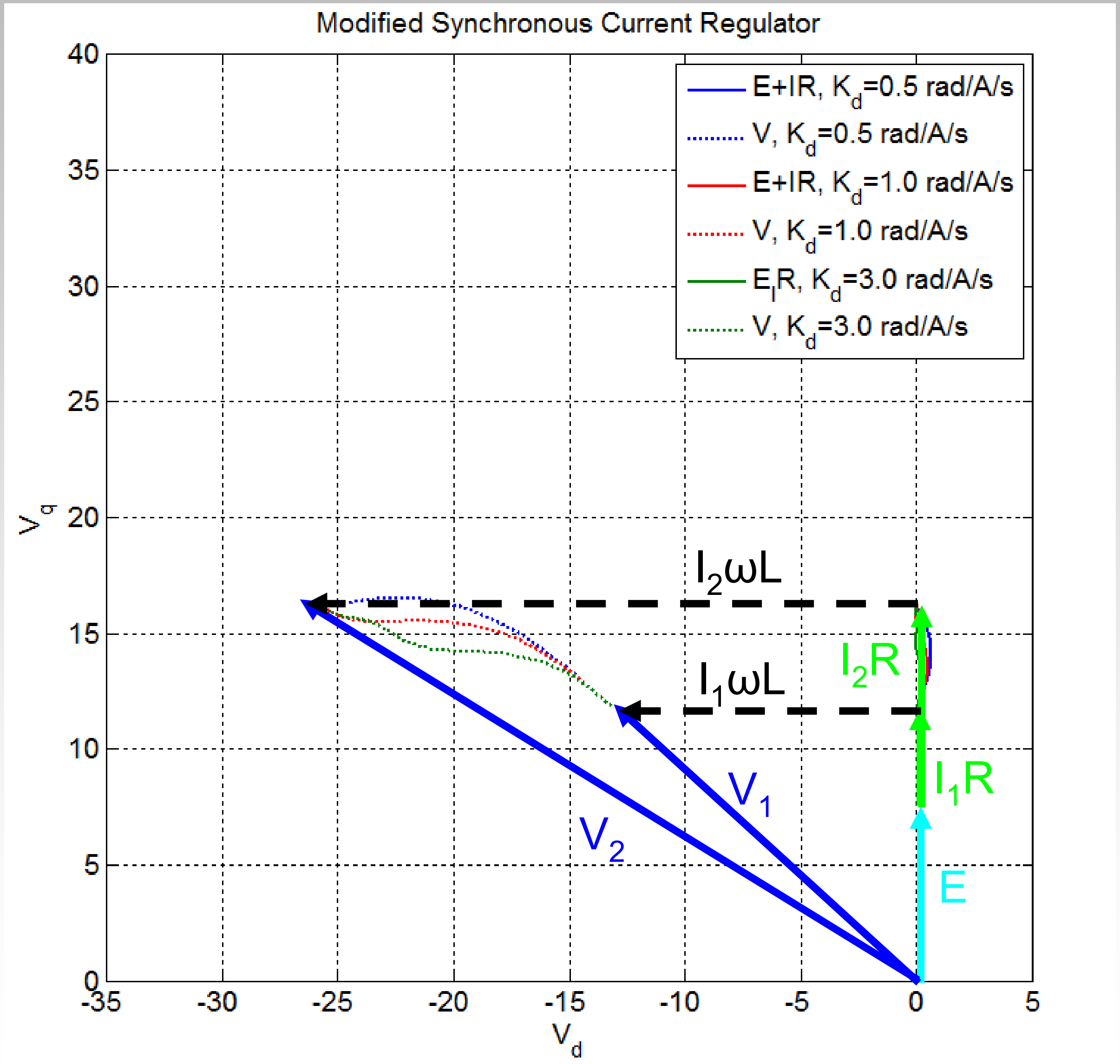


$K_q = 6$ V/A/s
$K_d = \{0.5, 1.0, 3.0\}$ rad/A/s

Initial response to I_q error of 5A:

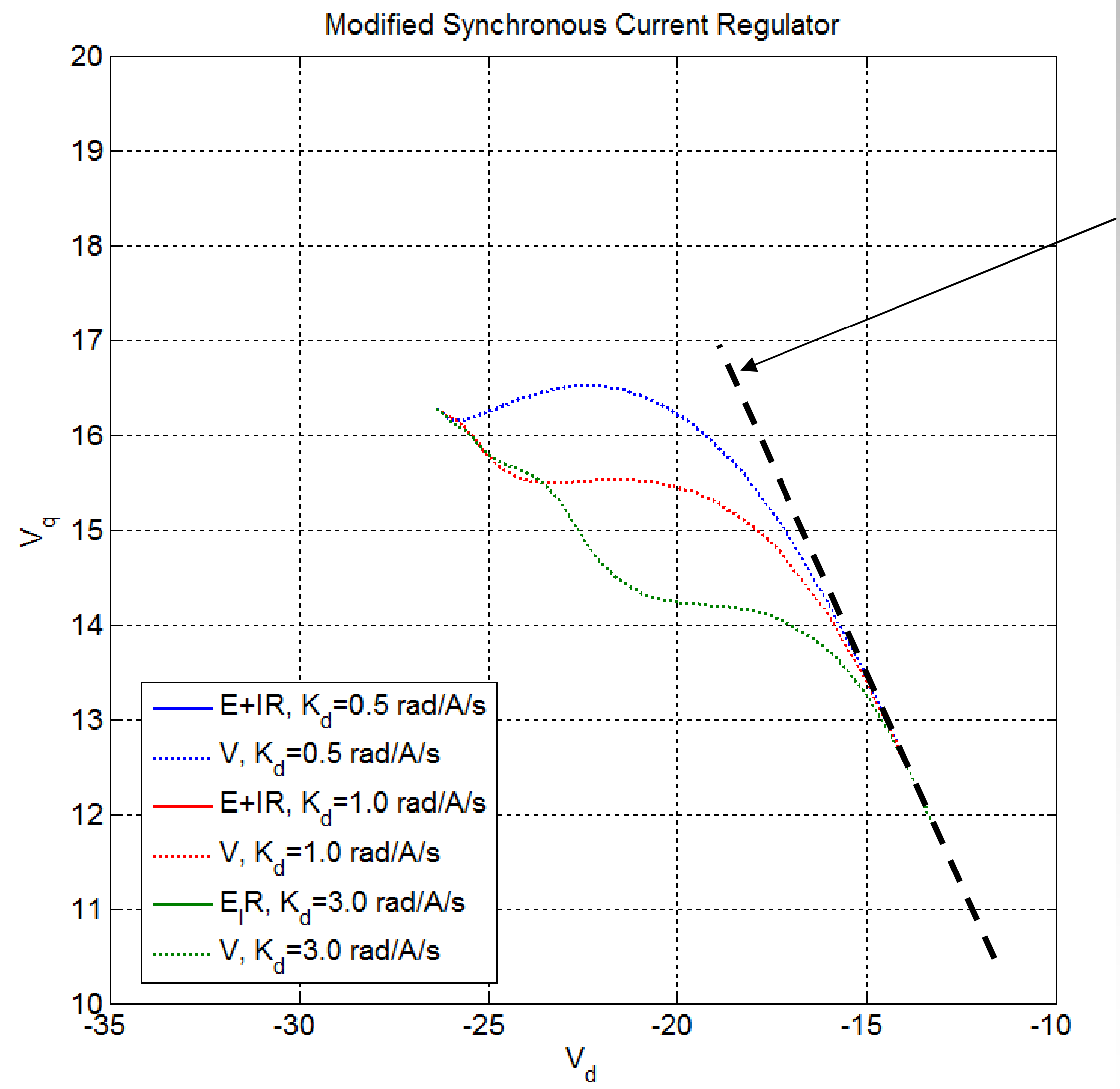
- $|V|$ slew rate of 30 V/s.
- $\angle V$ slew rate of 0 rad/s (since there is no intial d-axis error).
- Voltage vector trajectory leaves parallel to *initial voltage vector*.

Simulations



Simulations

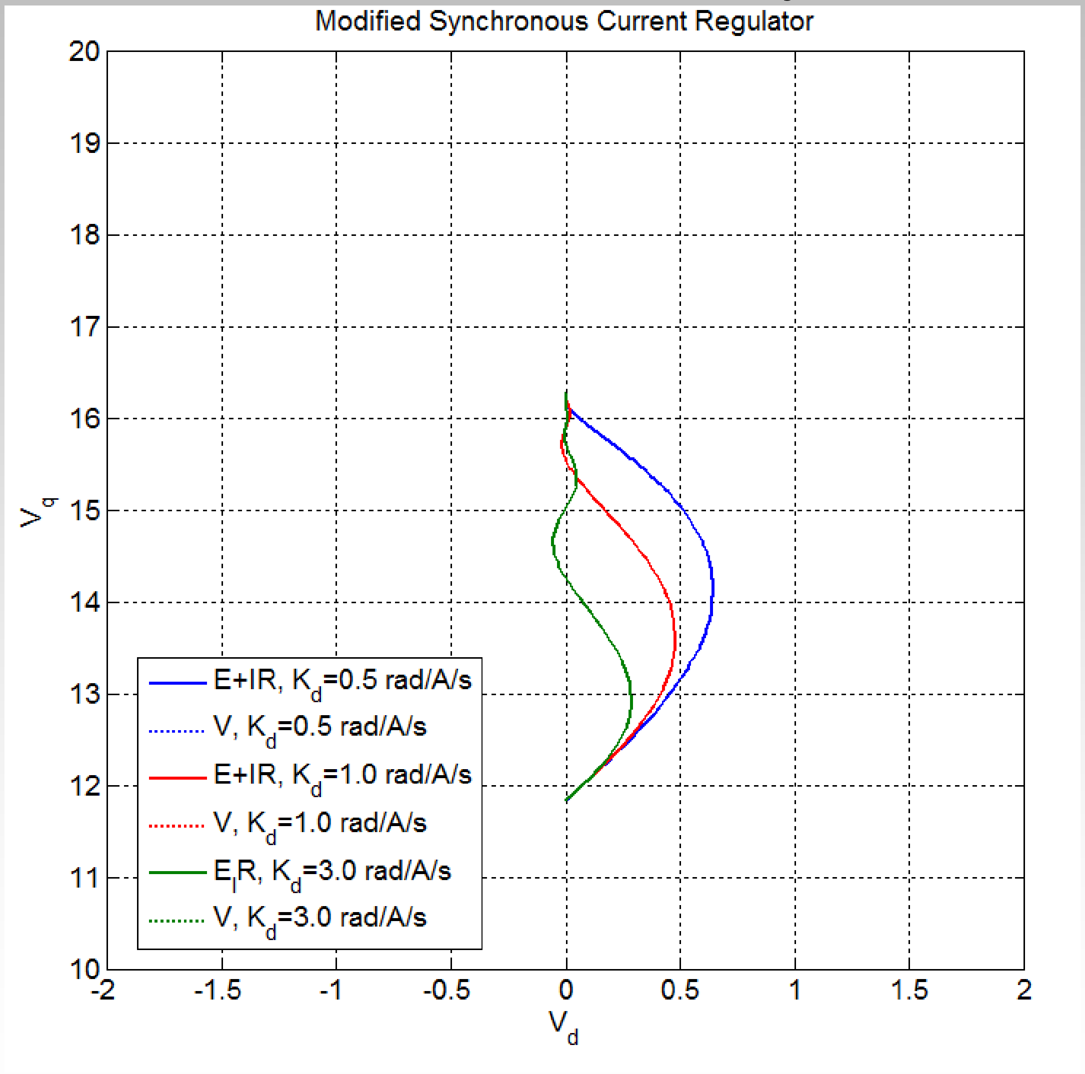
Scaled to show detailed voltage trajectories:



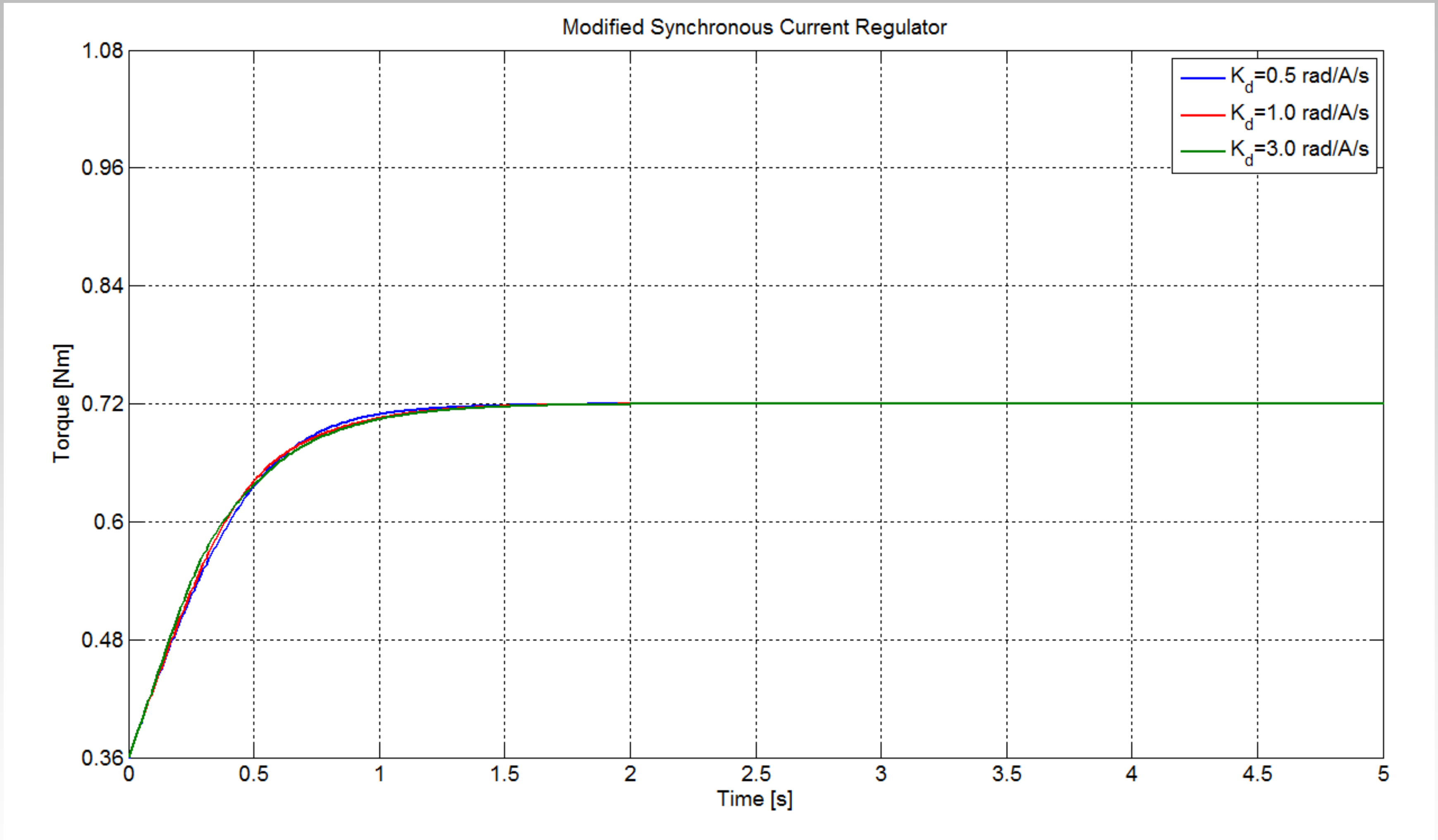
All trajectories leave parallel to the initial voltage vector.

Simulations

Scaled to show detailed current trajectories:

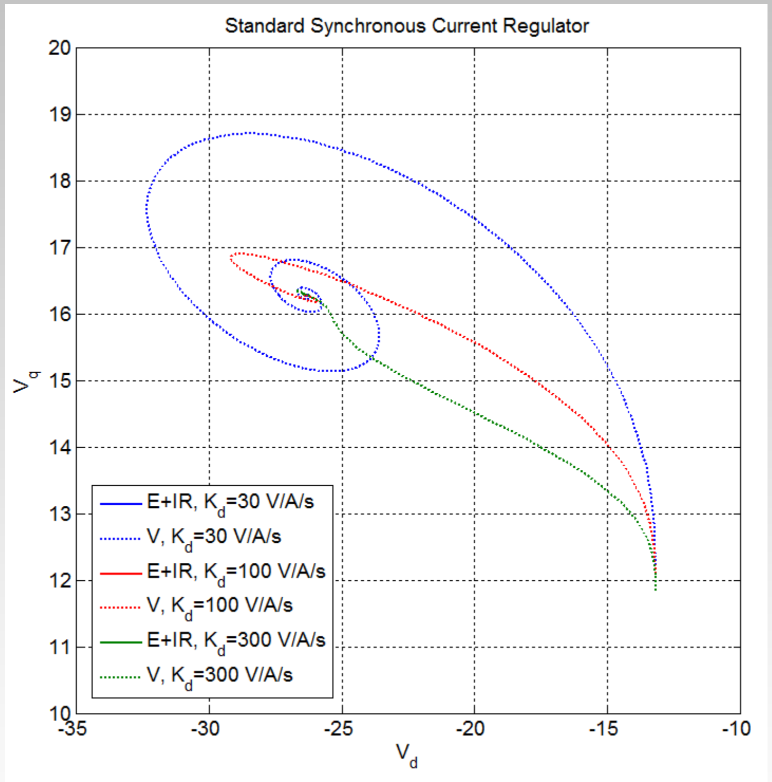


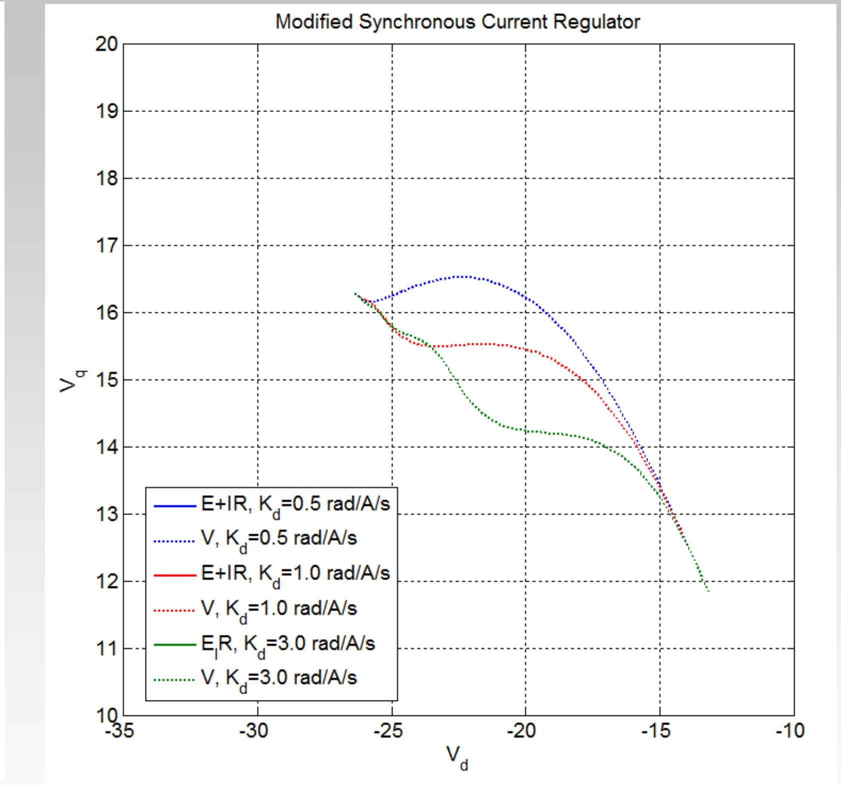
Simulations



Simulations

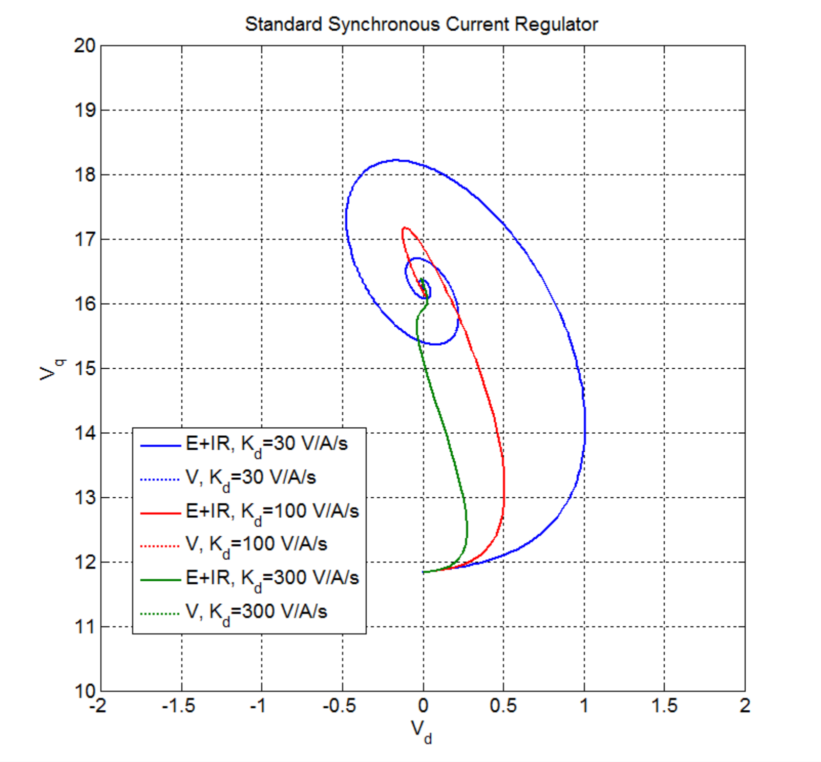
Voltage Trajectories, Side-by-Side:

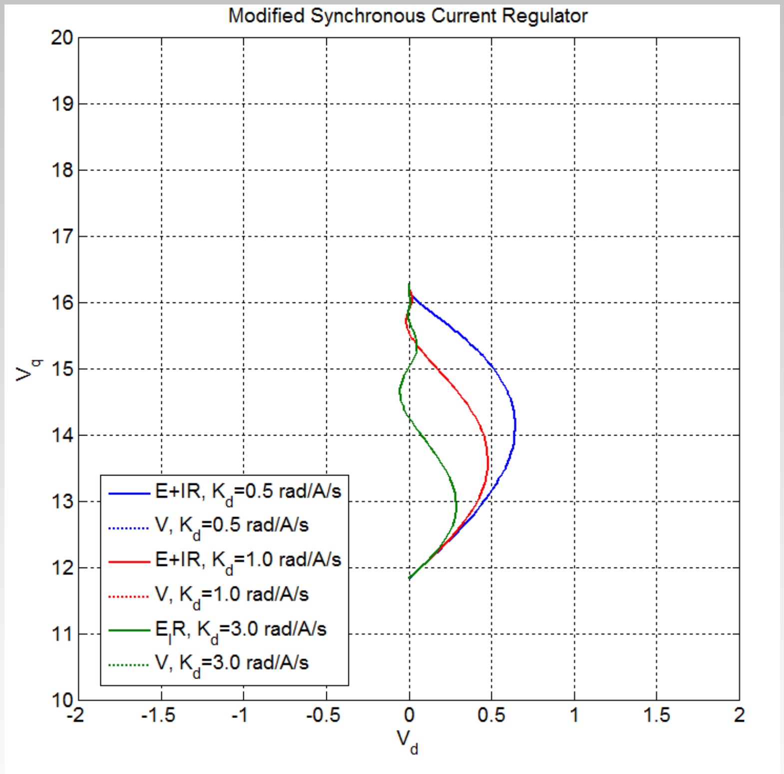




Simulations

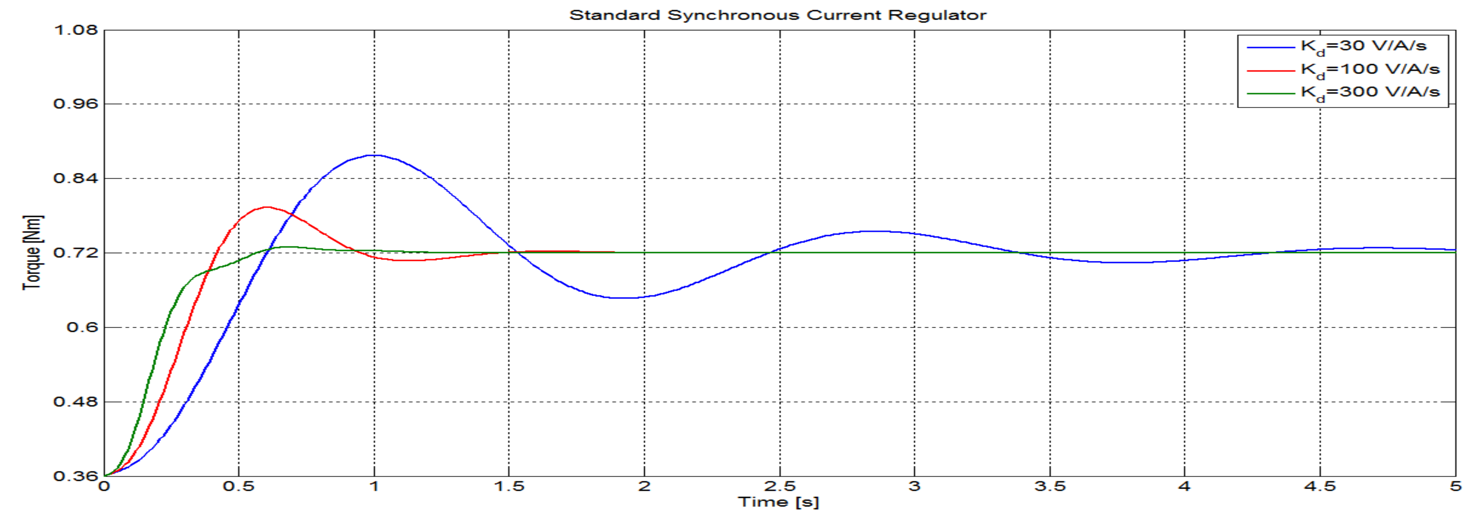
Current Trajectories, Side-by-Side:

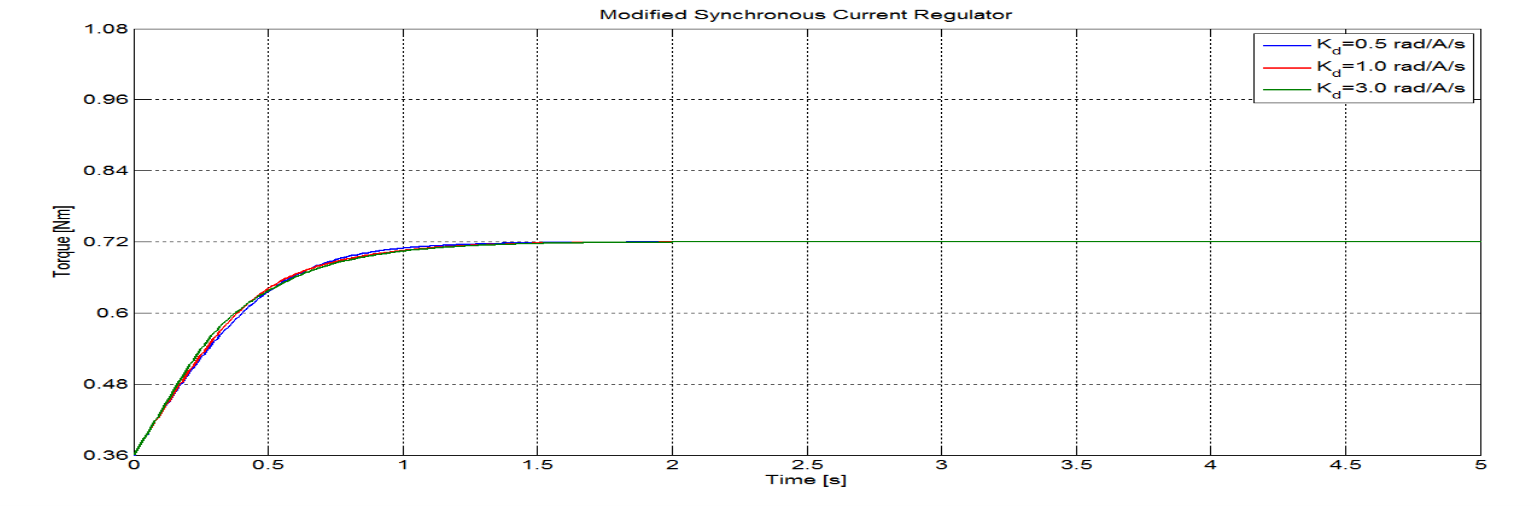




Simulations

Torque Response, Side-by-Side:





Simulations

In the modified synchronous current regulator, the voltage trajectories take a more direct path from the intial to the final operating points. As a result:

- The relative gain of the d-axis controller can be significantly reduced. Here's a ballpark method for comparing d-axis gains across the two controllers:
  - Take $K_d = 1.0$ rad/A/s, the intermediate gain in the simulation of the modified synchronous current regulator.
  - The voltage vector magnitude is $|V| \approx 20$V.
  - As an equivalent voltage gain, $K_d' \approx (20\text{V})(K_d) = 20$ V/A/s.
  - This is less than even the least aggressive gain in the simulation of the standard synchronous current regulator (30 V/A/s).
- **With a lower relative d-axis gain, d-axis noise tolerance is improved.** This is especially important given that the d-axis reference is typically zero.
- The relative gain of the q-axis controller can be increased with less impact on the trajectory. This can be used to improve overall torque response.

Practical Advantages

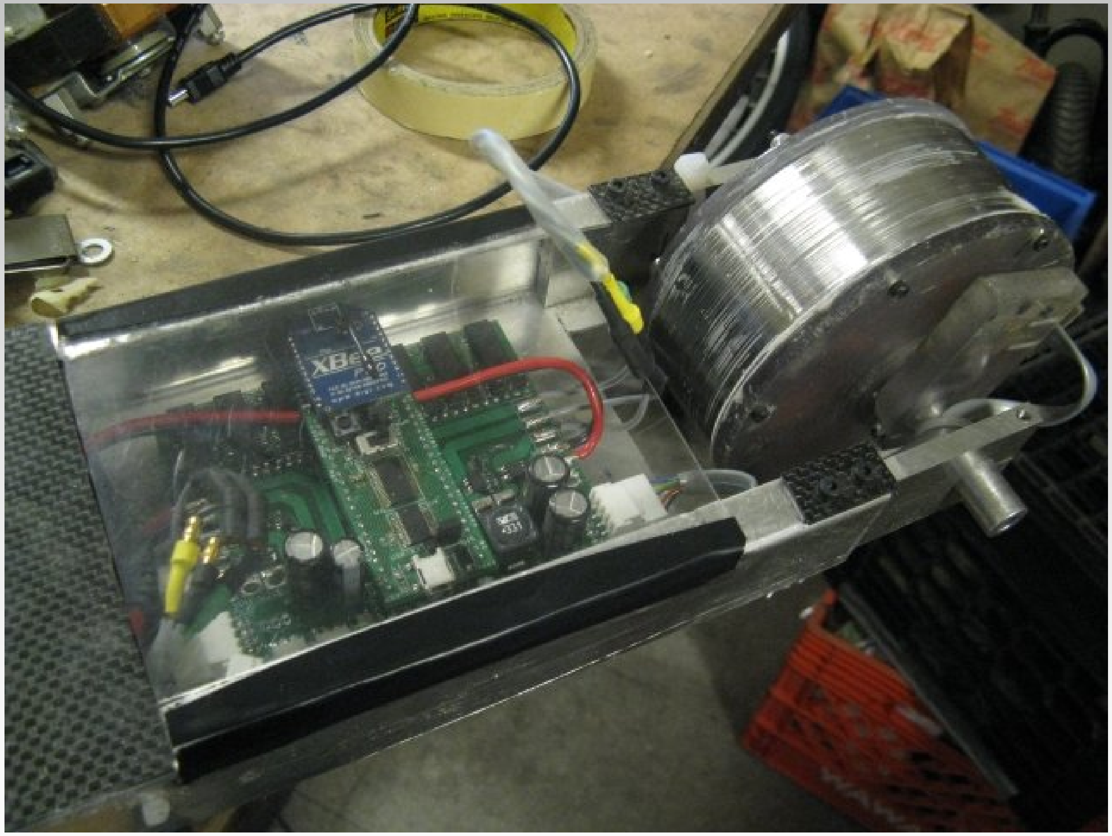
In addition to a more direct transient response to torque commands, the modified synchronous current regulator has some additional practical advantages:

- It is computational efficient.
    - Magnitude and phase are “easier” to handle than an inverse Park transform. Magnitude is a scaling factor and phase is a shift in a look-up table. All three voltage vectors are generated by shifts in a look-up table.
    - The “slow loop” bandwith is arbitrary. Only the look-up-and-scale operations need to run faster than the commutation frequency.

- It can be implemented in inexpensive hardware.
    - 8-bit or 16-bit fixed-point micoprocessors with interrupt capability can handle the computation. No DSP or 32-bit floating-point processor necessary.
    - The Hall effect interpolation routine works with inexpensive brushless DC motors. No encoders necessary.

Real-World Implemenation

Dual Motor Controller w/ Field-Oriented Control and Wireless Data Acquisition



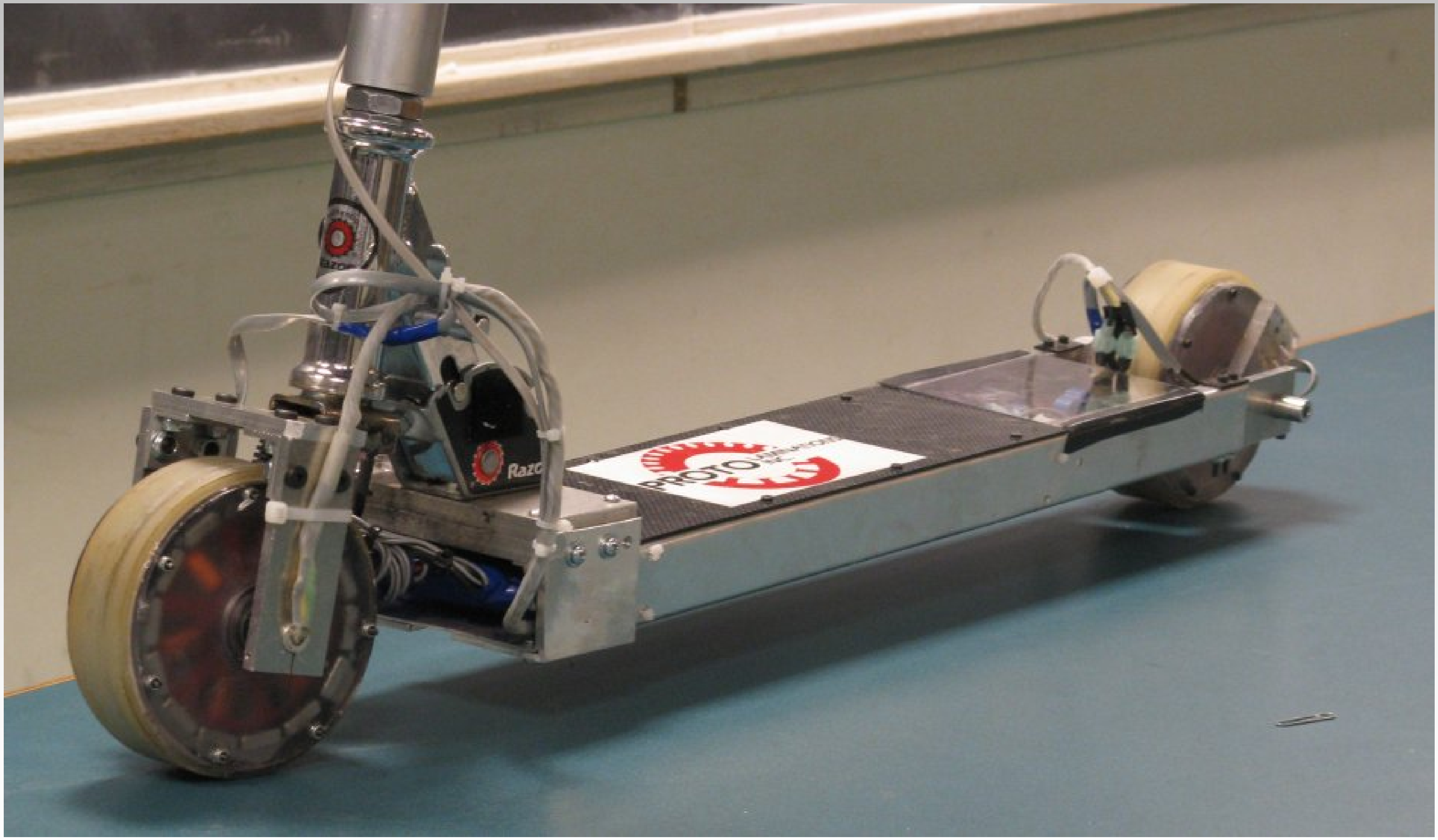
- Dual 1kW Inverters, each: (20A@48V) or (40A@24V)
- Phase current sensing.
- TI MSP430F2274
    - 16-bit, fixed-point
    - 16Mhz clock
    - 6 independent PWMs
- XBee Pro 2.4GHz Module
    - 9600bps 2-Way Data

- Modified Synchronous Current Regulator x2 (w/ Hall sensored motors)

This controller would likely not be able to run the standard S.C.R. on two motors simultaneously. (Not enough processing power.)

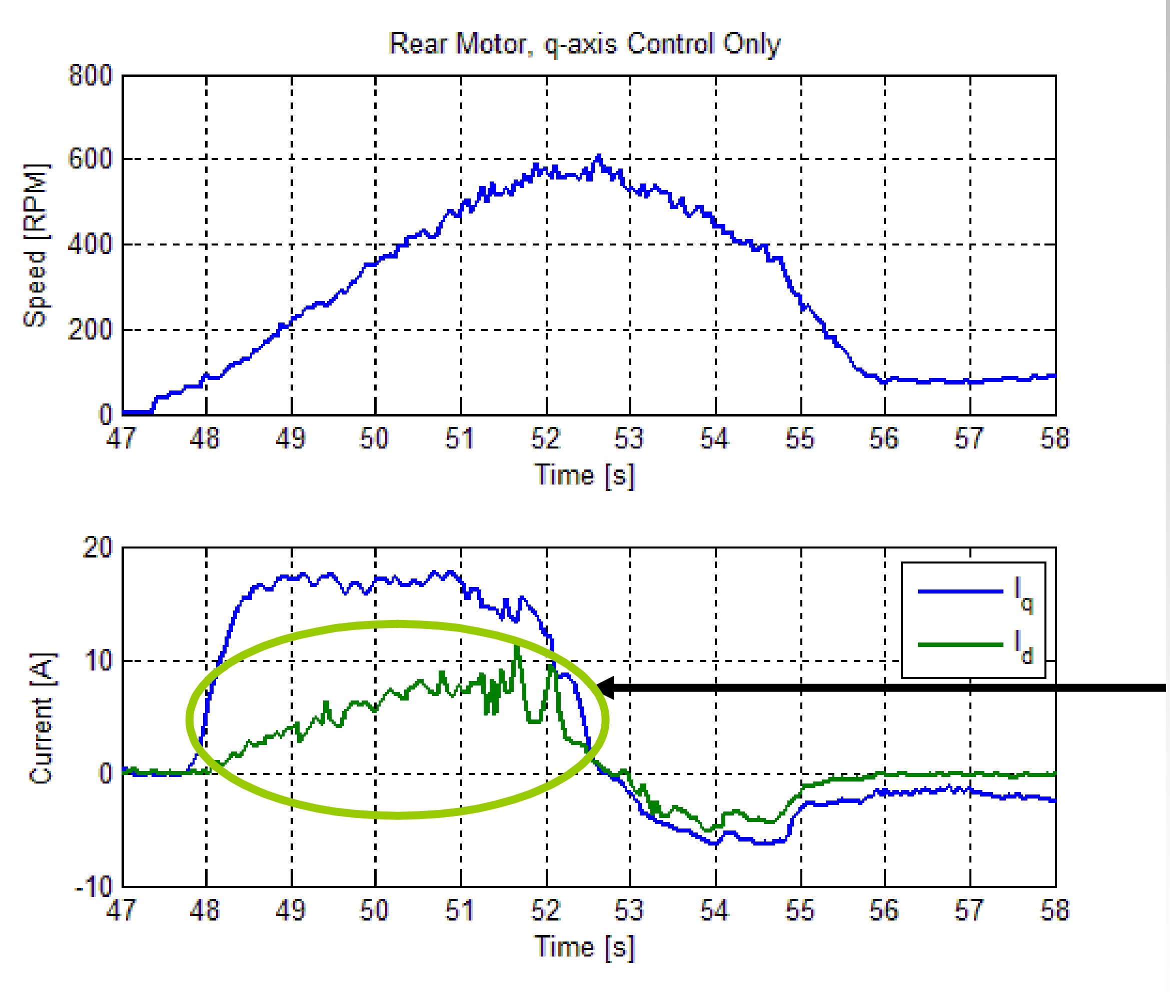
Real-World Implemenation

Direct-Drive Scooter Motors



Real-World Implemenation

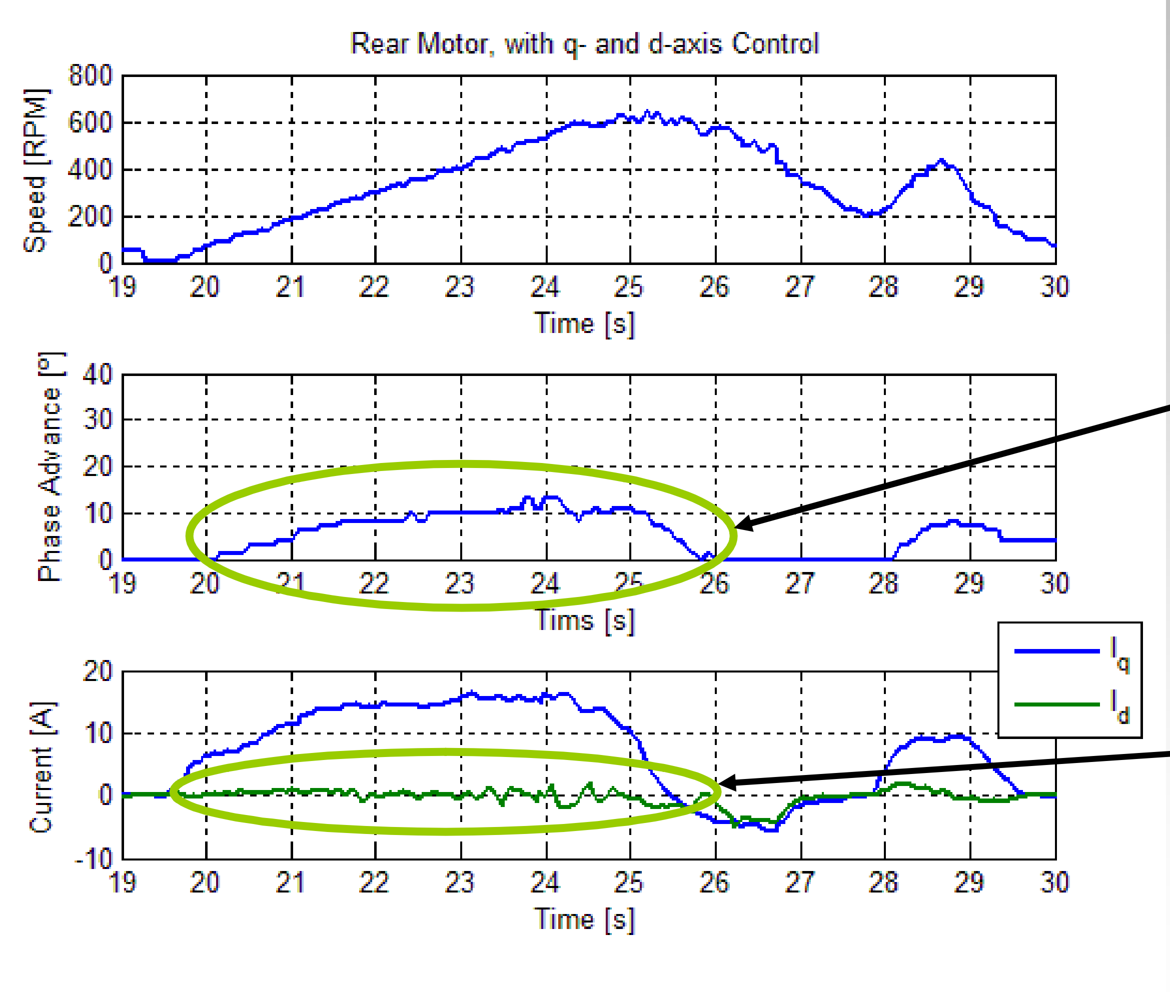
Baseline Data: Rear scooter motor with no d-axis control.



d-axis current increases with speed. ($X_s = \omega L_s$)

Real-World Implemenation

Modified S.C.R. Data: Same motor, with modified S.C.R. impelmented.



$\angle V$ used to counteract current lag.

$\Downarrow$

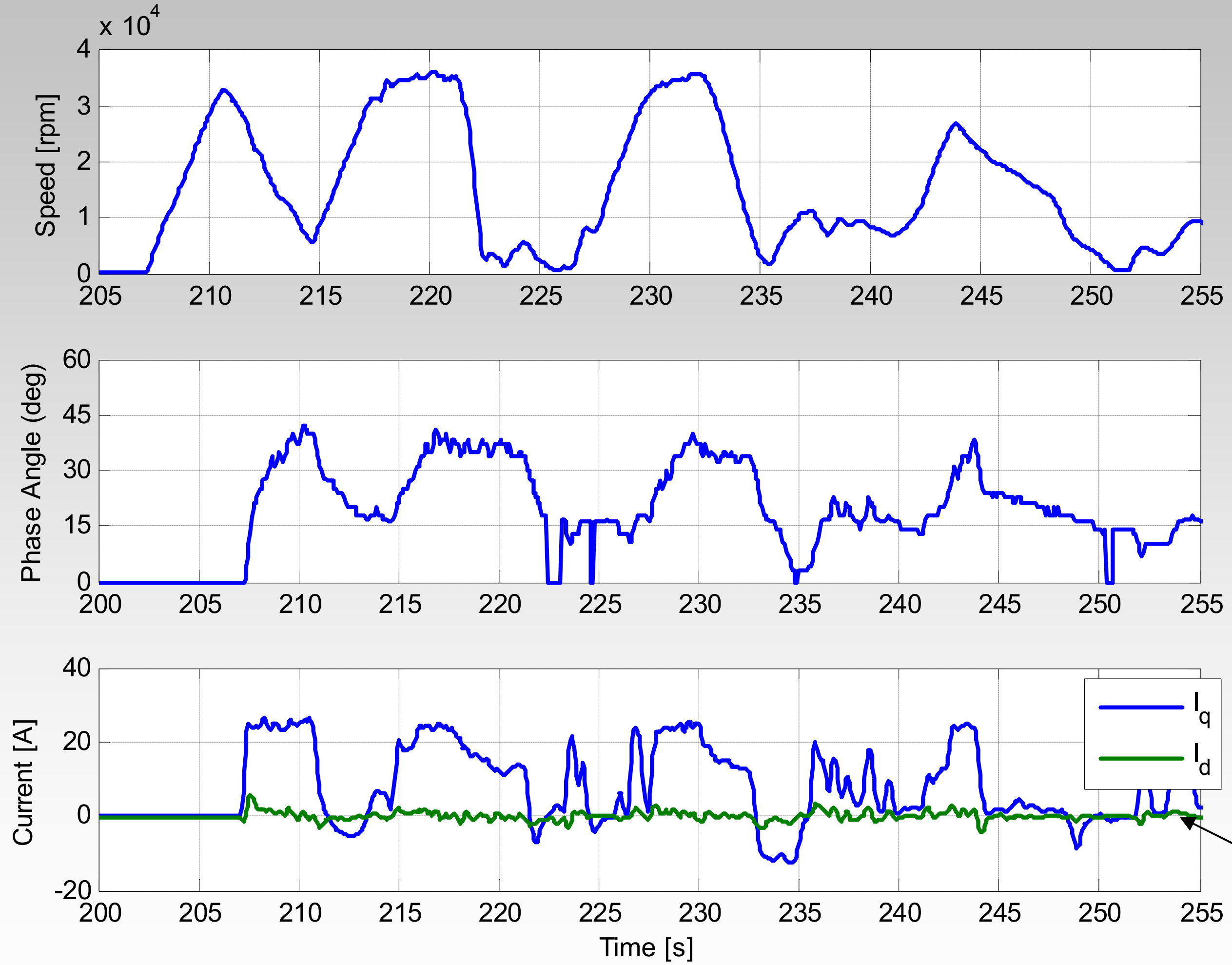
d-axis current controlled to be zero

Real-World Implemenation

High-Speed (40,000rpm) RC Car Motor

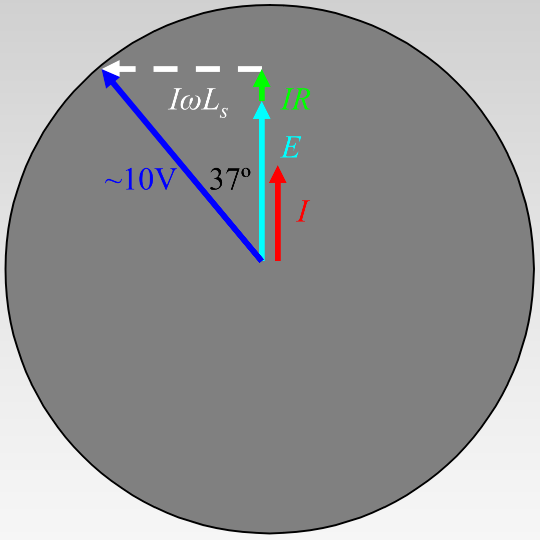
Real-World Implemenation

Modified S.C.R. Data: High-speed RC car motor. (Large phase angle test.)



d-axis current held at zero.

$\angle V$ is
37° at 35,000RPM
~3,700 rad/s



Conclusions

- The modified synchronous current regulator has been demonstrated in both simulation and two real world applications.
- It retains the ability to place the current vector on the q-axis (or anywhere else).
- It has theoretical advantages in transient torque response, since the voltage vector takes a more direct path between operating points.
- It can run on fixed-point processors due to efficient loop structure and the look-up table-based inverse Park transform. (Demonstrated simultaenous control of two motors from one fixed-point processor.)
- It uses Hall effect sensor interpolation to derive rotor position. These sensors are typical on inexpensive motors designed for BLDC (six-step) control. No expensive feedback device (encoder, resolver) is required.