Switched Doubly-Fed Machine Drive For High Power Applications

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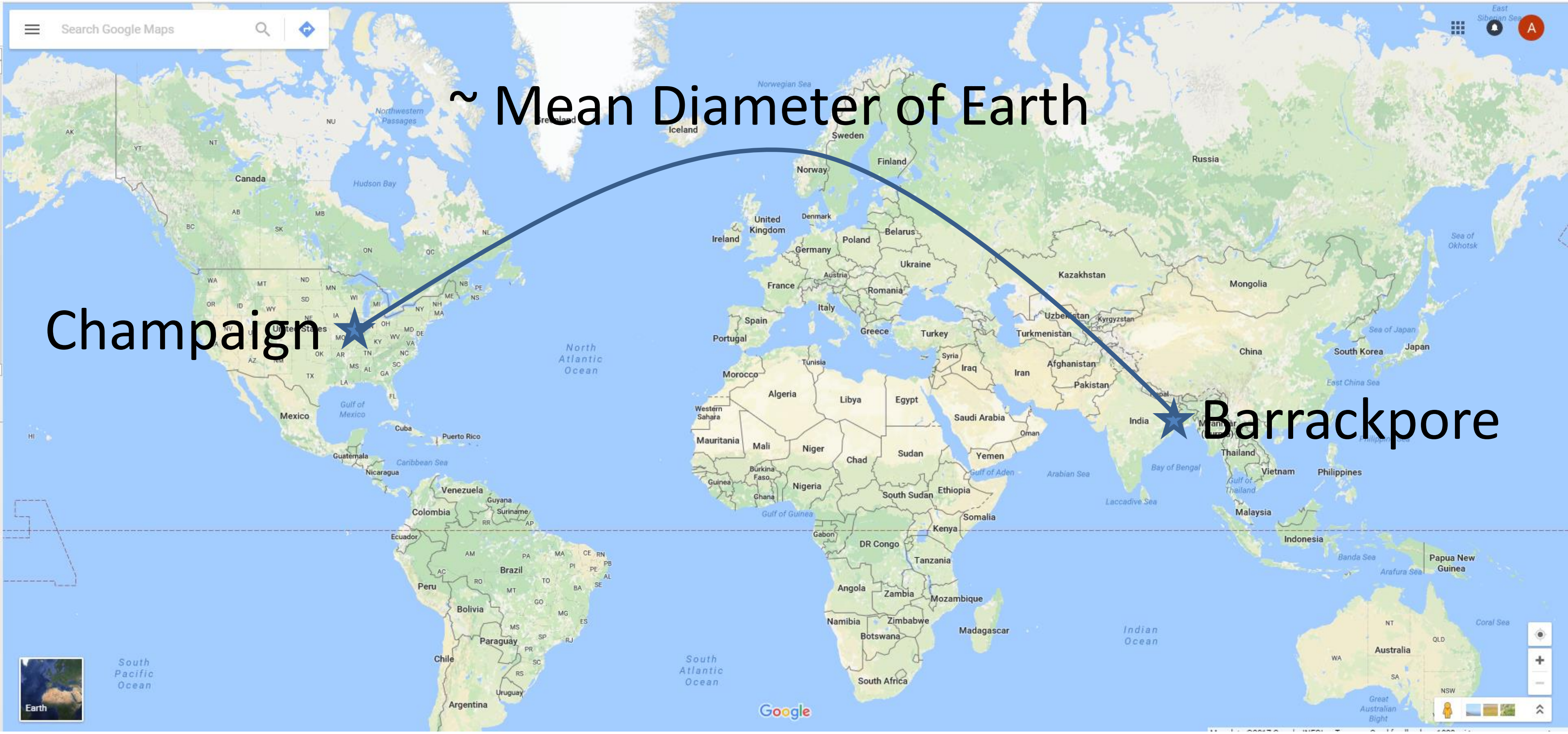
88° East Latitude to 88° West Latitude

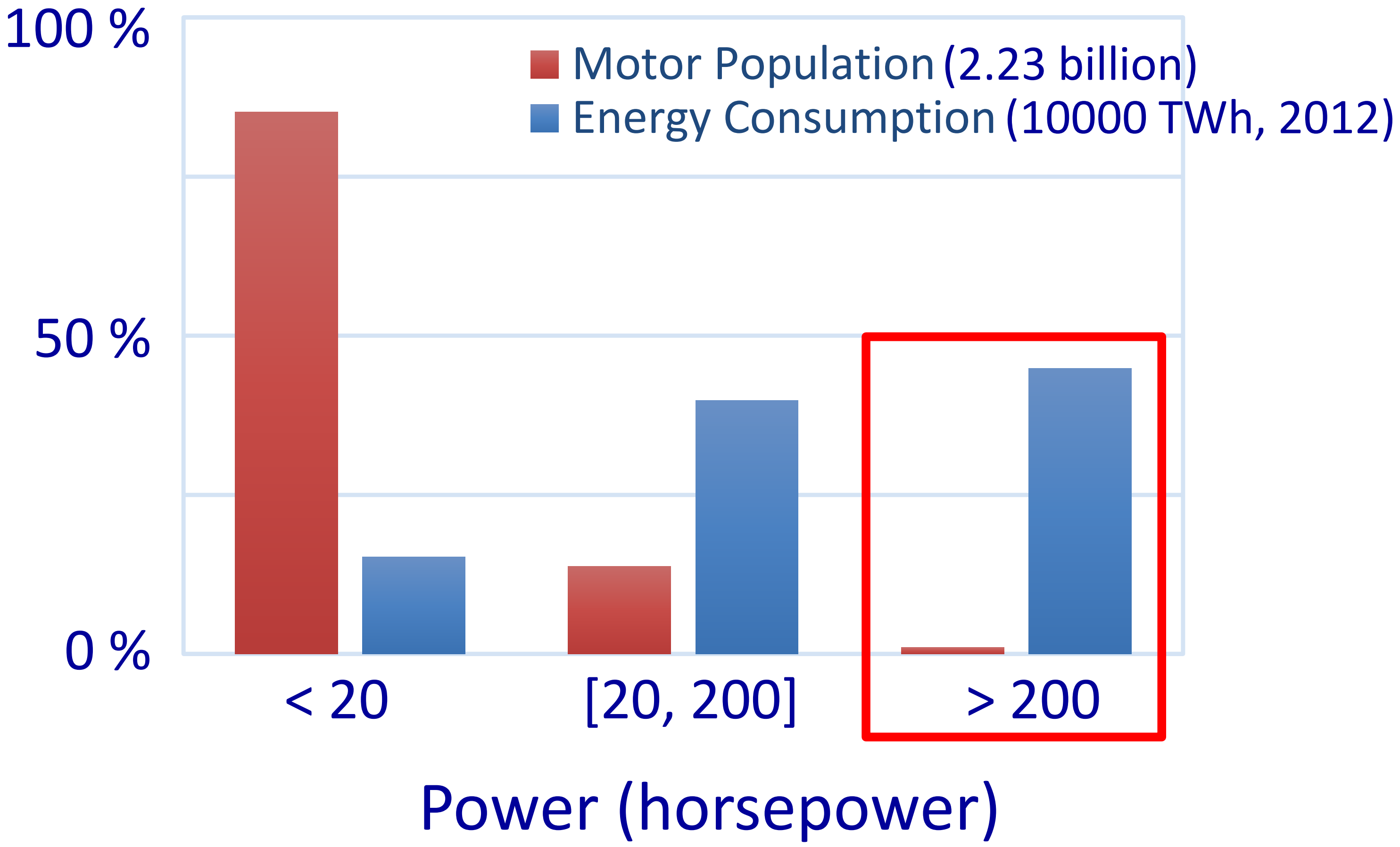


~ Mean Diameter of Earth

Champaign

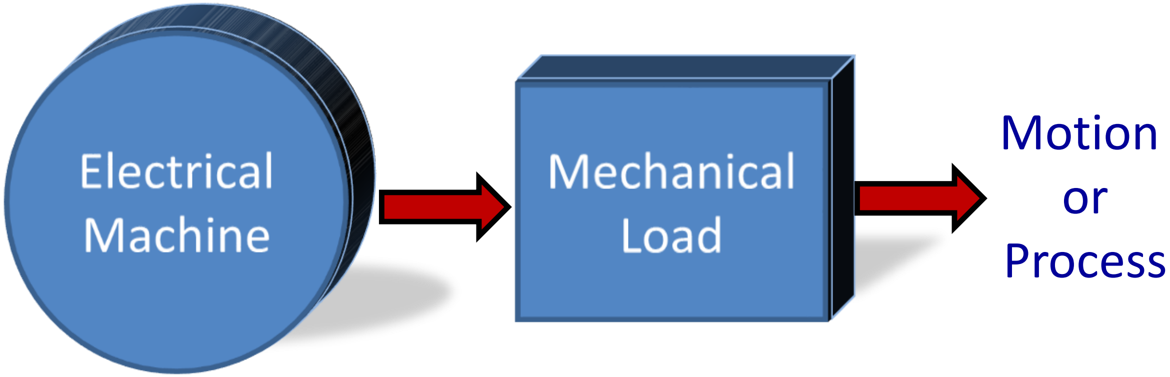
Barrackpore

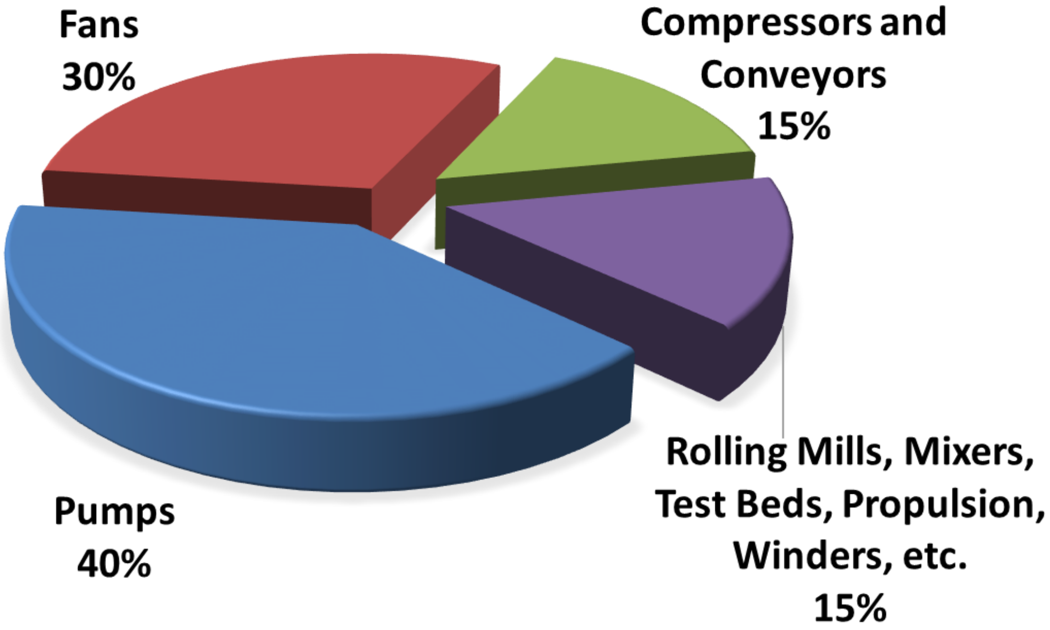
High-power motors are 1% of motor population but consume 45% of total motor energy



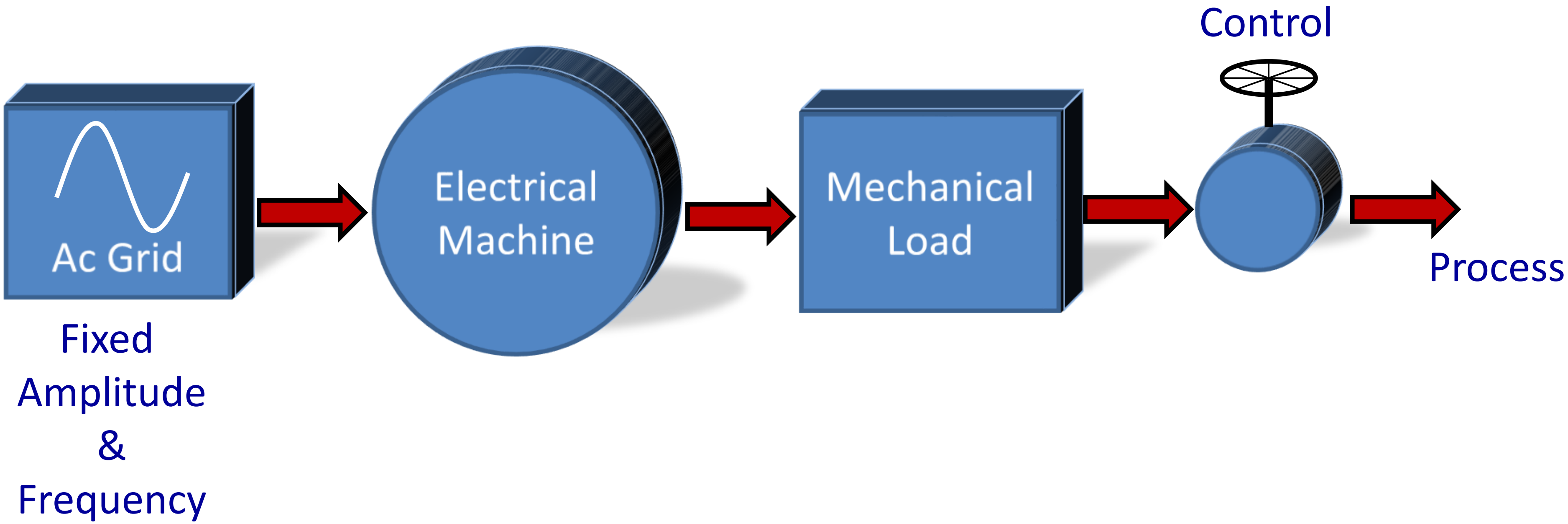
International Energy Agency, 2011

Wide range of applications for high power motors





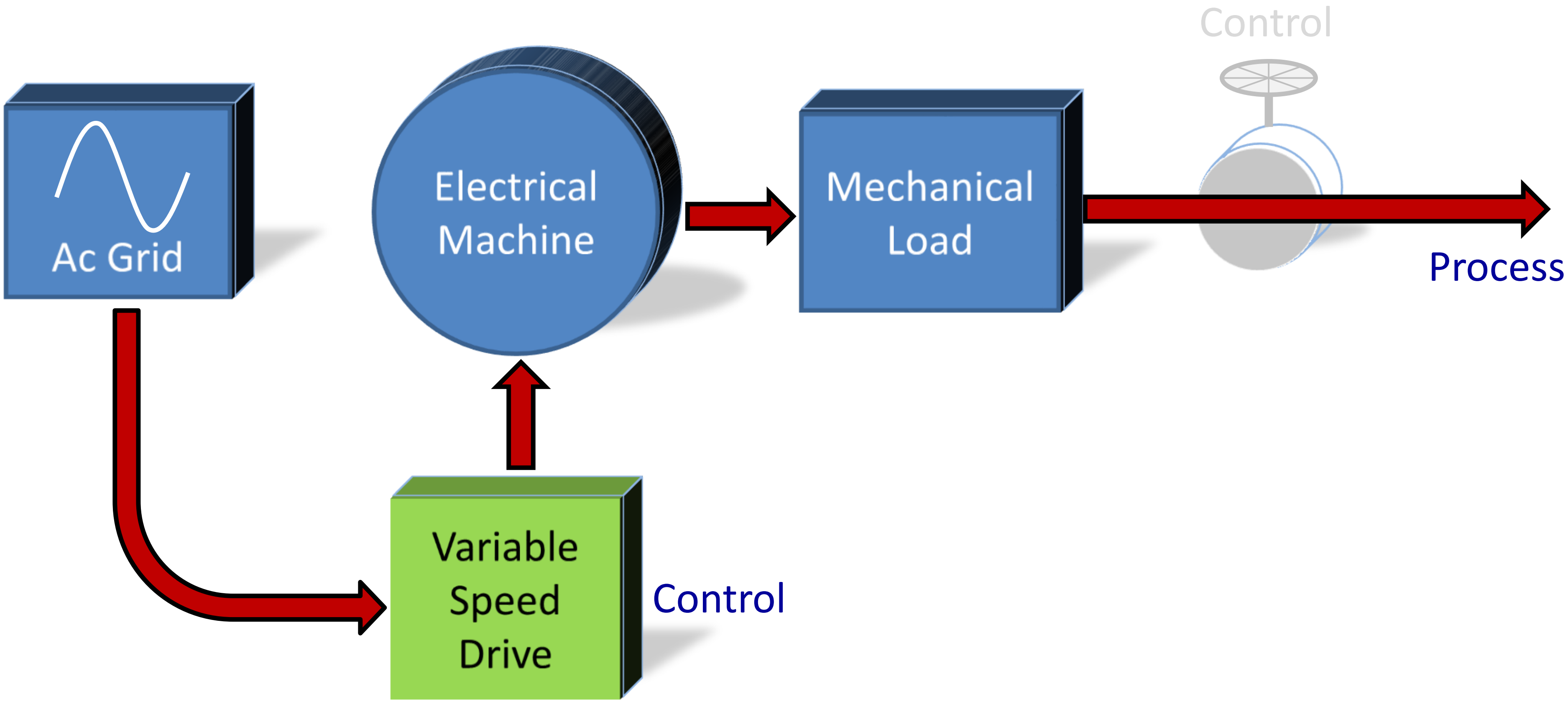
87% of high-power motors are directly connected to ac grid



Drawbacks:

- 30% - 80% loss in control mechanism
- Reactive power sink from Ac grid perspective

Variable speed drives are advantageous for process control

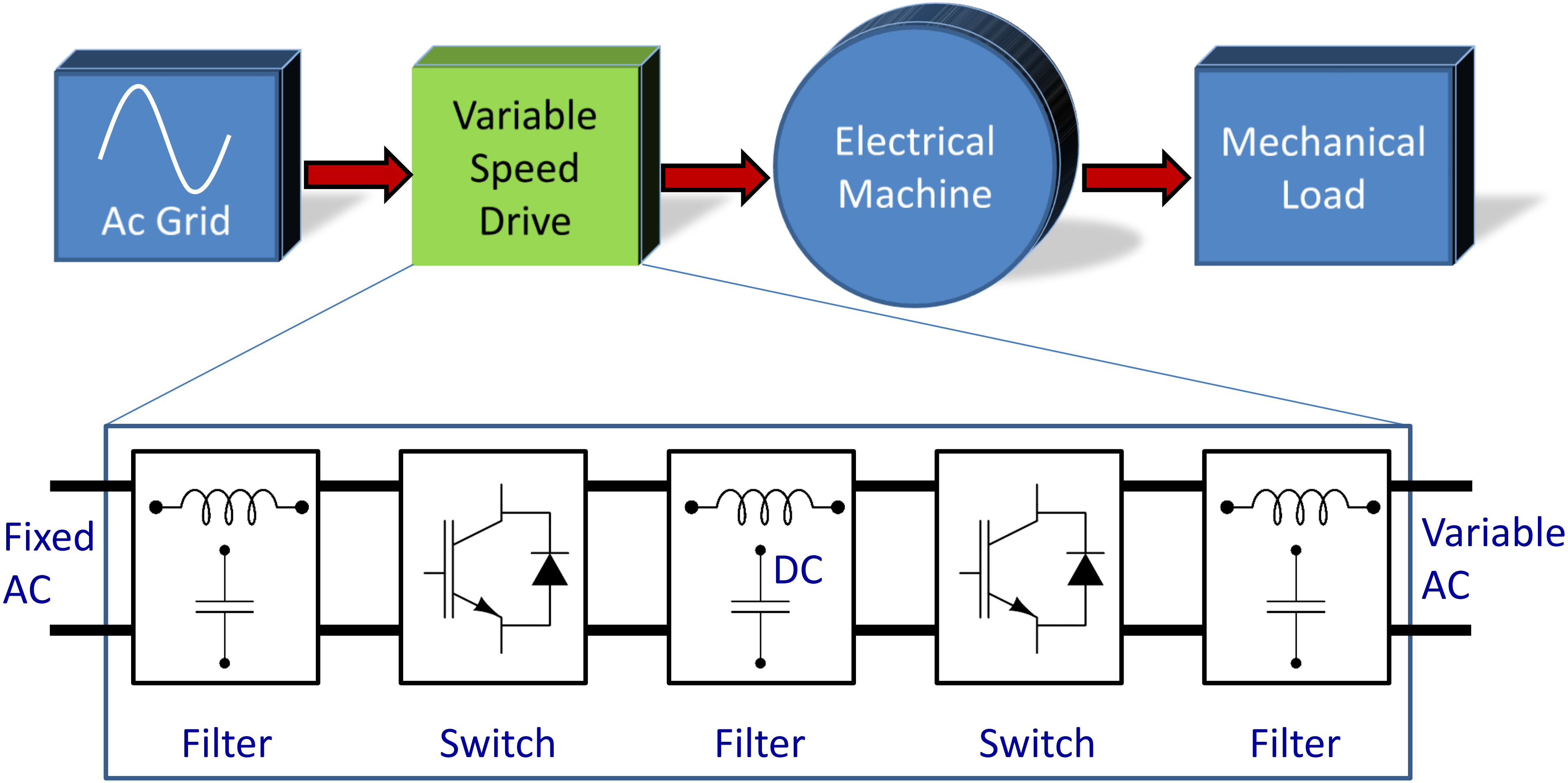


Estimated annual benefits just in U.S.

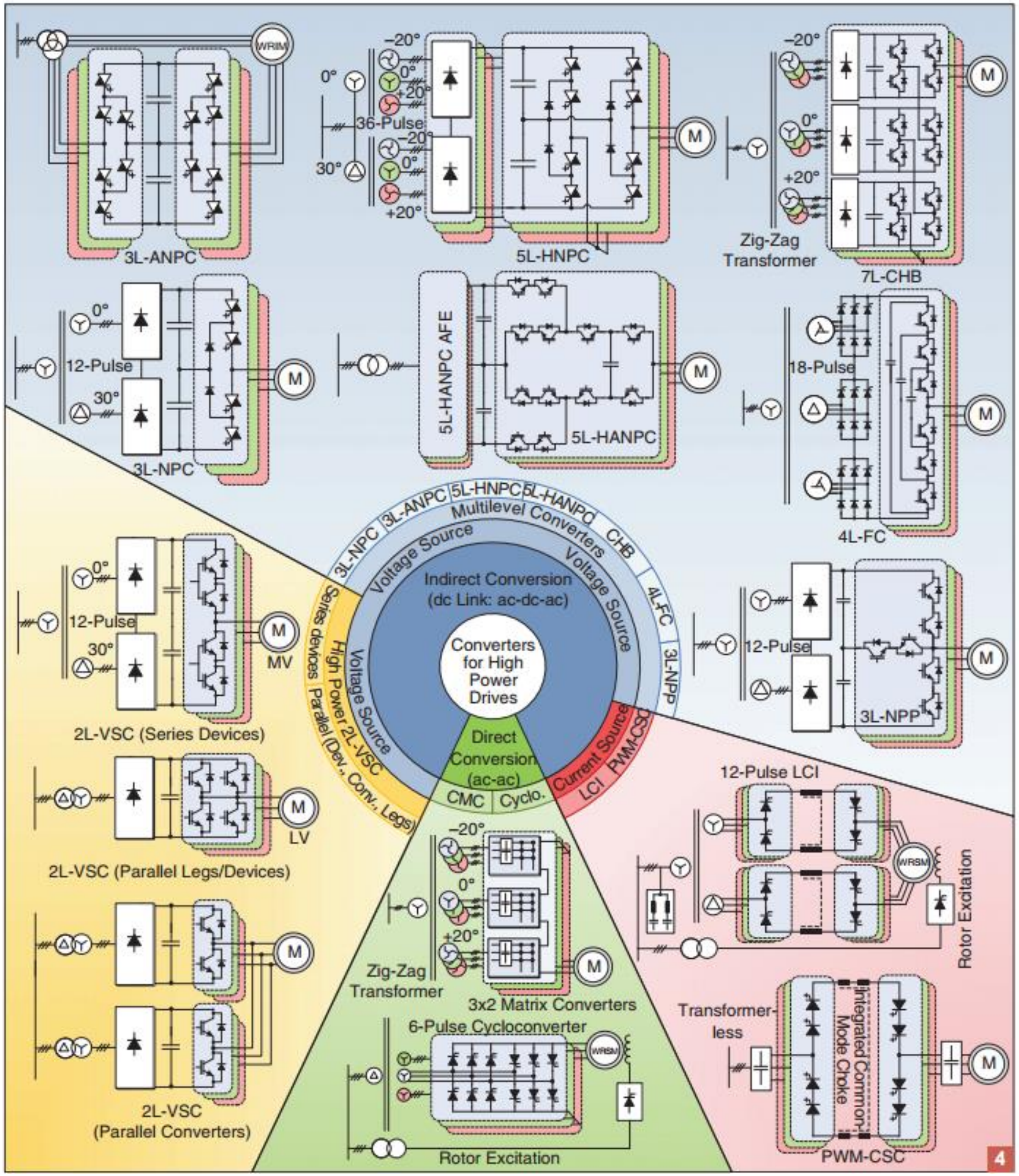
- Energy savings - **$2.7B**
- Carbon emission reduction - **27 million tons**

The Office of EERE, DOE , 2015

Anatomy of a variable speed drive



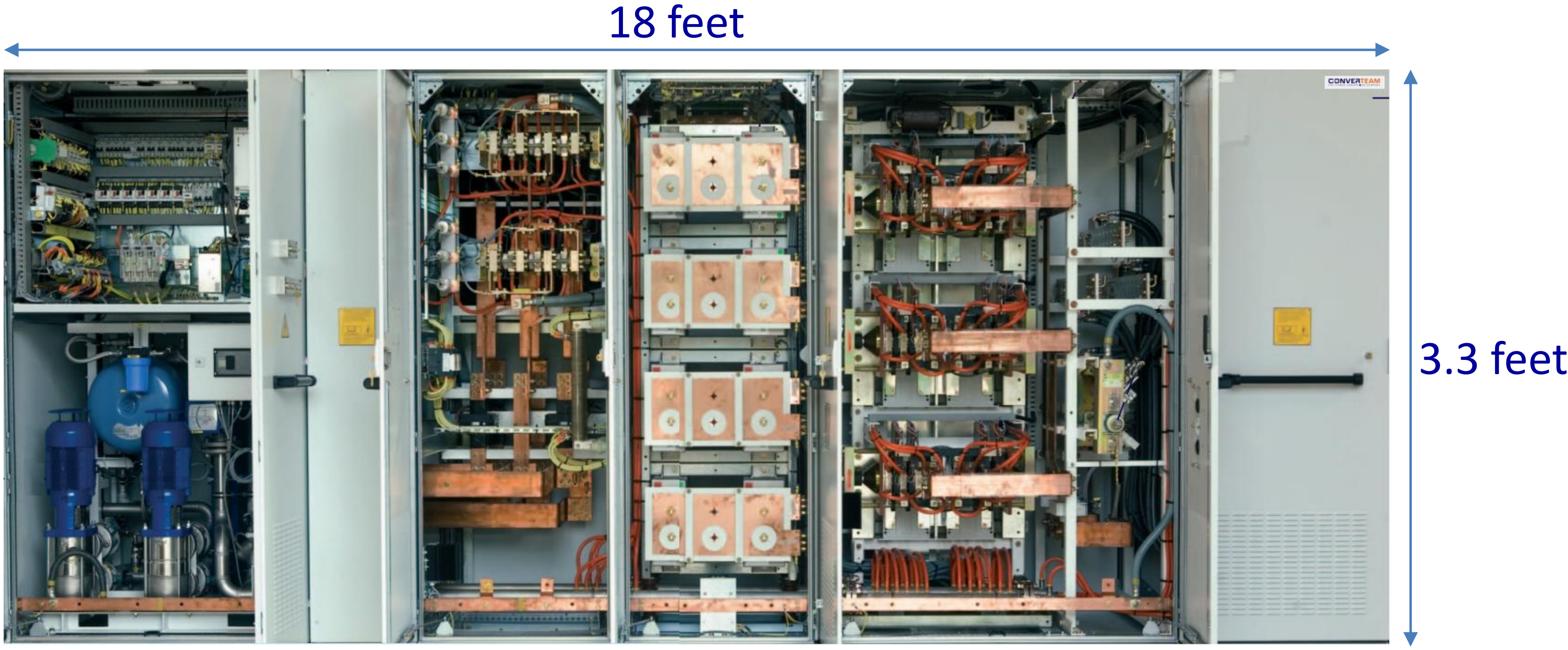
State-of-the-art: High-power variable speed drive topologies



- Series/parallel switches
- Multi-level converters
- Thyristor based Cyclo-converters

Kouro et al., IEEE IAS, 2012

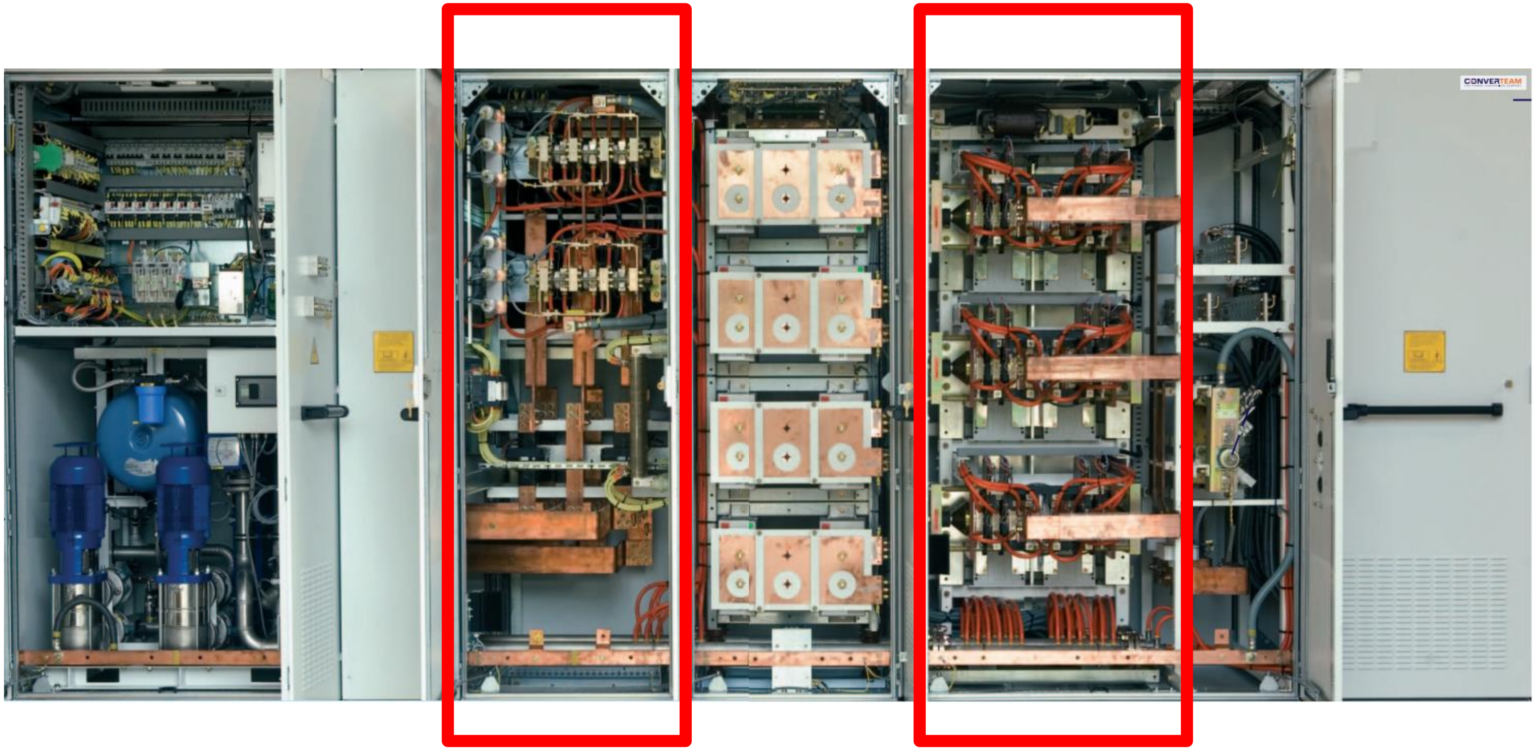
Example: Nine megawatt commercial variable speed drive



Volume: ~ 318 cubic meters
Weight: ~ 6 metric tons

MV7000 Brochure

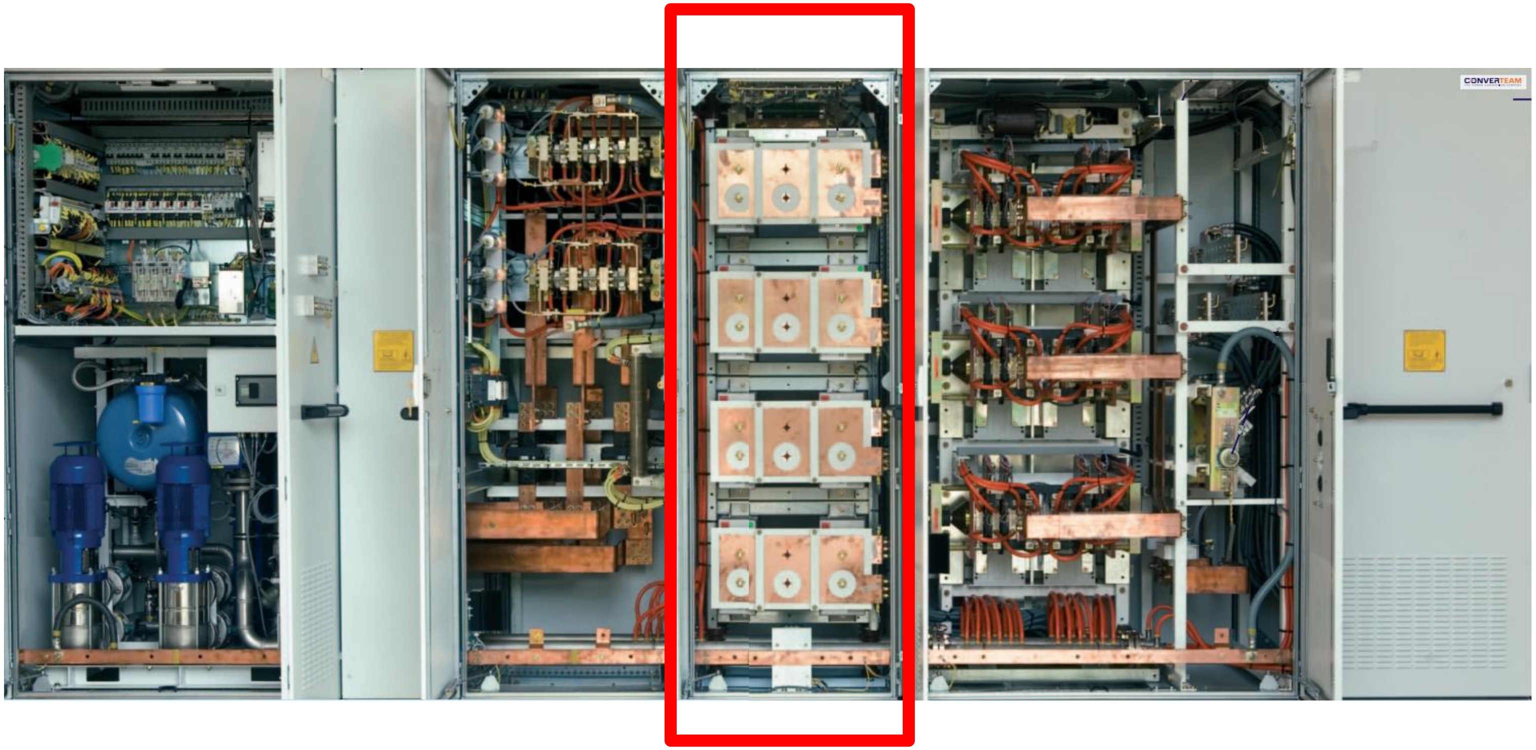
Example: Nine megawatt commercial variable speed drive



Multiple Switches & Low Switching Frequency

MV7000 Brochure

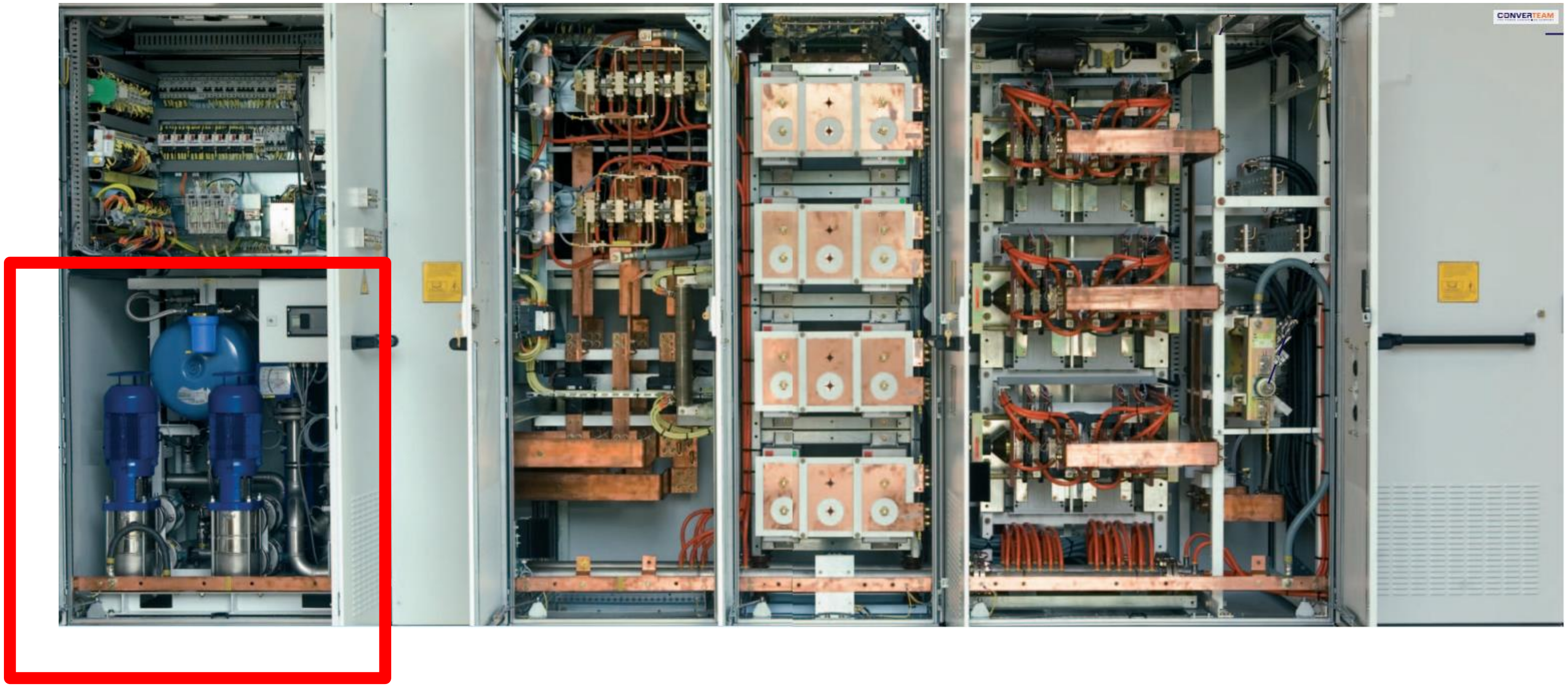
Example: Nine megawatt commercial variable speed drive



Bulky Filter

MV7000 Brochure

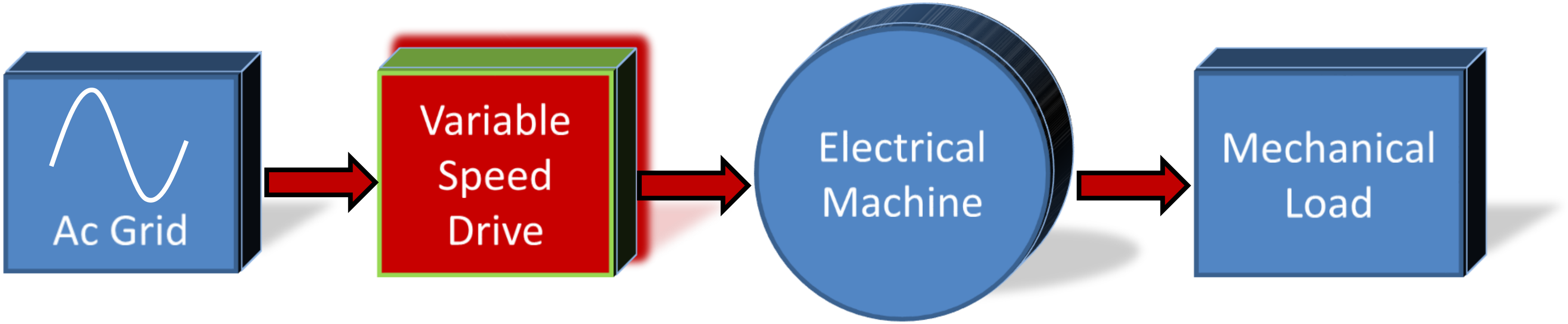
Example: Nine megawatt commercial variable speed drive



Significant Cooling

MV7000 Brochure

Doctoral Thesis objective

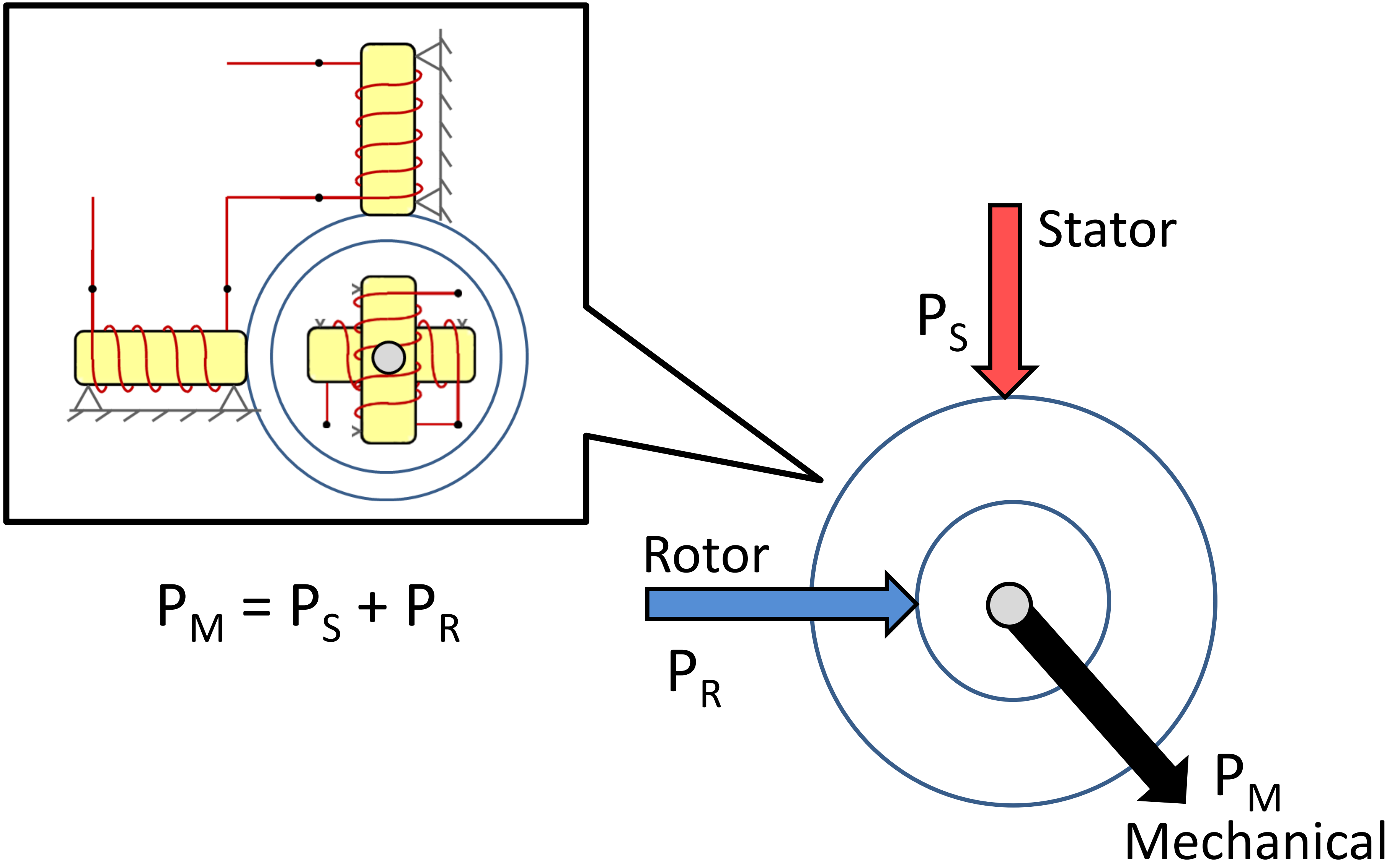


Reduce the size of the variable speed drive

&

provide reactive power support to the grid

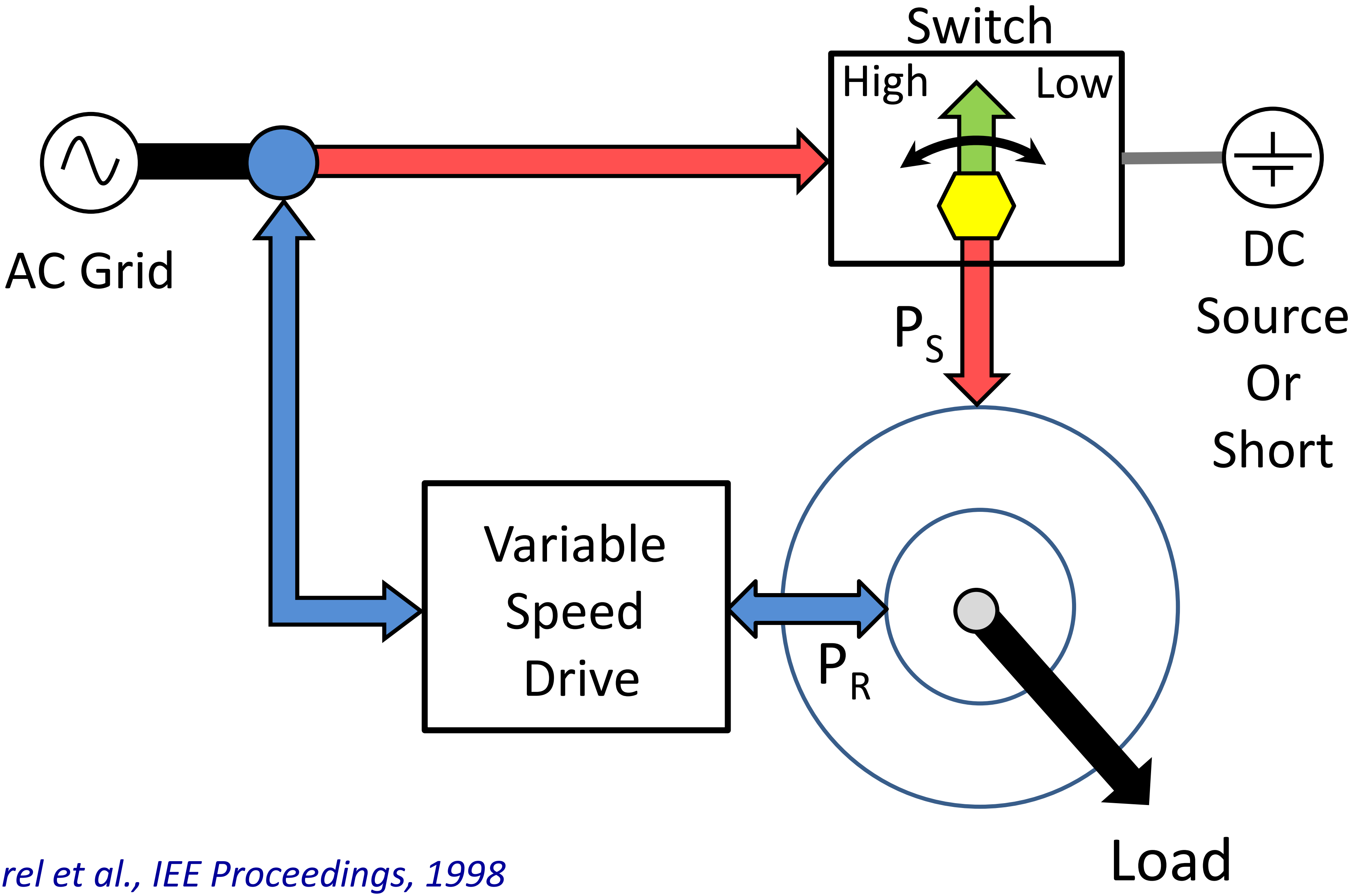
Thesis approach: Doubly-fed machines



$$P_M = P_S + P_R$$

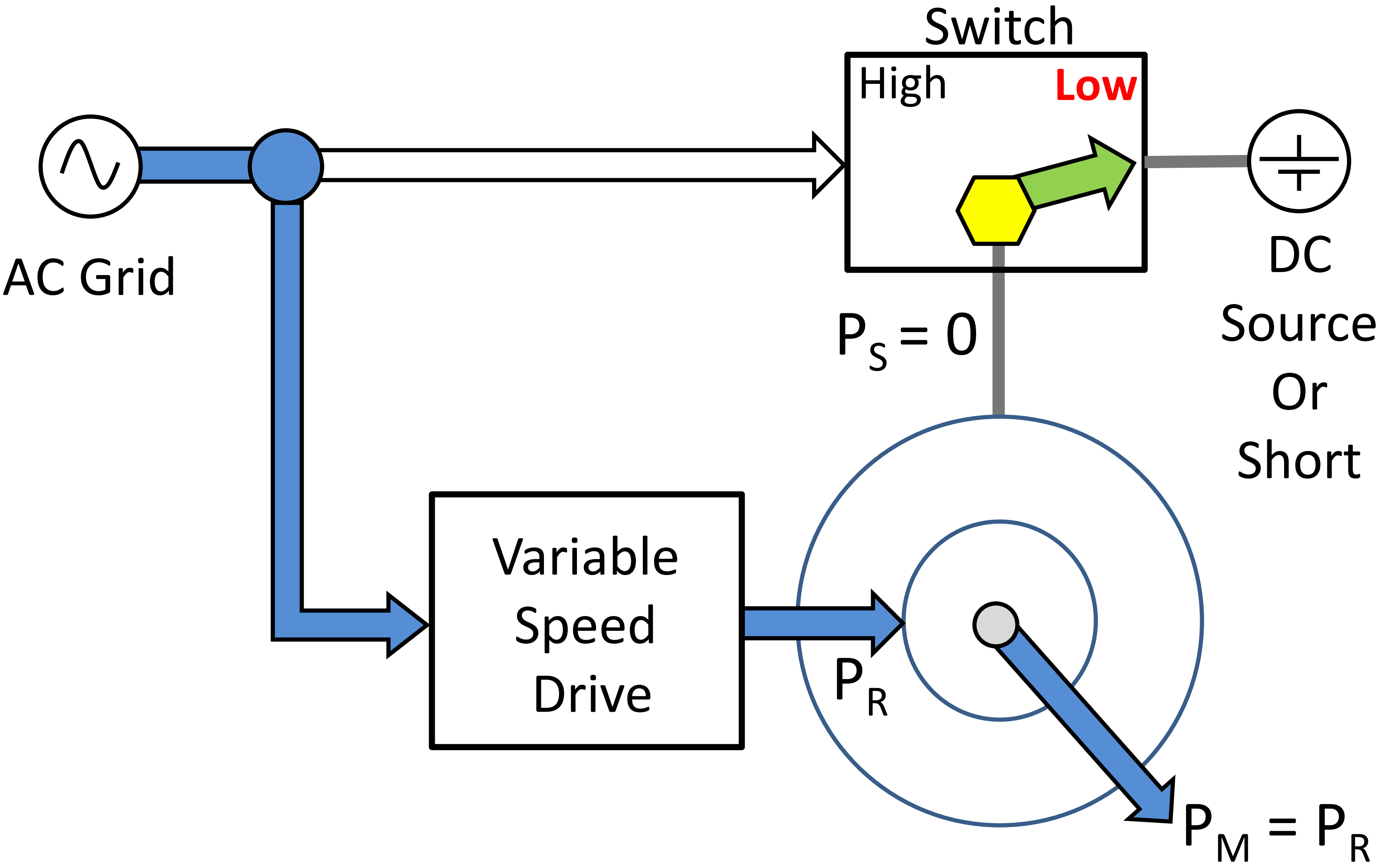
Pena et al., IEE Proceedings, 1996

Switched-Doubly-fed-Machine drive architecture

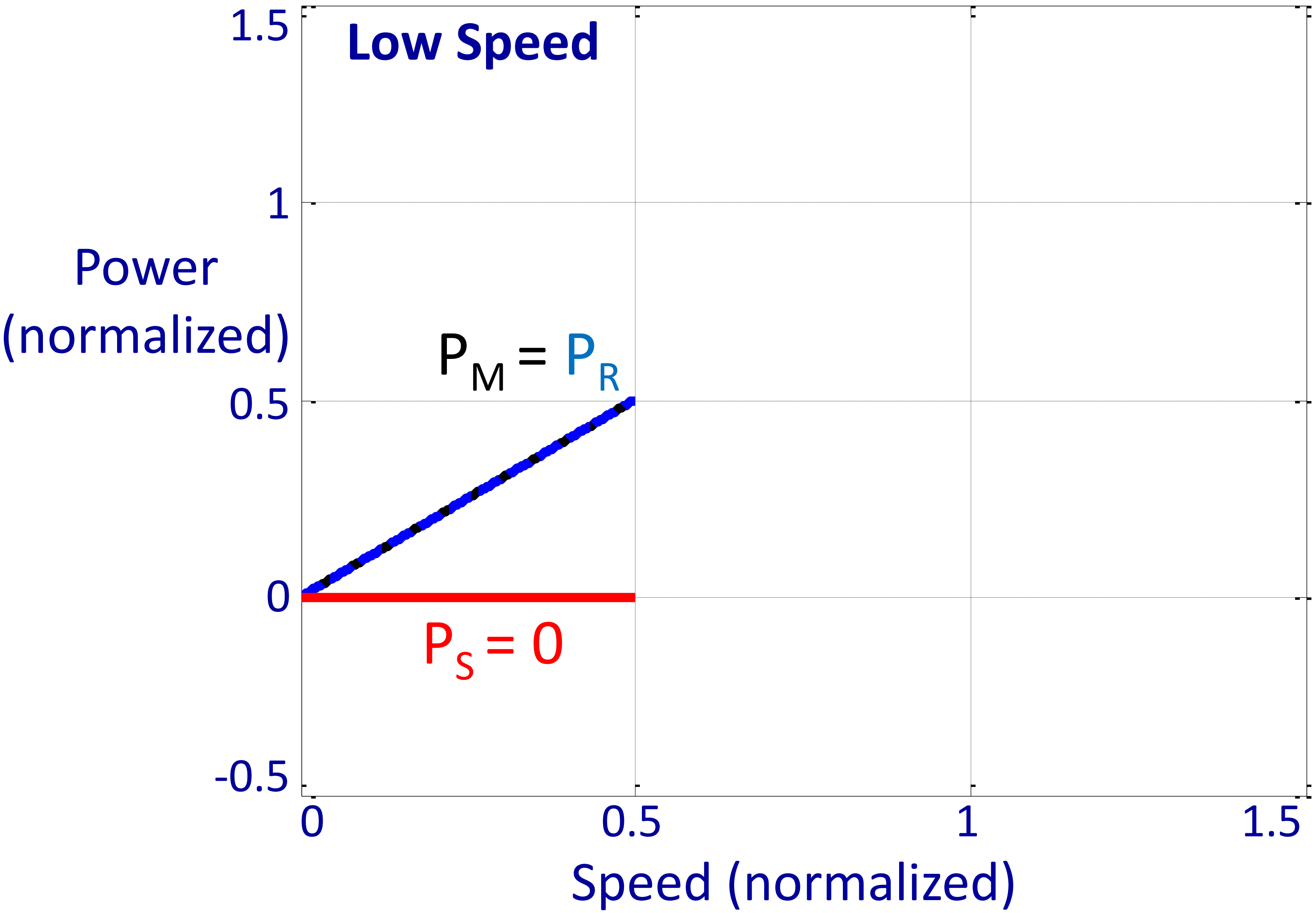


Morel et al., IEE Proceedings, 1998
Leeb et al., Naval Engineers Journal, 2010
Banerjee et al., IEEE IAS, 2015

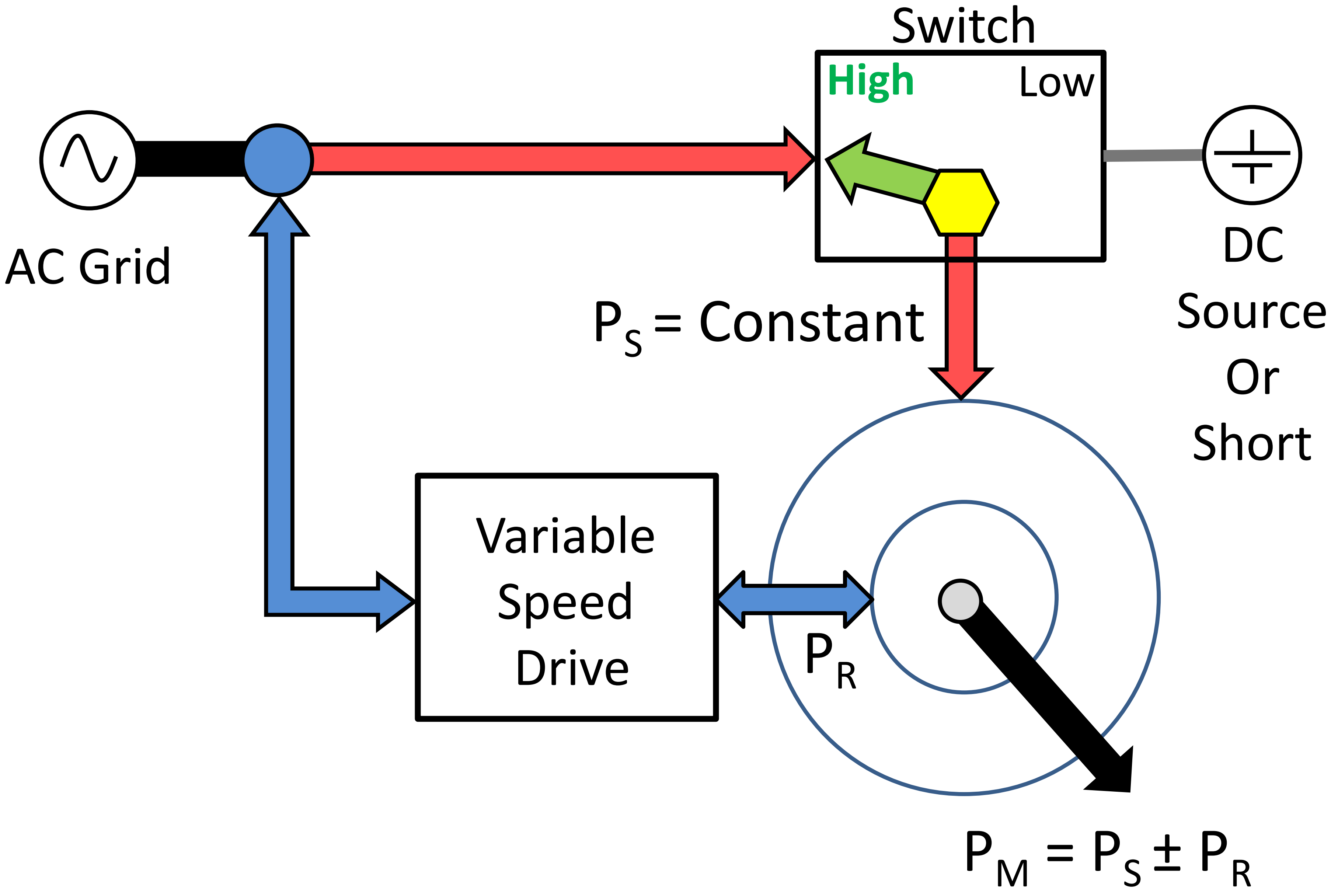
Switch is turned "Low" during low-speed, low-power mode



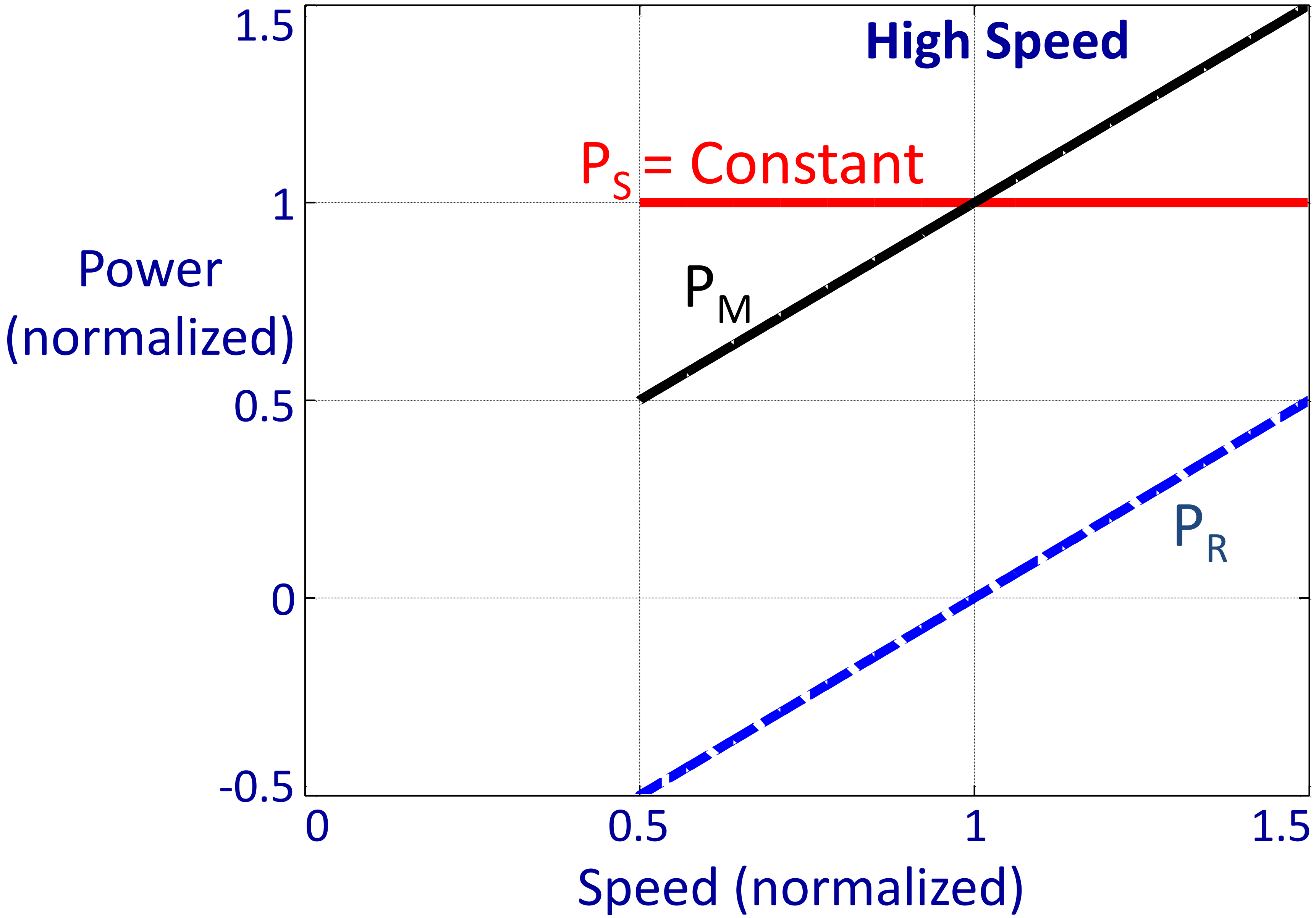
Rotor port provides all the mechanical power



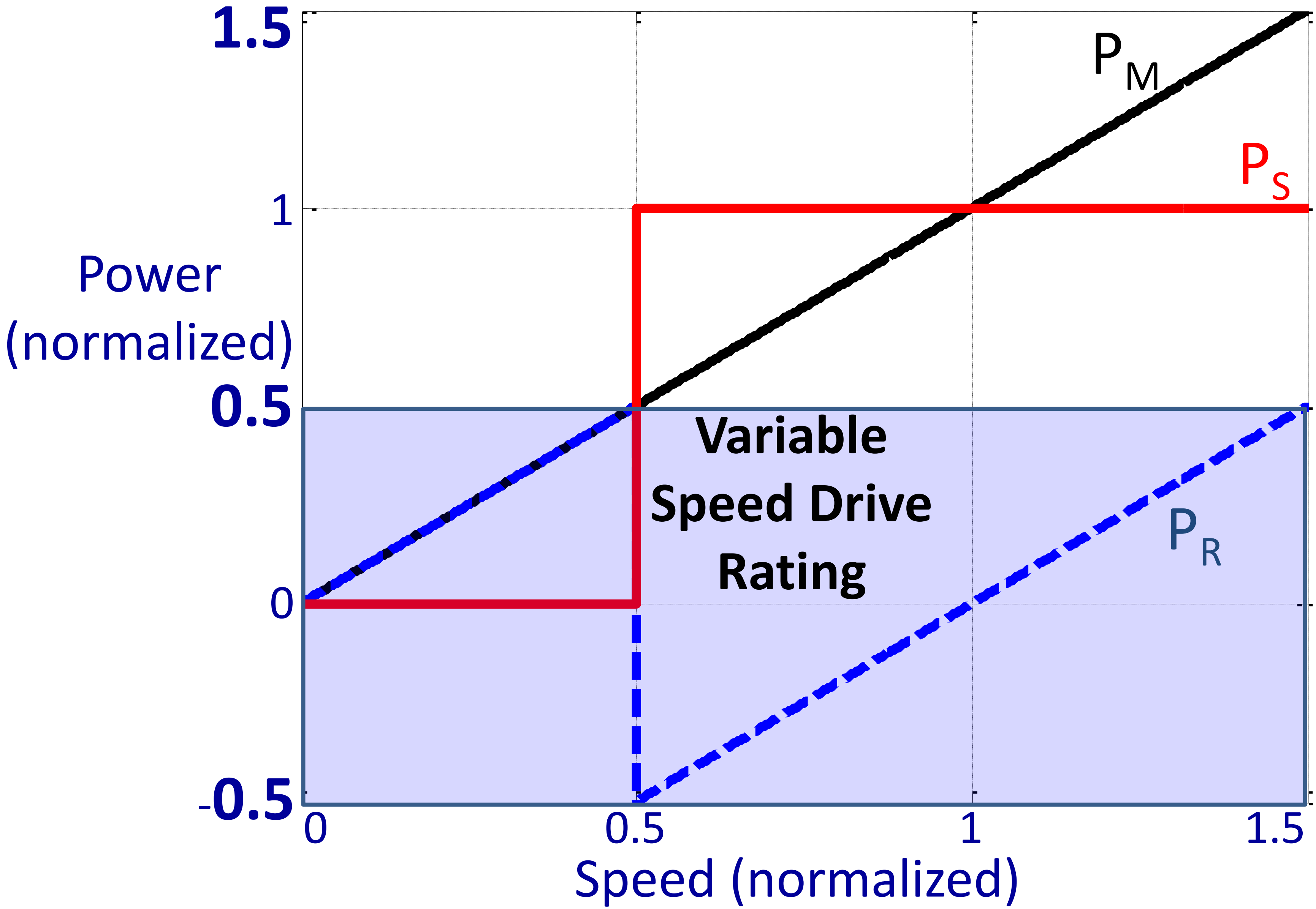
Switch is turned "High" during high-speed, high-power mode



Rotor port processes only the differential power

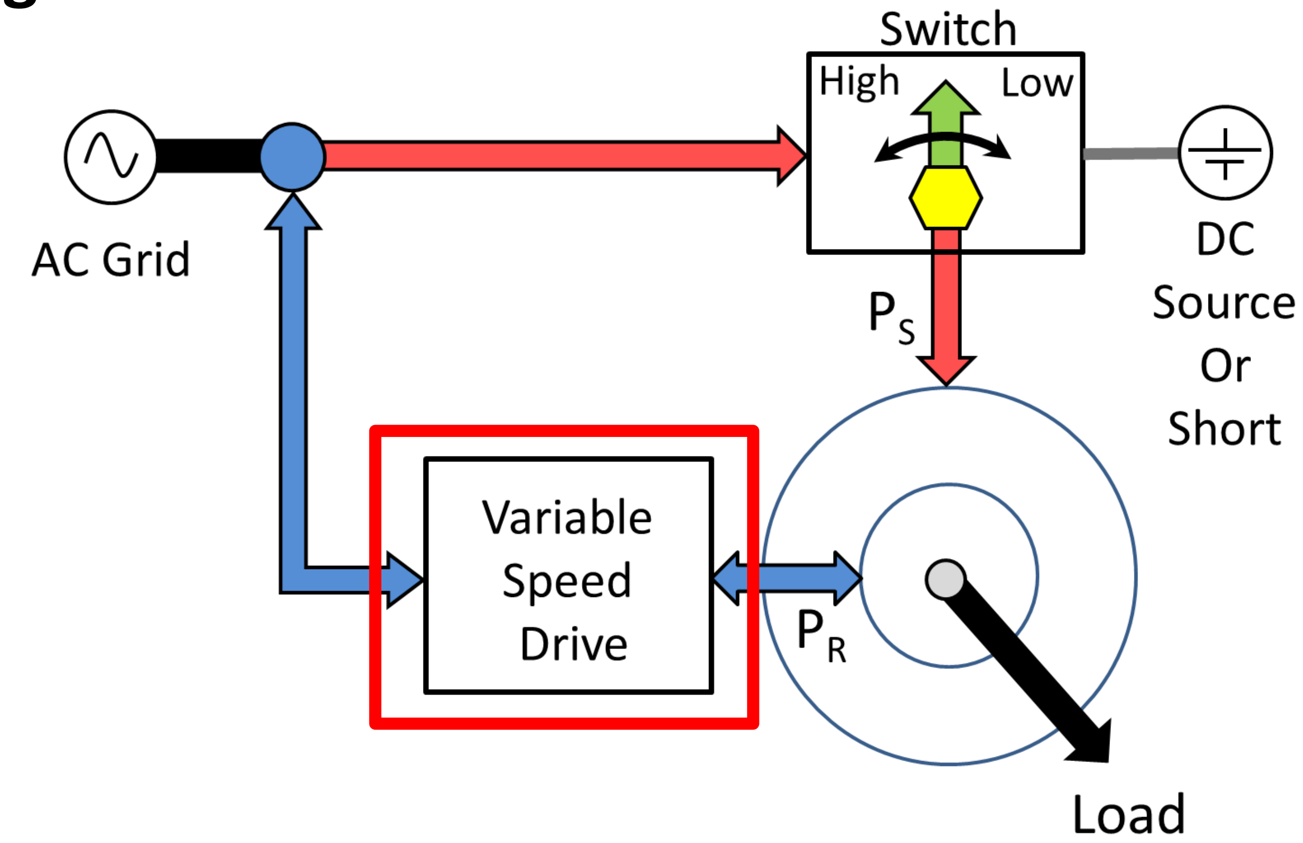


Size of variable speed drive reduces by two-thirds



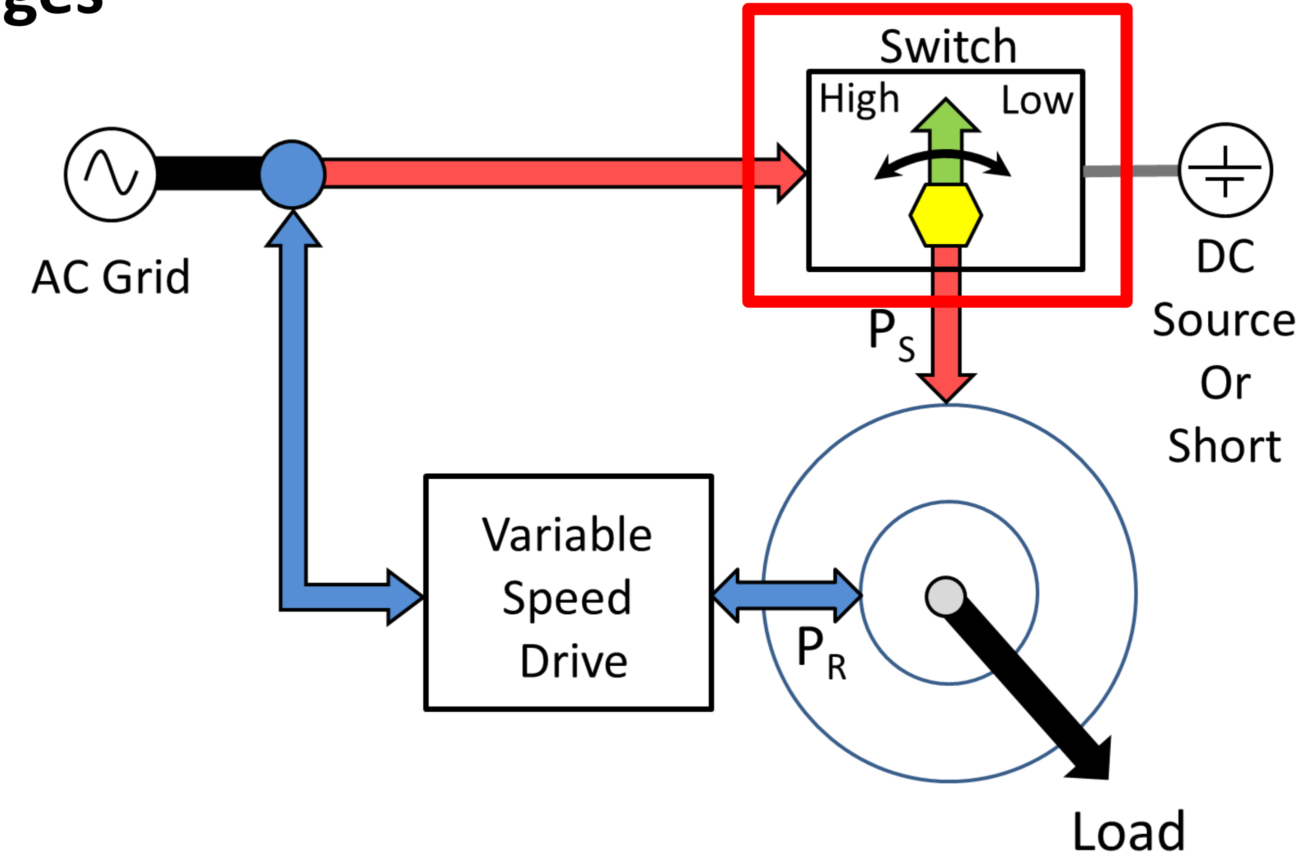
Banerjee et al., IEEE Trans. Industry Applications, 2015

Challenges



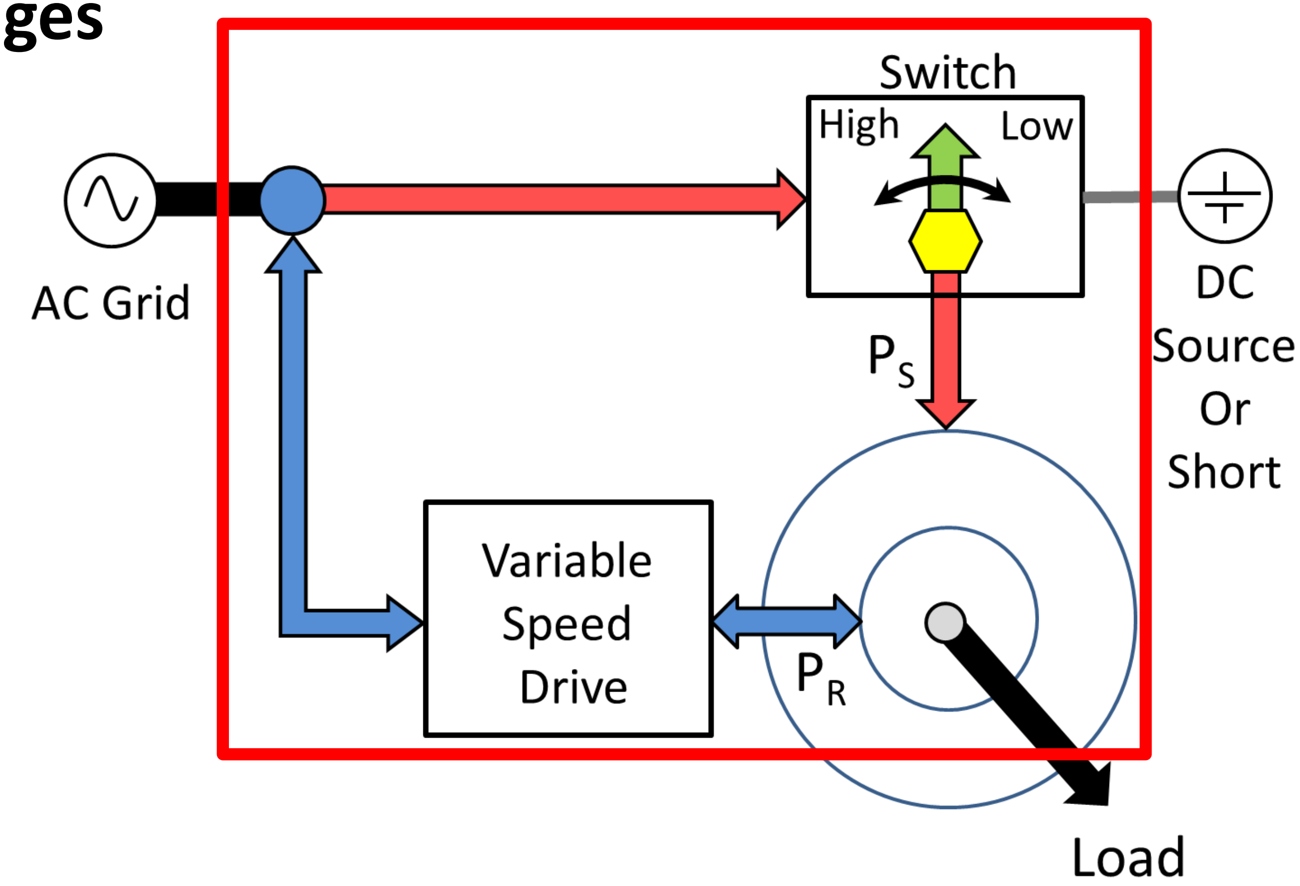
- Drive design

Challenges



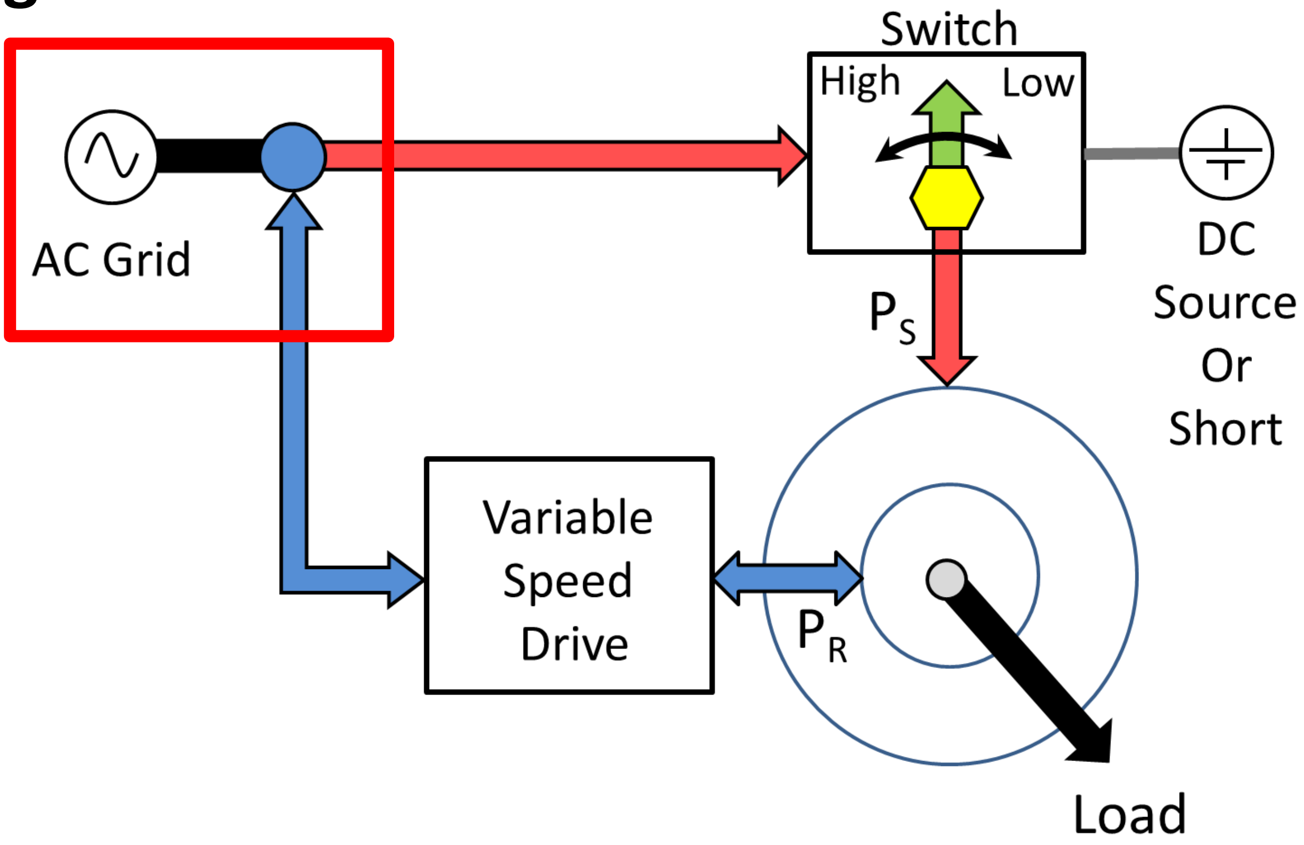
- Drive design
- Switch realization

Challenges



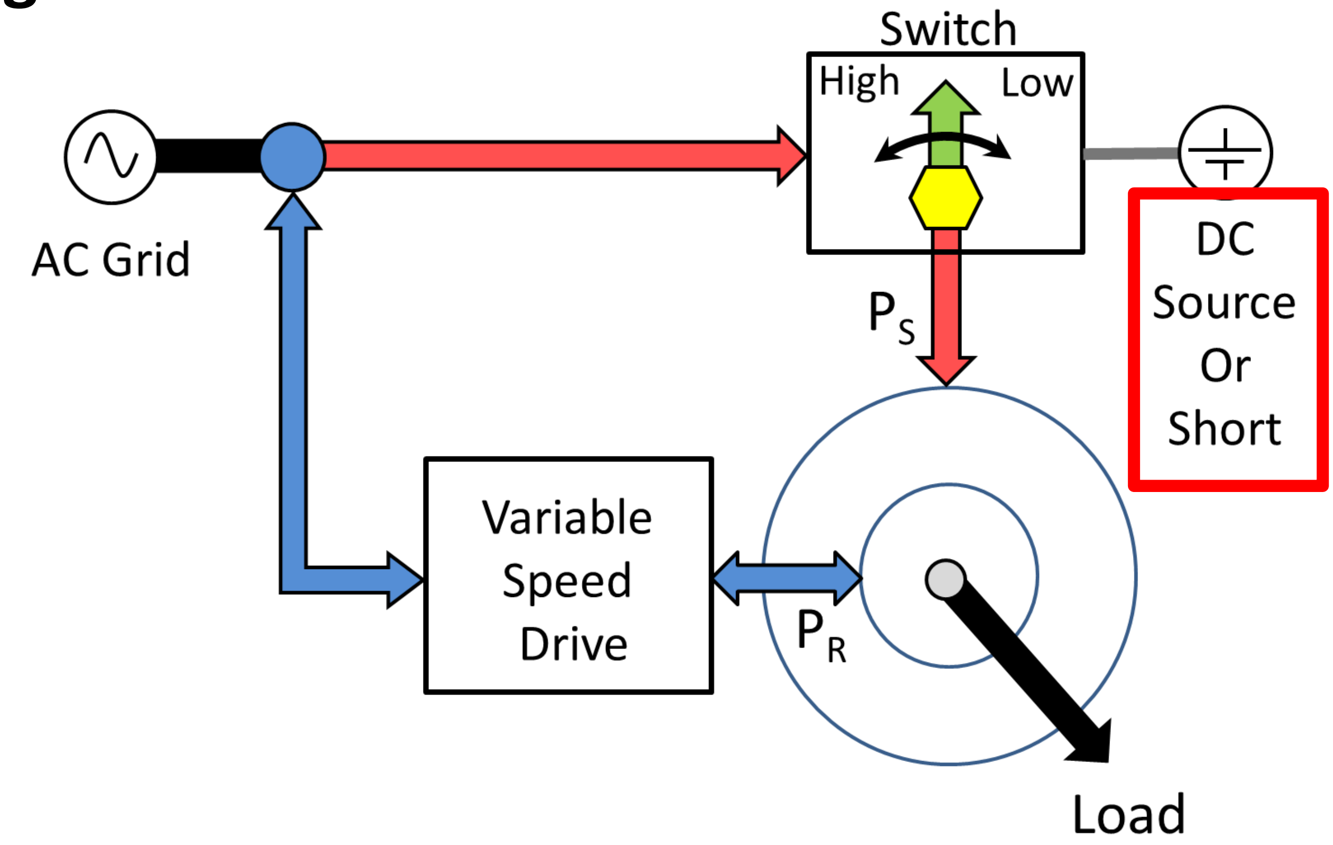
- Drive design
- Switch realization
- Seamless control

Challenges



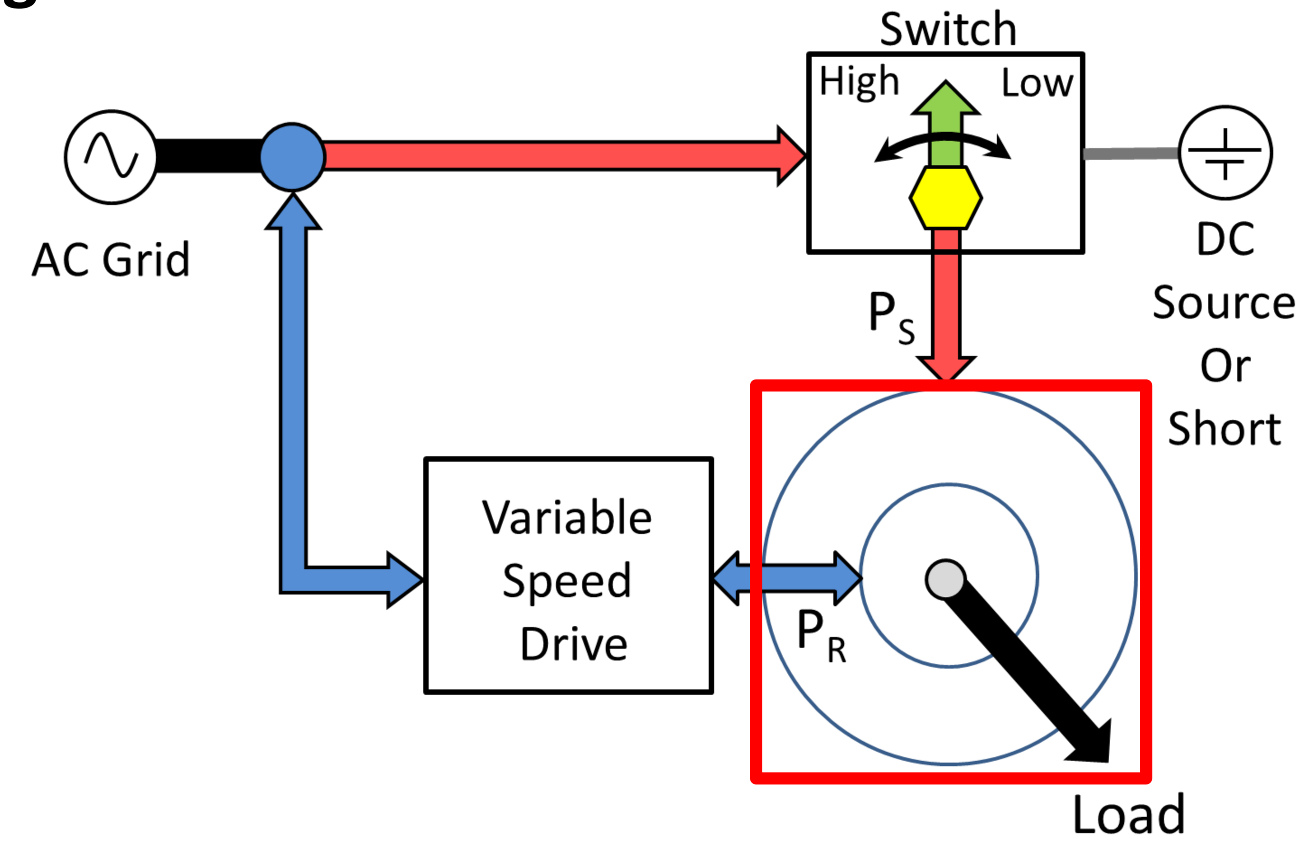
- Drive design
- Switch realization
- Seamless control
- Grid interaction

Challenges



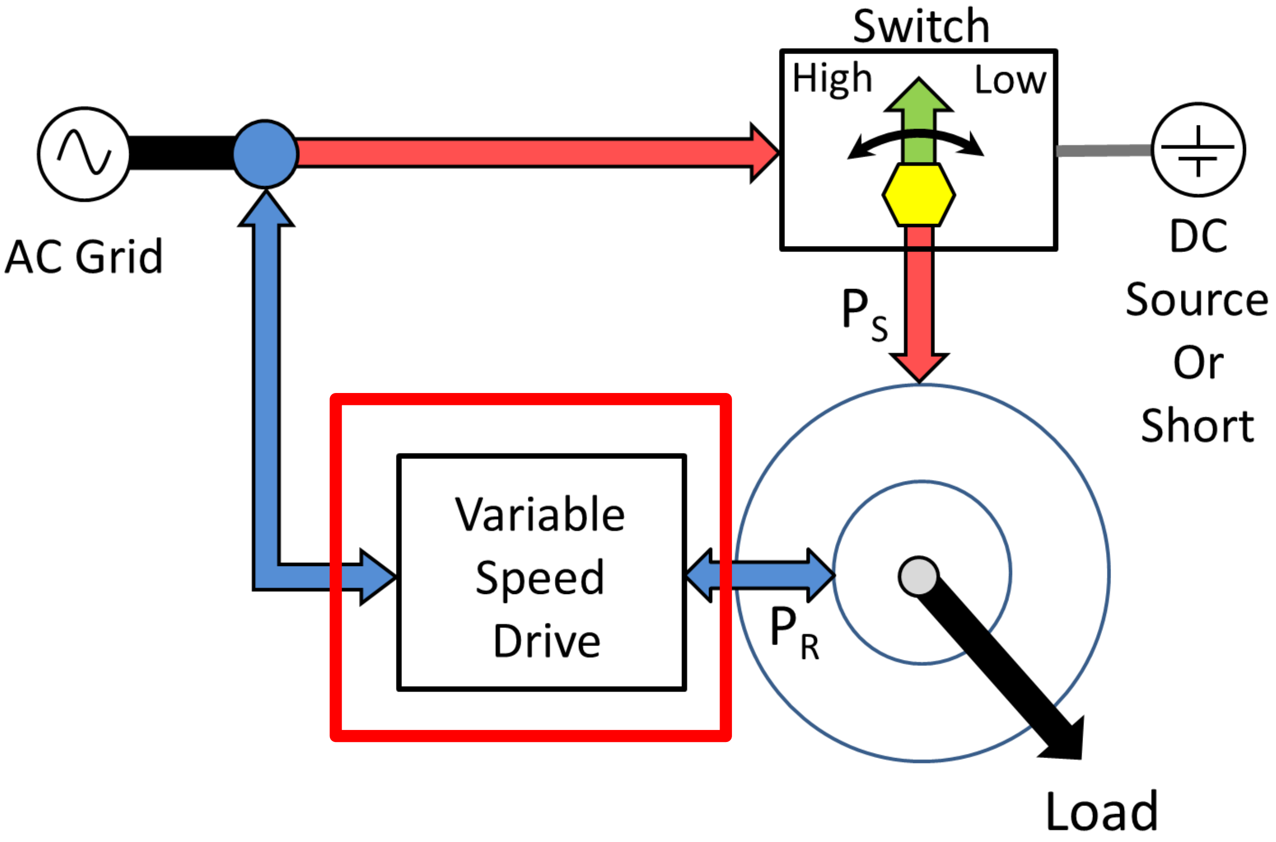
- Drive design
- Switch realization
- Seamless control
- Grid interaction
- Drive topology comparison

Challenges



- Drive design
- Switch realization
- Seamless control
- Grid interaction
- Drive topology comparison
- DFM design considerations

Contributions

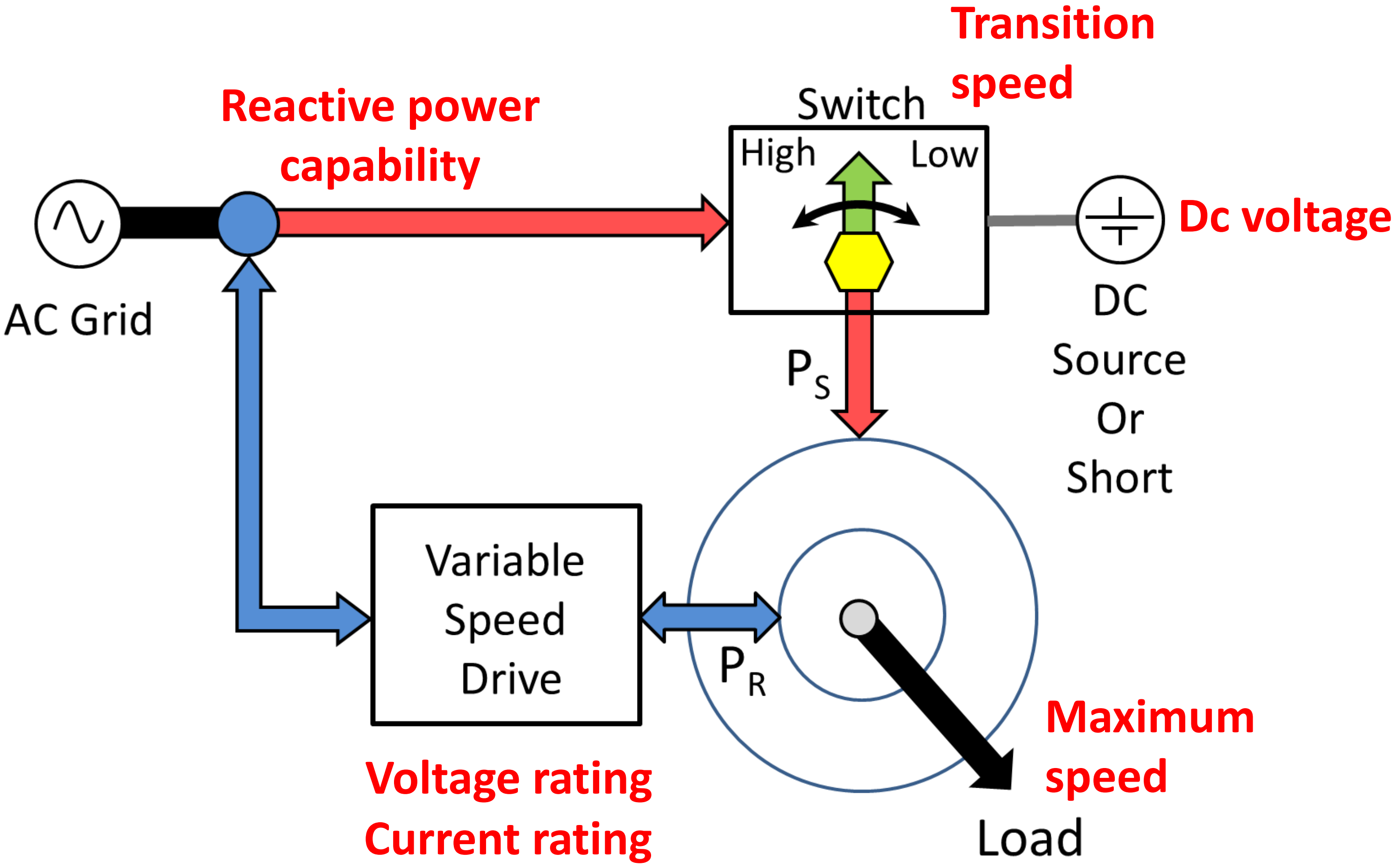


- **Drive design**
- Switch realization
- Seamless control
- Grid interaction
- Drive topology comparison
- DFM design considerations

Drive Design: Minimize variable speed drive rating

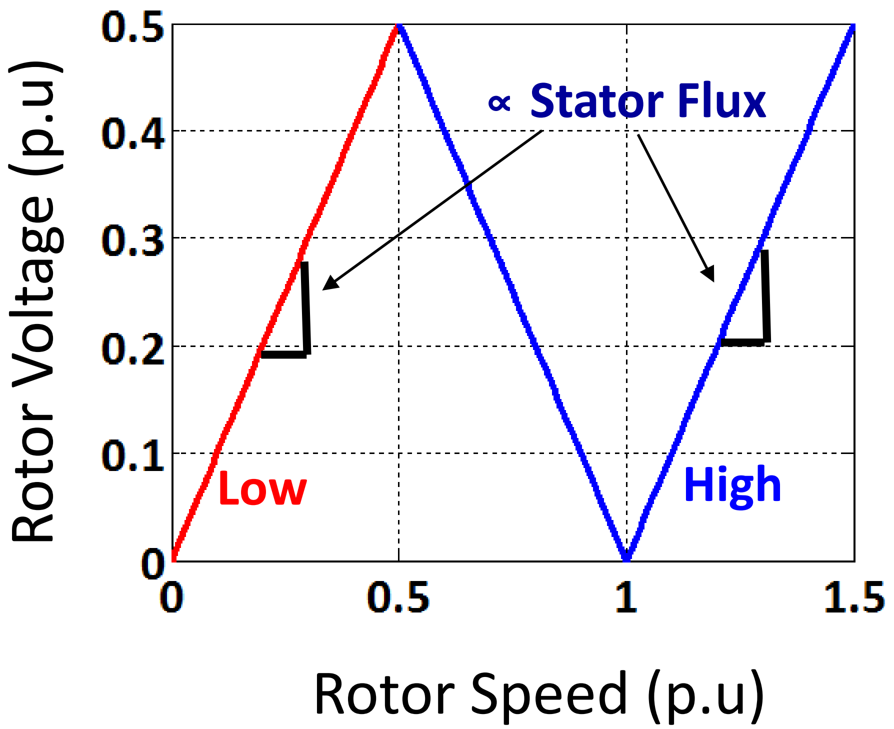
subject to:

1. Machine operating within its rated condition
2. Matches drive torque-speed requirement
3. Available ac source



Choice of stator flux drives the entire VSD design space

Low-speed mode stator flux = High-speed mode stator flux

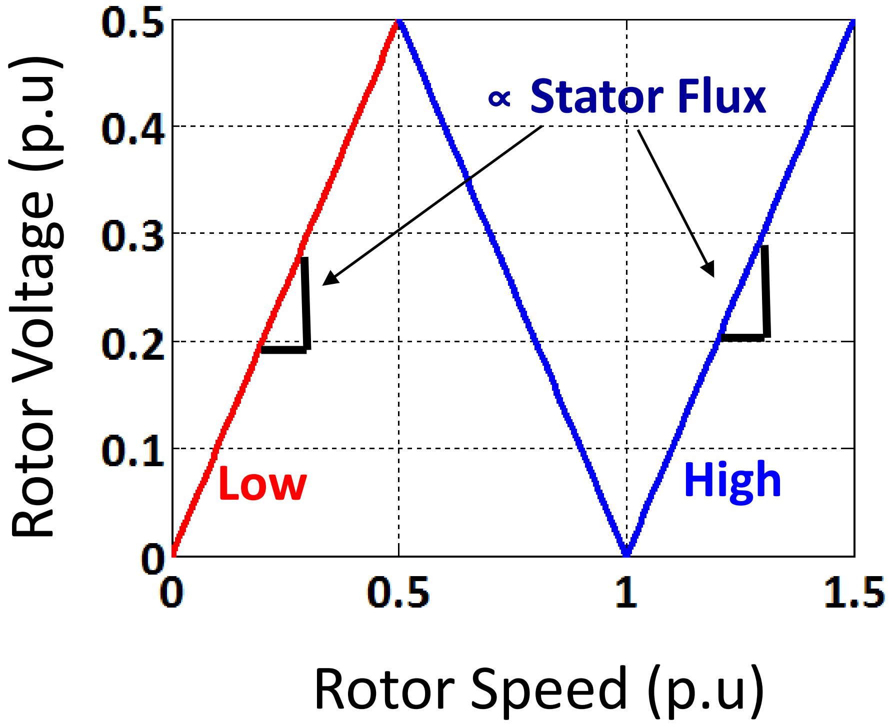


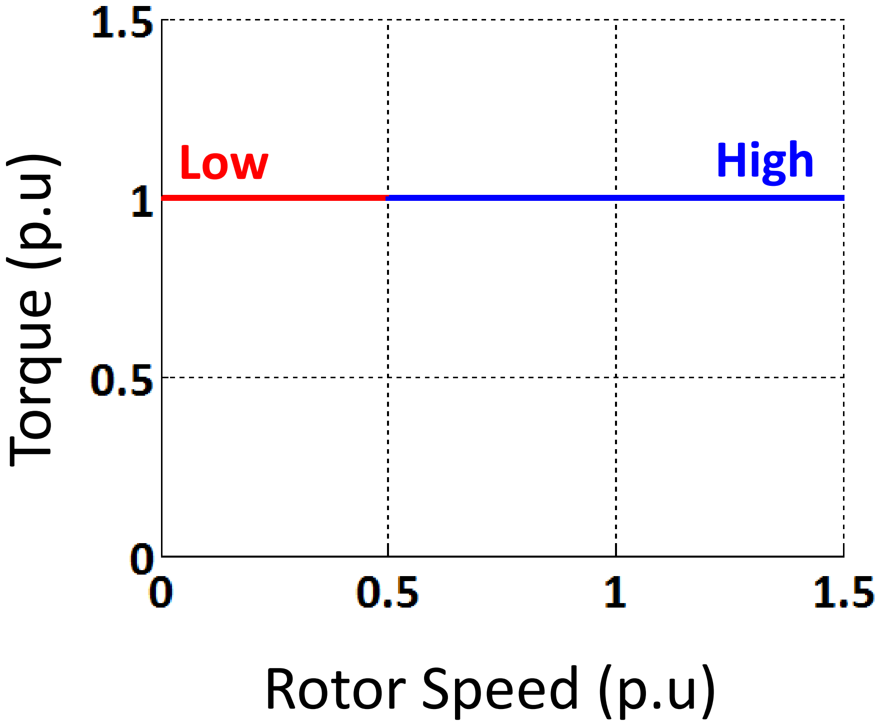
$$V = \frac{d}{dt}\,\text{flux}$$

$$= \text{relative speed X flux}$$

VSD “current rating” is driven by high-speed mode torque

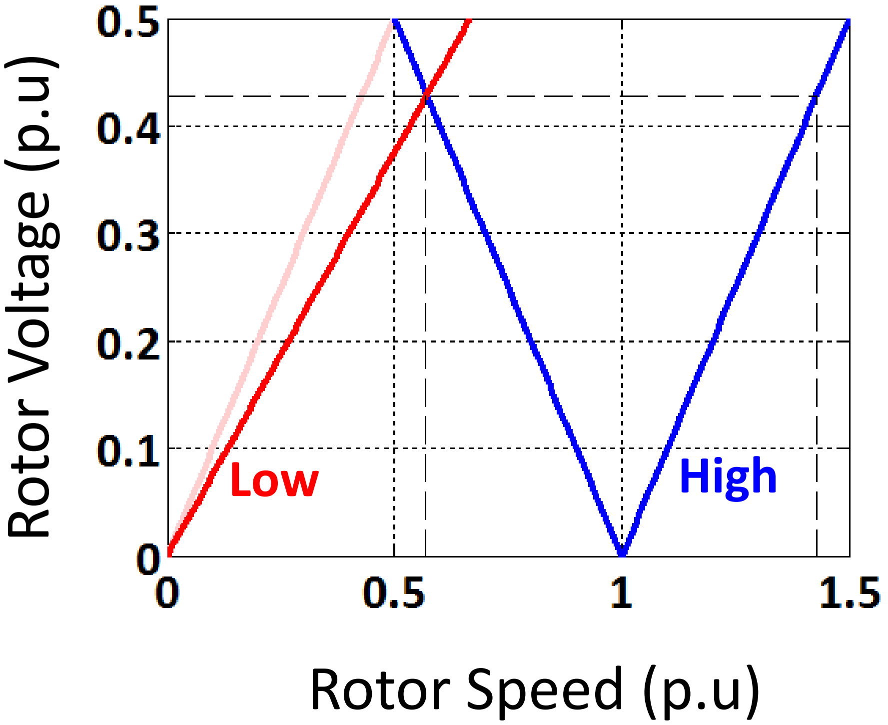
Low-speed mode stator flux = High-speed mode stator flux

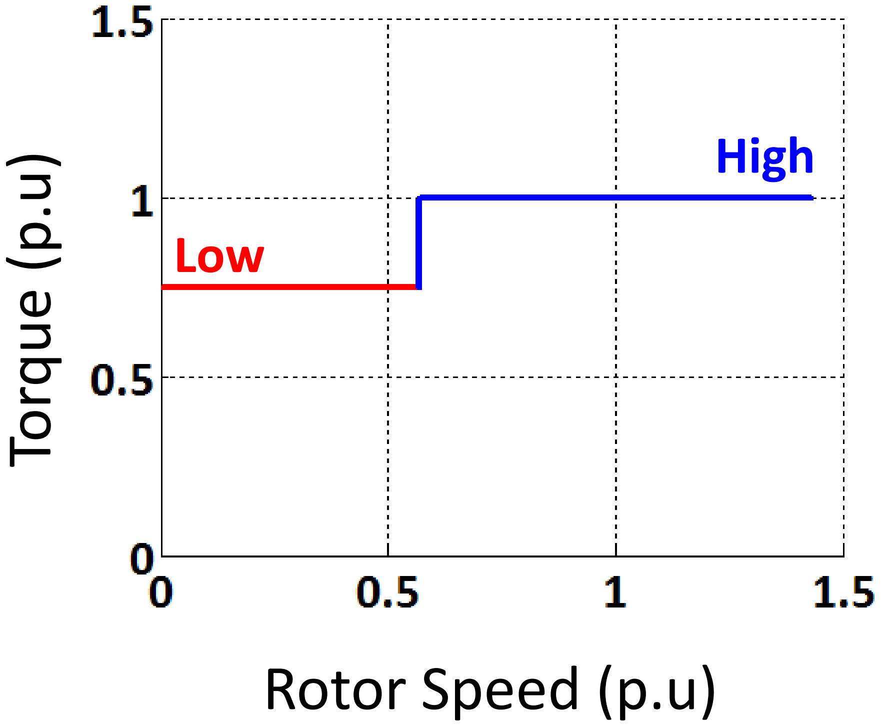




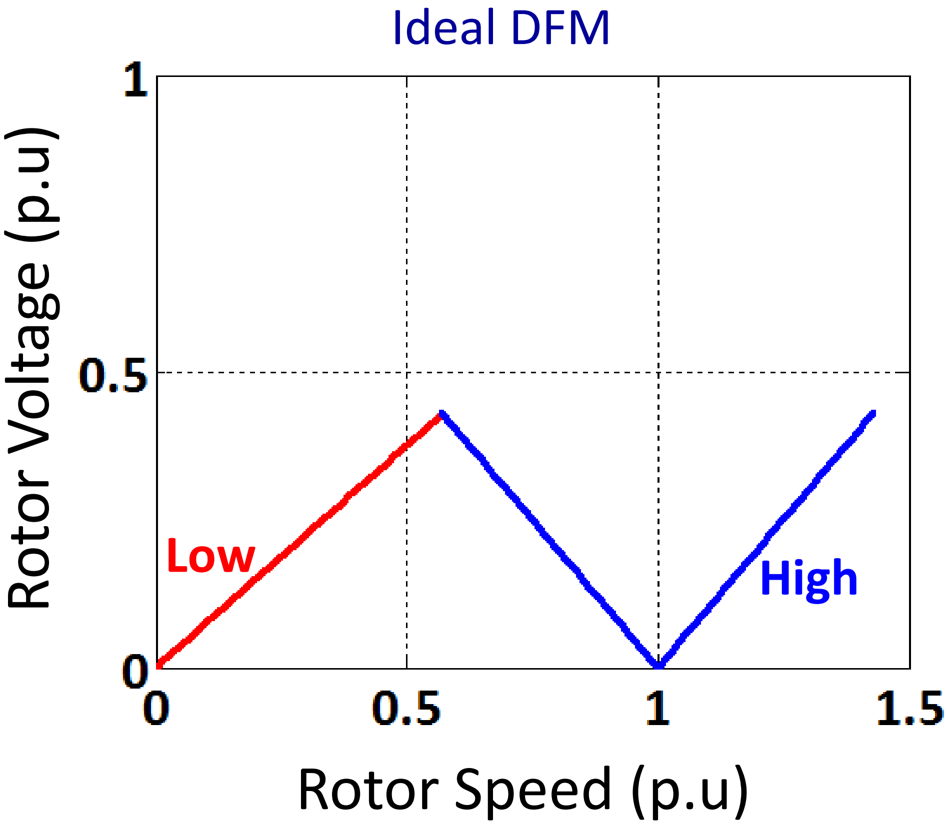
VSD “voltage rating” is driven by low-speed mode torque

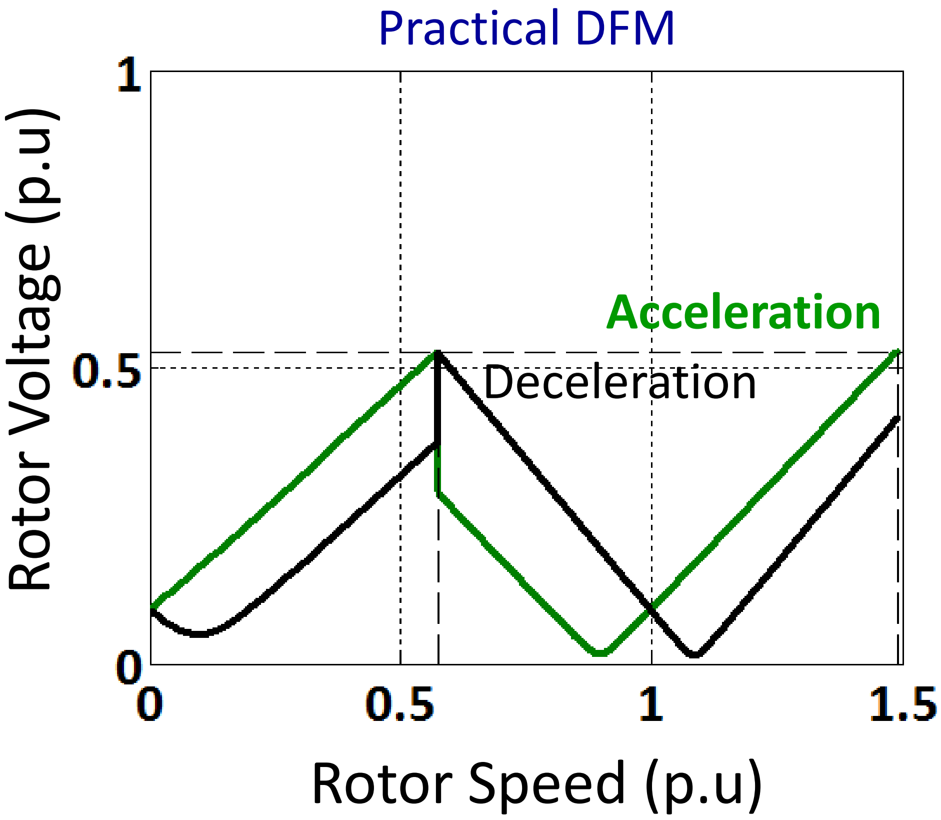
Low-speed mode stator flux = 0.75 X High-speed mode stator flux





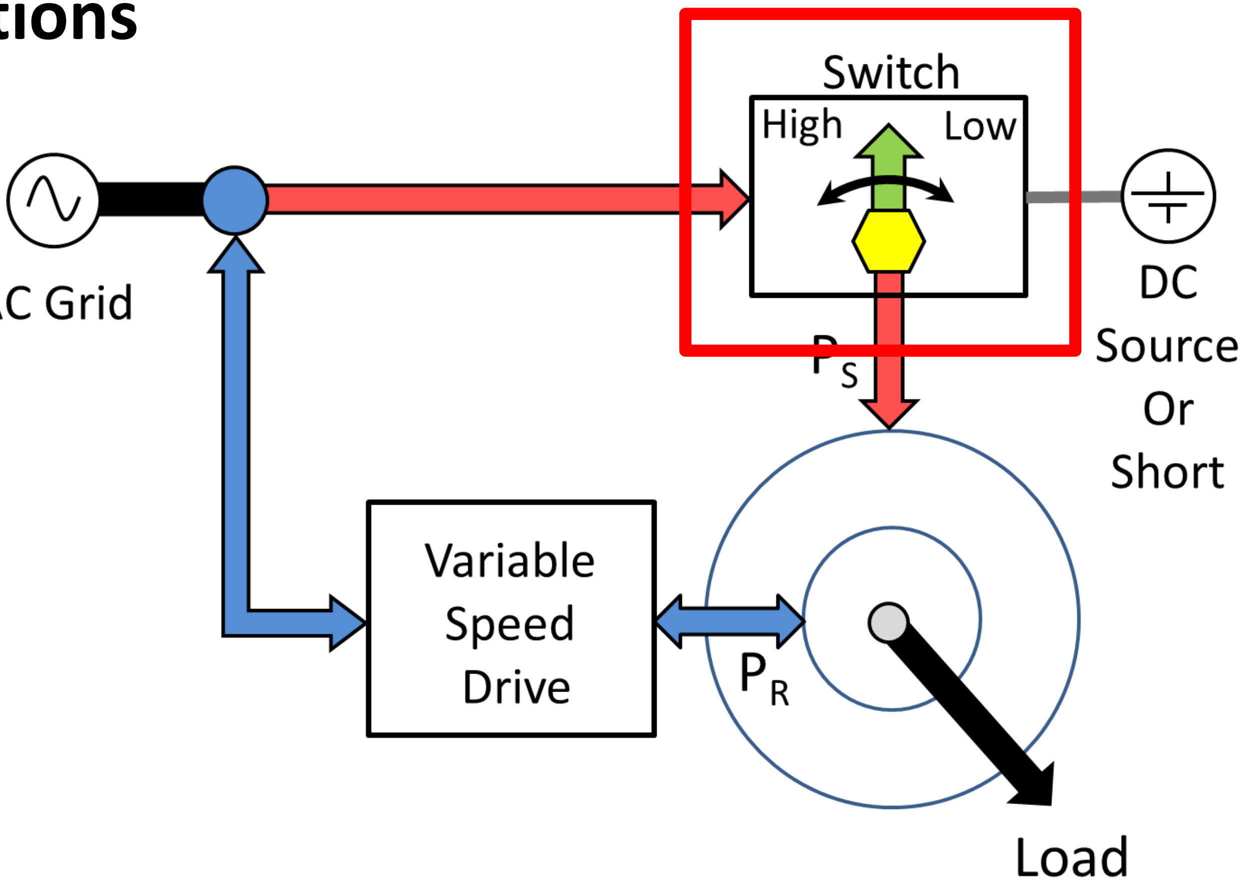
Non-idealities in DFM lead to design challenges for remaining within constraints





A. Banerjee, M. S. Tomovich, S. B. Leeb and J. L. Kirtley, "Power Converter Sizing for a Switched Doubly Fed Machine Propulsion Drive," in *IEEE Transactions on Industry Applications*, vol. 51, no. 1, pp. 248-258, Jan.-Feb. 2015.

Contributions



- Drive design
- **Switch realization**
- Seamless control
- Grid interaction
- Drive topology comparison
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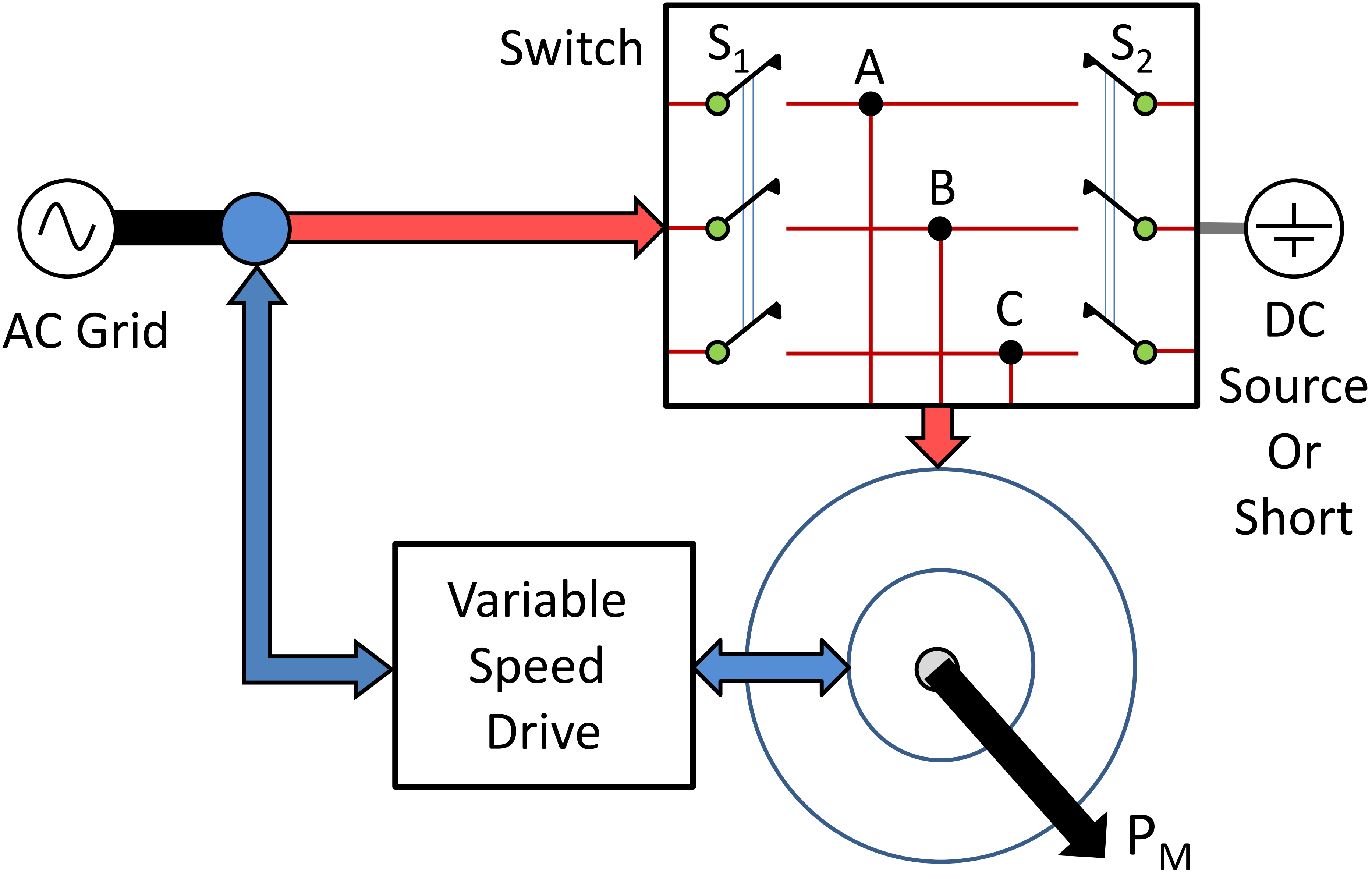
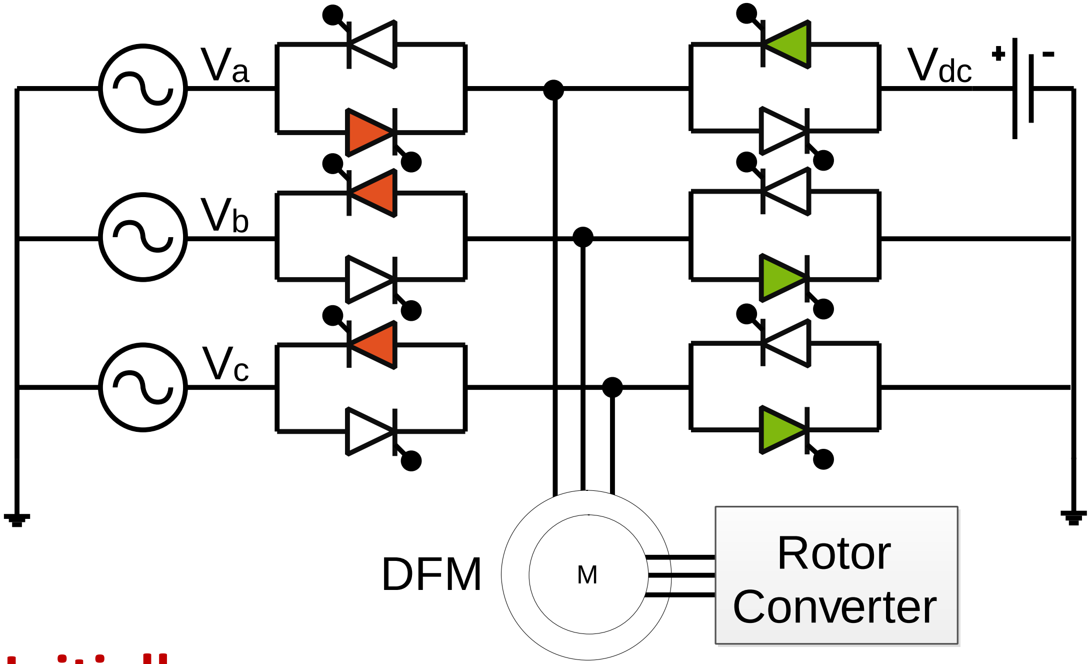
Switch realization critical for smooth performance



Example: Dc-to-ac mode transition

DC → AC



Initially :

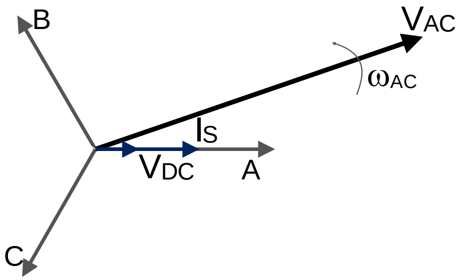
stator connected to dc source

Finally :

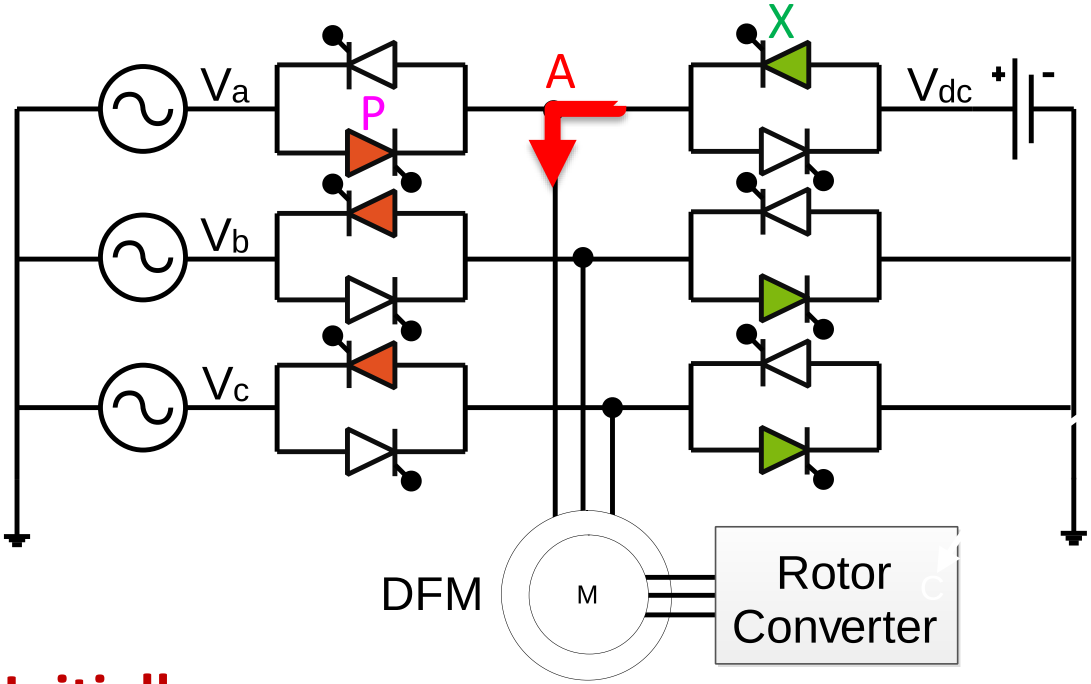
stator connected to ac source

Goal :

Natural commutation of all dc side SCRs simultaneously



Condition for natural commutation of A phase SCR



DC ⇒ AC

Initially :

stator connected to dc source

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stator connected to ac source

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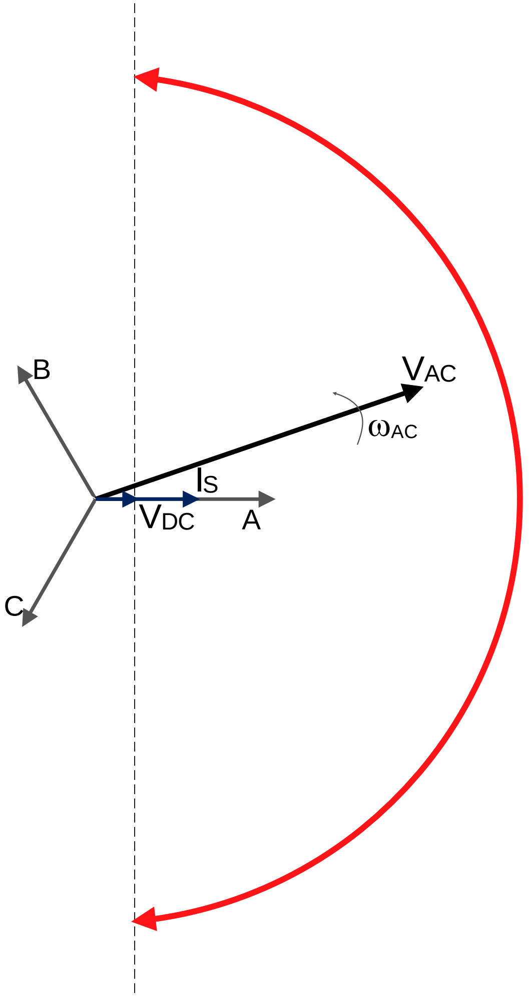
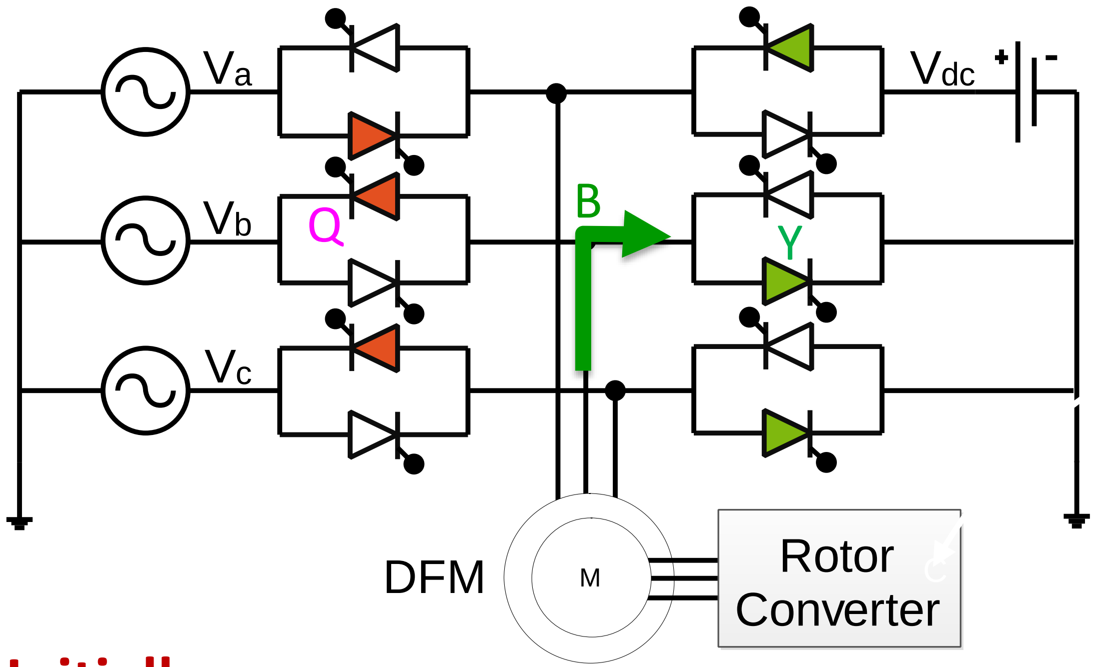
Natural commutation of all dc side SCRs simultaneously



Condition for natural commutation of B phase SCR



DC → AC

Initially :

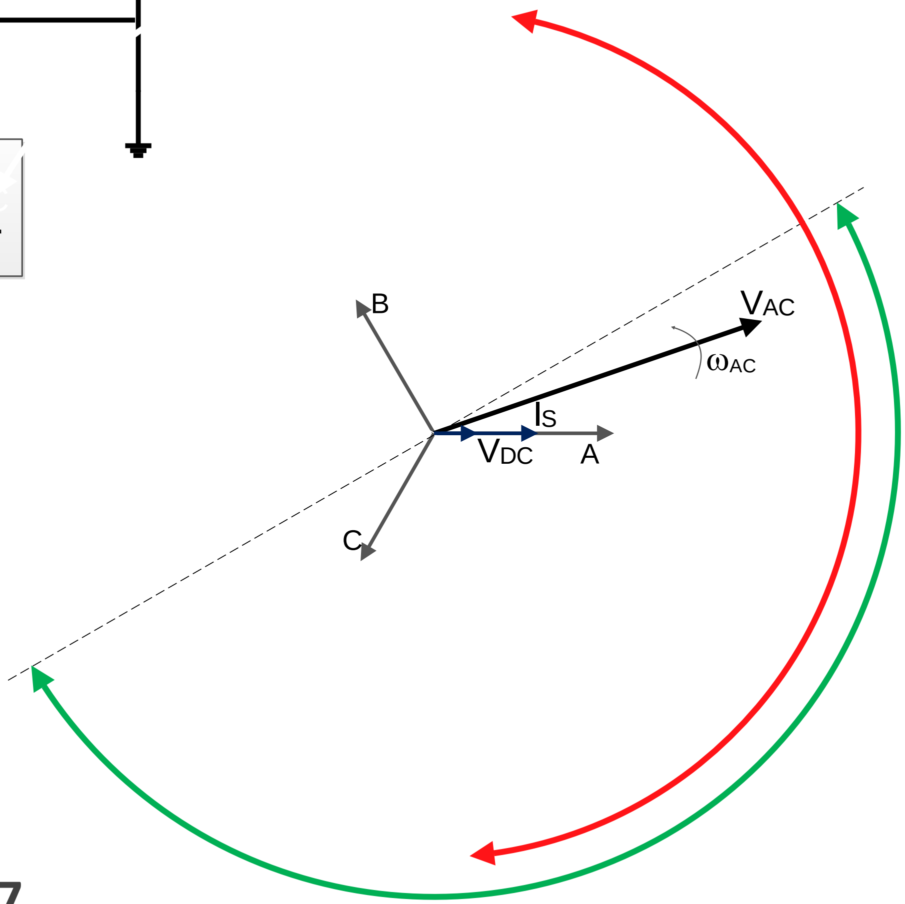
stator connected to dc source

Finally :

stator connected to ac source

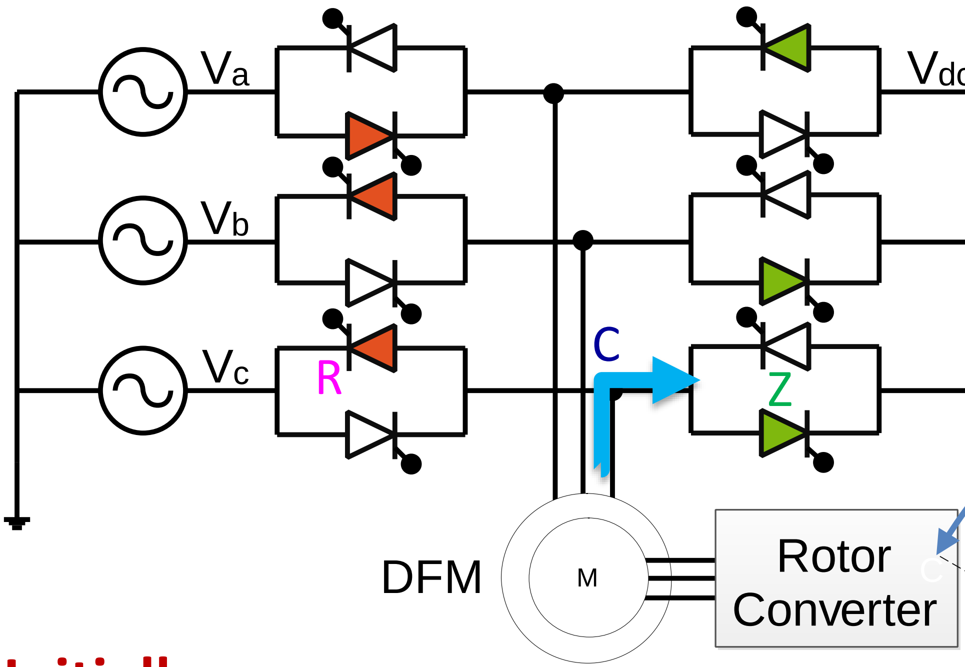
Goal :

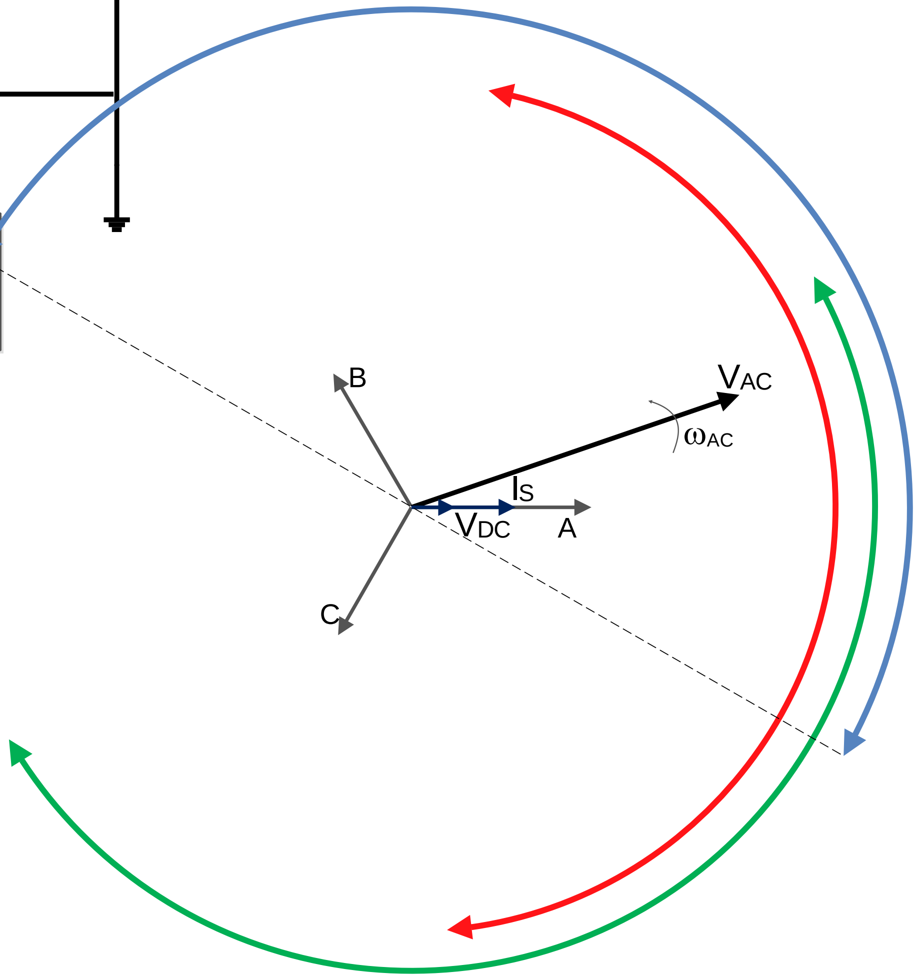
Natural commutation of all dc side SCRs simultaneously



Condition for natural commutation of C phase SCR

DC ⇒ AC





Initially :

stator connected to dc source

Finally :

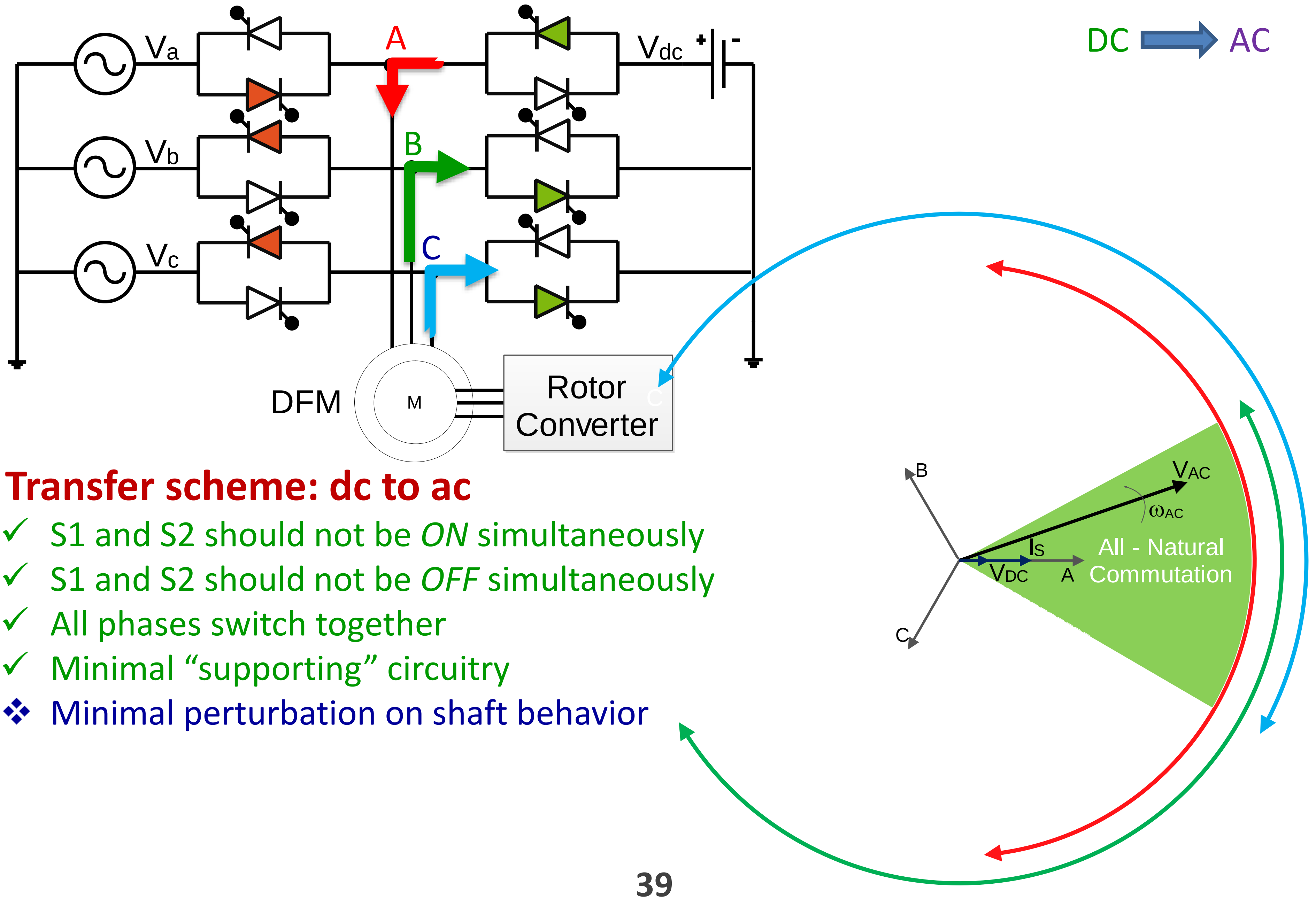
stator connected to ac source

Goal :

Natural commutation of all dc side SCRs simultaneously

Natural commutation of ABC phase SCRs simultaneously

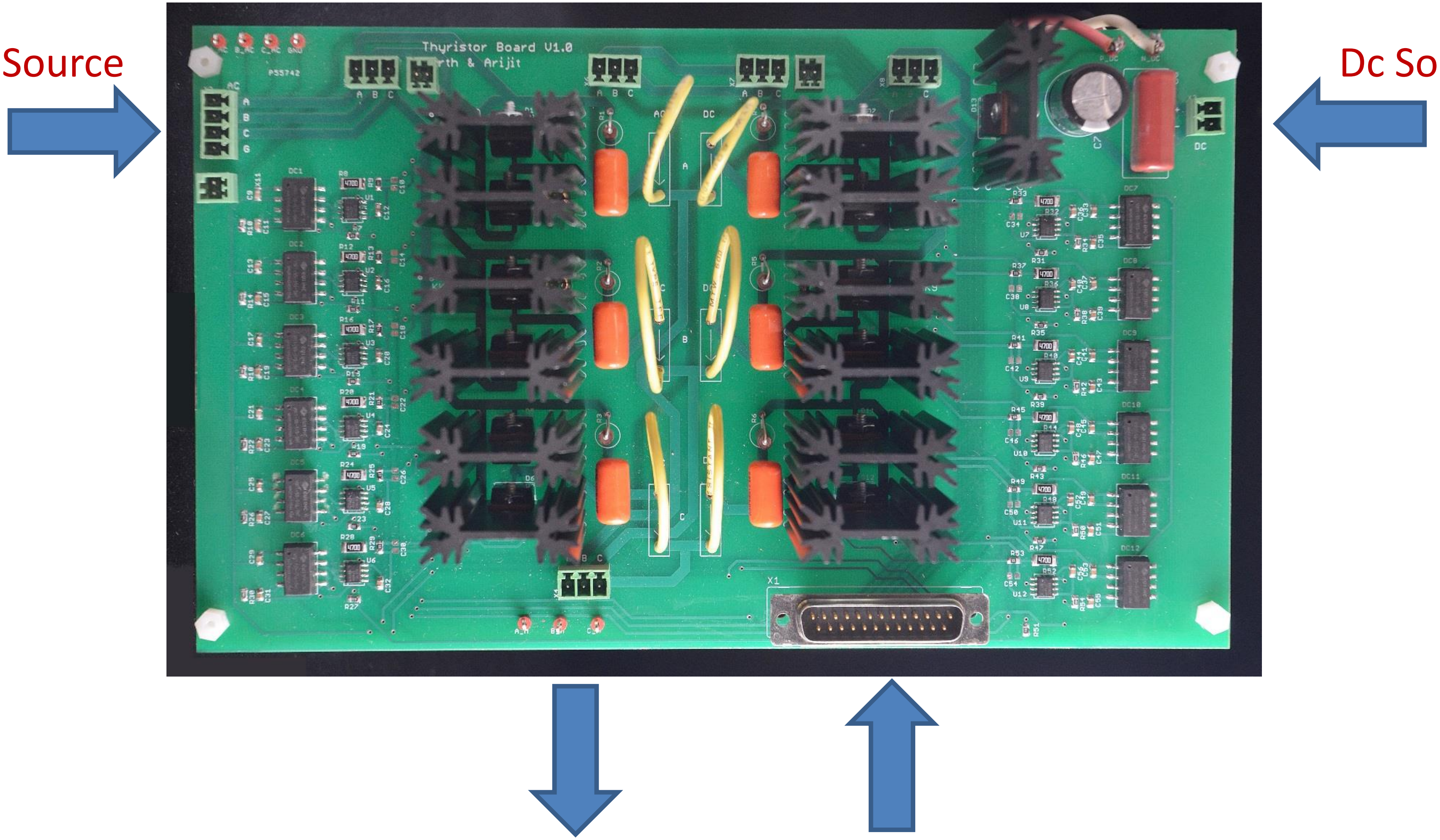
DC ⇒ AC



Transfer scheme: dc to ac

- ✓ S1 and S2 should not be *ON* simultaneously
- ✓ S1 and S2 should not be *OFF* simultaneously
- ✓ All phases switch together
- ✓ Minimal “supporting” circuitry
- ❖ Minimal perturbation on shaft behavior

Prototype SCR-based Transfer Switch



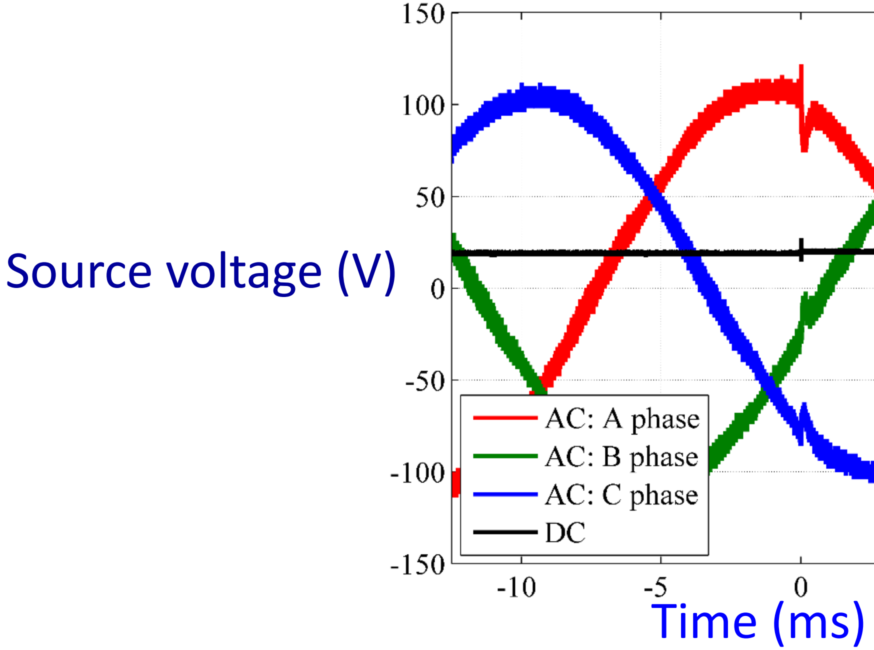
Ac Source

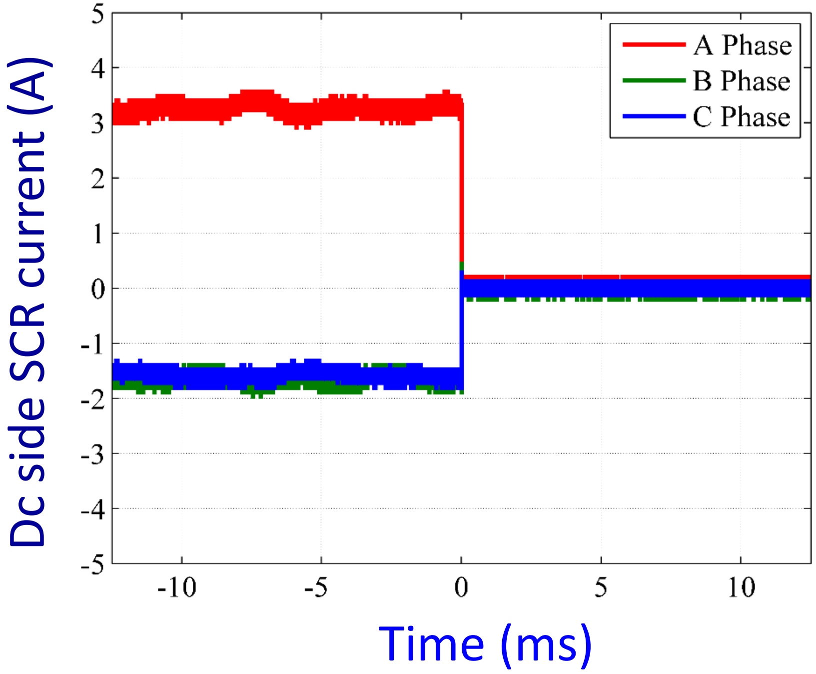
Dc Source

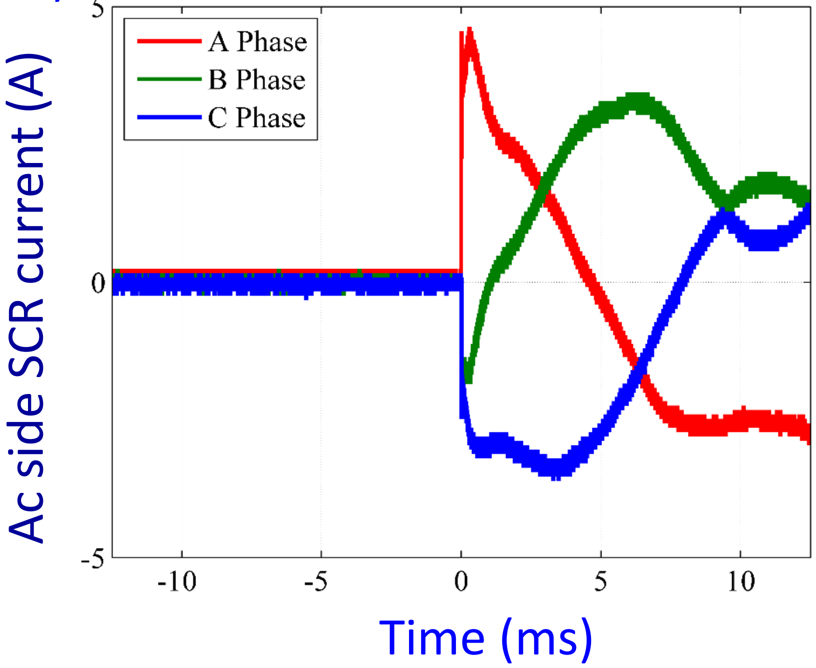
DFM Stator

SCR Gate Signal

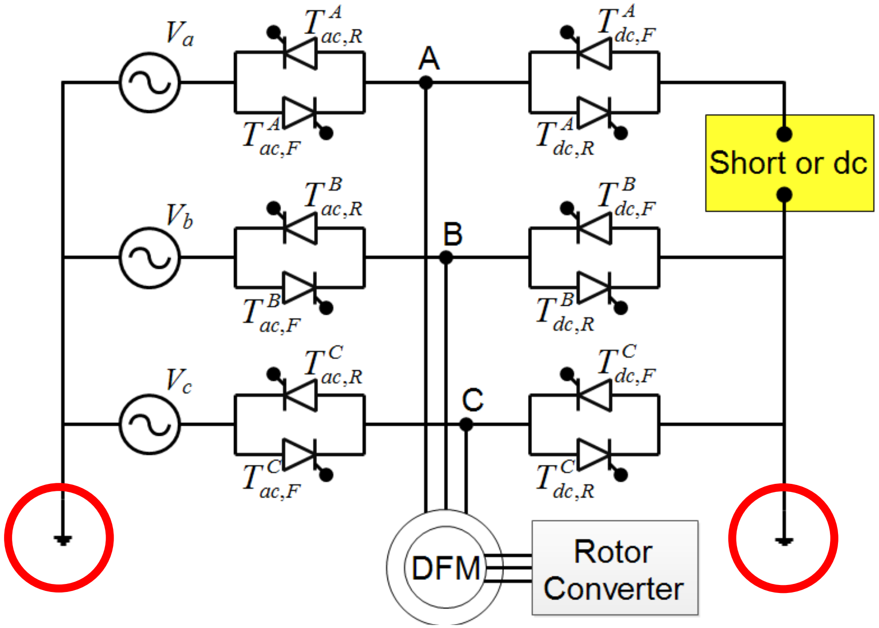
Experimental Result: Dc to Ac Source Transition

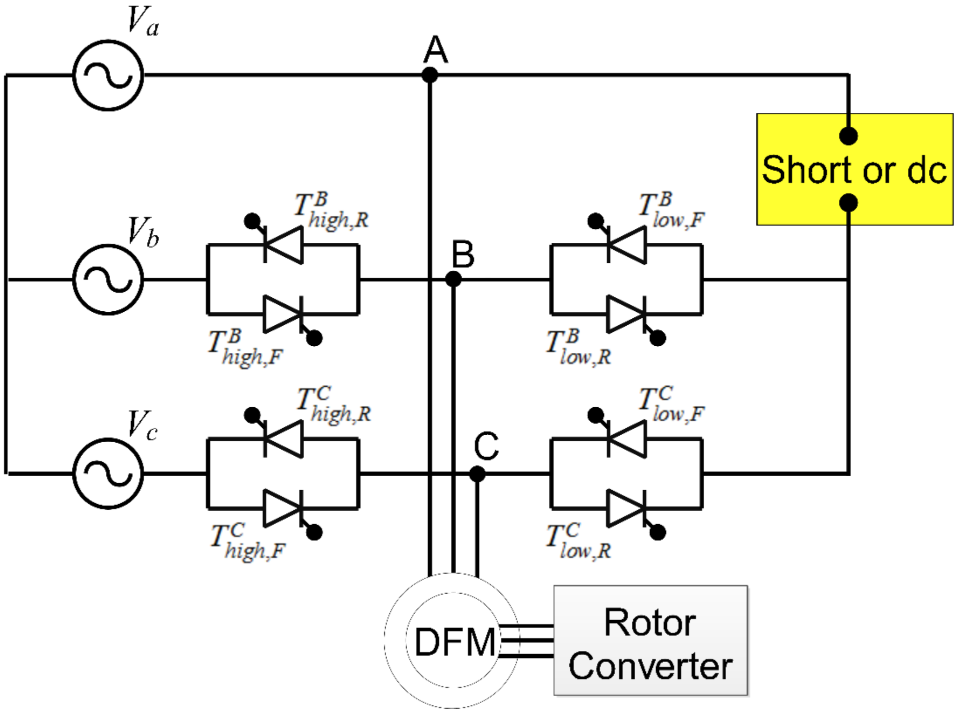


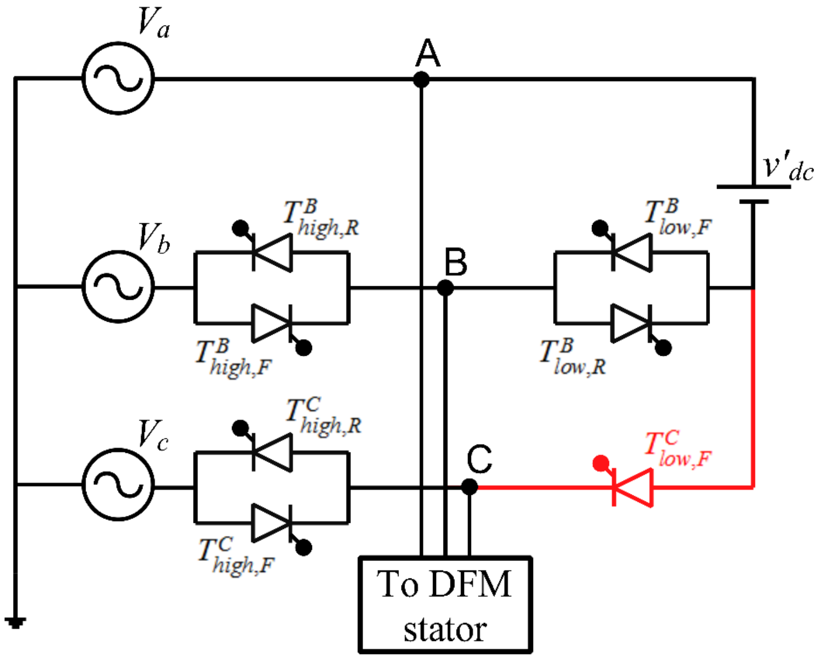




Alternative transfer switch topology



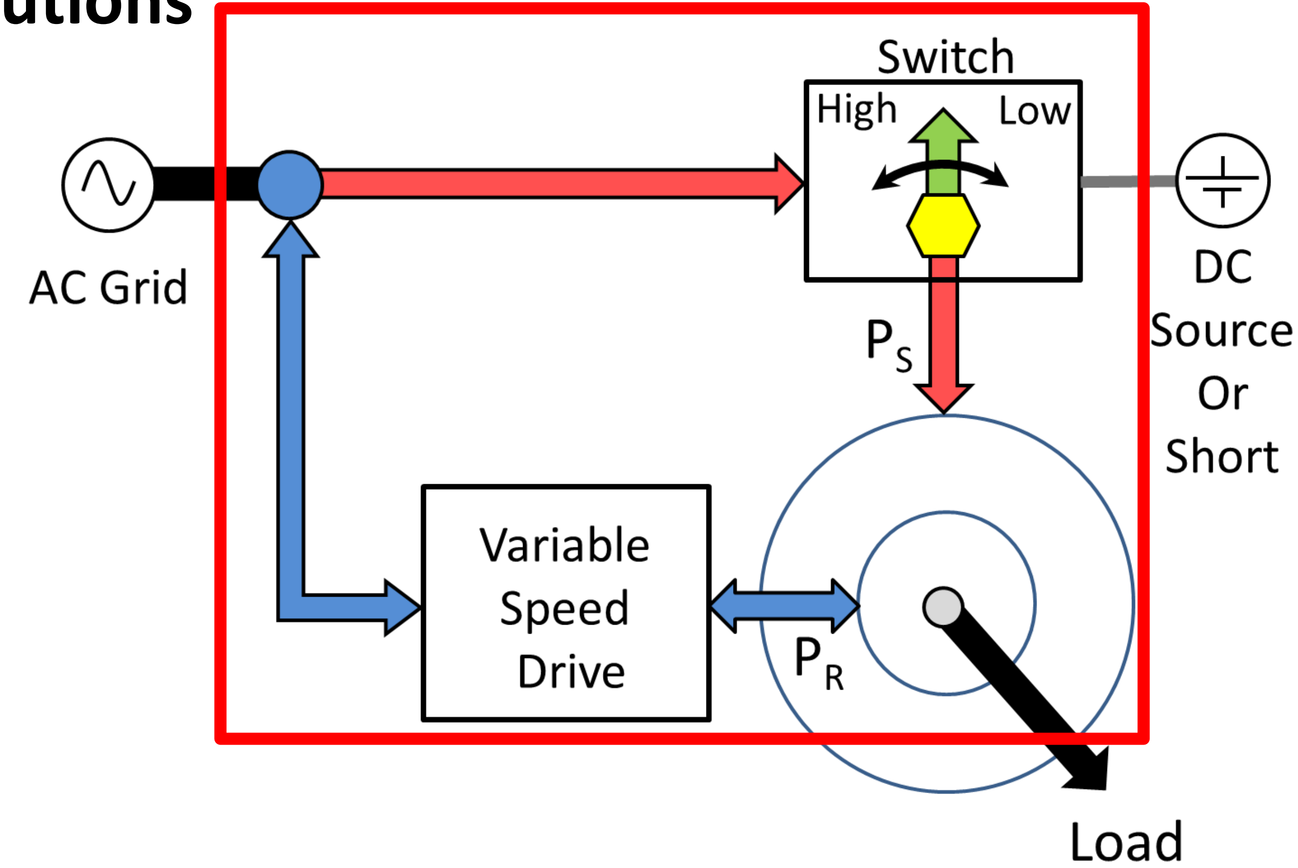




Banerjee et. al. "Solid-State Transfer Switch Topologies for a Switched Doubly Fed Machine Drive," in *IEEE Transactions on Power Electronics*, Aug. 2016.

Banerjee et. al., "Bumpless Automatic Transfer for a Switched-Doubly-Fed-Machine Propulsion Drive," in IEEE Transactions on Industry Applications, July-Aug. 2015.

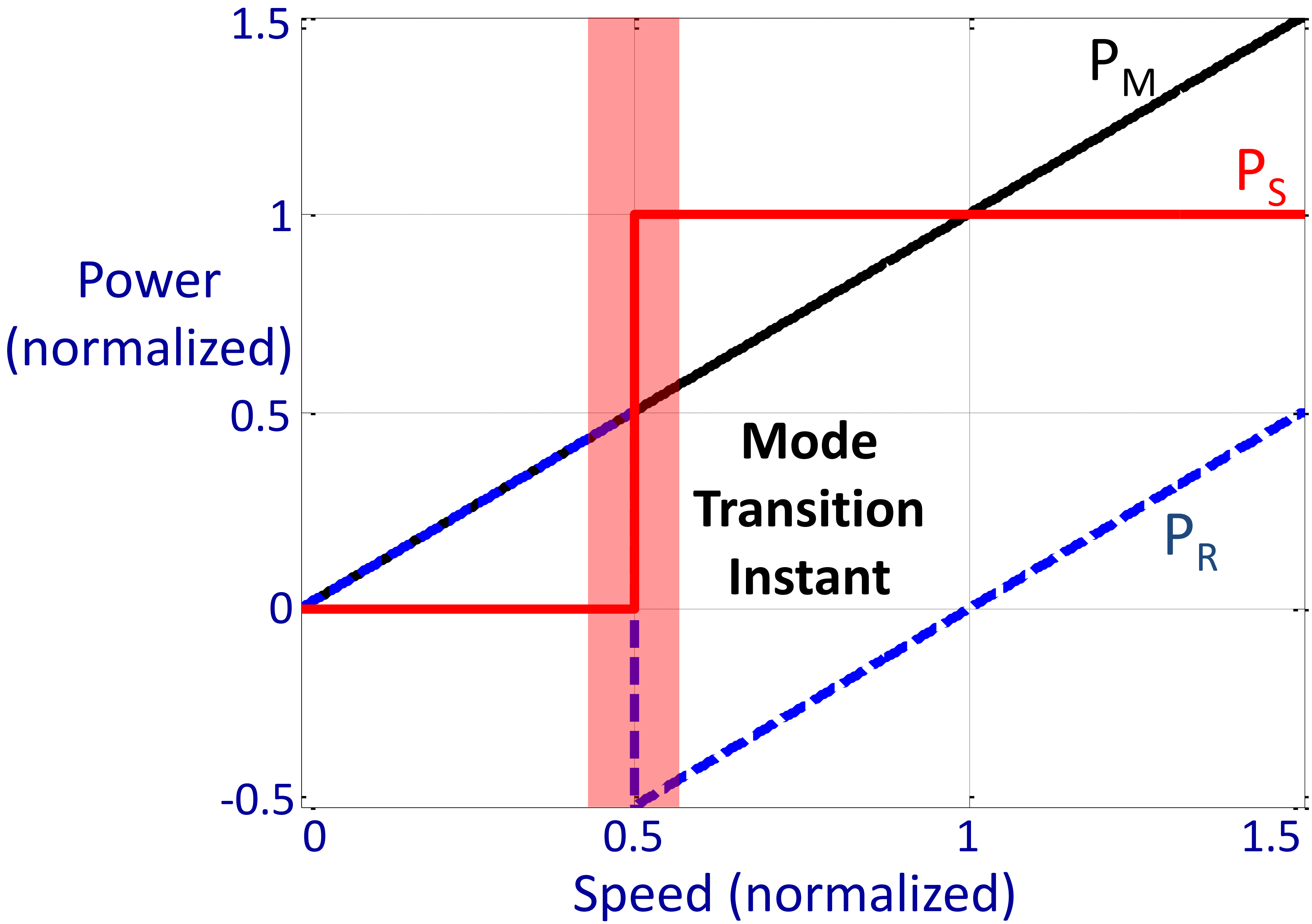
Contributions



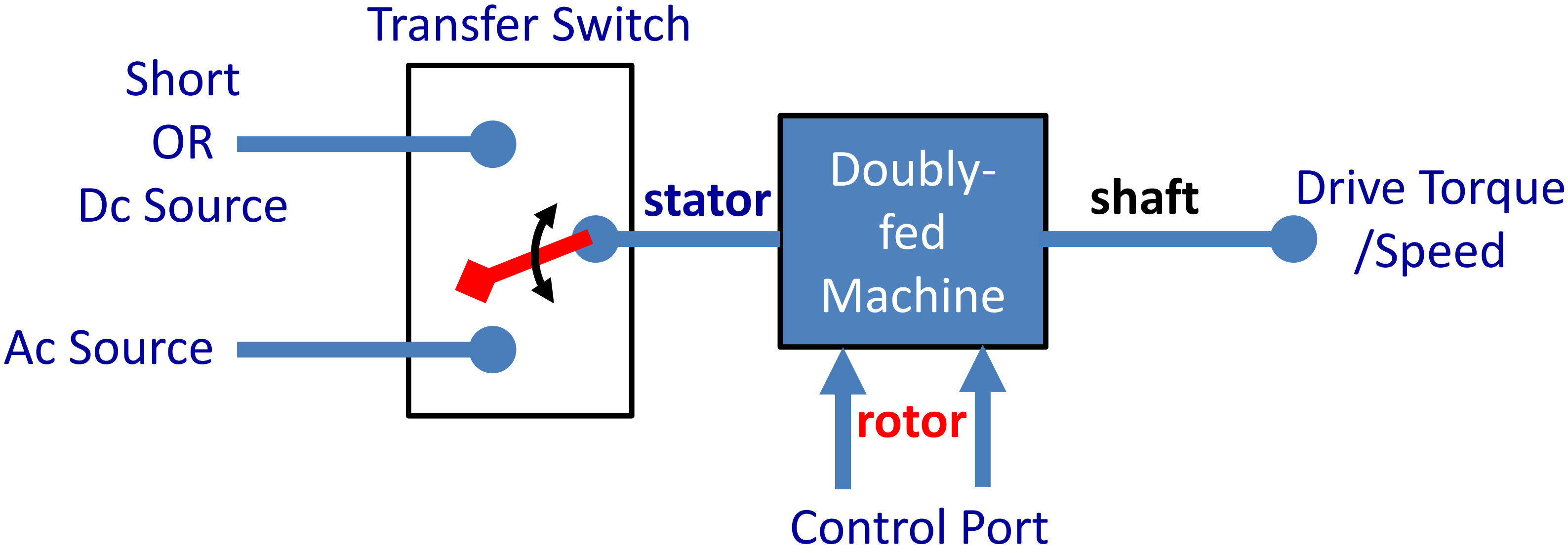
- Drive design
- Switch realization
- **Seamless control**

- Grid interaction
- Drive topology comparison
- DFM design considerations

Challenge: Seamless performance across entire speed range



Common framework for control and transition analysis



Transfer Switch

Short
OR
Dc Source

Ac Source

stator

Doubly-fed Machine

shaft

Drive Torque /Speed

rotor

Control Port

State variables

Stator (2)

Stator flux
- magnitude
- angle

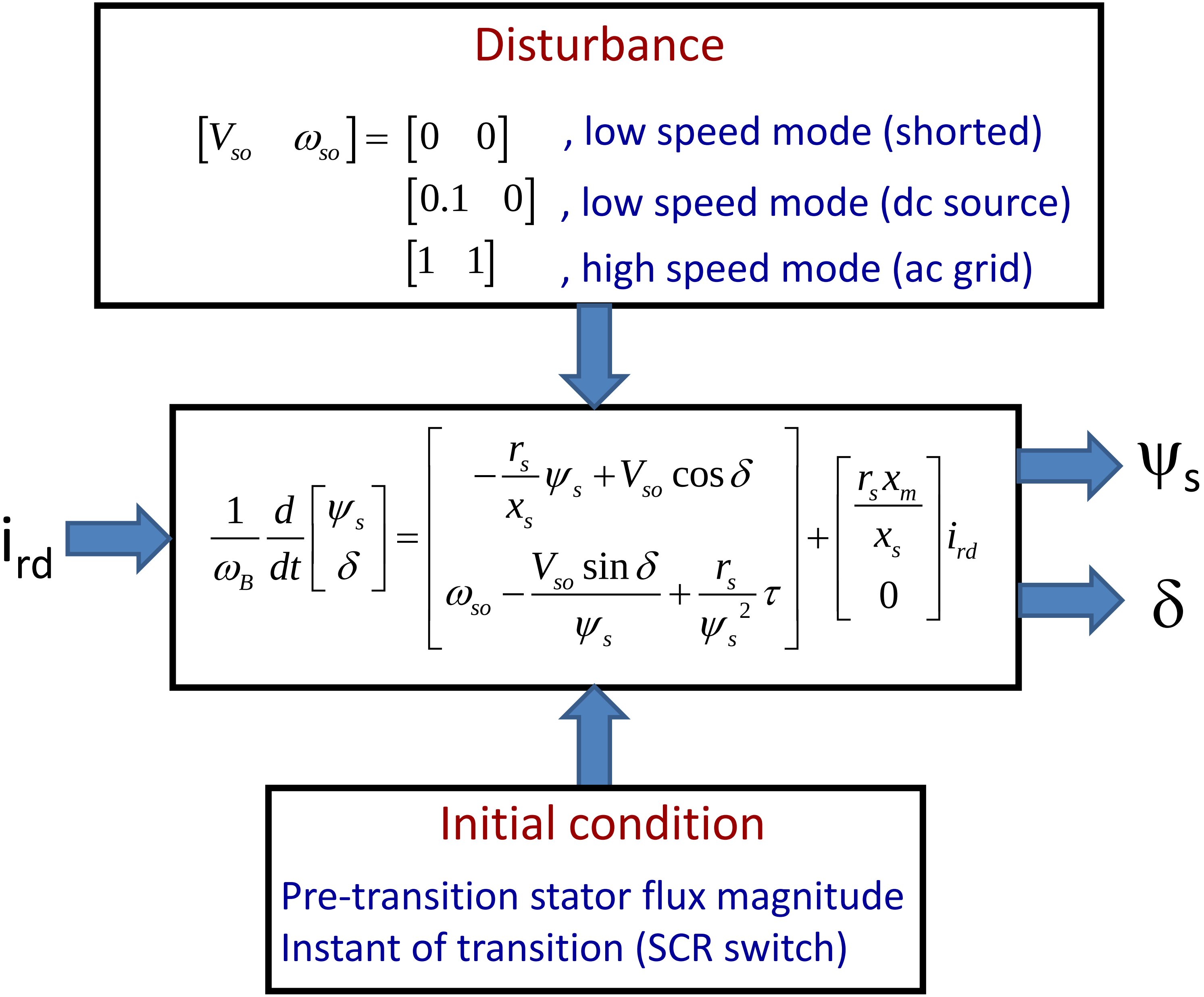
Rotor (2)

D-axis current
Q-axis current

Shaft (1)

Speed

Stator flux transition model



Disturbance

$[V_{so} \quad \omega_{so}] = [0 \quad 0]$, low speed mode (shorted)

$[0.1 \quad 0]$, low speed mode (dc source)

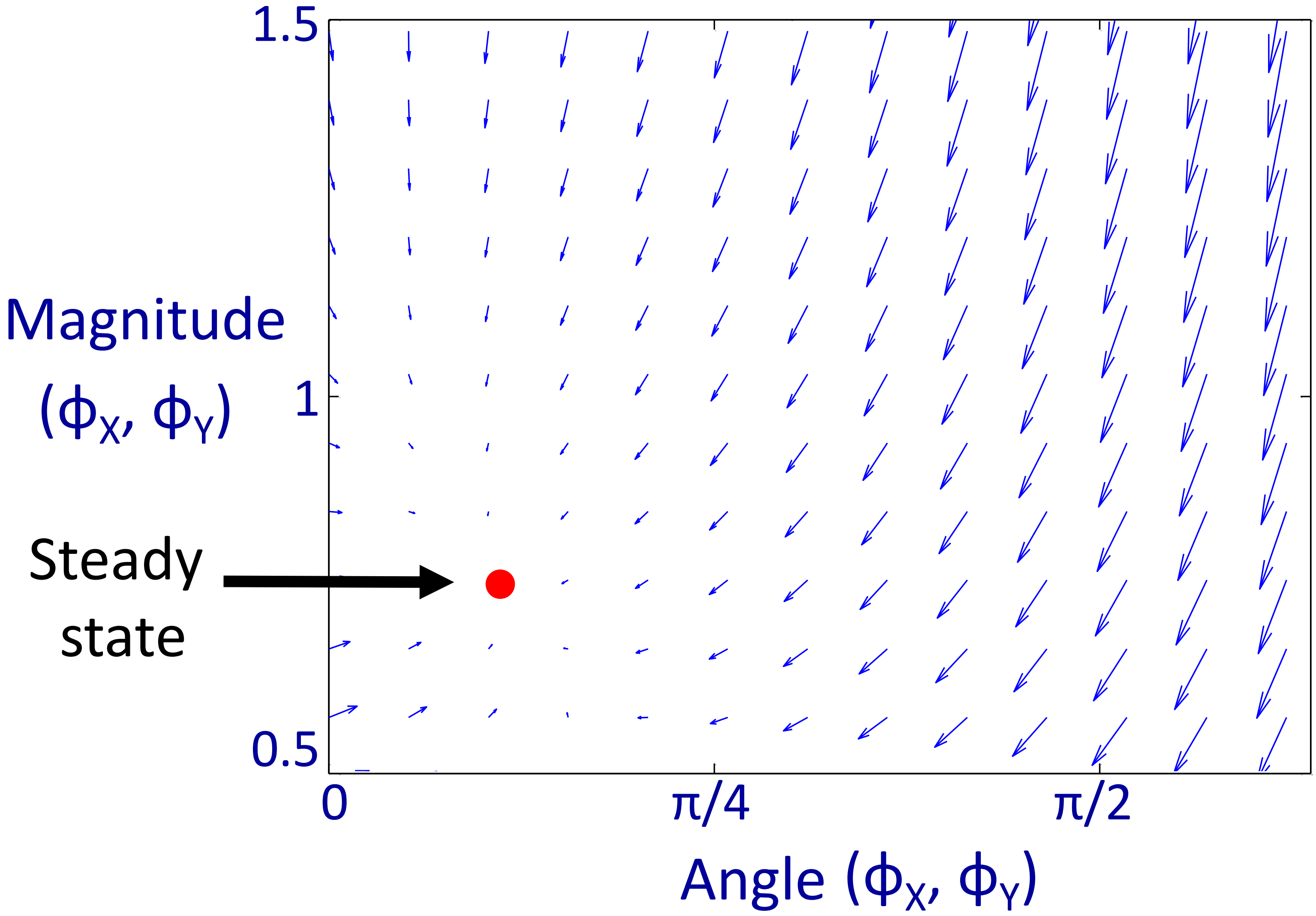
$[1 \quad 1]$, high speed mode (ac grid)

$$\frac{1}{\omega_B}\frac{d}{dt}\begin{bmatrix}\psi_s \\ \delta\end{bmatrix} = \begin{bmatrix} -\frac{r_s}{x_s}\psi_s + V_{so}\cos\delta \\ \omega_{so} - \frac{V_{so}\sin\delta}{\psi_s} + \frac{r_s}{\psi_s^2}\tau \end{bmatrix} + \begin{bmatrix}\frac{r_s x_m}{x_s} \\ 0\end{bmatrix} i_{rd}$$

Initial condition

Pre-transition stator flux magnitude
Instant of transition (SCR switch)

Phase plane captures machine dynamics in low speed mode

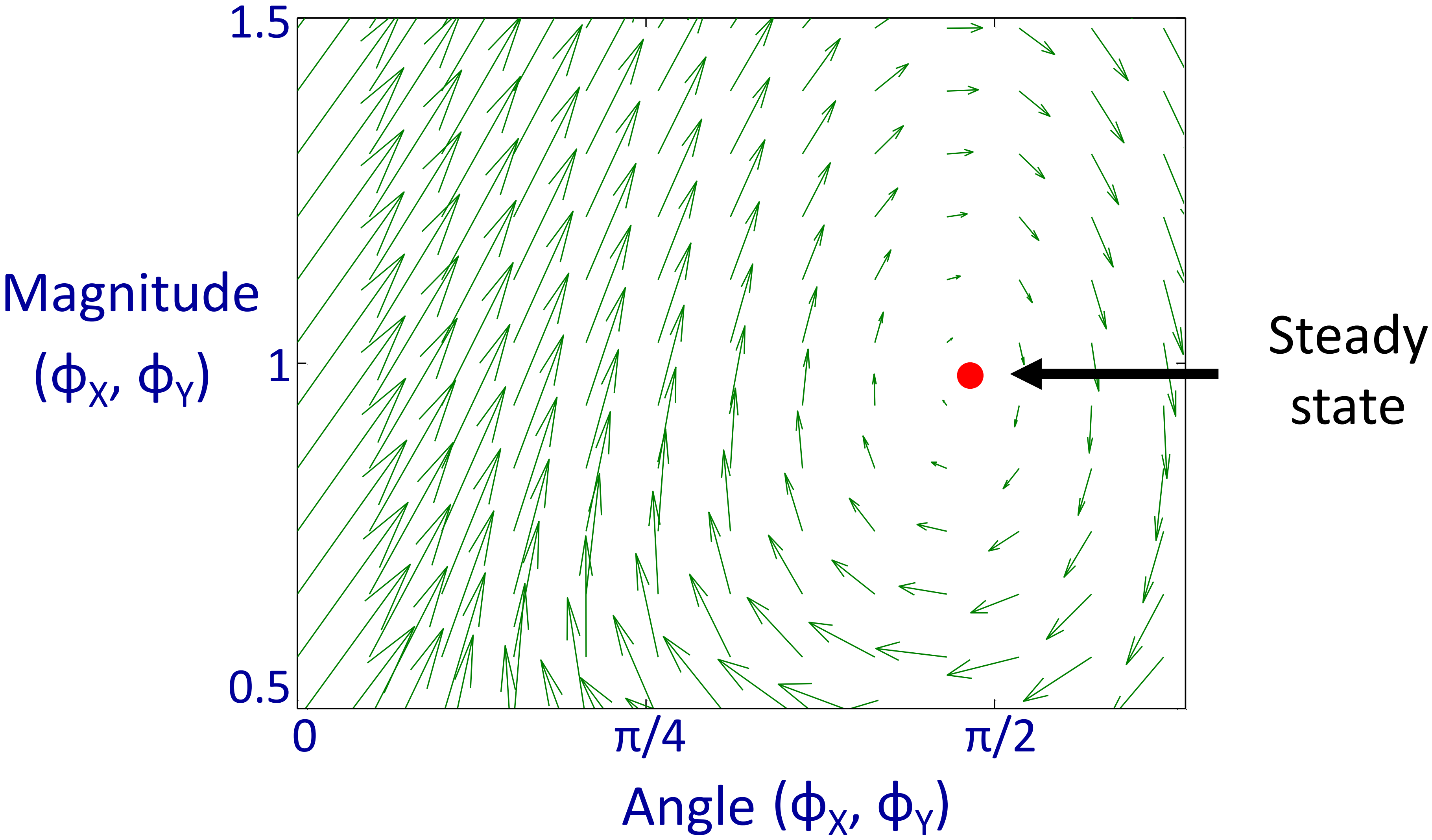


Steady state

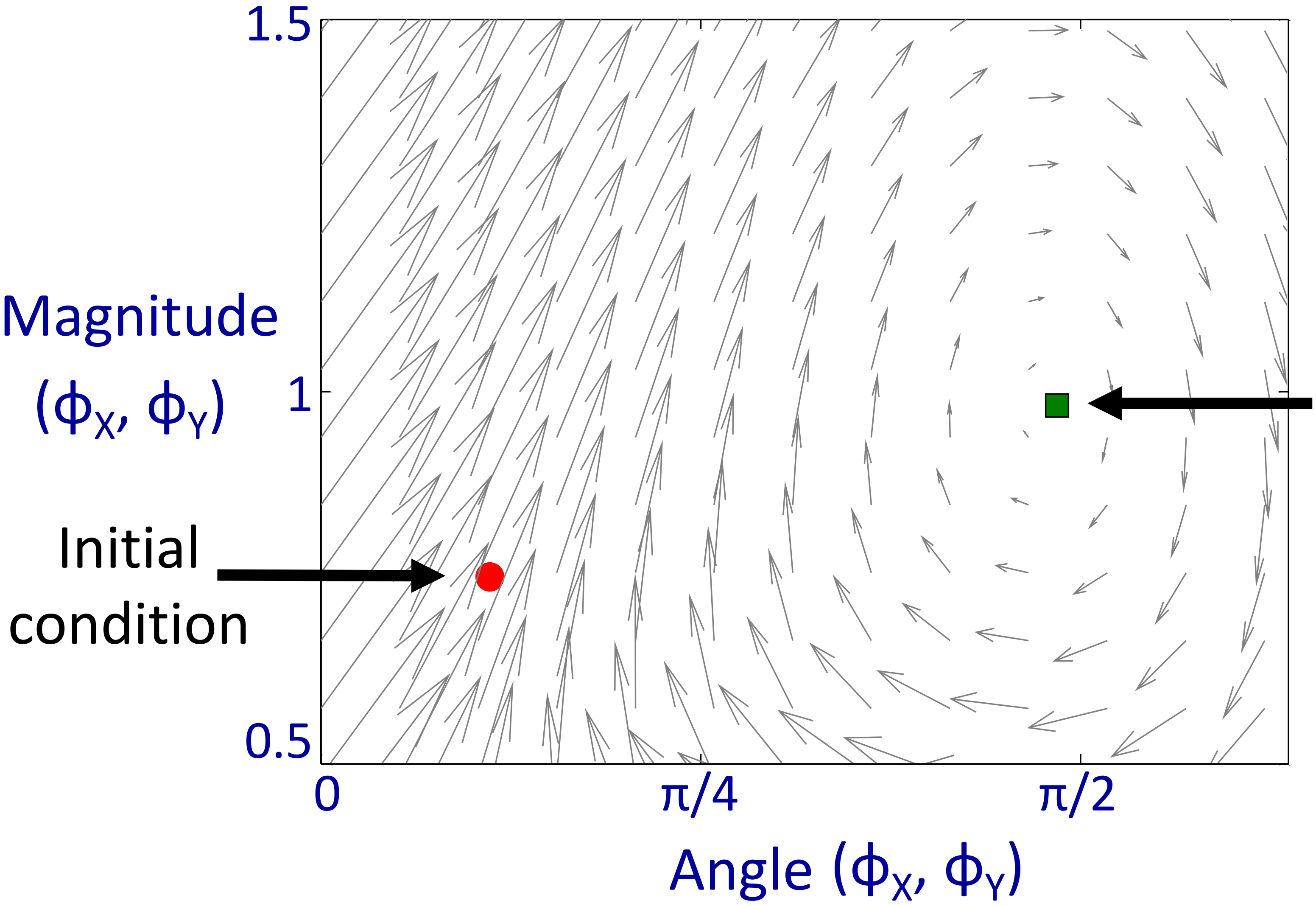
Banerjee et al., IEEE Trans. Industry Applications, 2015

-- , ITEC, 2015

Phase plane captures machine dynamics in high speed mode



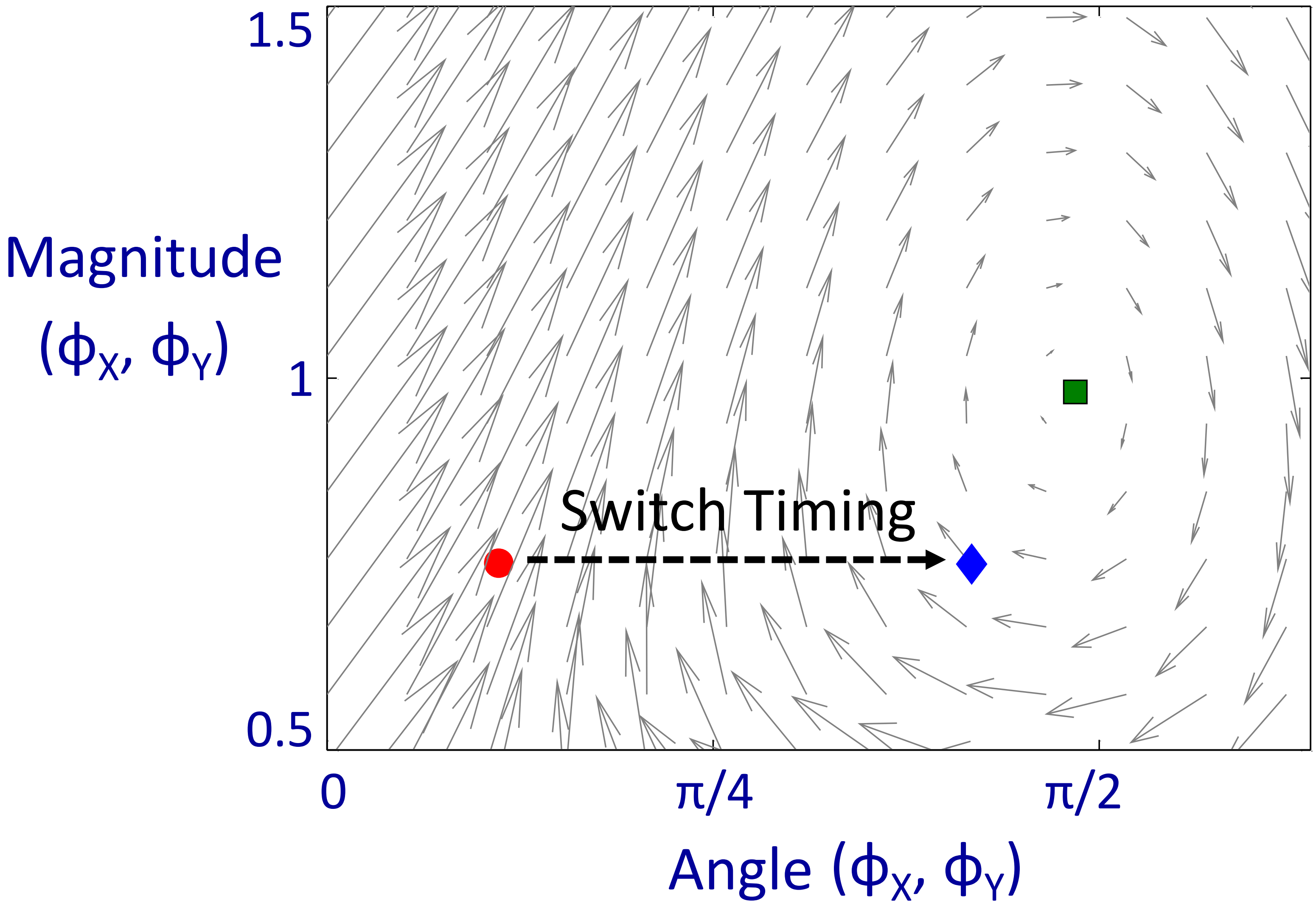
Example: Low-to-high speed mode transition



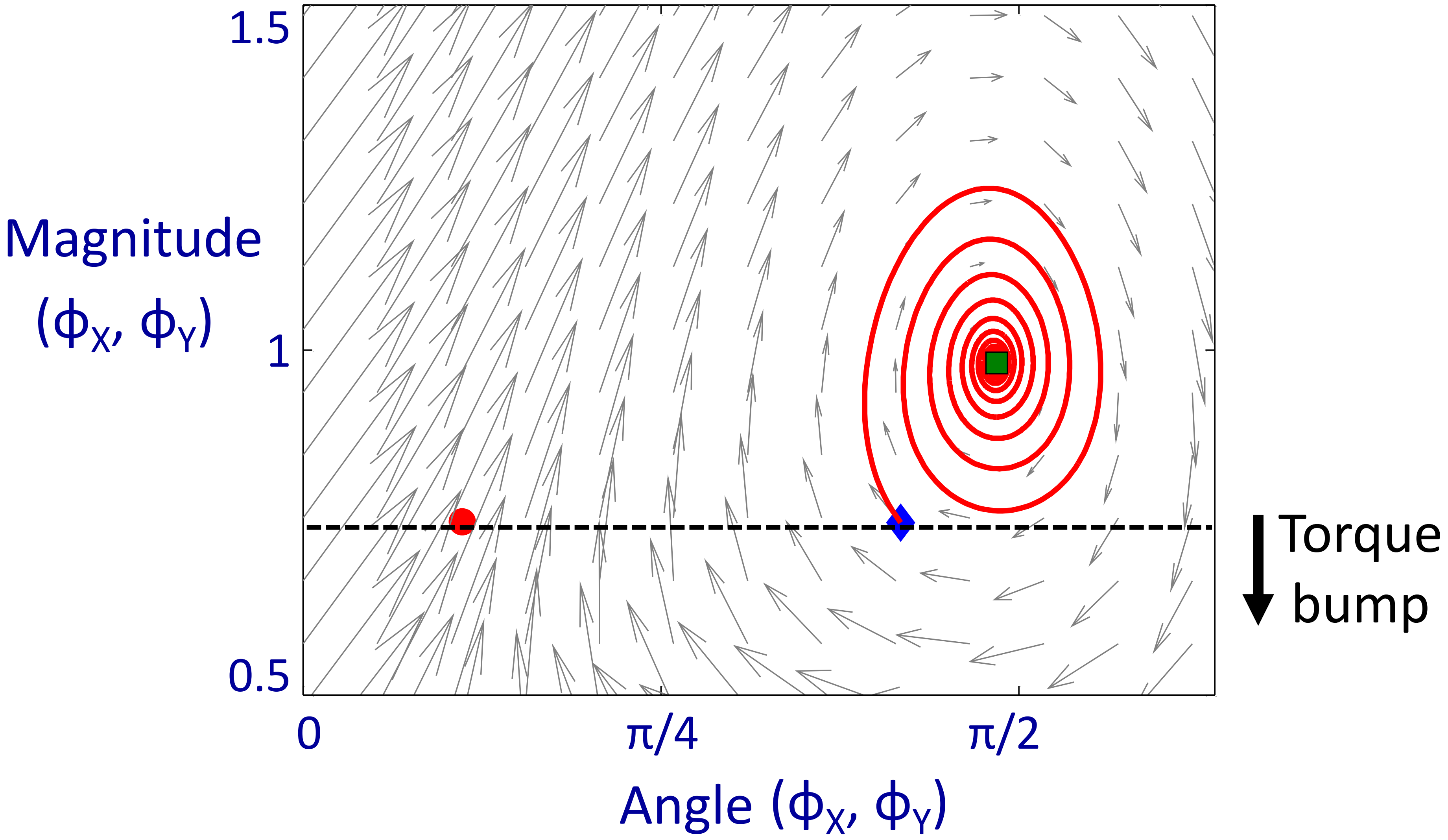
Initial condition

Target steady state

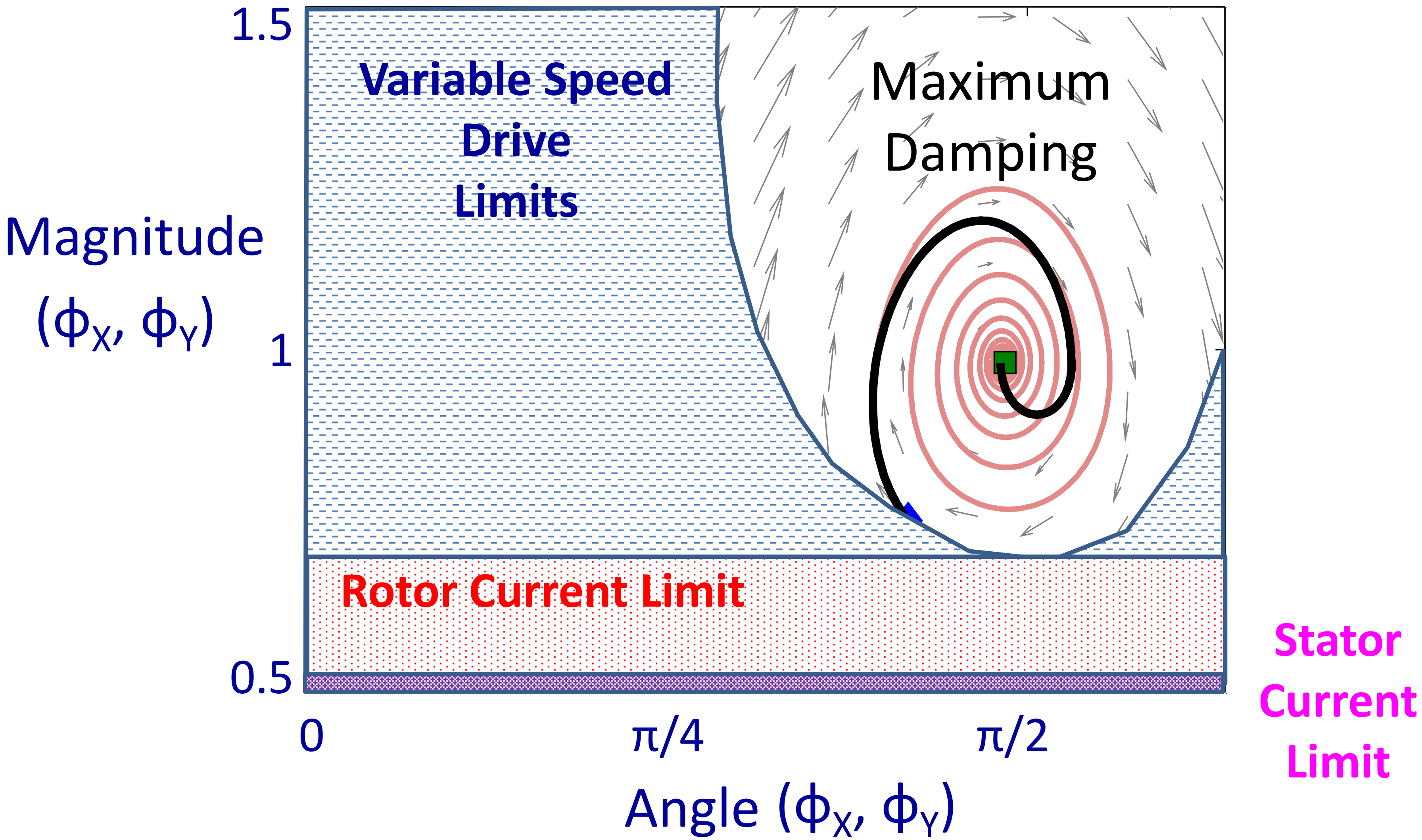
Switch timing is critical for smoother transition



Autonomous behavior during mode transition using the switch timing



Maximum damping enables smooth transition from AC grid perspective



Banerjee et al., APEC, 2016

Mode Transition: Mapping of Operating Point on the State-plane

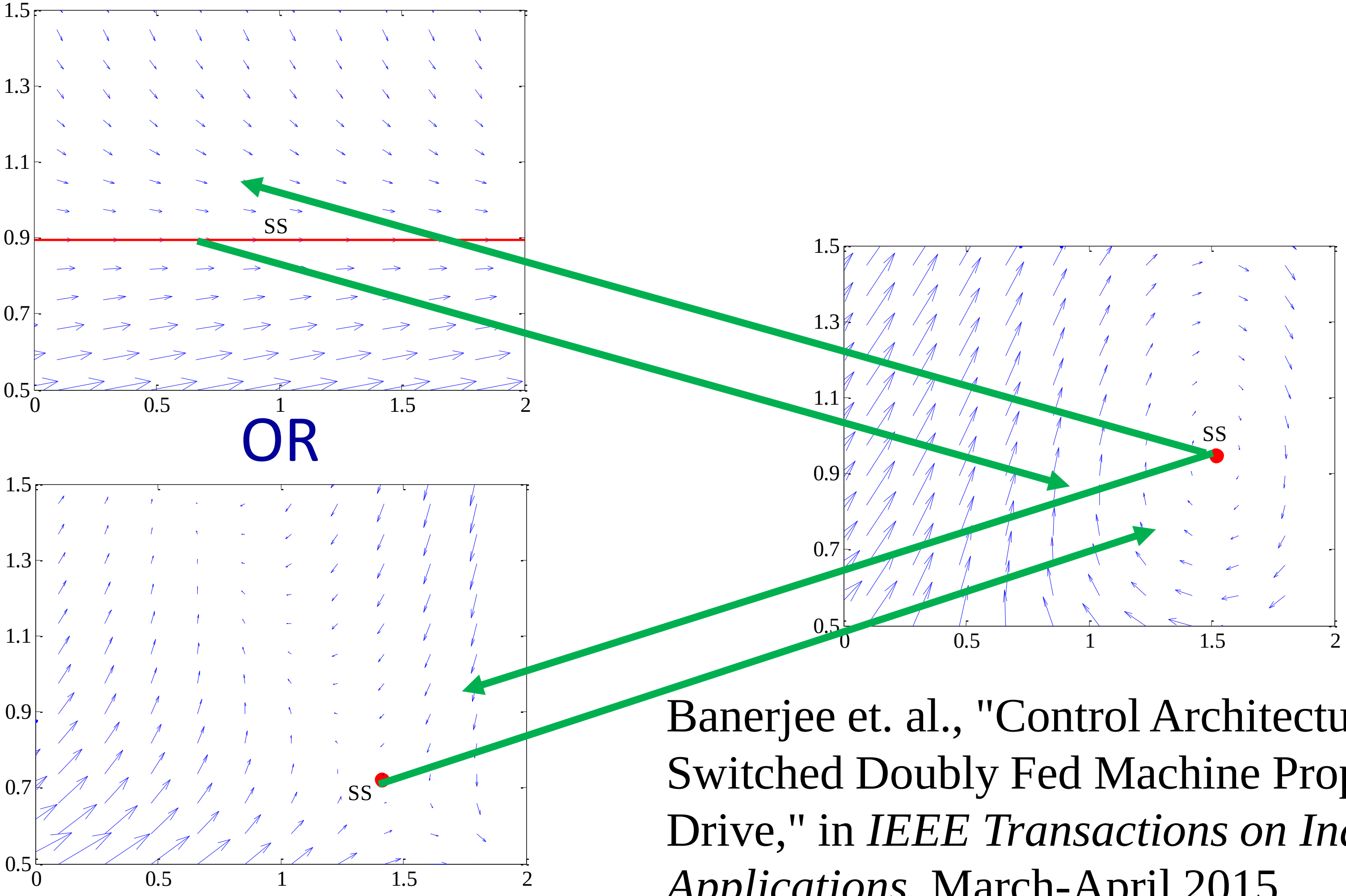
Low-speed operation

High-speed operation

Short

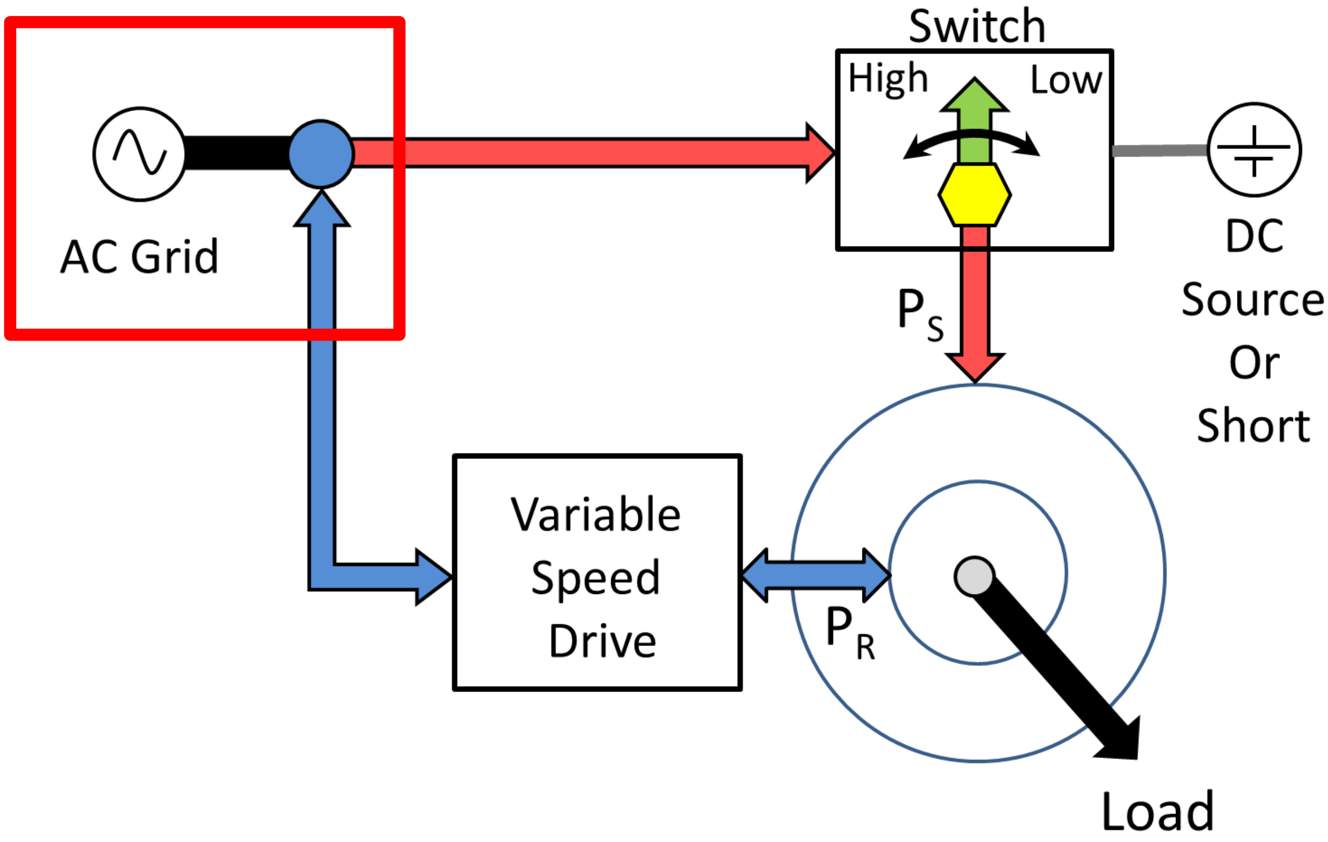
OR

Dc source



Banerjee et. al., "Control Architecture for a Switched Doubly Fed Machine Propulsion Drive," in *IEEE Transactions on Industry Applications*, March-April 2015.

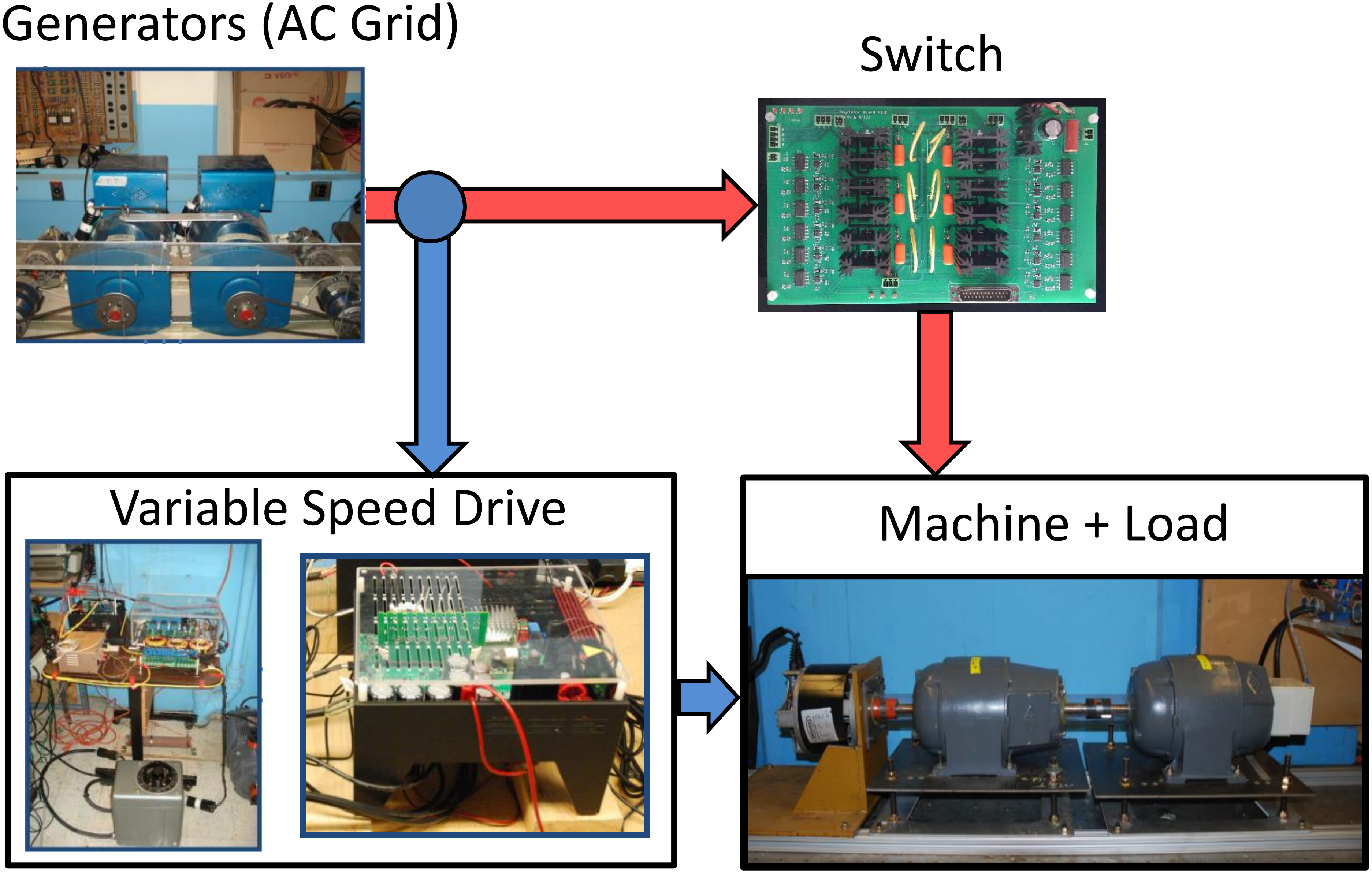
Contributions



- Drive design
- Switch realization
- Seamless control

- Grid interaction
- Drive topology comparison
- DFM design considerations

Laboratory-scaled power system as experimental setup



Generators (AC Grid)

Switch

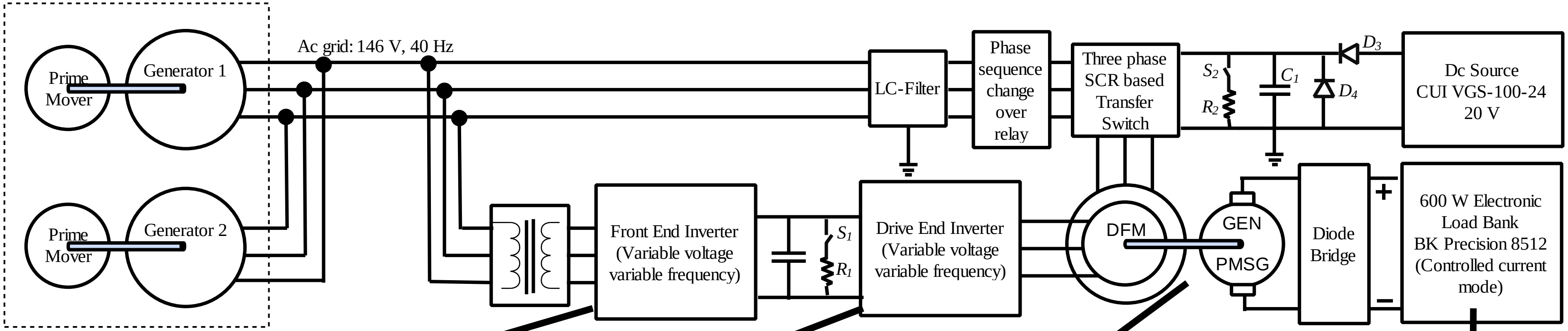
Variable Speed Drive

Machine + Load

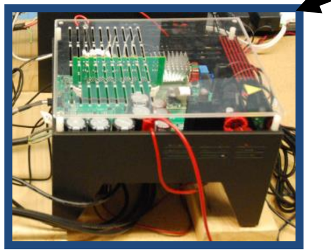
Designed and built entire power system as laboratory setup

Generators (1.4 kW)

- **6** Machines
- **5** Control platforms (TI, NI, Matlab RTW, PSoC)
- **3** Data acquisition systems
- **2** Converters + Filters



Grid-side Conv.

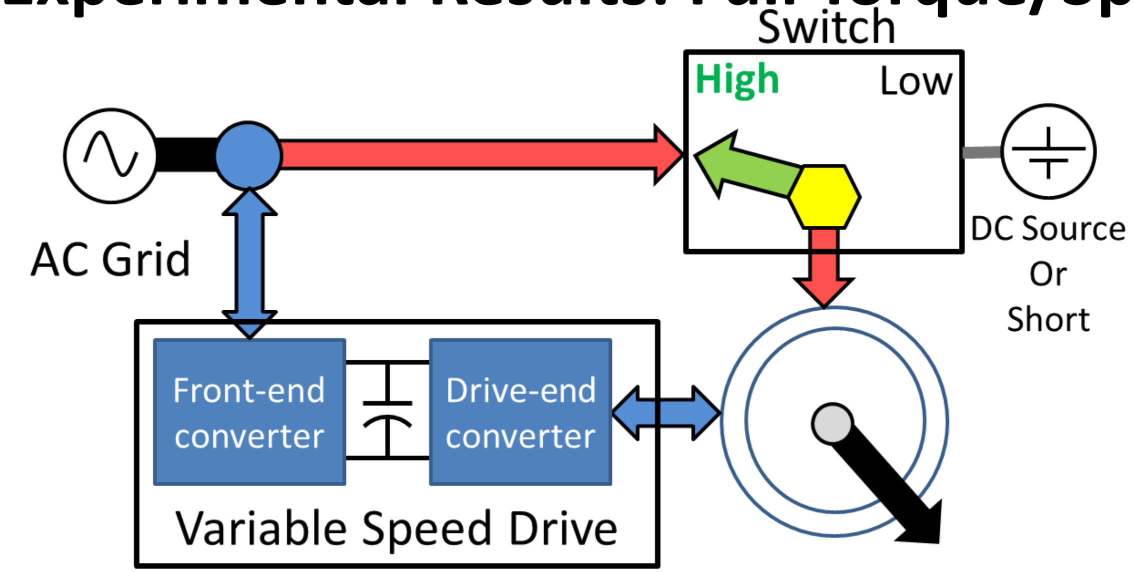


TI C2000

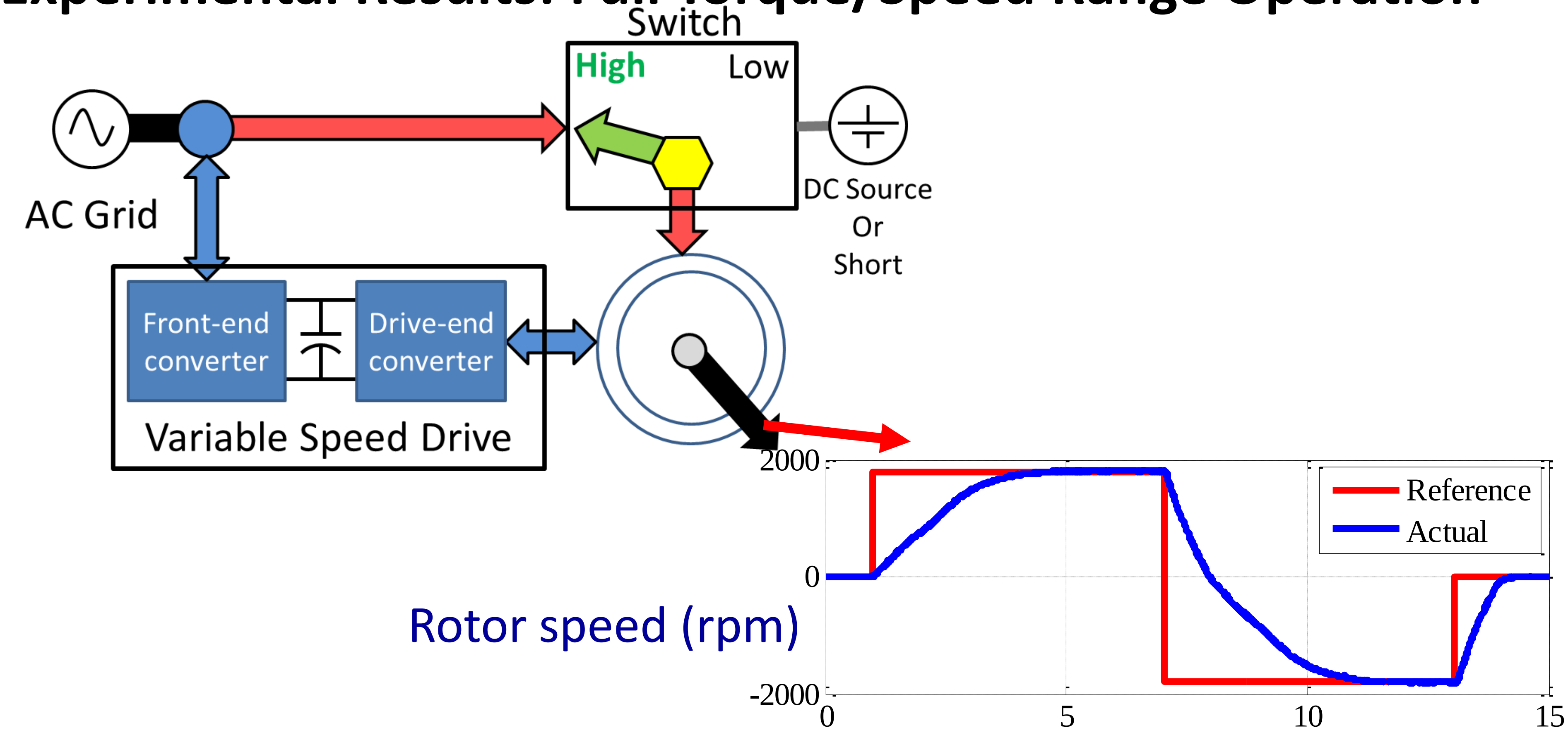
PM Gen. DFM (1.1 kW)

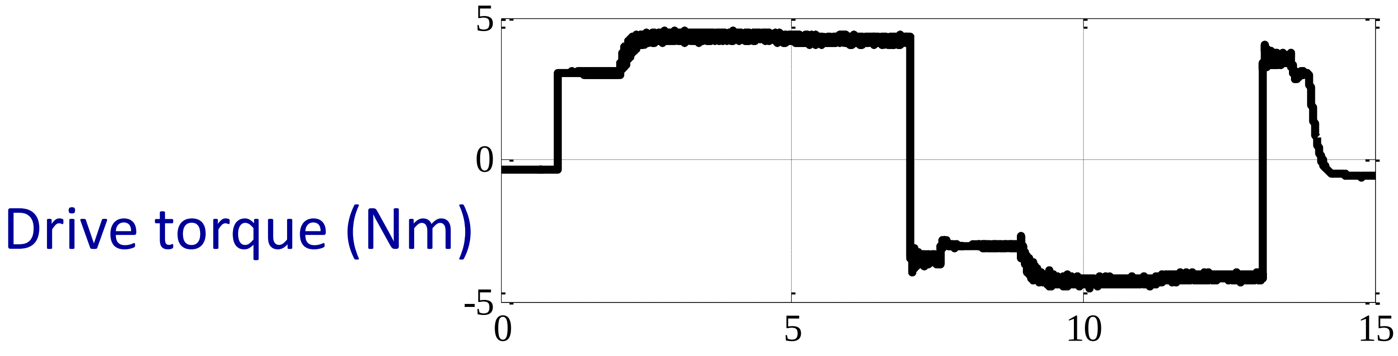
DC Electronic Load Bank

Experimental Results: Full Torque/Speed Range Operation

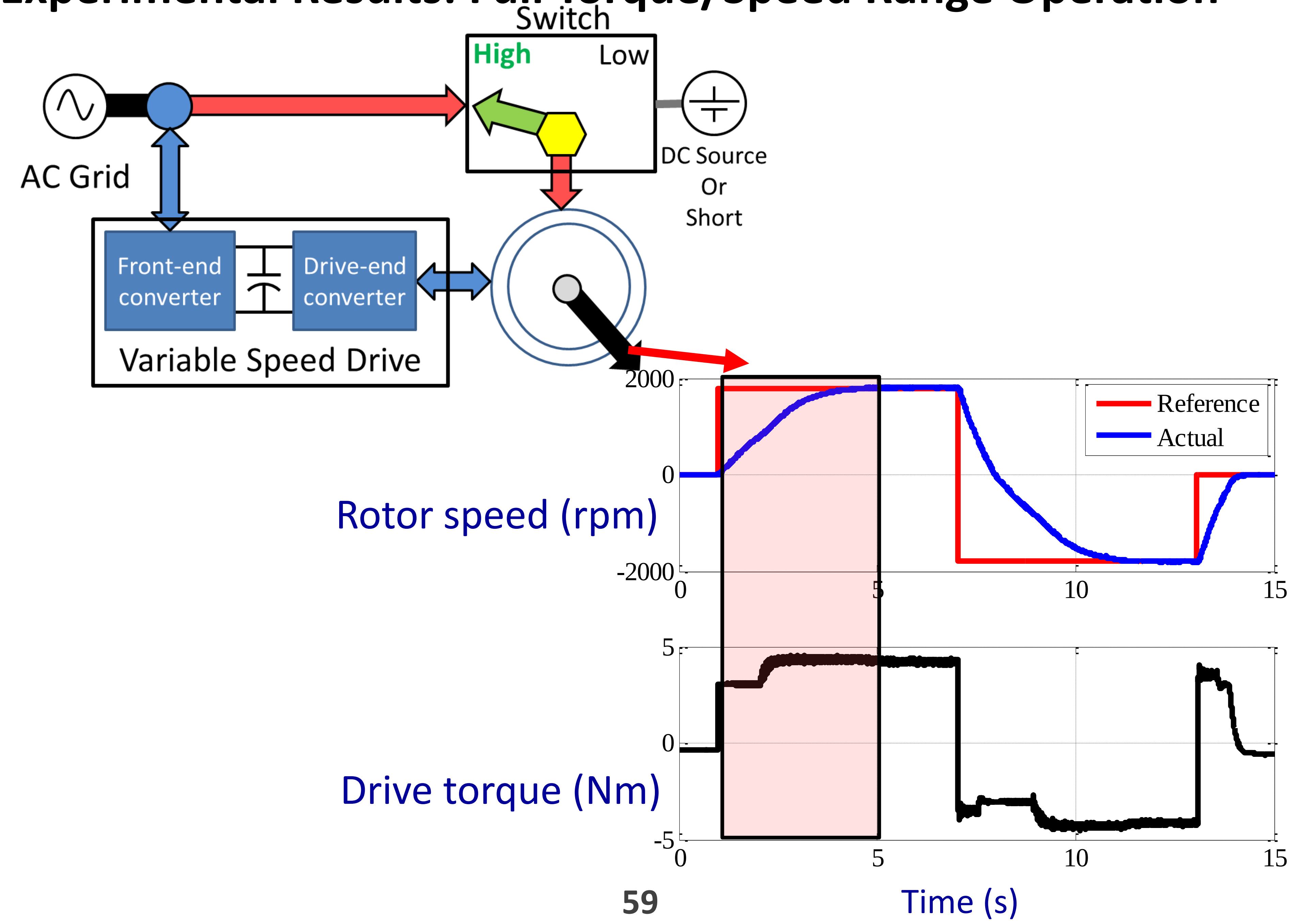


Experimental Results: Full Torque/Speed Range Operation

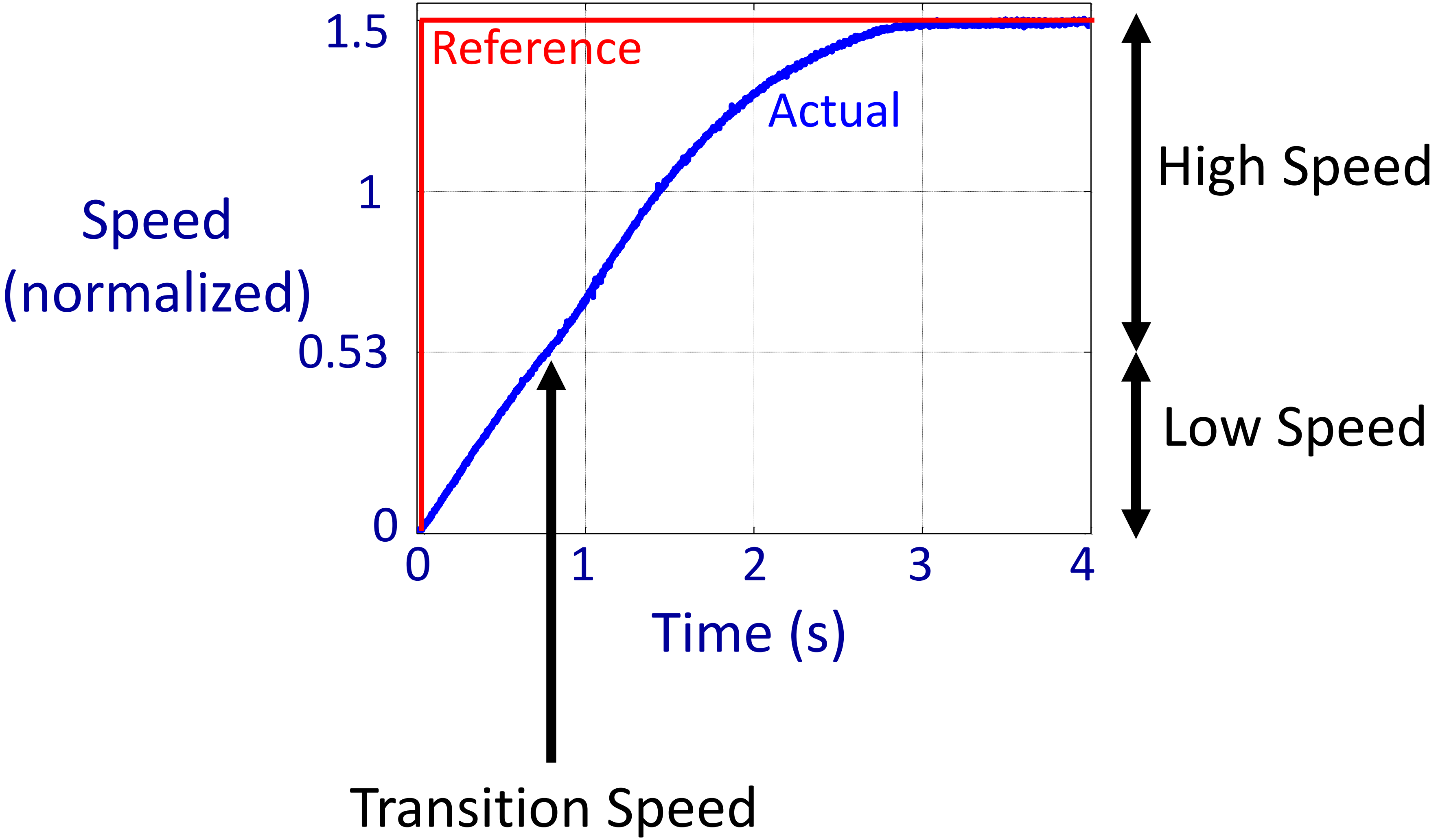




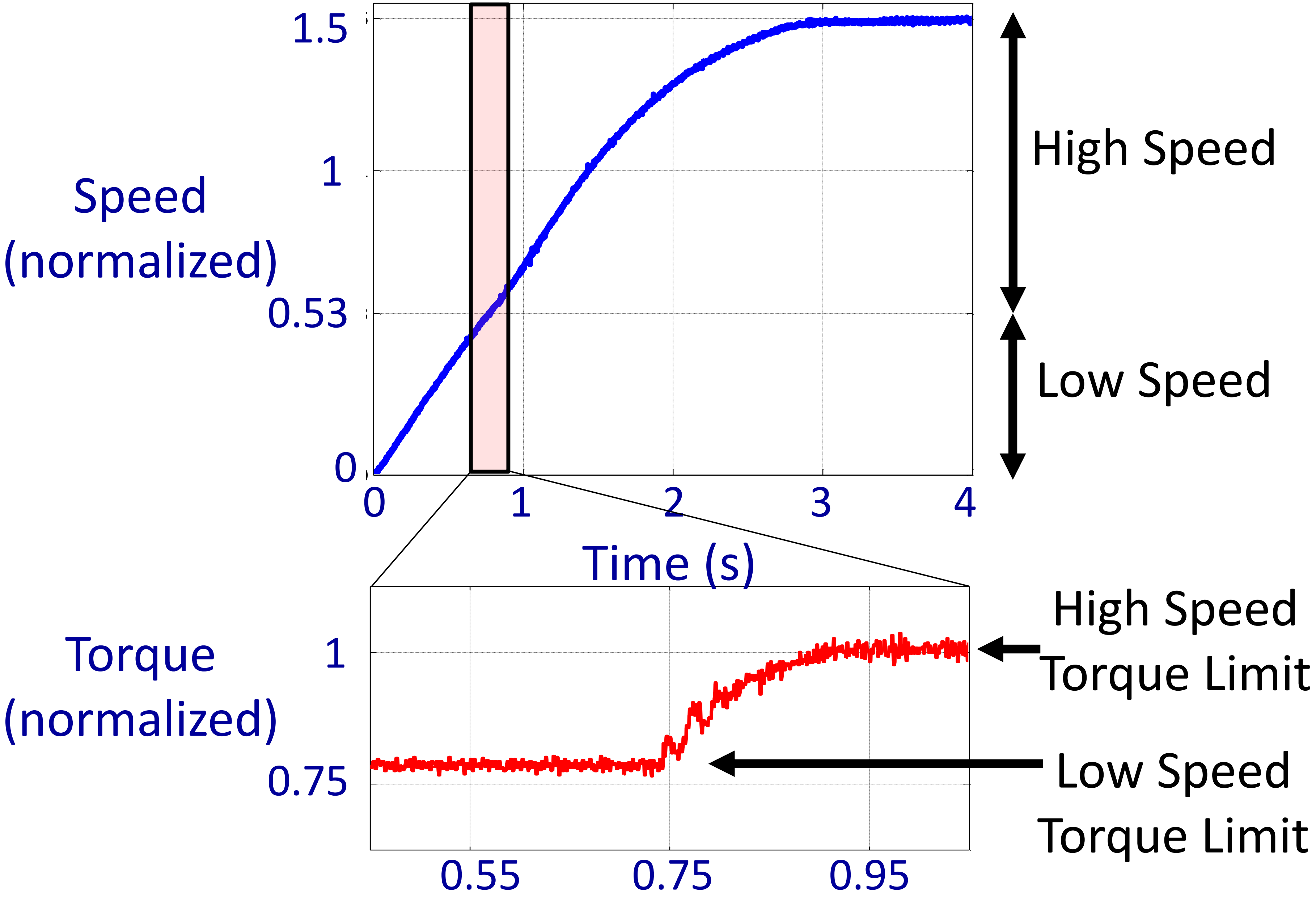
Experimental Results: Full Torque/Speed Range Operation



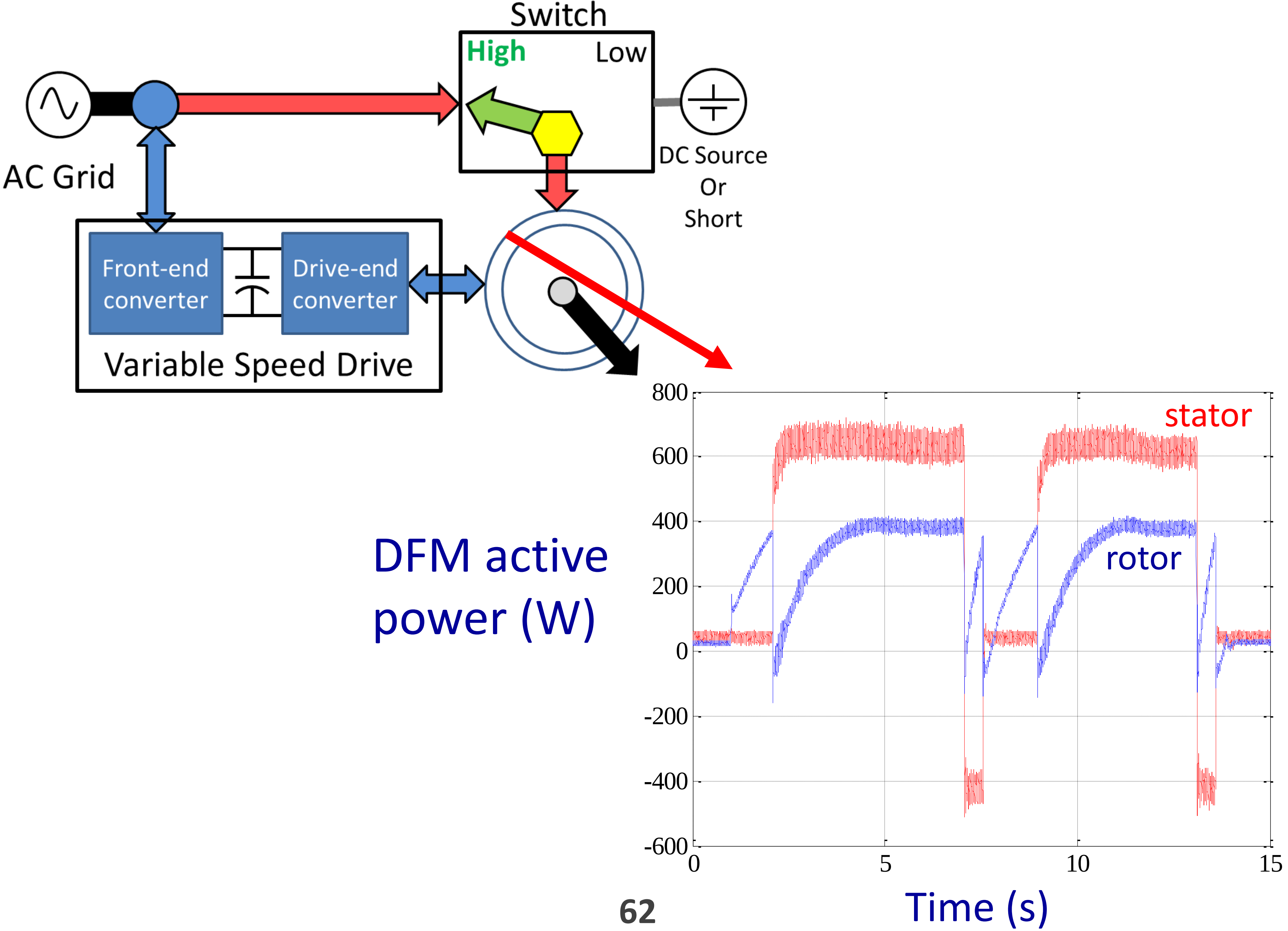
Experimental result: Seamless mechanical port



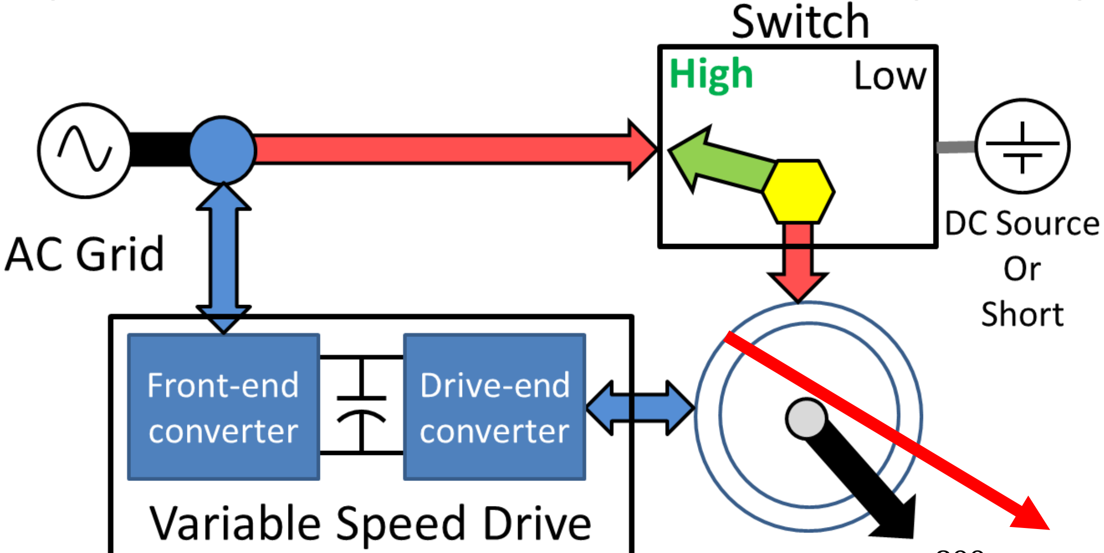
Experimental result: Seamless mechanical port

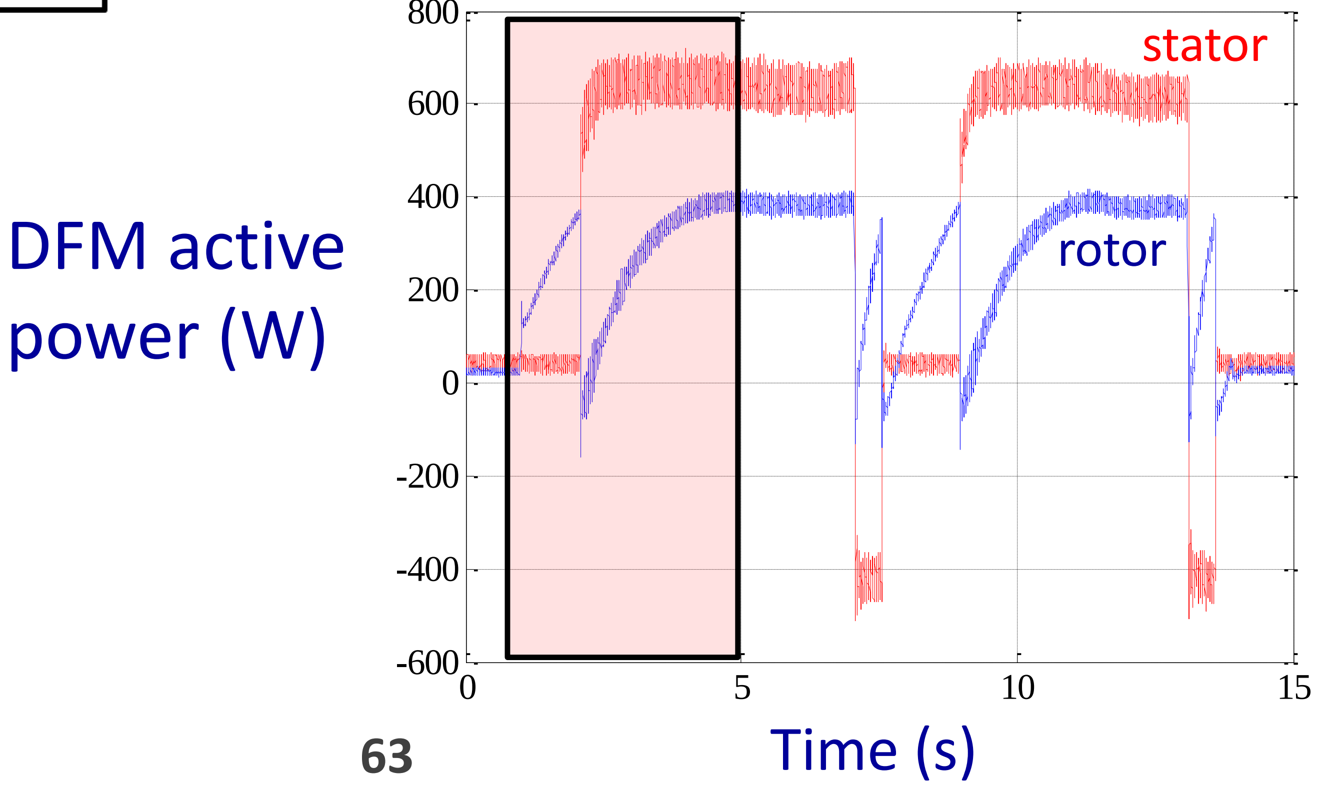


Experimental Results: Full Torque/Speed Range Operation

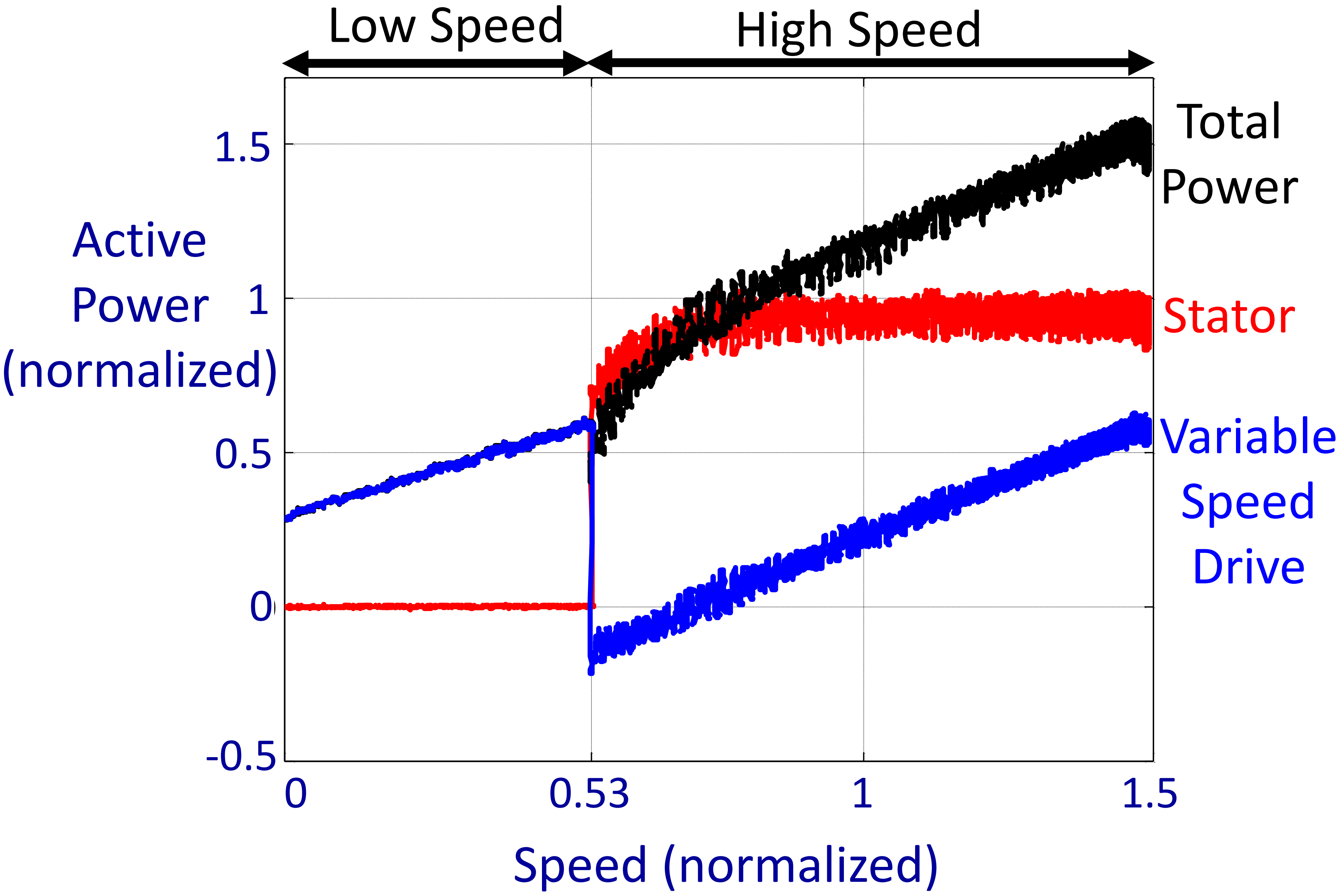


Experimental Results: Full Torque/Speed Range Operation

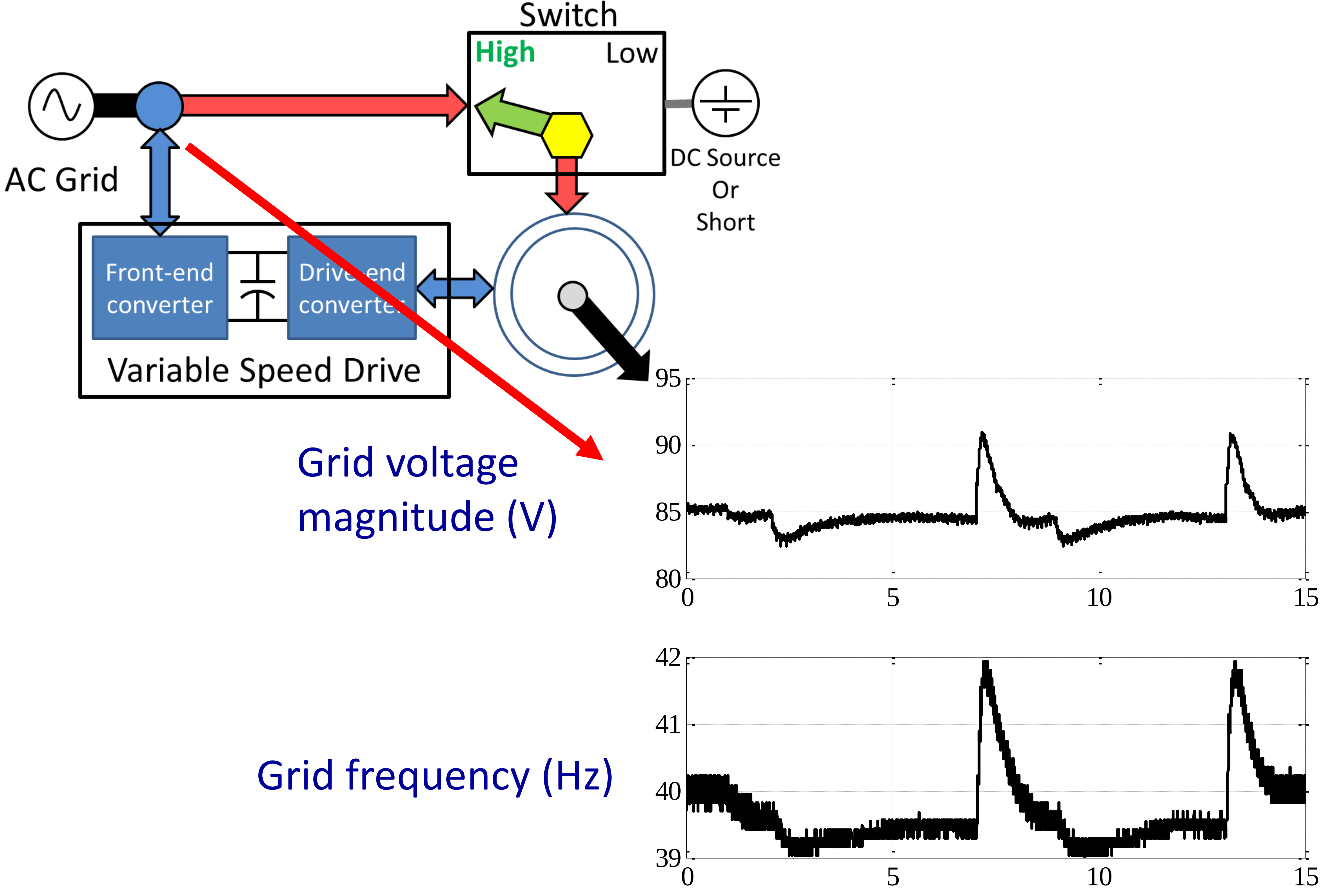




Experimental result: Seamless electrical ports



Experimental Results: Full Torque/Speed Range Operation

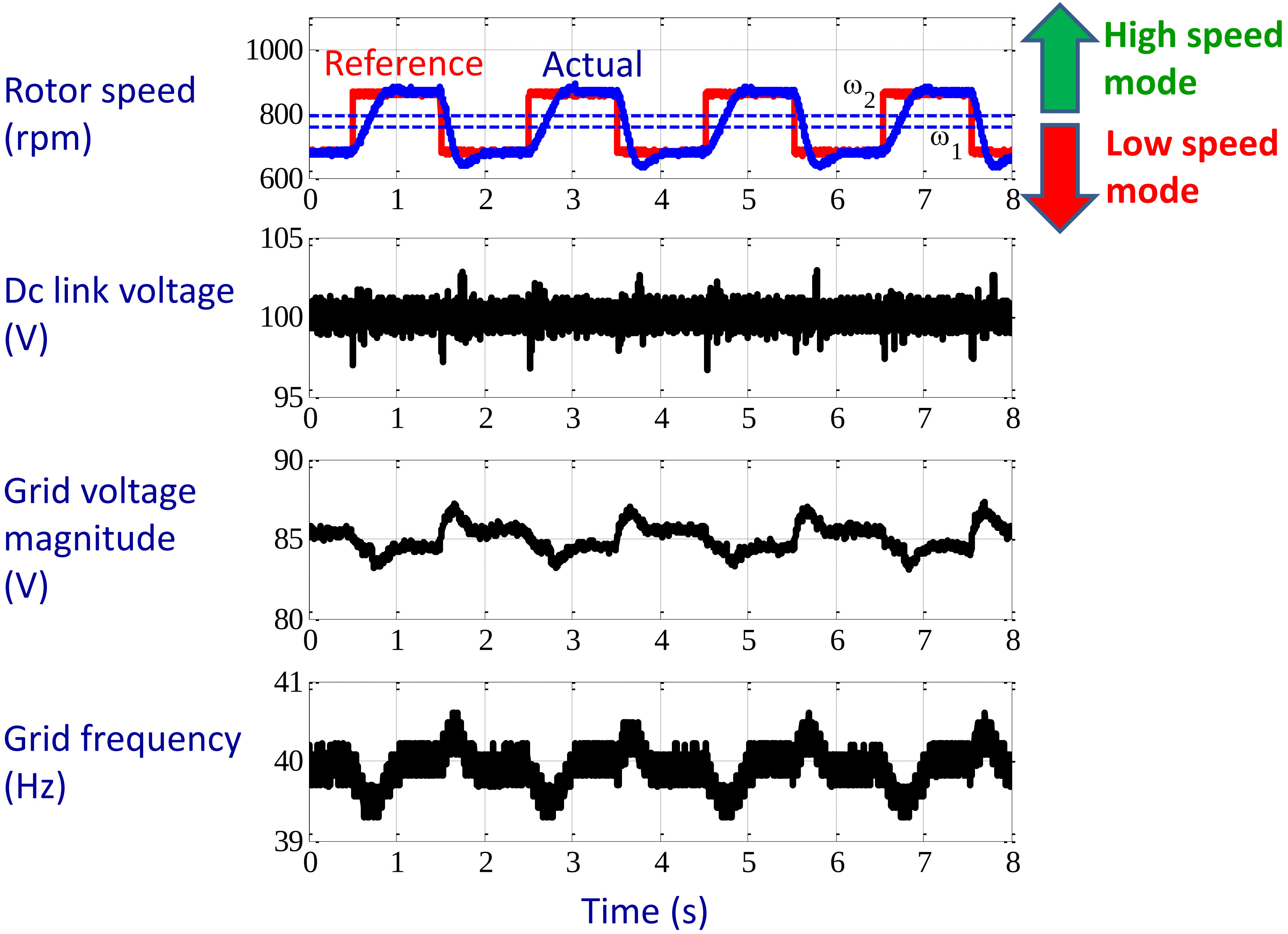


Grid voltage magnitude (V)

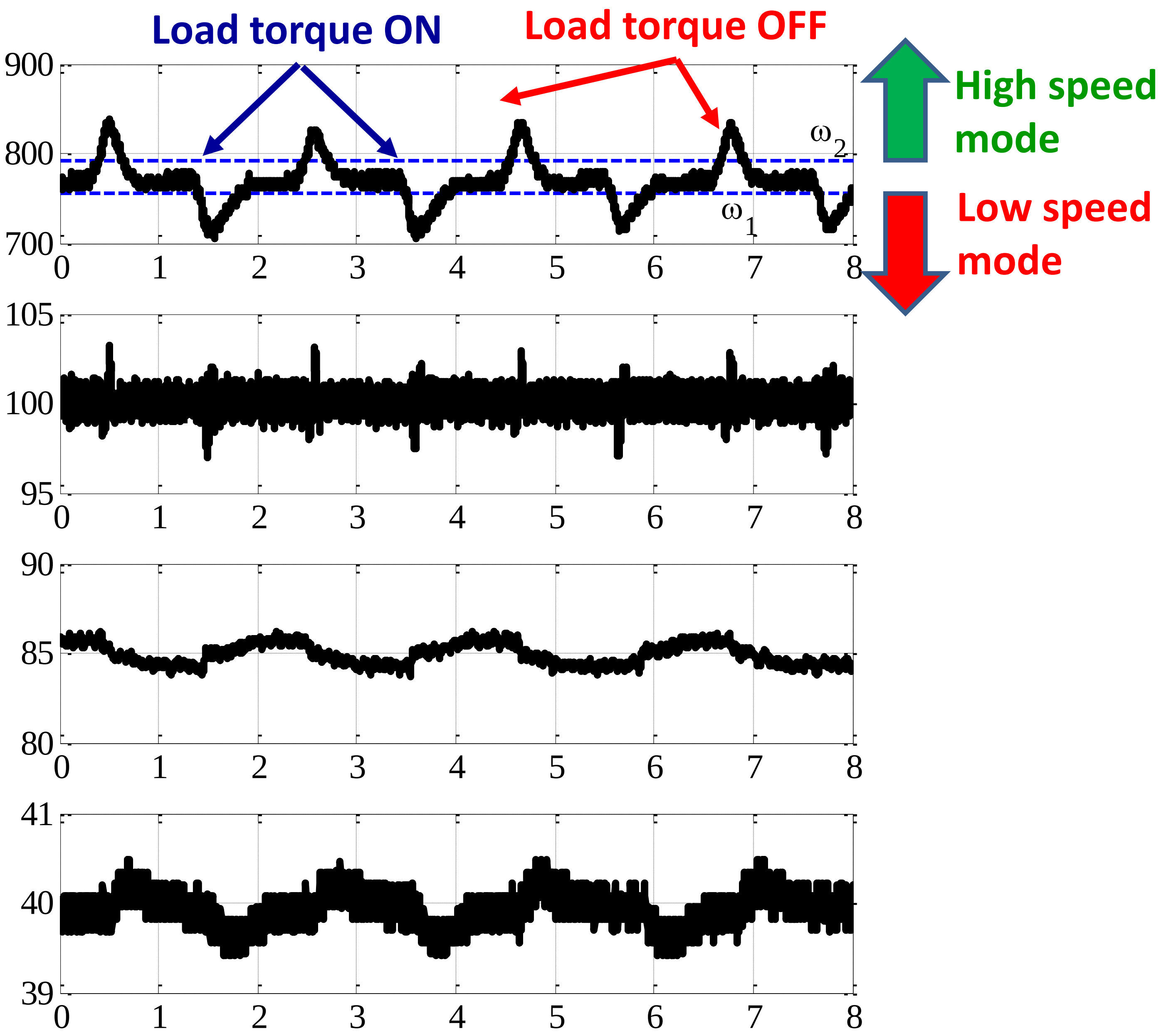
Grid frequency (Hz)

Time (s)

Experimental Results: Speed Reference Oscillation



Experimental Results: Load Torque Oscillation



Load torque ON

Load torque OFF

High speed mode

Low speed mode

Rotor speed (rpm)

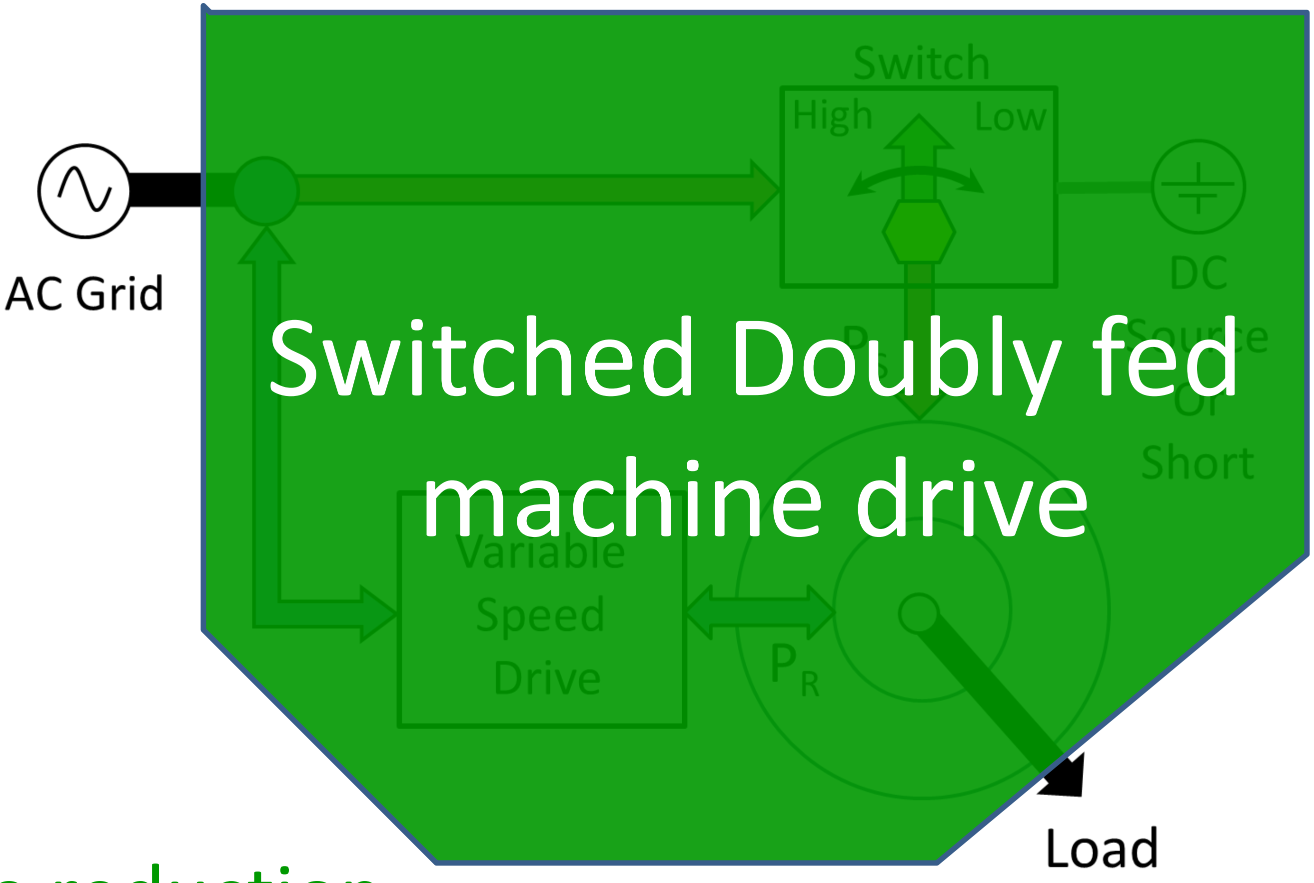
Dc link voltage (V)

Grid voltage magnitude (V)

Grid frequency (Hz)

Time (s)

Conclusion



Switched Doubly fed machine drive

- Two-thirds size reduction
- Grid-friendly
- Better efficiency
- Reduced cost
- Better reliability

Publications

	Conference	Journal
Power converter sizing	IEMDC 2013	IAS Jan '15
Control architecture	APEC 2013	IAS Mar '15
12-SCR Based transfer switch	APEC 2014	IAS Jul '15
8-SCR Based transfer switch	APEC 2016	pels Sep '16
Fault tolerant capability	ASNE EMTS 2014	
Comparison of topology	ITEC2015	
Grid-friendly operation	IEMDC 2015	

Acknowledgment

ESRDC
ELECTRIC SHIP RESEARCH AND DEVELOPMENT CONSORTIUM

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ONR
Science & Technology

The Grainger Foundation

KFAS
مؤسسة الكويت للتقدم العلمي
Kuwait Foundation for the Advancement of Sciences

Dr. Manny Landsman (Fellowship)

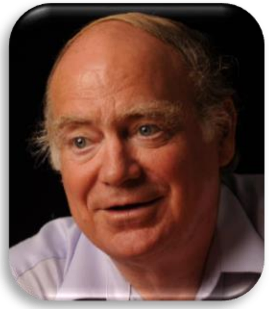
MIT Skoltech Initiative


North Surakit., S.B.


Mike Tomovich, S.M.

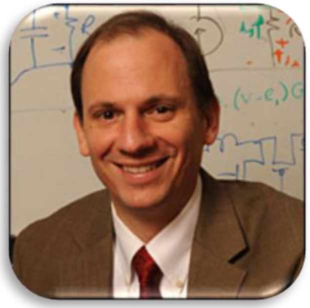

Arthur Chang, Ph.D.


Prof. Al Avestruz

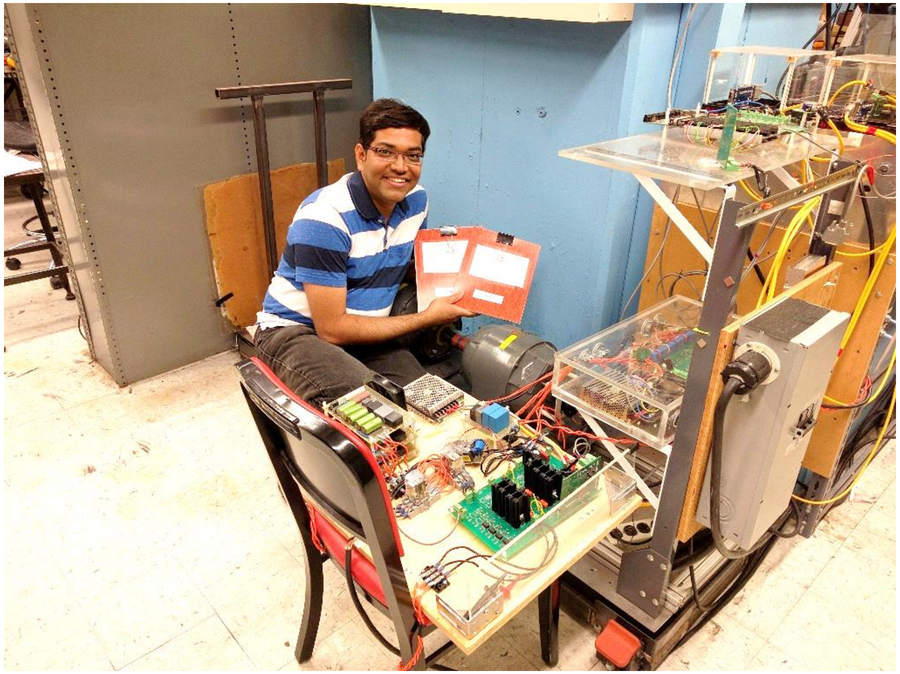

Prof. J. Kirtley


Prof. S. Leeb


Prof. J. Lang


Prof. D. Perreault

Massachusetts Institute of Technology

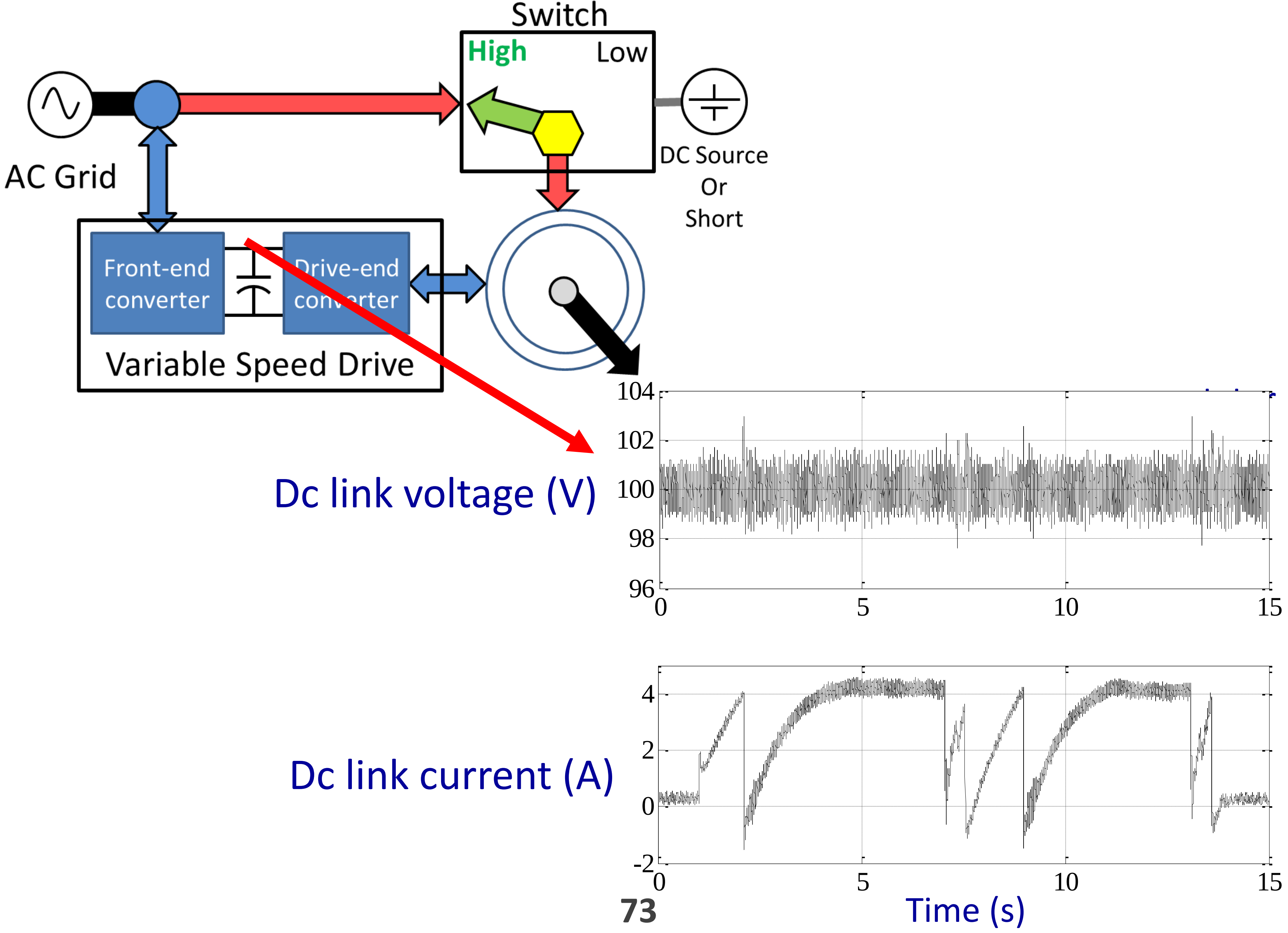


It’s about the journey
not the destination

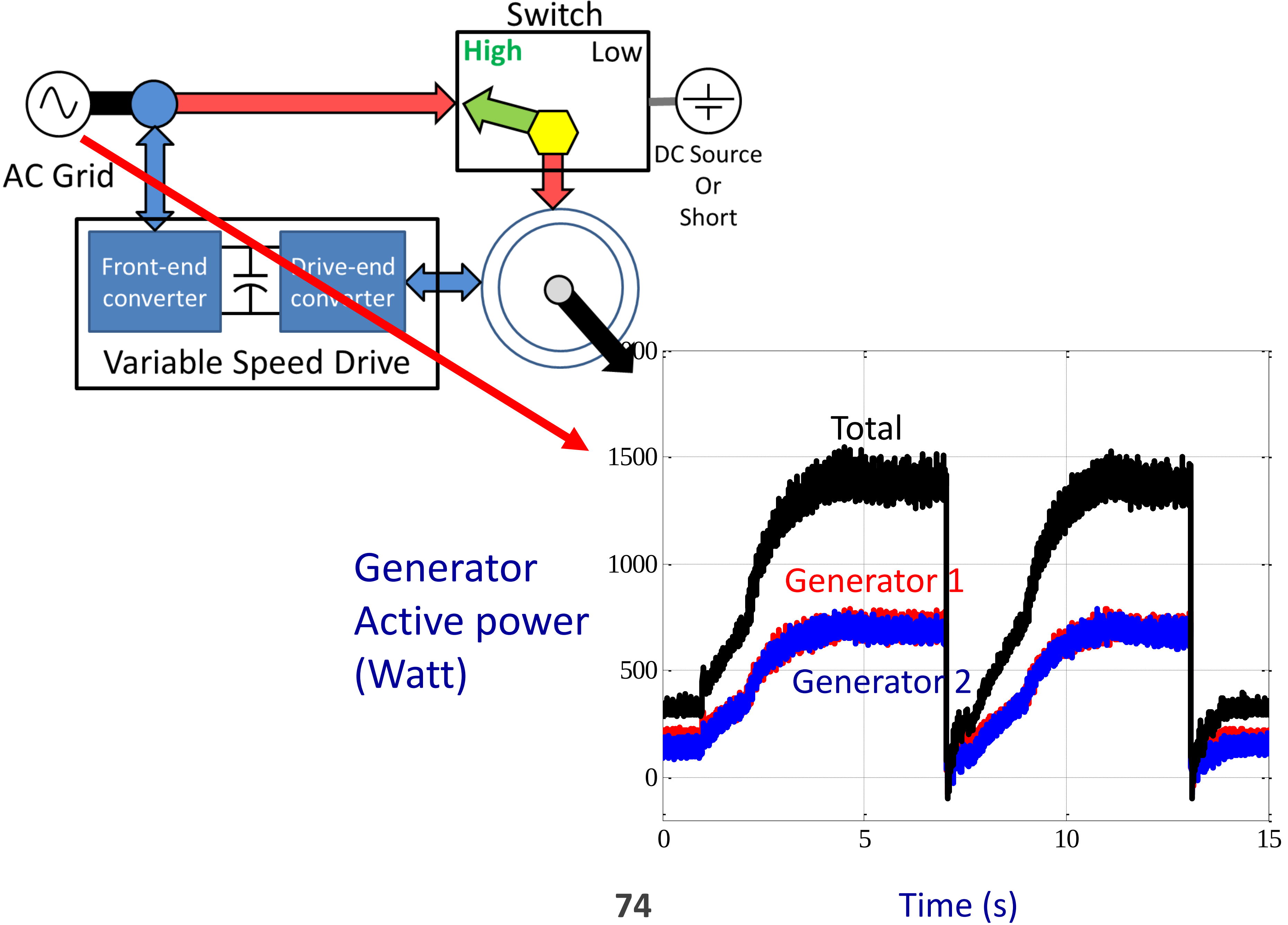
Thank you!

Back up

Experimental Results: Full Torque/Speed Range Operation



Experimental Results: Full Torque/Speed Range Operation



Future Work

- DFM electromagnetic design optimization
- Evaluation in a MW-scale application
- Brushless operation

Transportation

Industrial Drives

Energy Harvesting

Contributions

- Design methodology of a switched-DFM drive based on a required drive torque capability

- Solid-state transfer switch architectures for on-the-fly reconfiguration of the DFM

- Control platform for a seamless operation of the drive at the mechanical and electrical ports

- Enabling reactive power support to the grid without adding extra power electronics

- Performance comparison of different switched-DFM drive topology leading to machine design guidelines

Additional Publications

Single sided induction heating

IECON'2013

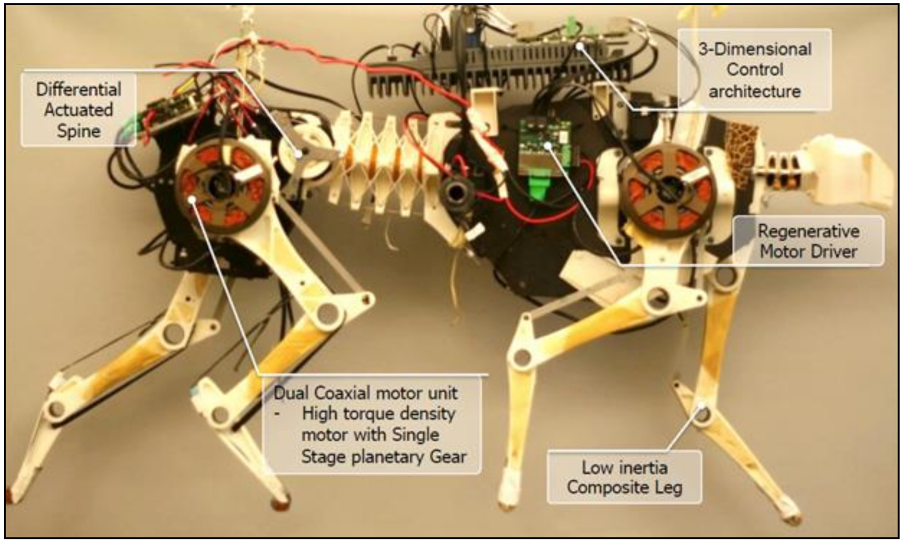
Uniform heating + optimized winding

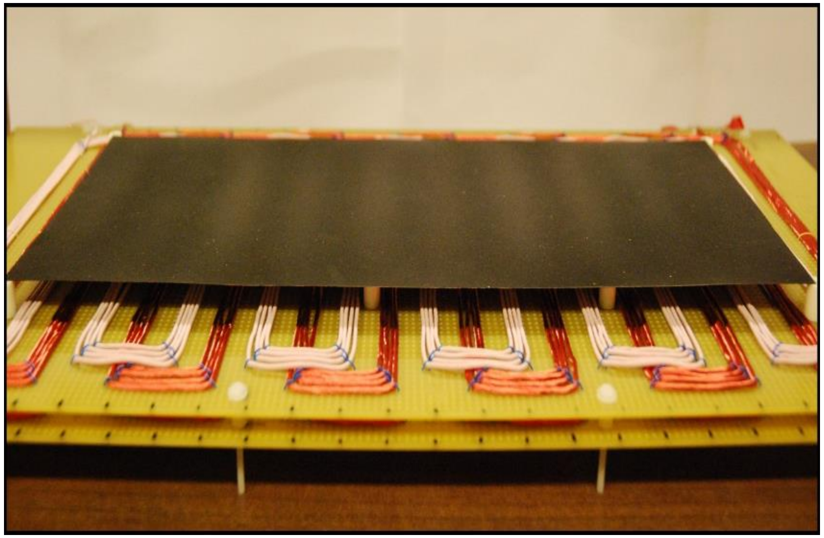
APEC 2014

pels (To be submitted)

MIT Cheetah robotic actuator design

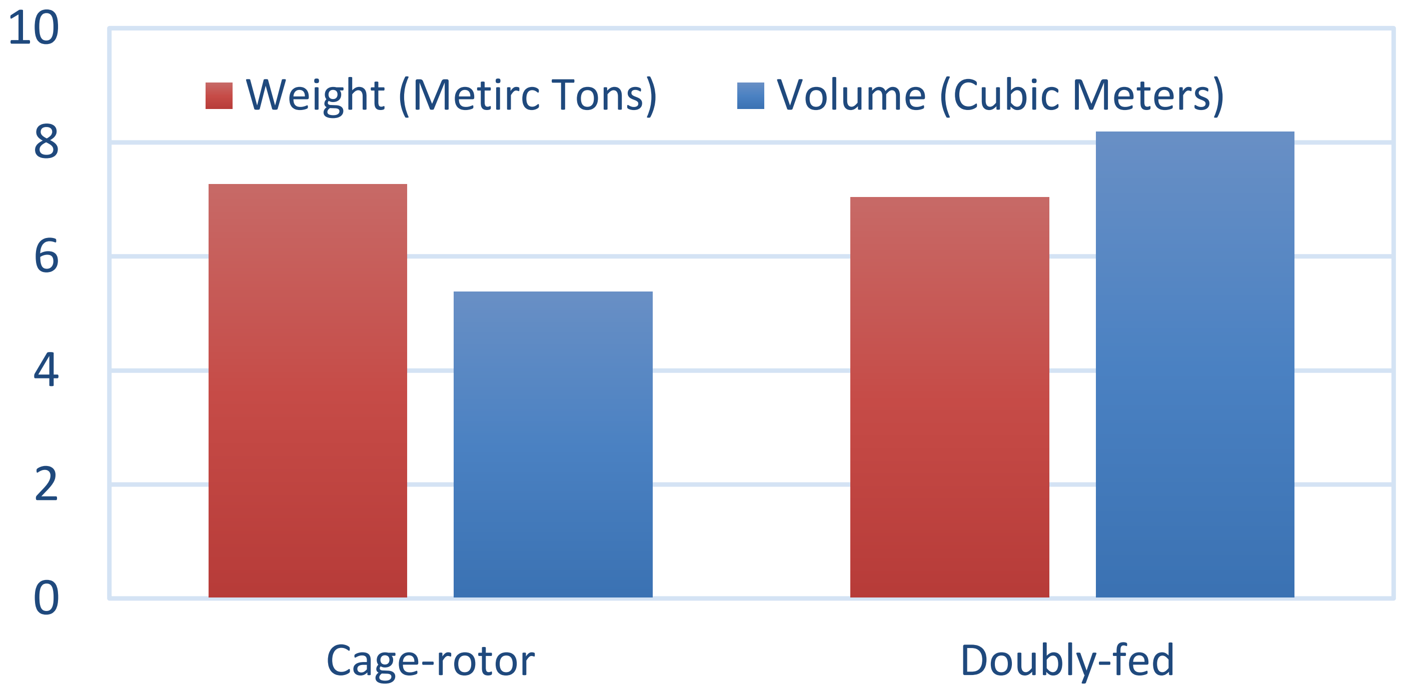
ICEM International Conference on Electrical Machines 2012





Comparison of induction motor technology

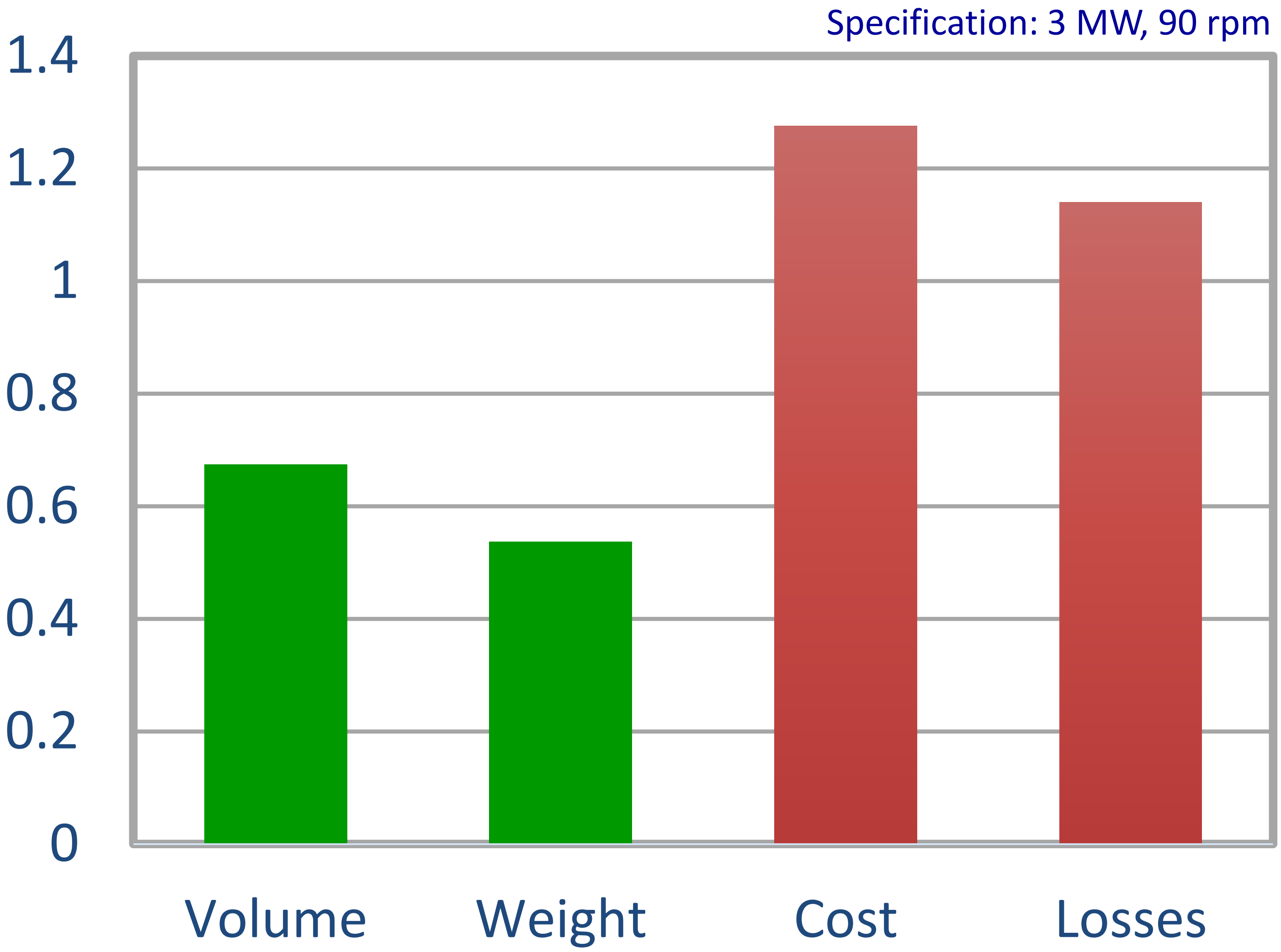
Specification: 1250 HP, 4160 V, 900 rpm, Air-cooled



TECO Westinghouse JH12508 Induction Motor

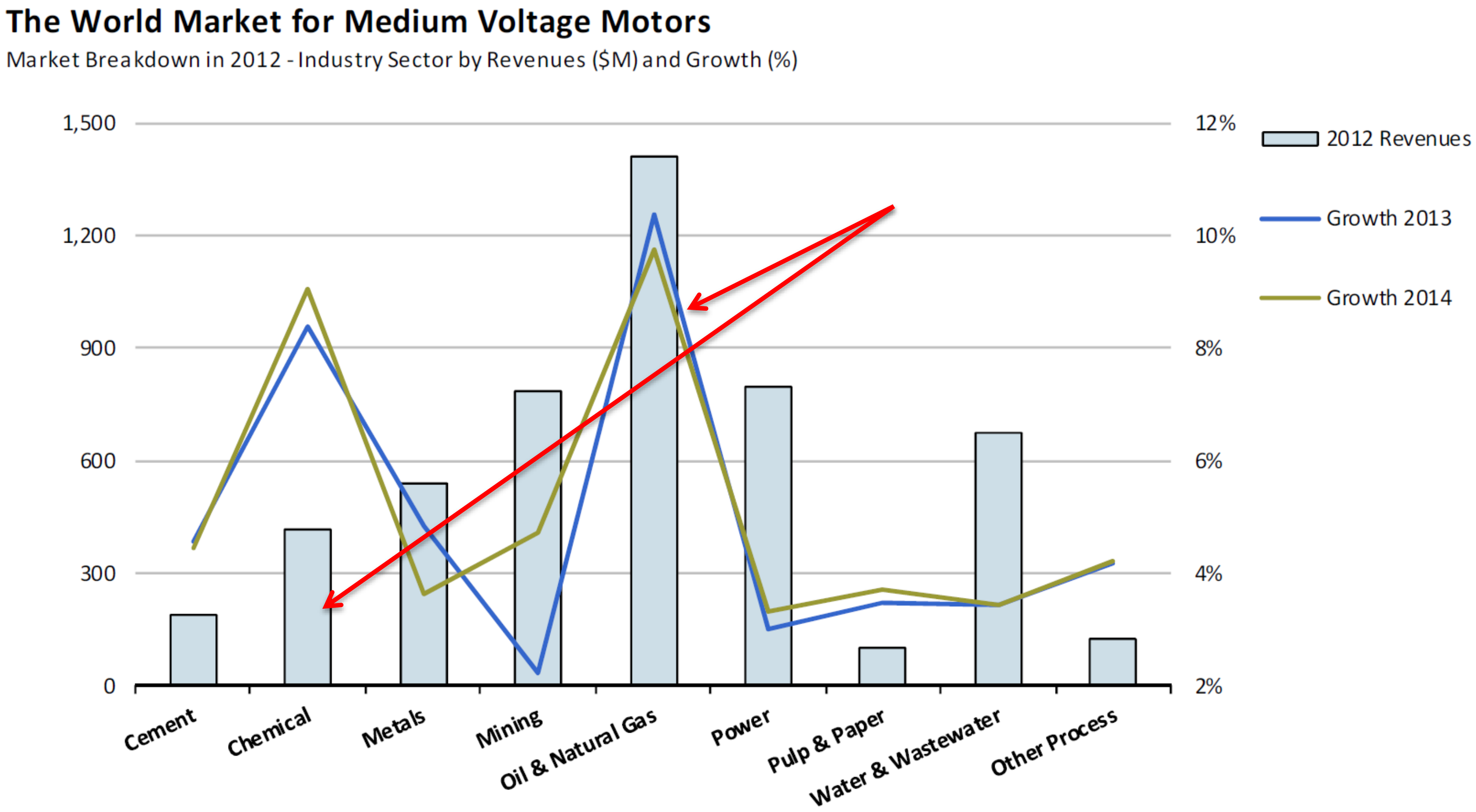
GE 8411S Slip-ring Induction Motor

Comparison: PMSG + full converter relative to DFM + partial converter for wind power generation



Polinder et al., IEEE Transactions on Energy Conversion, Sept. 2006.

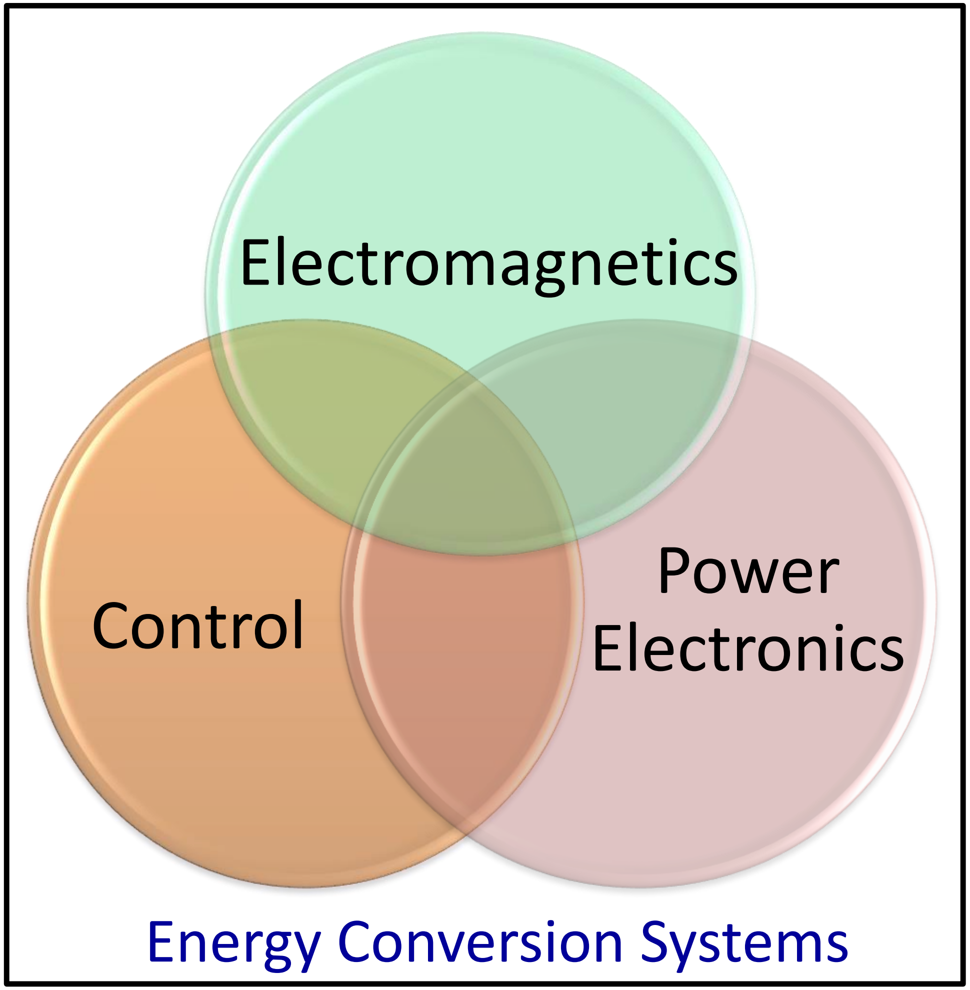
$4.5 B Worldwide Market in MV Motors



Source: IHS Market breakdown in 2012. Industry Sector by Revenues ($M) and Growth (%) **Feb-14**

Agarwal et al., NIST/DOE Workshop NGEM, 2014

Research theme



Information World

Electromagnetics

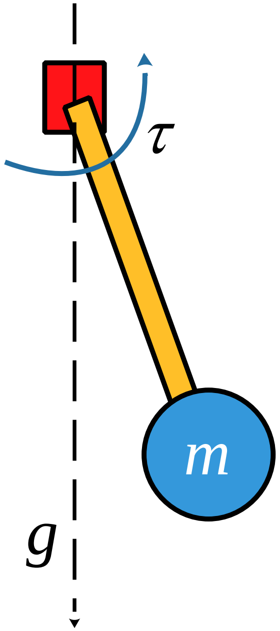
Control

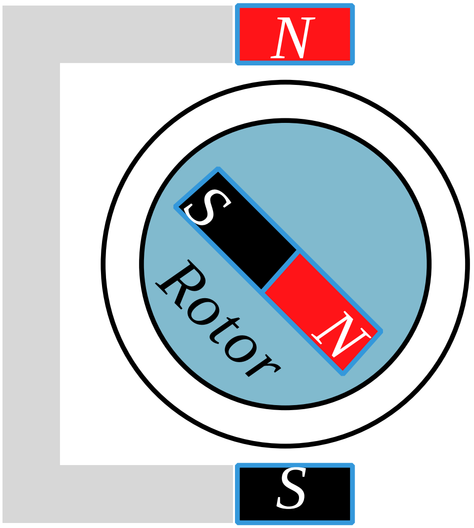
Power Electronics

Energy Conversion Systems

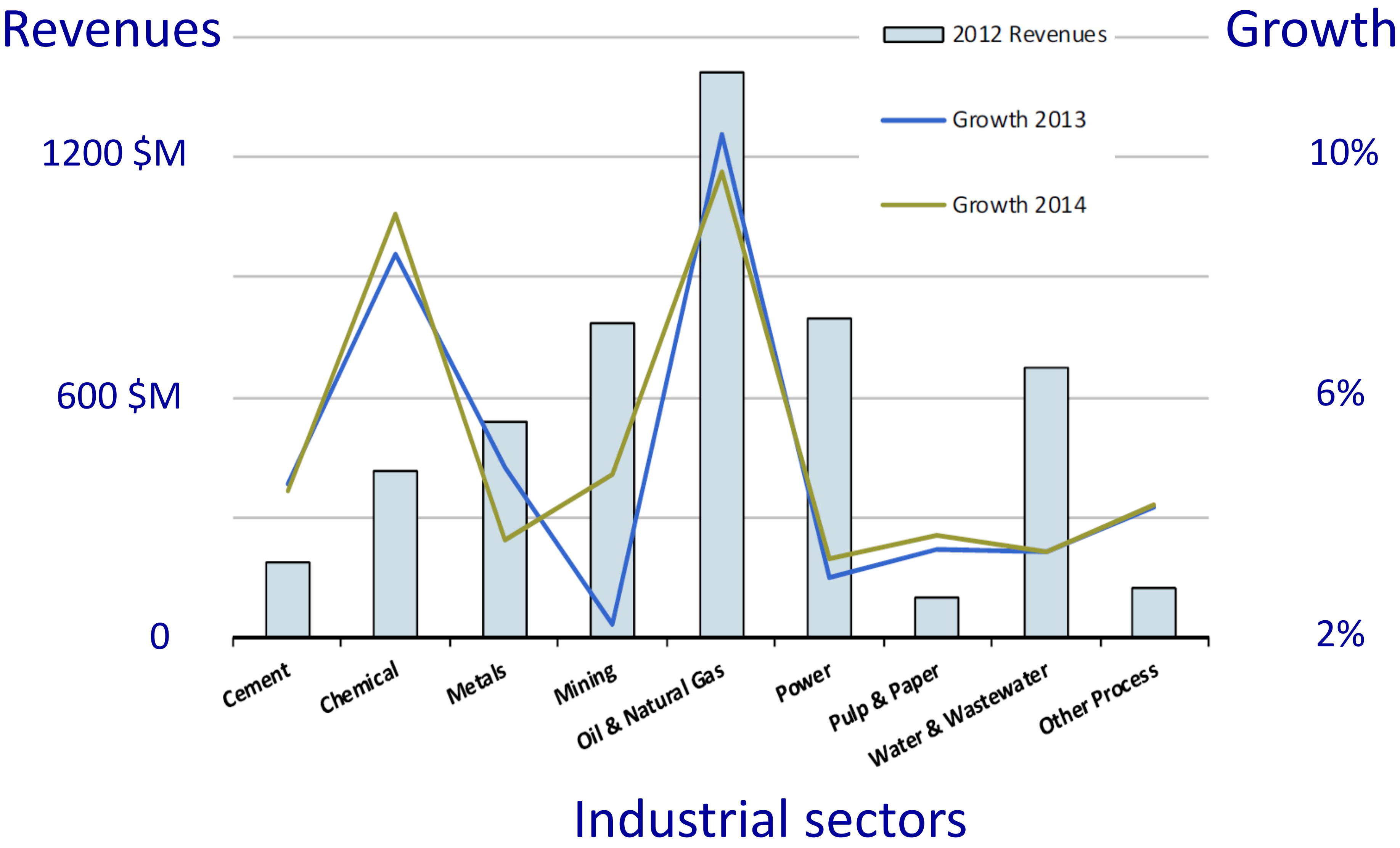
Physical World

Motors + Energy Storage



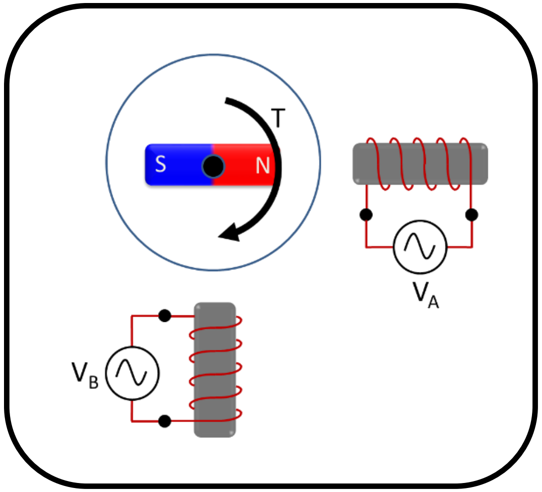


Medium voltage motors market: $4.5 B Worldwide

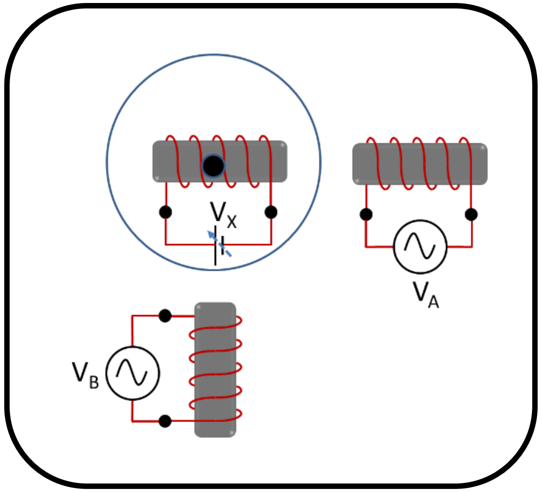


Electromechanical Actuators 101

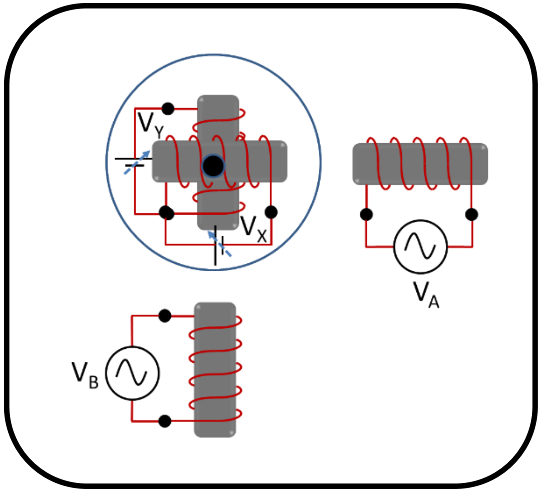
2 Degrees of Freedom



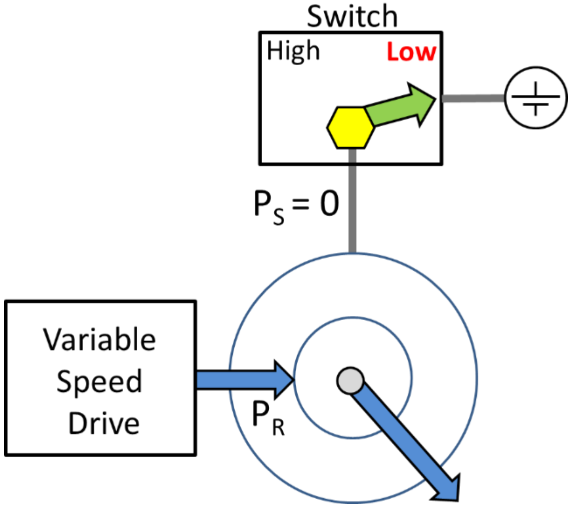
3 Degrees of Freedom



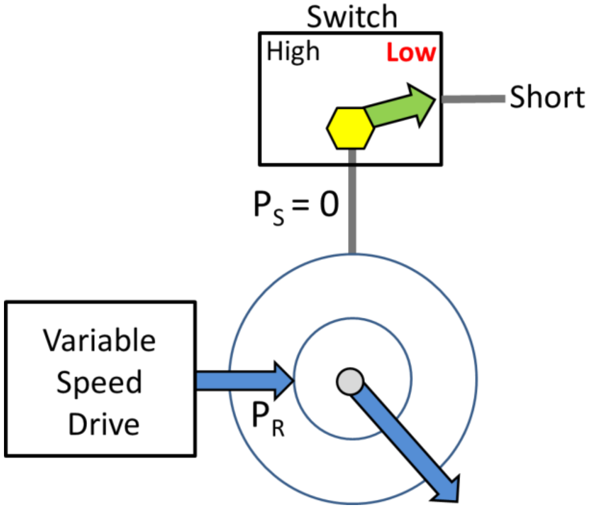
4 Degrees of Freedom



Torque production mechanism and control



Low speed synchronous



Low speed induction

Stator flux

- aided by the dc source
- controlled by the rotor d-axis current

Torque current

- controlled by the rotor q-axis current

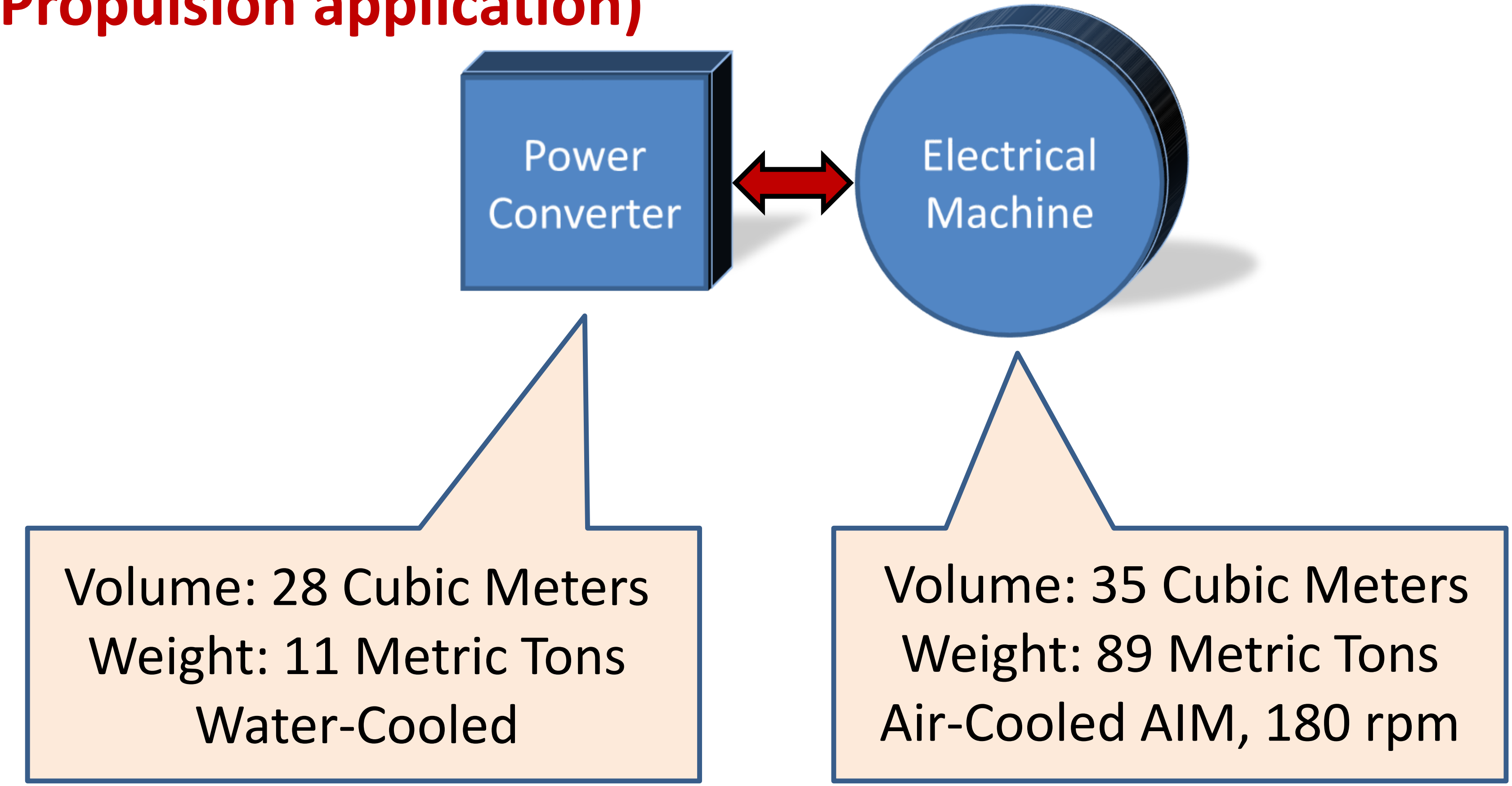
Stator flux

- controlled by the rotor d-axis current

Torque current

- controlled by the rotor q-axis current

Example 1 : 3.3 kV, 20 MW Induction Motor Drive (Propulsion application)

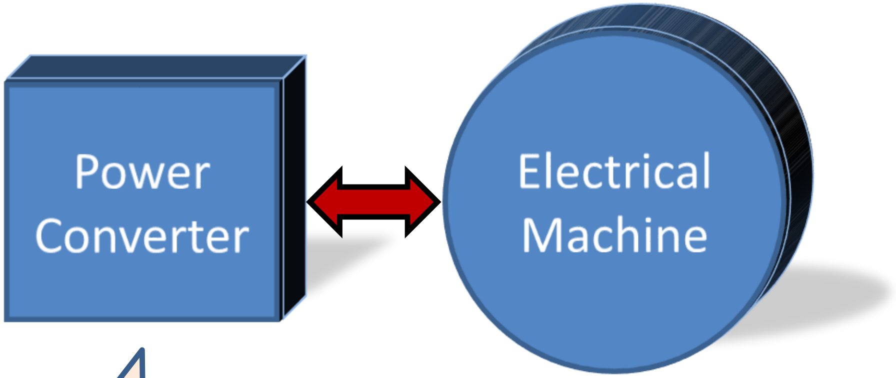


Volume: 28 Cubic Meters
Weight: 11 Metric Tons
Water-Cooled

Volume: 35 Cubic Meters
Weight: 89 Metric Tons
Air-Cooled AIM, 180 rpm

Source: *ACS6000, MV7000 Medium Voltage Drive Brochure*; Lewis et.al, *Advanced Induction Motor*

Example 2 : 3.7 kV, 20 MW Induction Motor Drive



Power Converter

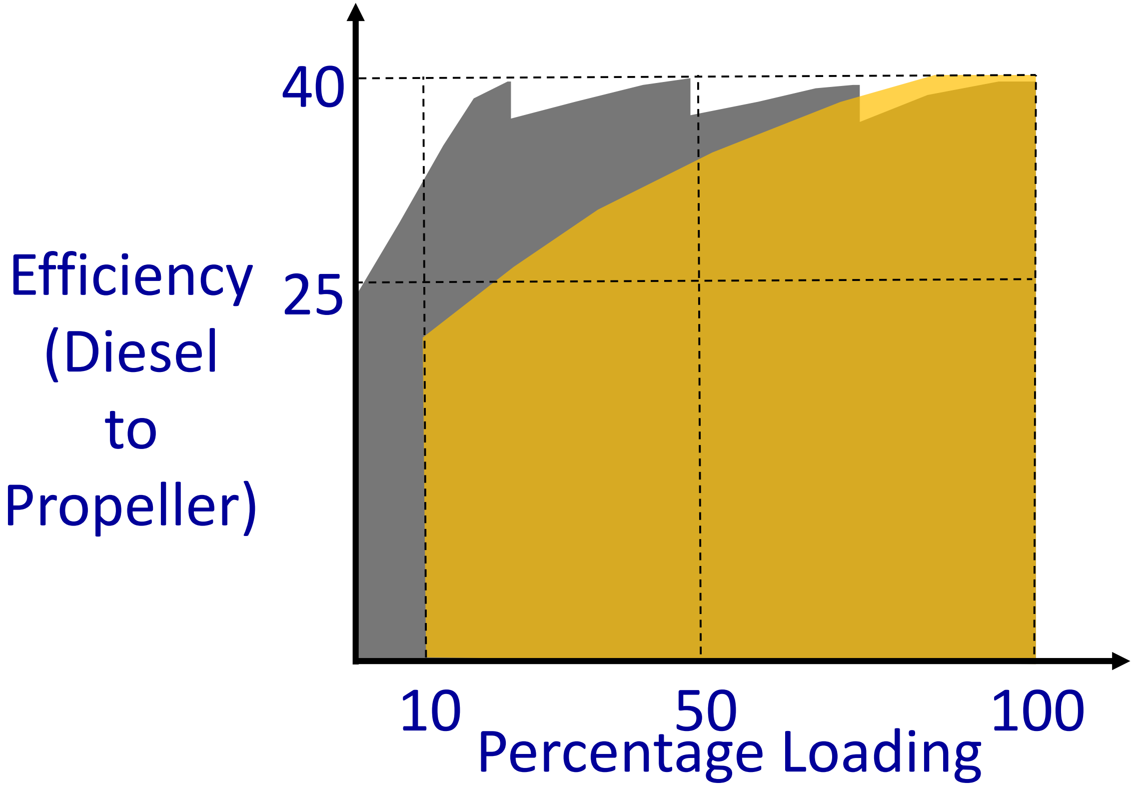
Electrical Machine

Volume: 19 Cubic Meters
Weight: 16 Metric Tons
Water-Cooled

Volume: 49 Cubic Meters
Weight: 97 Metric Tons
Water-Cooled PM, 150 rpm

Source: *Hebner* et.al, *Design and analysis of a 20 MW Propulsion power train, 2004*

Ship efficiency improvement due to electrification



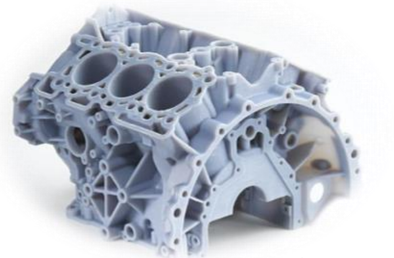
Enabling technology drives what is possible with electromechanical energy systems

Power
Semiconductor
Devices

Old Power
Network

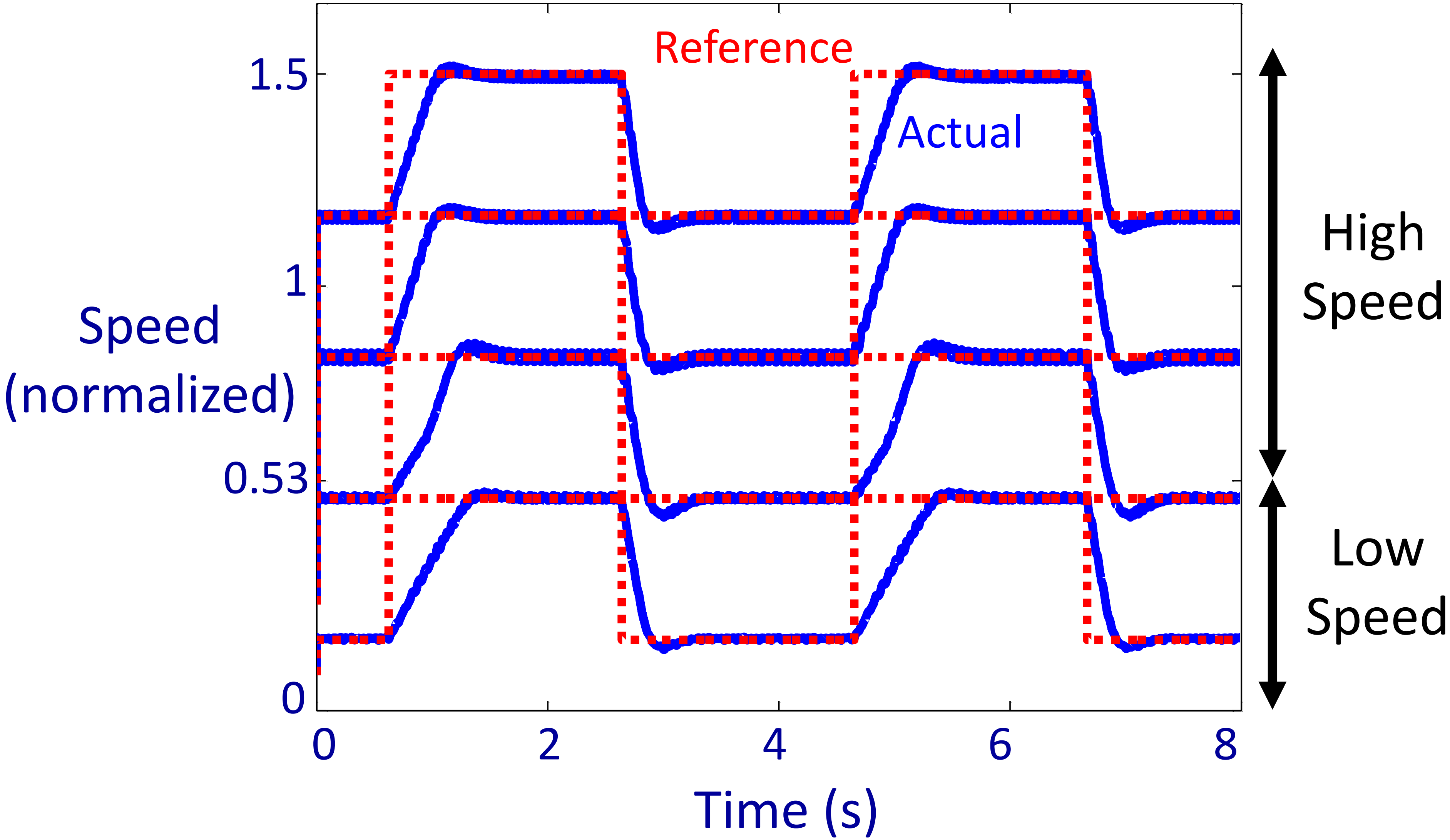
Power
Networks

Process line
manufacturing

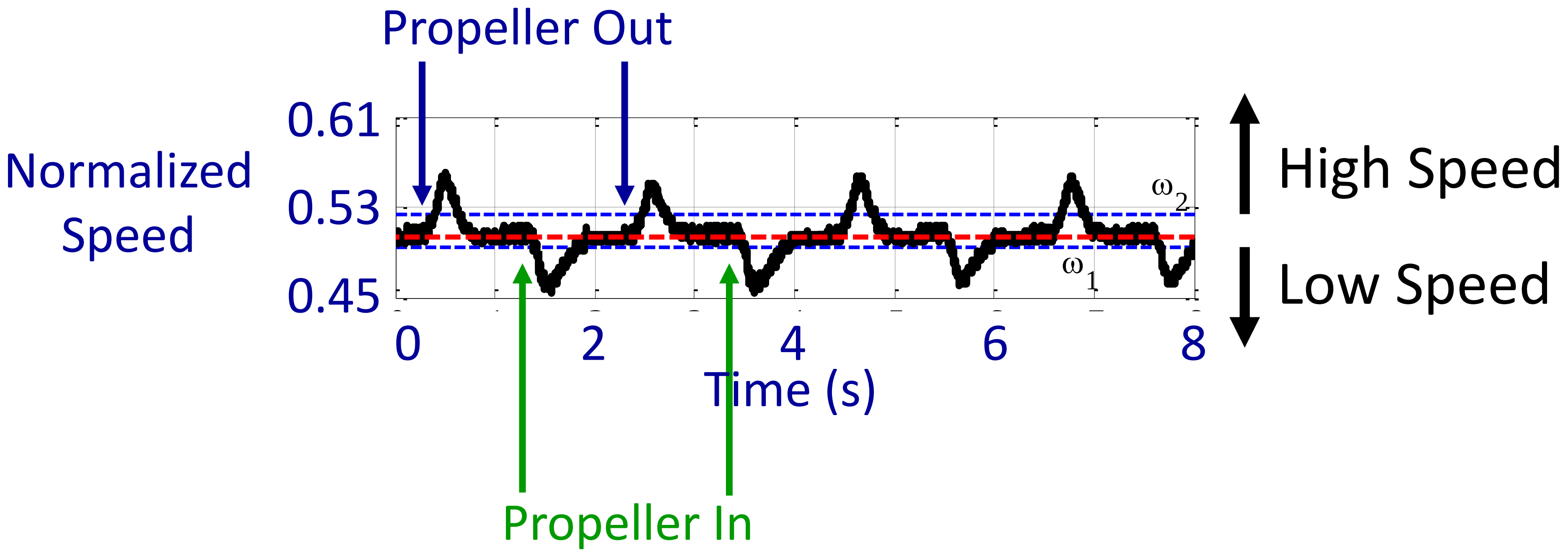


Additive
Manufacturing
(e.g. 3d printing)

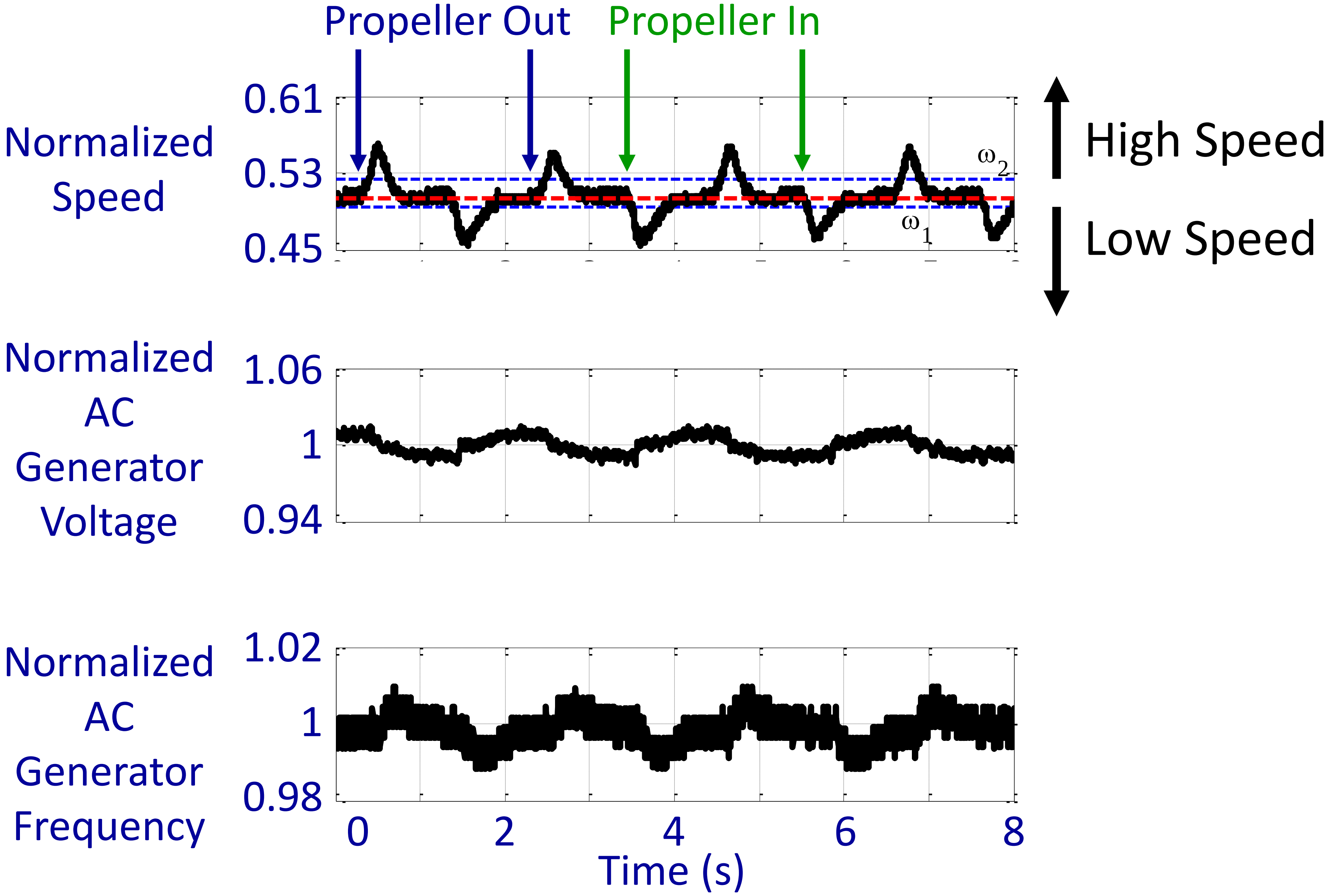
Seamless dynamic performance across entire speed range



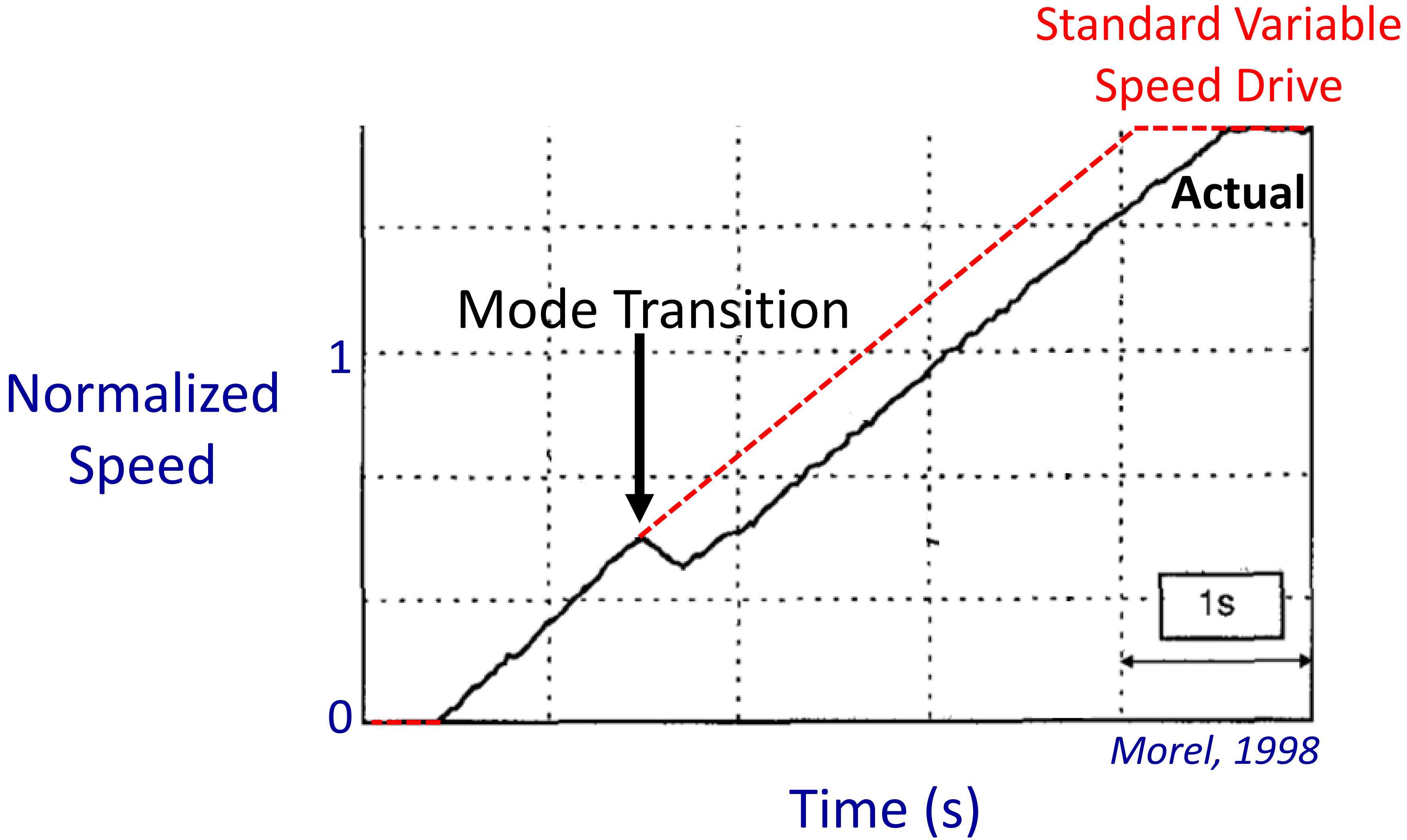
Severe Test: Mimics a ship in a turbulent weather



Stable AC generator under severe mode swinging

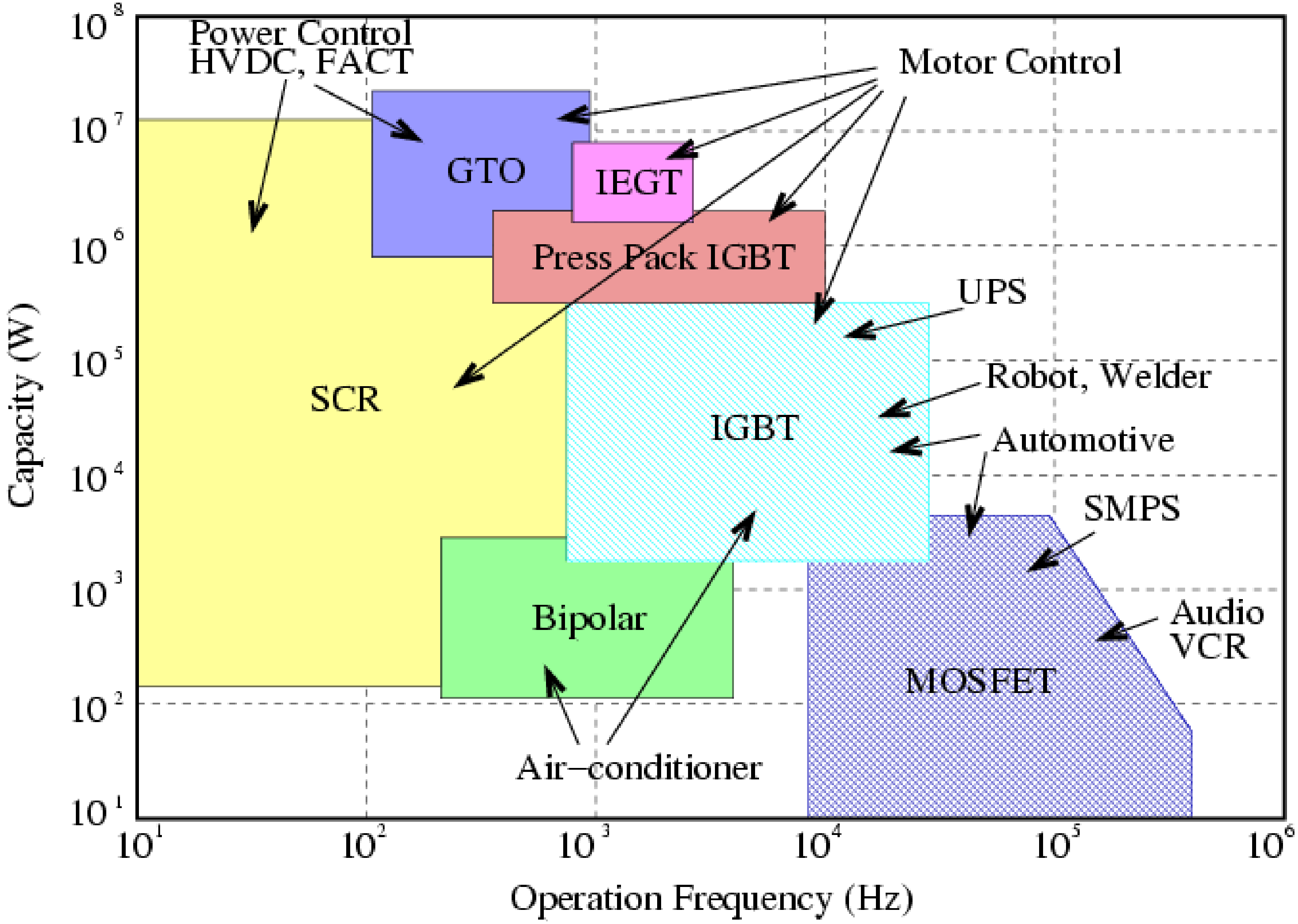


Proposed power flow architecture: Prior Art

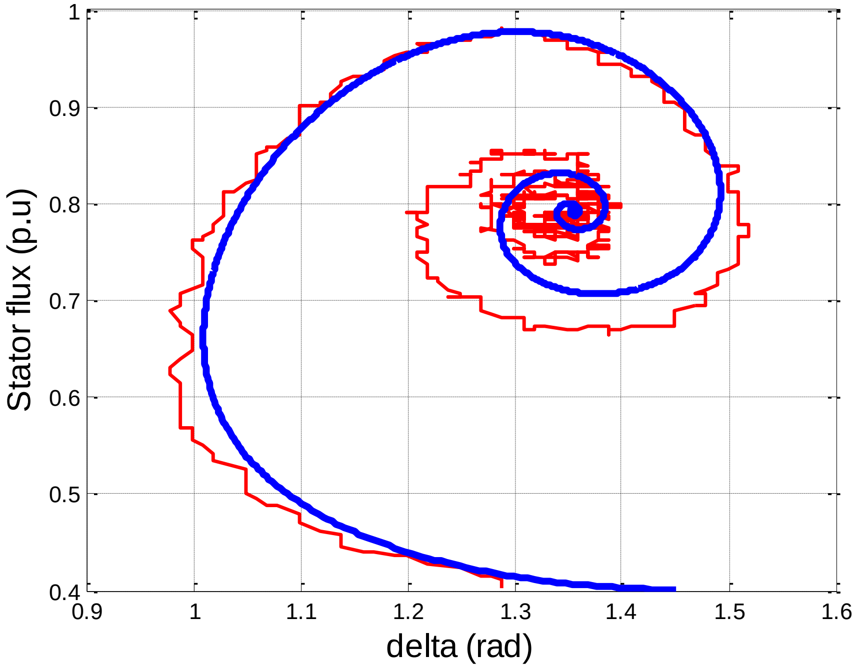


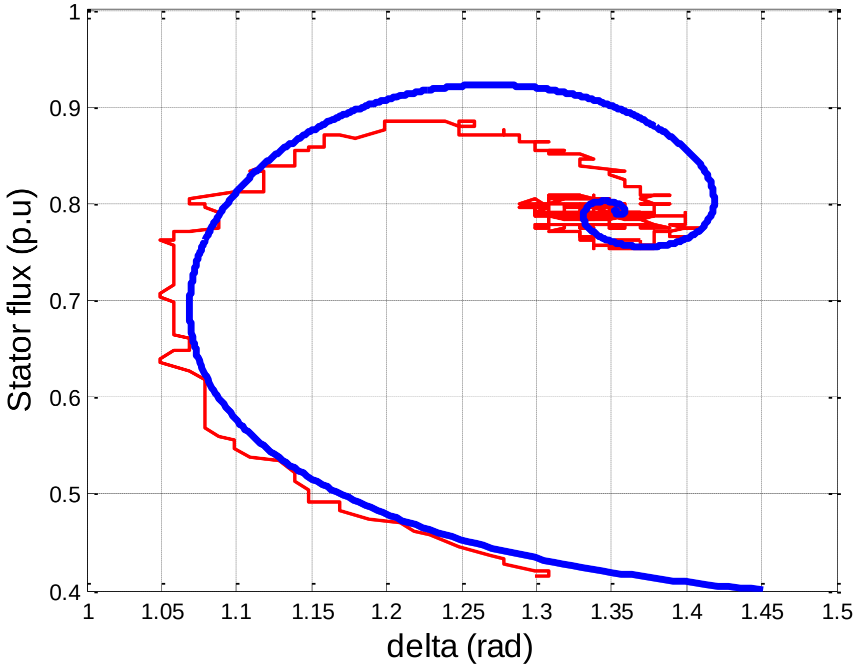
Morel, 1998

Power Electronic Devices

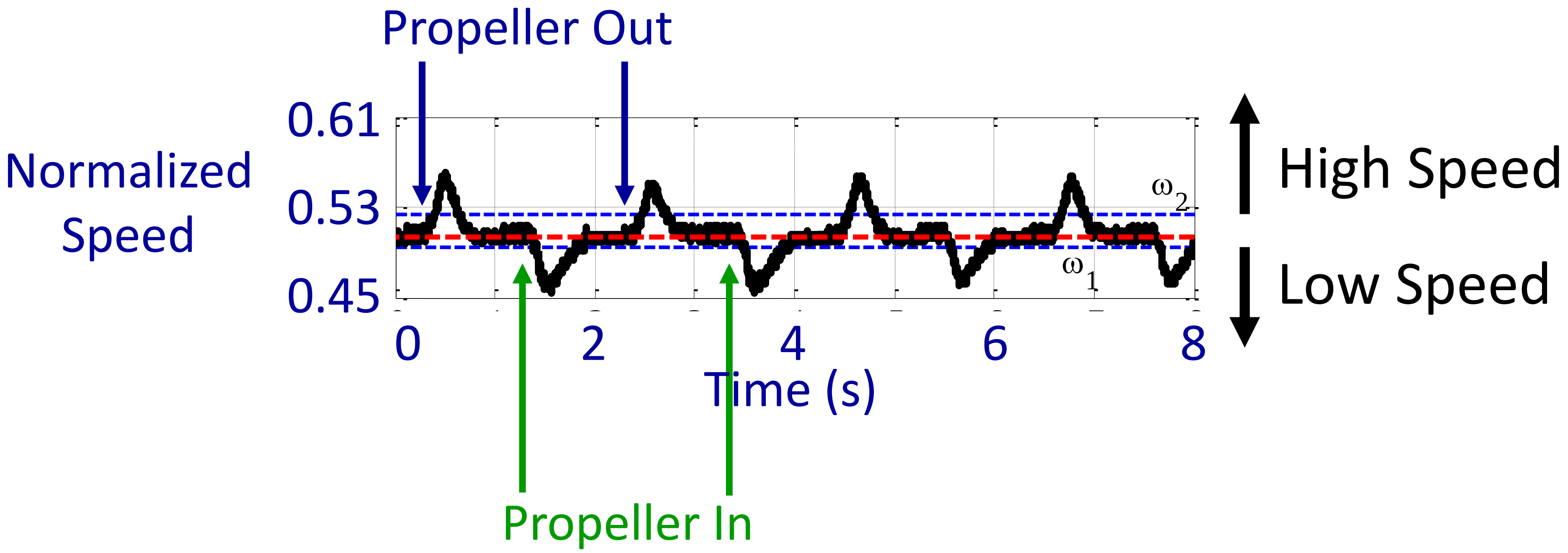


Experimental results: Stator flux transition

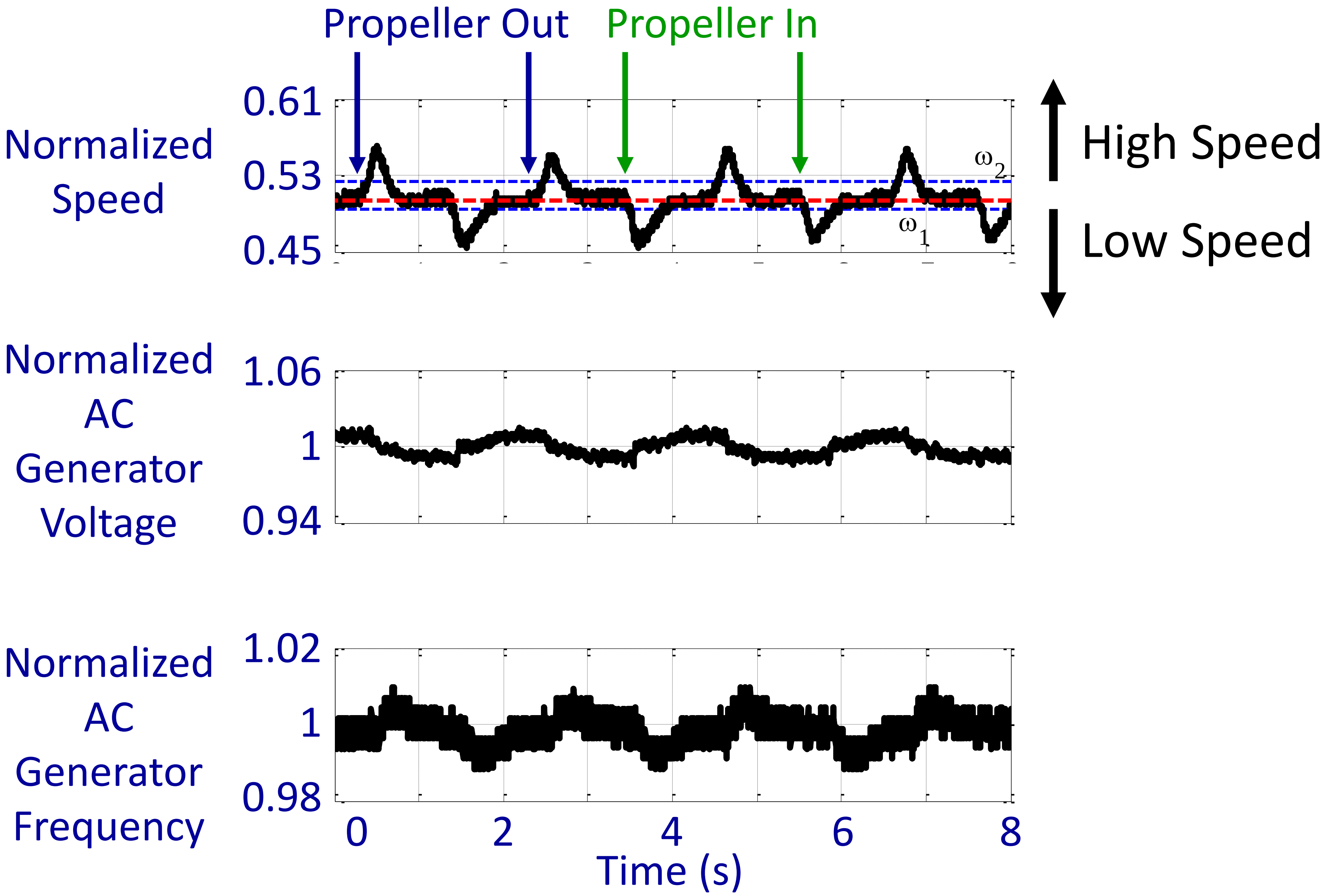




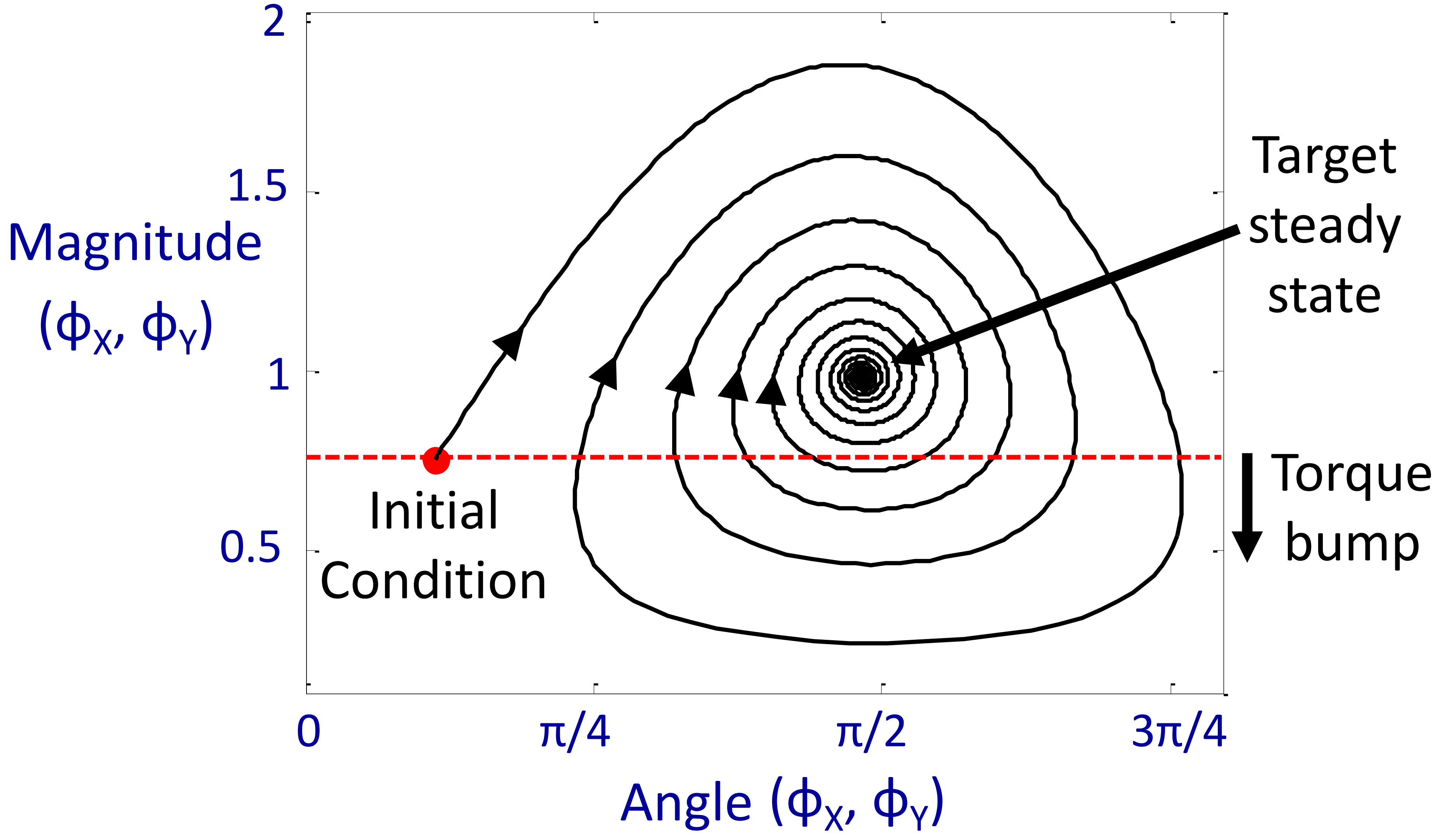
Severe Test: Mimics a ship in a turbulent weather



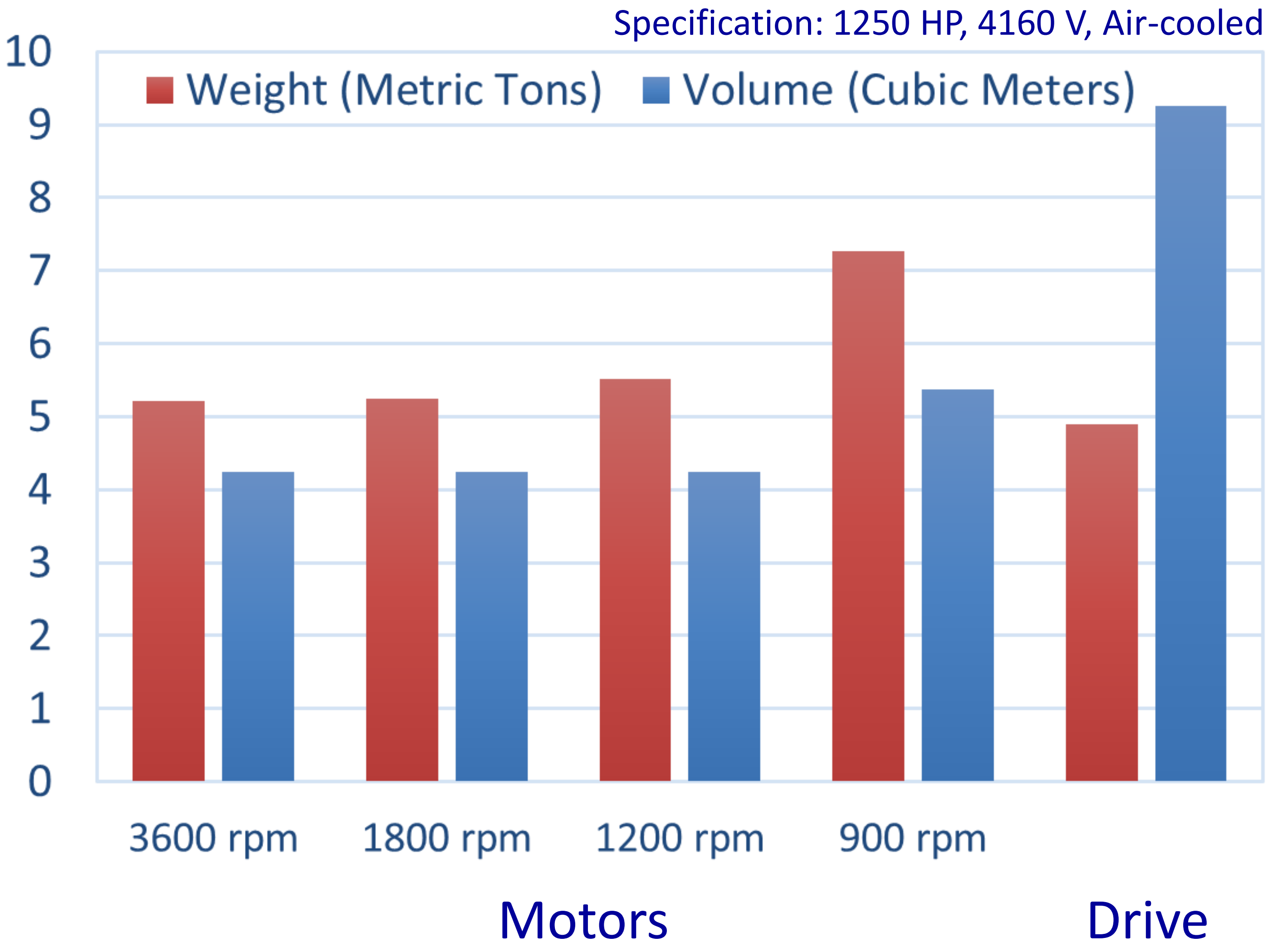
Stable AC generator under severe mode swinging



Transition trajectory causes massive power swing at the grid and torque bump at the shaft



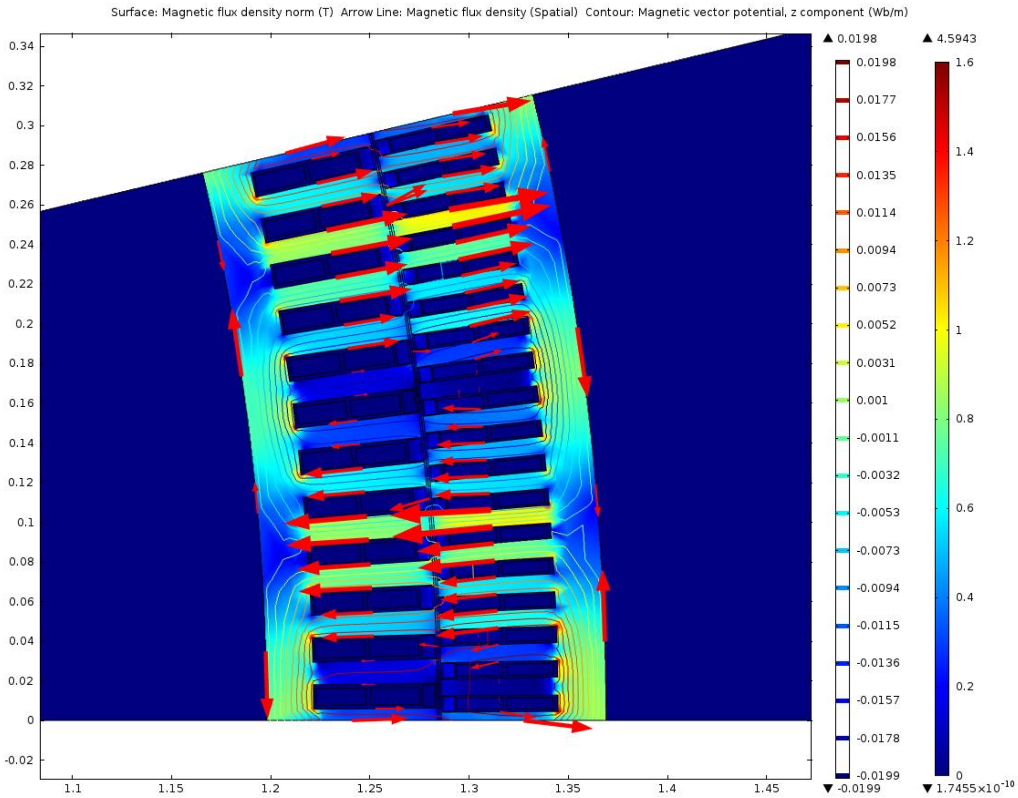
Sizing comparison: High-power motors and variable speed drive



Medium voltage High Efficiency Induction Motors, TECO Westinghouse price book
ABB ACS1000 Industrial Drive

Machine design: 30 MW, 200 rpm, 4160 V, 60 Hz

Parameter	Value
No. of pole	54
Stator rated current	2775 A
Rotor-to-stator turns ratio	2
Air gap flux density	0.75 T
Stator and rotor volume current densities	6.5 A/mm^2
Active length	2.55 m
Stator outside diameter	2.75 m
Rotor inside diameter	2.4 m
Rotor magnetizing current	480 A



Rotodrive: Induction/grid connected mode

a, b: Mechanical Switch

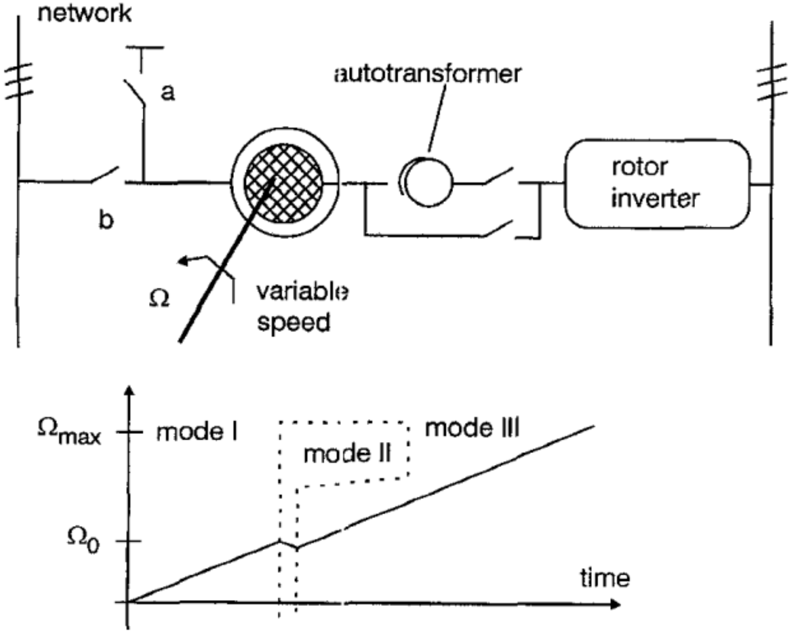


Fig. 1 *Principle of Rotodrive and operating modes*

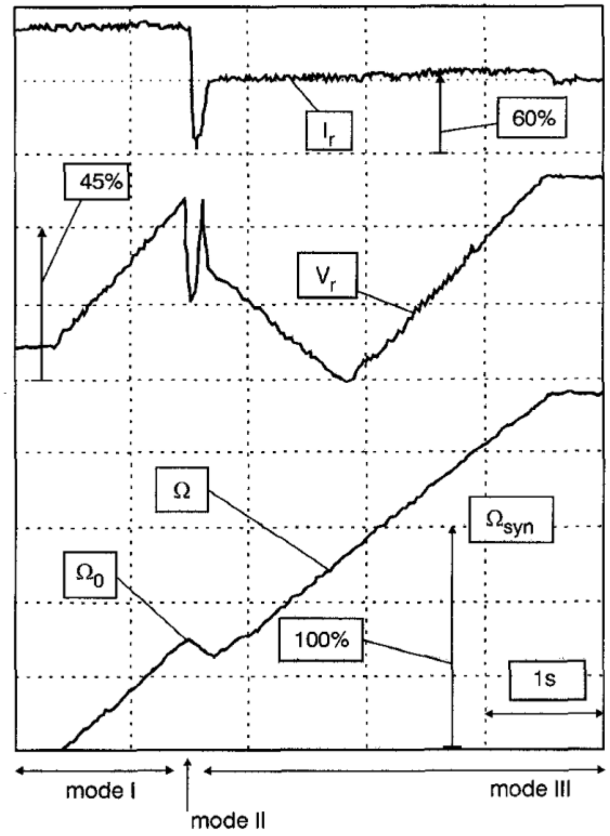


Fig. 2 *Experimental rotor RMS voltage and current against speed, constant torque*

L. Morel IAS Transaction, Jul 1998

Used as discrete operation regimes

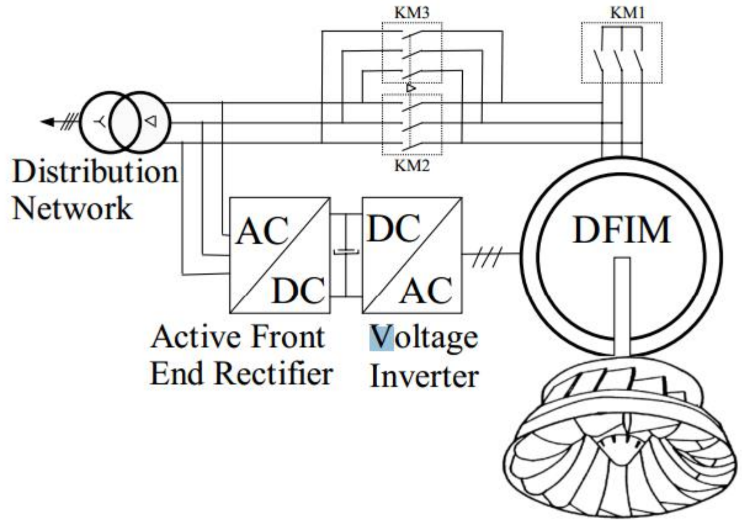


Fig.2. DFIM electric configuration

Hydro-electric power station

François BONNET, ECPE, Sept 2007

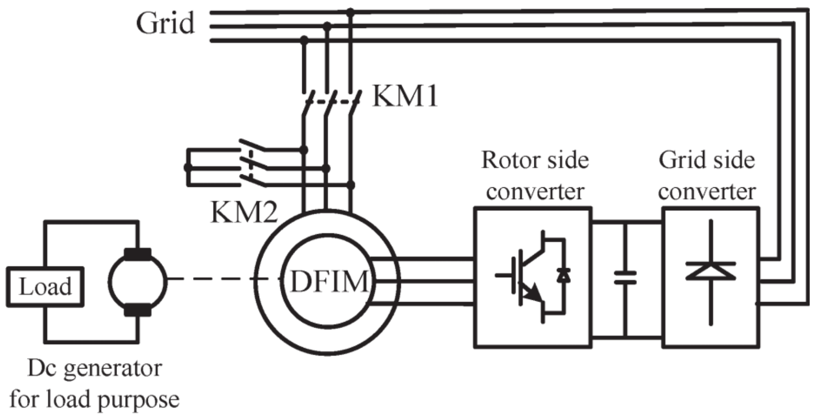


Fig. 1. Configuration of a DFIM system.

Starting method for drives

Xibo Yuan, IAS Transaction, June 2011

Ship Propulsion: Synchronous/grid connected mode

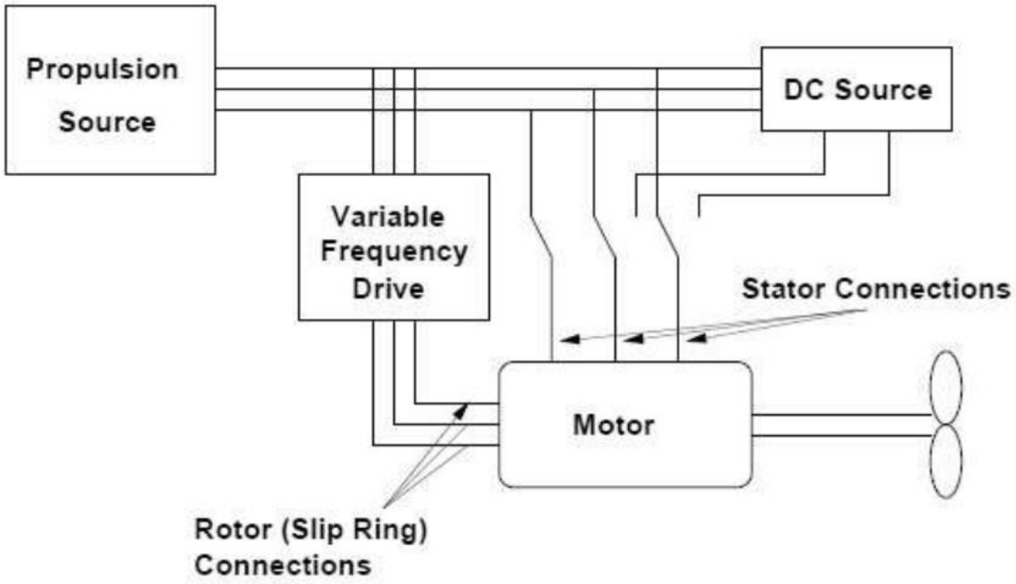


Figure 5: Doubly-fed machine (DFM) for propulsion

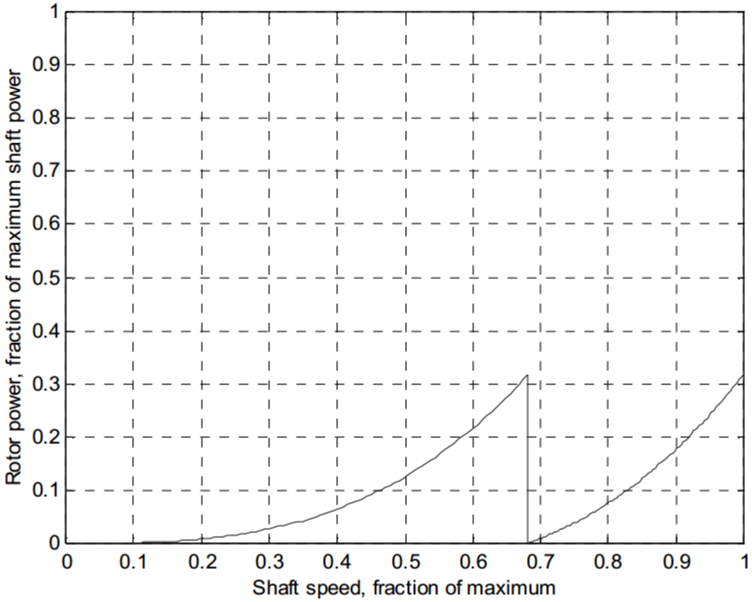
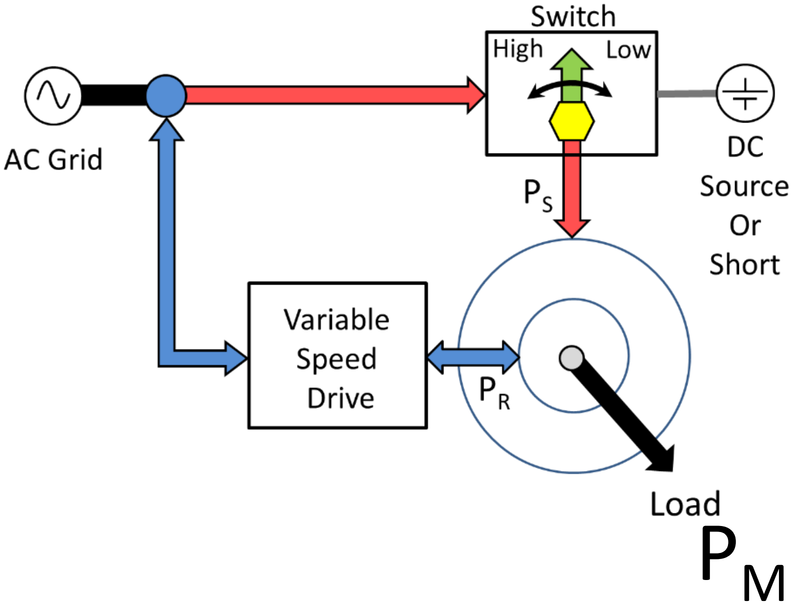
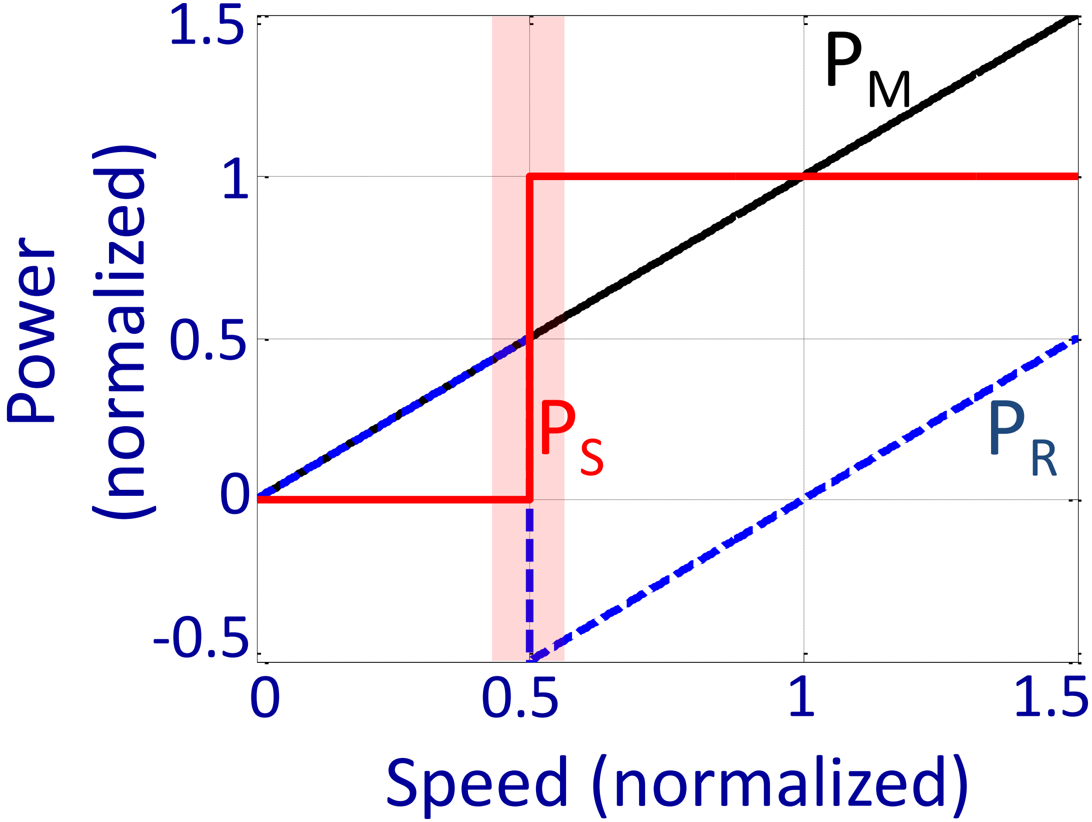


Figure 6: Normalized DFM rotor power – unity on the vertical and horizontal axes correspond to maximum power P_o and speed Ω_o.

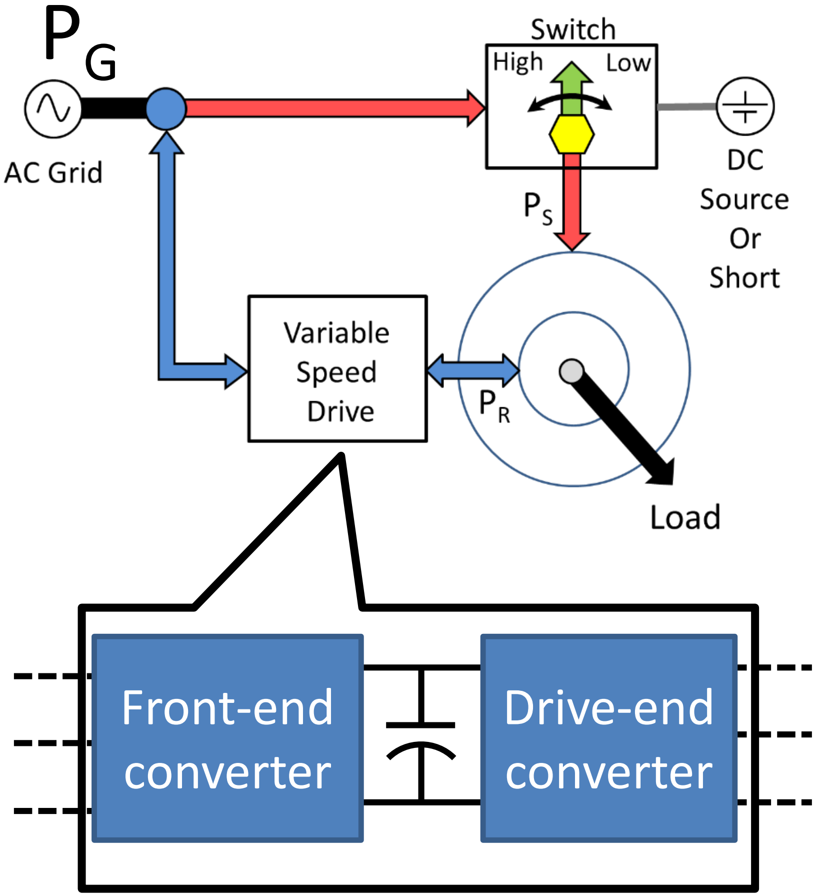
Steven Leeb & James Kirtley et al., Naval Eng. Journal, June 2010

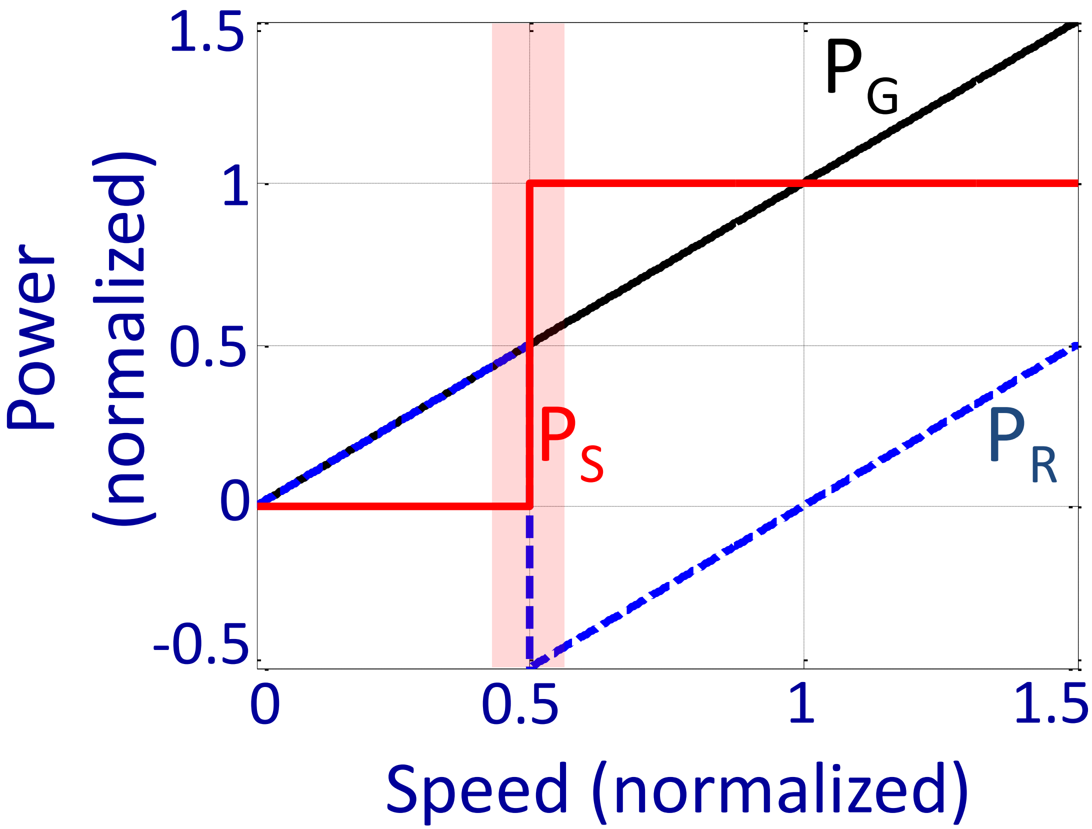
Seamless grid interaction to ensure stability of the ac grid





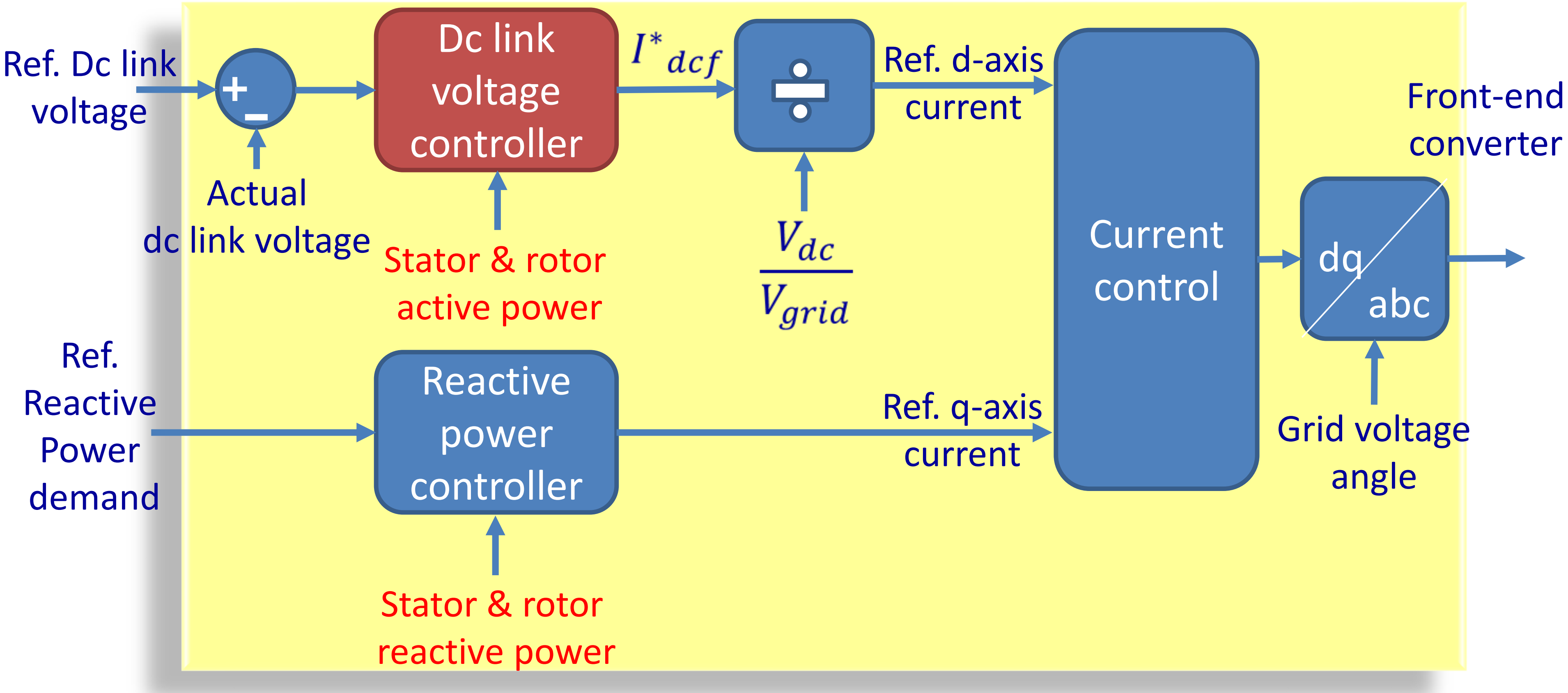
Seamless grid interaction to ensure stability of the ac grid





Solution: No intermittent energy storage in the variable speed drive

Coordinated Front-end converter control



Ref. Dc link voltage

+

–

Actual dc link voltage

Dc link voltage controller

Stator & rotor active power

I^*_{dcf}

÷

$\frac{V_{dc}}{V_{grid}}$

Ref. d-axis current

Ref. Reactive Power demand

Reactive power controller

Stator & rotor reactive power

Ref. q-axis current

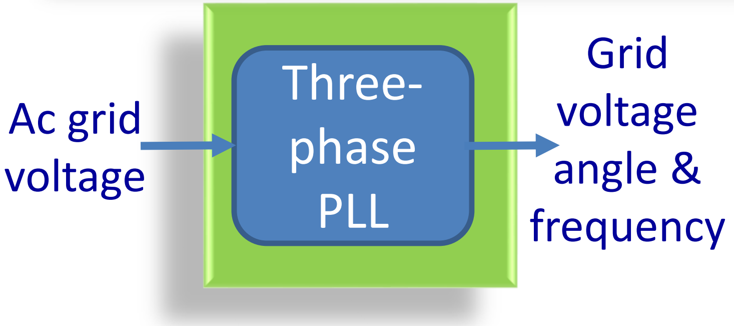
Current control

dq

abc

Grid voltage angle

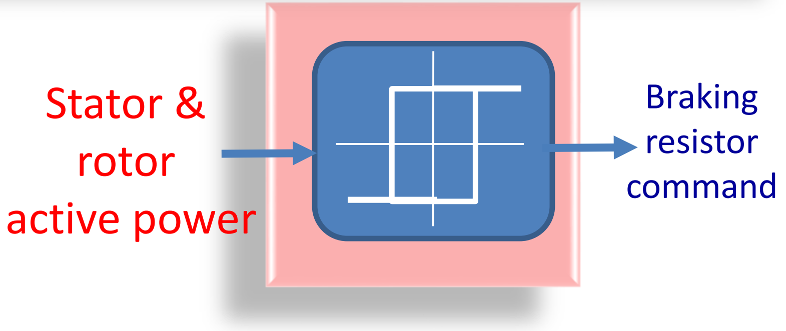
Front-end converter



Ac grid voltage

Three-phase PLL

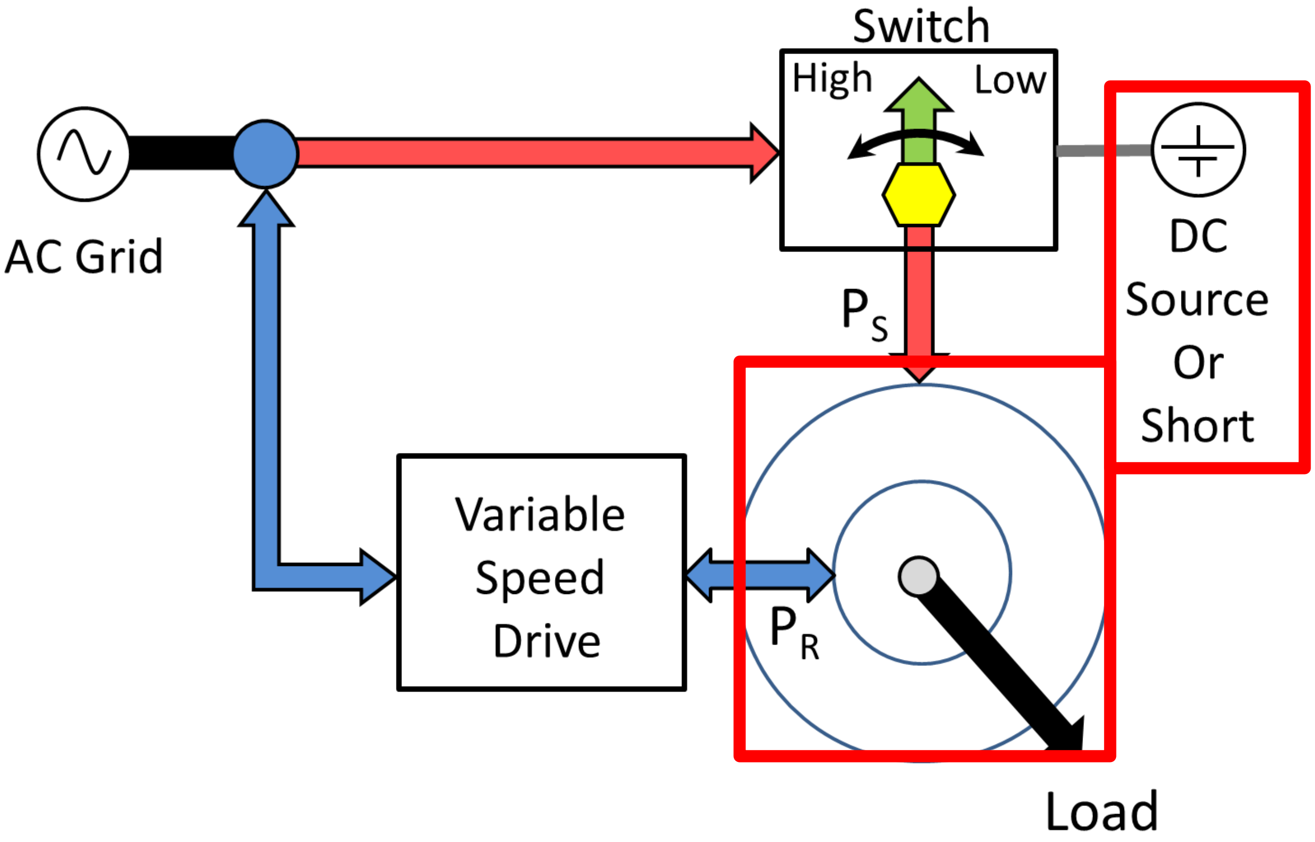
Grid voltage angle & frequency



Stator & rotor active power

Braking resistor command

Contributions



- Drive design
- Switch realization
- Seamless control
- Grid interaction
- **Drive topology comparison**
- **DFM design considerations**