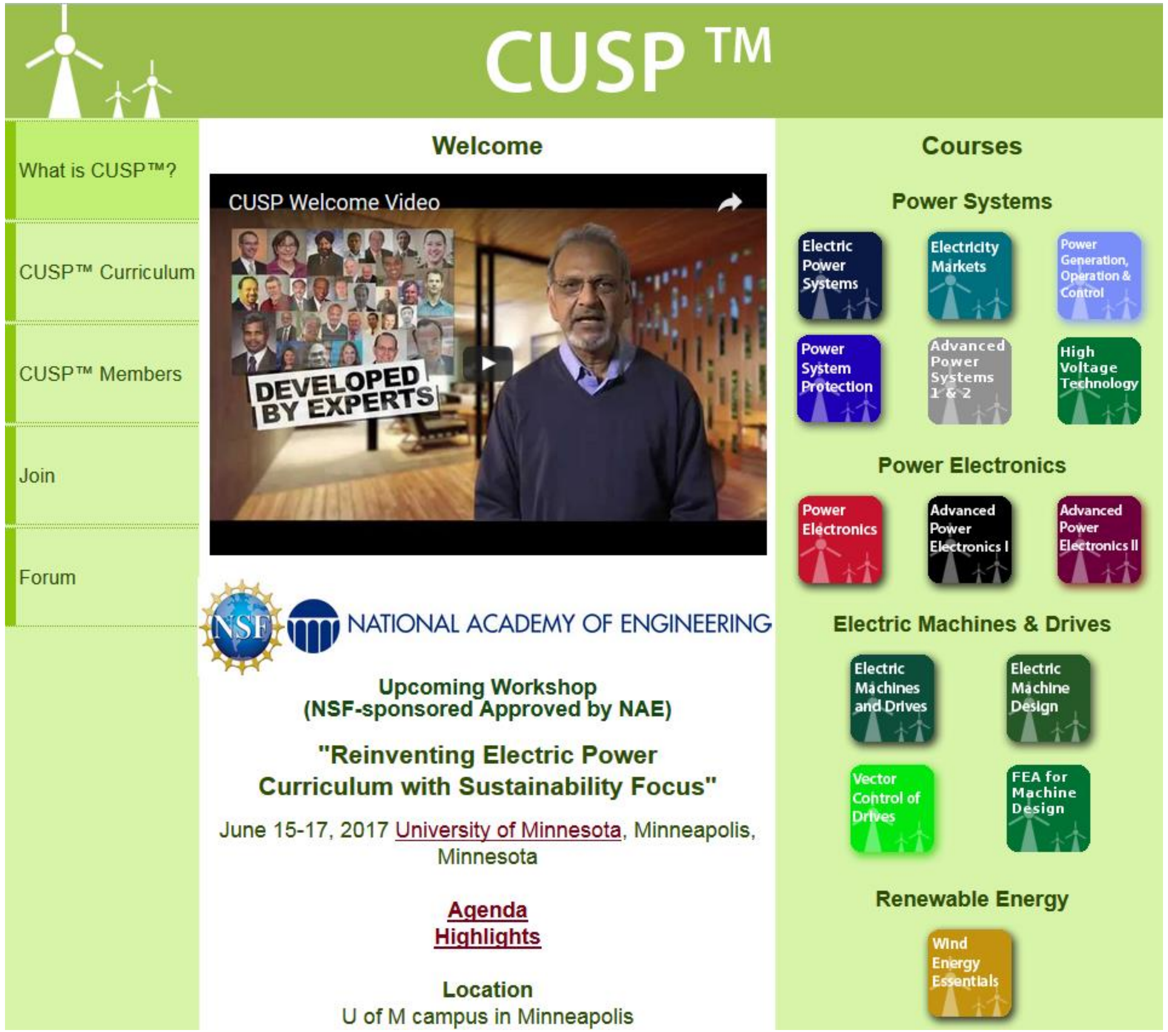
A New Paradigm for Online Education and Research in "Power" Worldwide

Using ONR-funded Low-cost Rapid Real-time Platform

University of Minnesota

CUSP™

Consortium of Universities for Sustainable Power (CUSP)

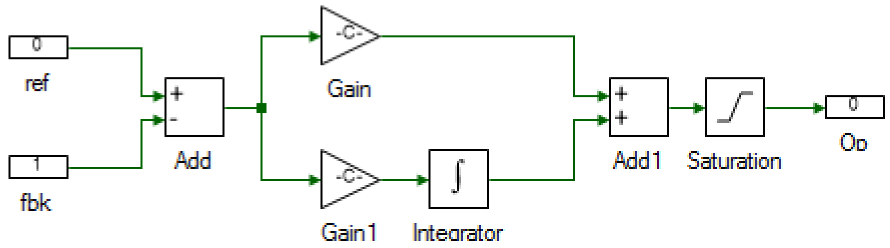


235 U.S. Universities as members (over 450 faculty)

Increasing course adoption

- Cost of laboratory infrastructure major impediment
- Software such as MATLAB are essential but inaccessible
  1. Costs around $4,500 for educational purpose
  2. Upwards of $21,000 for commercial use
  3. Unaffordable to community colleges, universities in developing countries and startups
- Real-time prototyping hardware such as dSpace are equally expensive and not best suited for power electronics

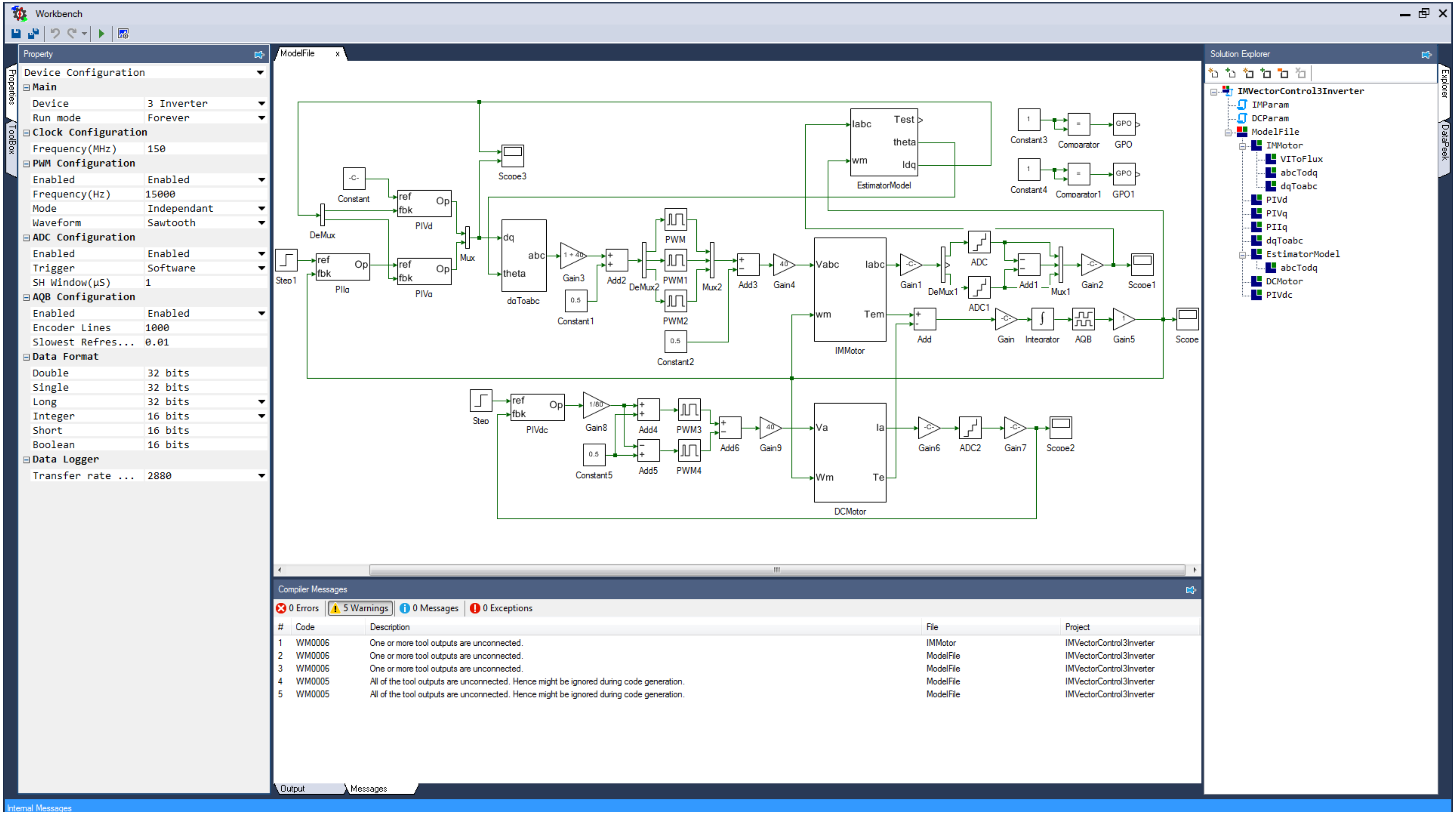
Sciamble Workbench



- Numerical simulation software.
- Model based drag and drop.
- Advanced coding environment.
- Supports matrix operations.

```
Public kpi As Native Double ! current loop proportional gain
Public kii As Native Double ! current loop integral gain

! Parameter initalization function
Public Function Init()
    ! local variables, just for the purpose of computation and
    Local λrdq0 As Native Double = √(λrd0² + λrq0²)
    Local λsdq0 As Native Double = √(λsd0² + λsq0²)
    Local θIsdq As Native Double = Math:ATan2(Isq0, Isd0)
    Local θVsdq As Native Double = Math:ATan2(Vsq0, Vsd0)
    Local Isdq0 As Native Double = √(Isq0² + Isd0²)
    Local Vsdq0 As Native Double = √(Vsq0² + Vsd0²)
```

Workbench – Model based numerical simulation and real-time code generation

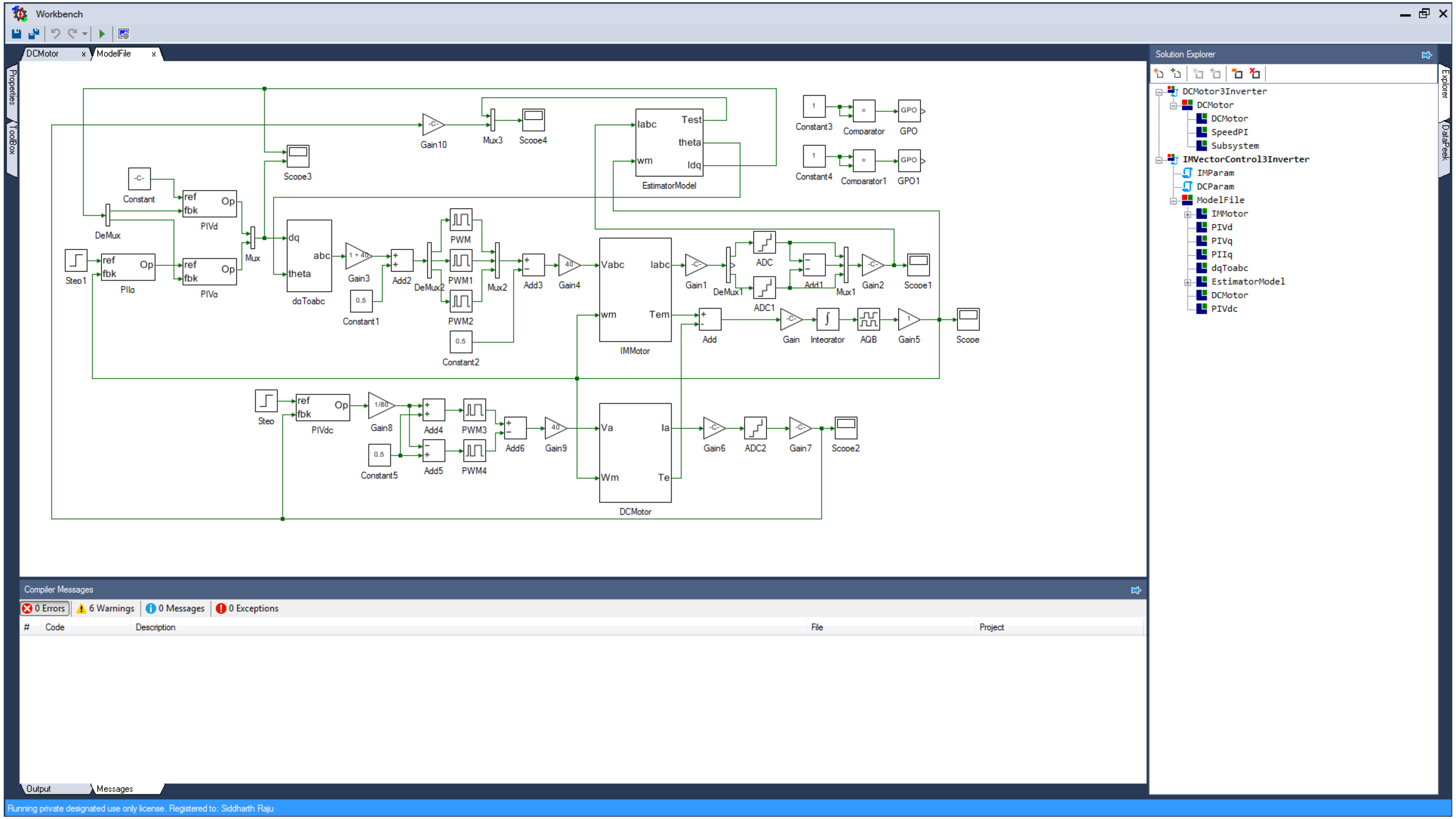


Workbench Features – Script Editor

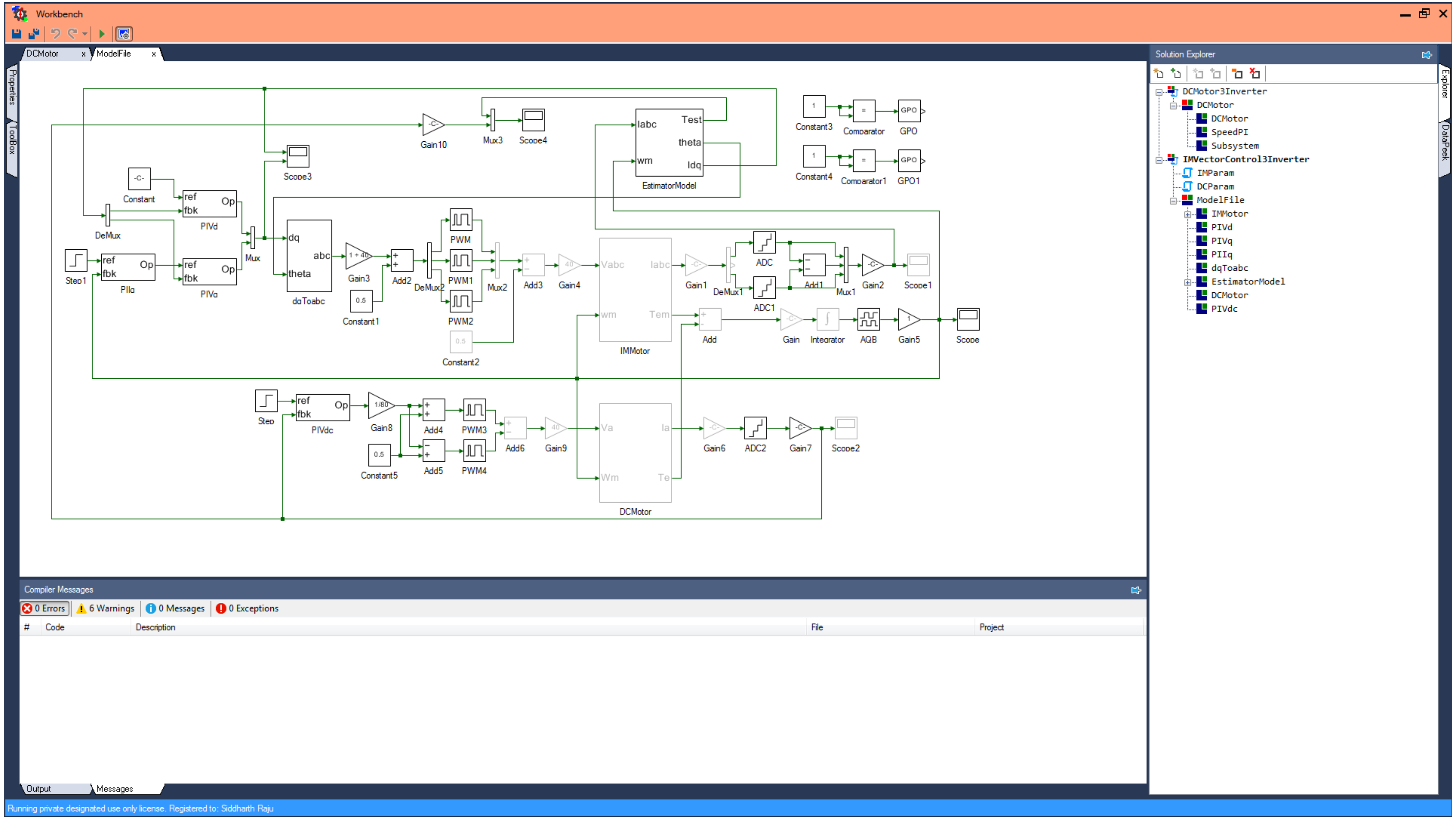
```
IMParam  x
Public Module IMParam ! Induction motor parameter
   Public sqrt2by3 As Native Double = √2 / √3

   Public Rs As Native Double = 1.79 ! Stator Resistance
   Public Rr As Native Double = 1.05 ! Rotor Resistance
   Public Lls As Native Double = 6.2E-3 ! Stator leakage inductance
   Public Llr As Native Double = 5.8E-3 ! Rotor leakage inductance
   Public Lm As Native Double = 30E-3 ! Mutual Inductance
   Public Jeq As Native Double = 0.00015 ! Rotor Inertia
   Public p As Native Double = 4 ! Number of poles


   Public Ls As Native Double = Lm + Lls ! Stator Inductance
   Public Lr As Native Double = Lm + Llr ! Rotor Inductance

   Public f As Native Double = 50 ! Rated frequency
   Public VLLrms As Native Double = 14.7 ! Rated line to line voltage
   Public s As Native Double = 0.01 ! Rated slip

   Public ωsyn As Native Double = 2 * π * f ! Synchonous speed at rated frequency
   Public ωm As Native Double = (1 - s) * ωsyn ! Speed at rated slip
   Public Va As Native Double = VLLrms * sqrt2by3 ! Phase voltage peak
   Public Vs0 As Native Double = 1.5 * Va

   Public θVs0 As Native Double = 0
   Public θda0 As Native Double = 0

   ! Initial stator dq Voltages
   Public Vsd0 As Native Double = sqrt2by3 * Math:Abs(Vs0) * Math:Cos(θVs0 - θda0)
   Public Vsq0 As Native Double = sqrt2by3 * Math:Abs(Vs0) * Math:Sin(θVs0 - θda0)

   Public τr As Native Double = Lr / Rr
   Public A As Double = [[Rs, -ωsyn * Ls, 0, -ωsyn * Lm], [ωsyn * Ls, Rs, ωsyn * Lm, 0], [0, -s * ωsyn * Lm, Rr, -s * ωs
   Public Ainv As Double = 1 / A
   ! Initial dq stator and rotor voltages (as row matrix)
   Public Vdq0 As Double = [[Vsd0], [Vsq0], [0], [0]]
   Public Idq0 As Double = Ainv * Vdq0 ! Initial dq stator and rotor currents
   ! Retriving individual current from row matrix
   Public Isd0 As Native Double = Idq0(|I|1)
```

- Language designed from scratch to support dynamic compilation.
- Extremely easy to use.
- Inbuilt matrix operation support.

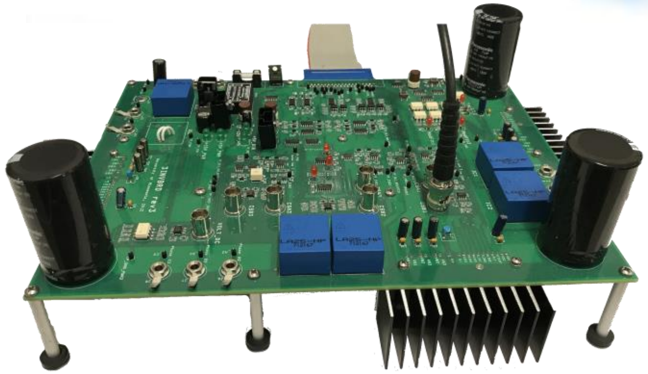
Workbench Features – Real-time Code Gen



Workbench Features – Real-time Code Gen



Previously used system in electric drives lab (Spring 2017)

Academic	Non-academic	
Cost: > $7,000	Cost: > $20,000	MATLAB
Cost: ≈ $6,000	Cost: ≈ $20,000	
Cost: ≈ $7,500	Cost: ≈ $7,500	
Total: > $20,500	Total: > $47,500	

Currently used system in electric drives lab (Spring 2018)

Academic/Non-academic

Cost: FREE!

Workbench

Cost: $3,300

Total: $3,300

Electric Drives Lab

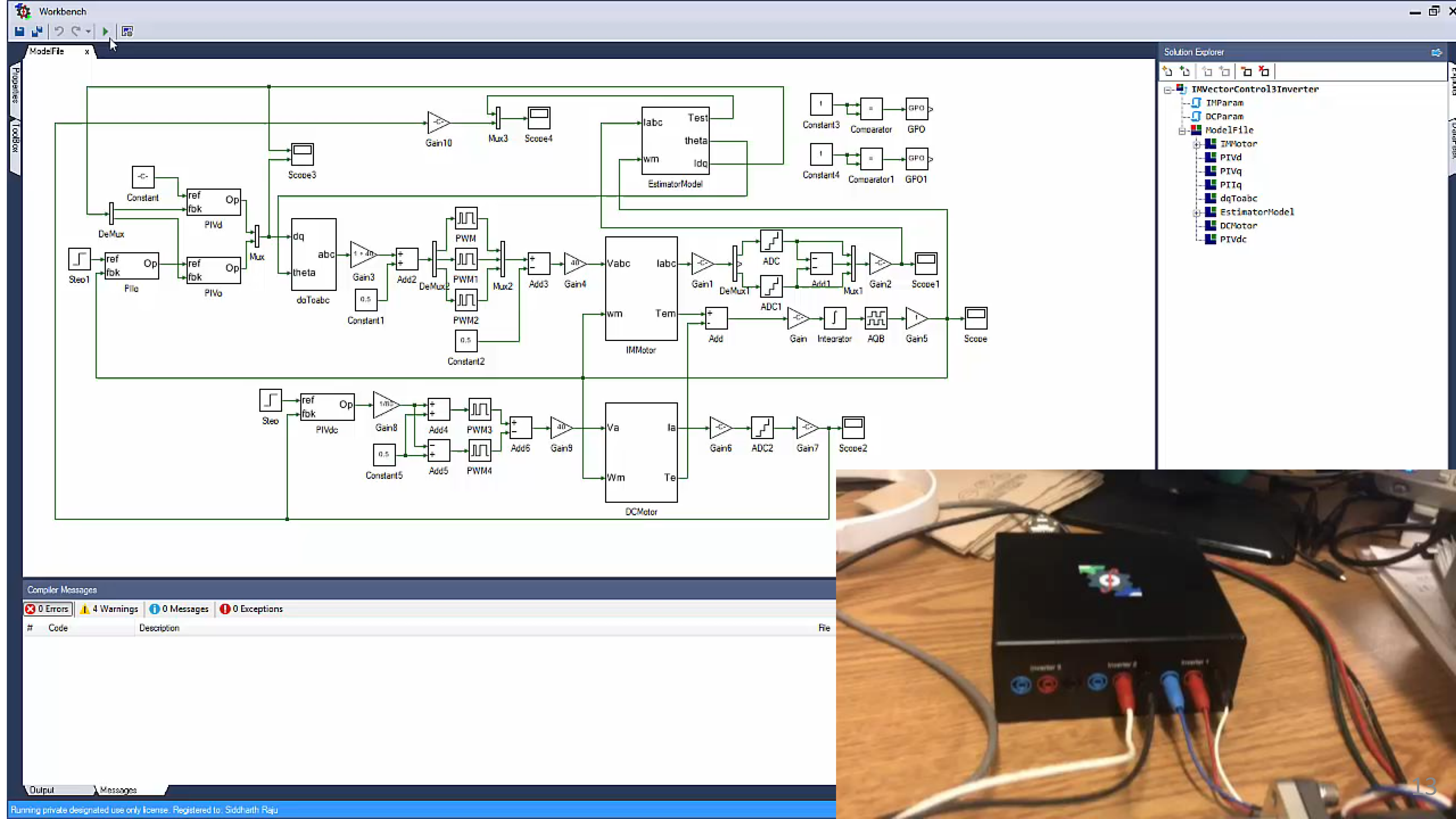
List of Experiments

Basic drives lab (undergraduate level)

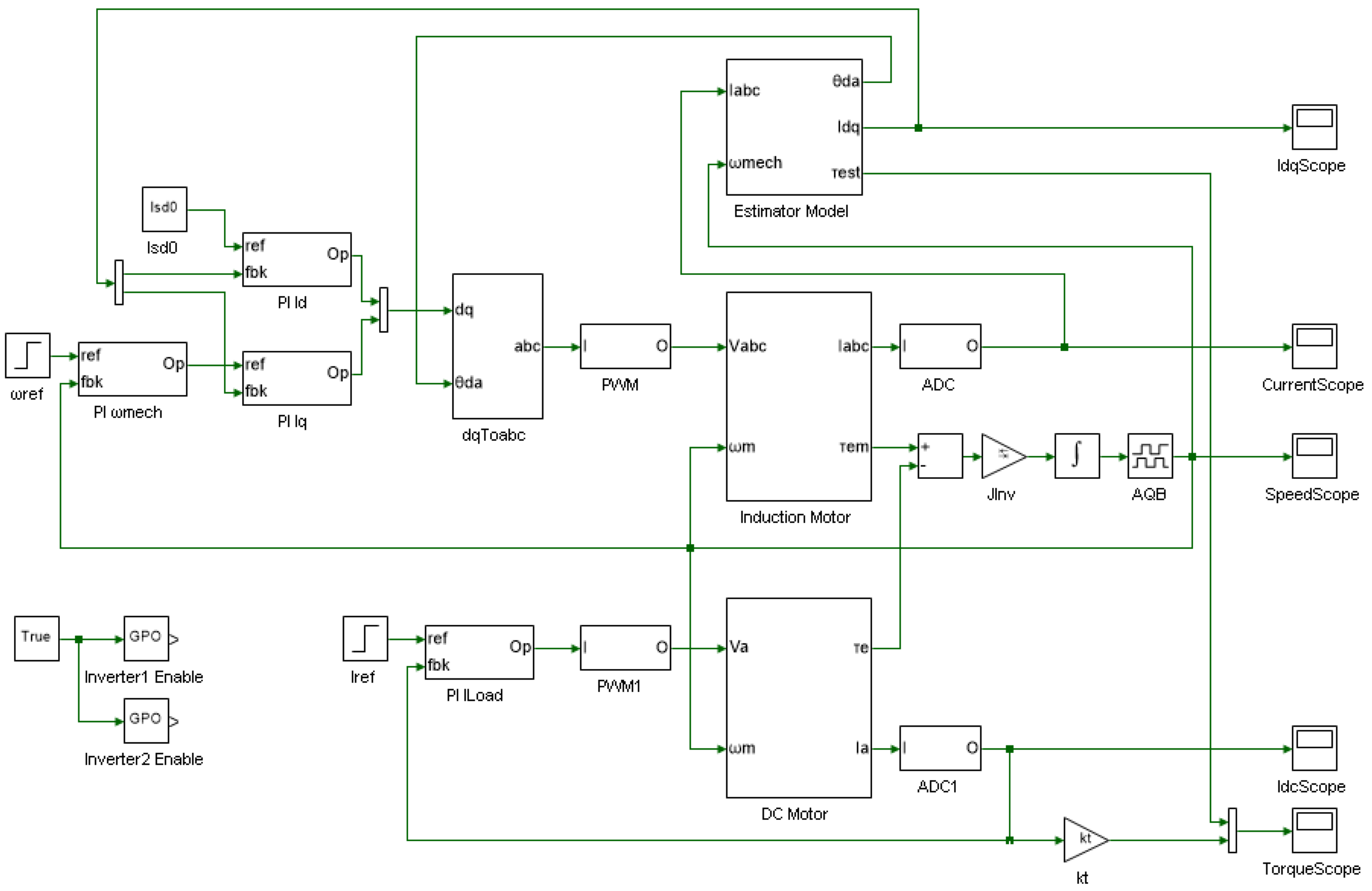
1. Switched-mode DC-DC converter
2. Characterization of DC motor
3. DC motor closed-loop speed control
4. Four-quadrant operation of DC motor
5. Torque-load angle characteristics and speed control of PMAC motor
6. Determination of Induction motor parameters
7. Torque-speed characteristics and speed control of Induction motor

Advanced drives lab (graduate level)

1. Characterization of Induction motor
2. Induction motor V/f control
3. Vector control of induction motor
4. Encoder-less vector control of induction motor
5. Direct torque control of induction motor
6. Space vector Pulse width modulation of two level three-phase inverter
7. Vector control of surface PMAC motor


Workbench
ModelFile
Solution Explorer
IMVectorControl3Inverter
IMParam
DCParam
ModelFile
IMMotor
PIVd
PIVq
PIIq
dqToabc
EstimatorModel
DCMotor
PIVdc
Gain10
Mux3
Scope4
Scope3
Iabc
wm
Test
theta
Idq
EstimatorModel
Constant3
Comparator
GPO
Constant4
Comparator1
GPO1
Constant
ref
fbk
Op
PIVd
DeMux
Step1
PIIq
PIVq
Mux
dq
theta
abc
dqToabc
Gain3
Constant1
Add2
DeMux2
PWM
PWM1
PWM2
Constant2
Mux2
Add3
Gain4
Vabc
Iabc
wm
Tem
IMMotor
Gain1
DeMux1
ADC
ADC1
Add1
Mux1
Gain2
Scope1
Add
Gain
Integrator
AQB
Gain5
Scope
Step
PIVdc
Gain8
Constant5
Add4
Add5
PWM3
PWM4
Add6
Gain9
Va
Wm
Ia
Te
DCMotor
Gain6
ADC2
Gain7
Scope2
Compiler Messages
0 Errors
4 Warnings
0 Messages
0 Exceptions
#
Code
Description
File
Output
Messages
Running private designated use only license. Registered to: Siddharth Raju

Workbench Induction motor vector control



Workbench Induction motor vector control

IMParam x

```
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   Public Vs0 As Native Double = 1.5 * Va

   Public θVs0 As Native Double = 0
   Public θda0 As Native Double = 0

   ! Initial stator dq Voltages
   Public Vsd0 As Native Double = sqrt2by3 * Math:Abs(Vs0) * Math:Cos(θVs0 - θda0)
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   Public τr As Native Double = Lr / Rr
   Public A As Double = [[Rs, -ωsyn * Ls, 0, -ωsyn * Lm], [ωsyn * Ls, Rs, ωsyn * Lm, 0], [0, -s * ωsyn * Lm, Rr, -s * ωs
   Public Ainv As Double = 1 / A
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   ! Retriving individual current from row matrix
   Public Isd0 As Native Double = Idq0(|I|1)
```
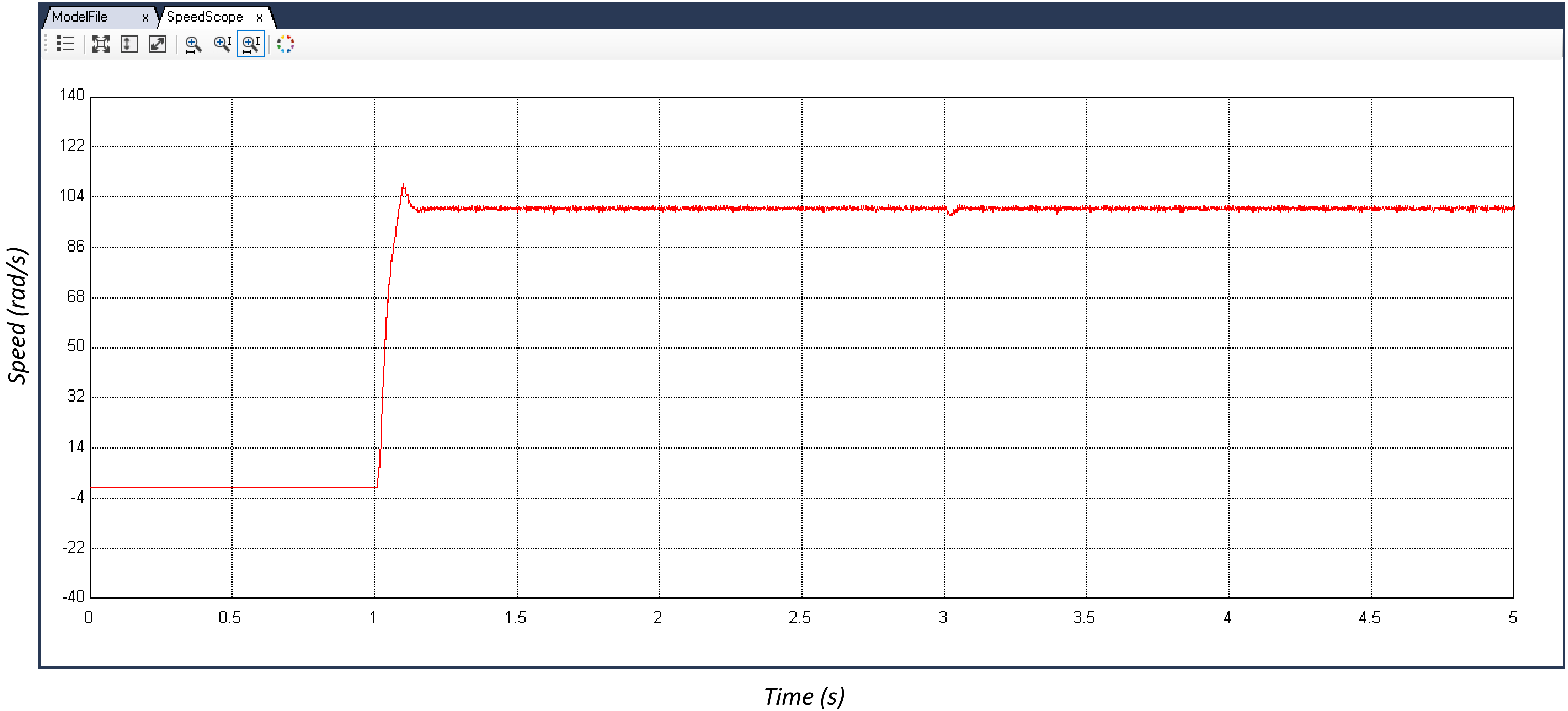
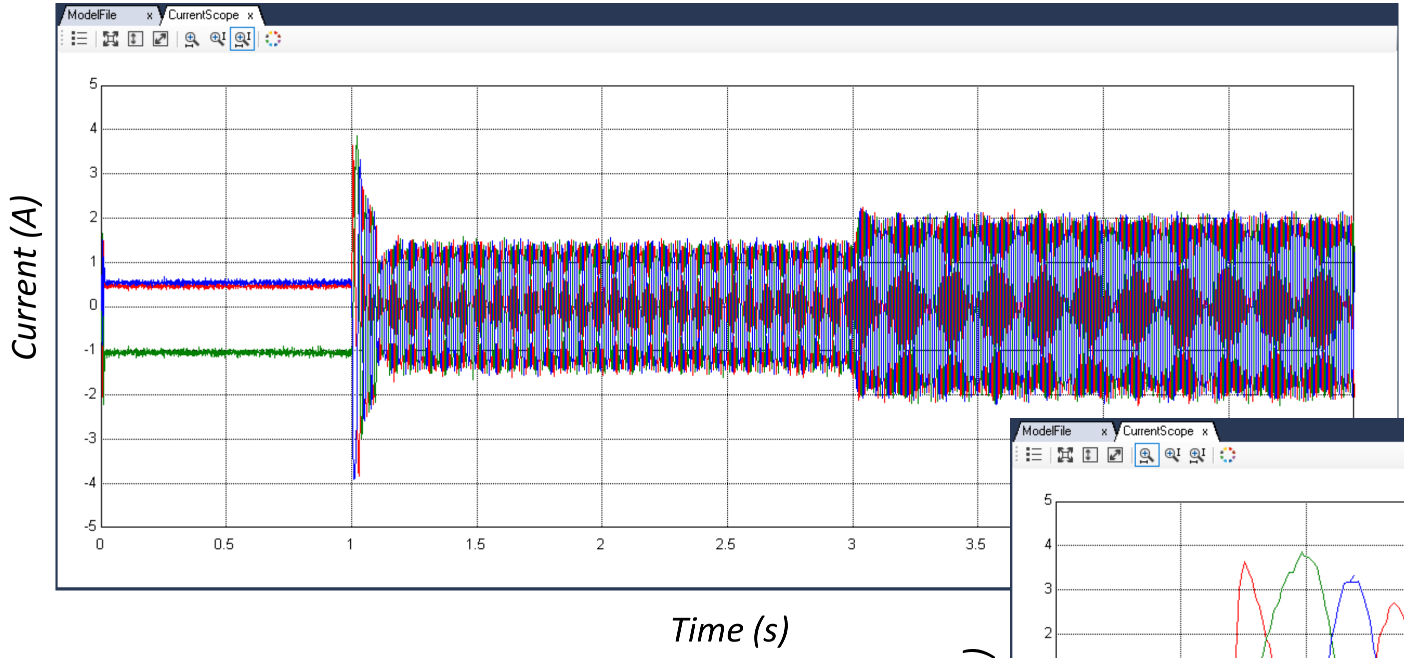

Induction motor real-time vector control results

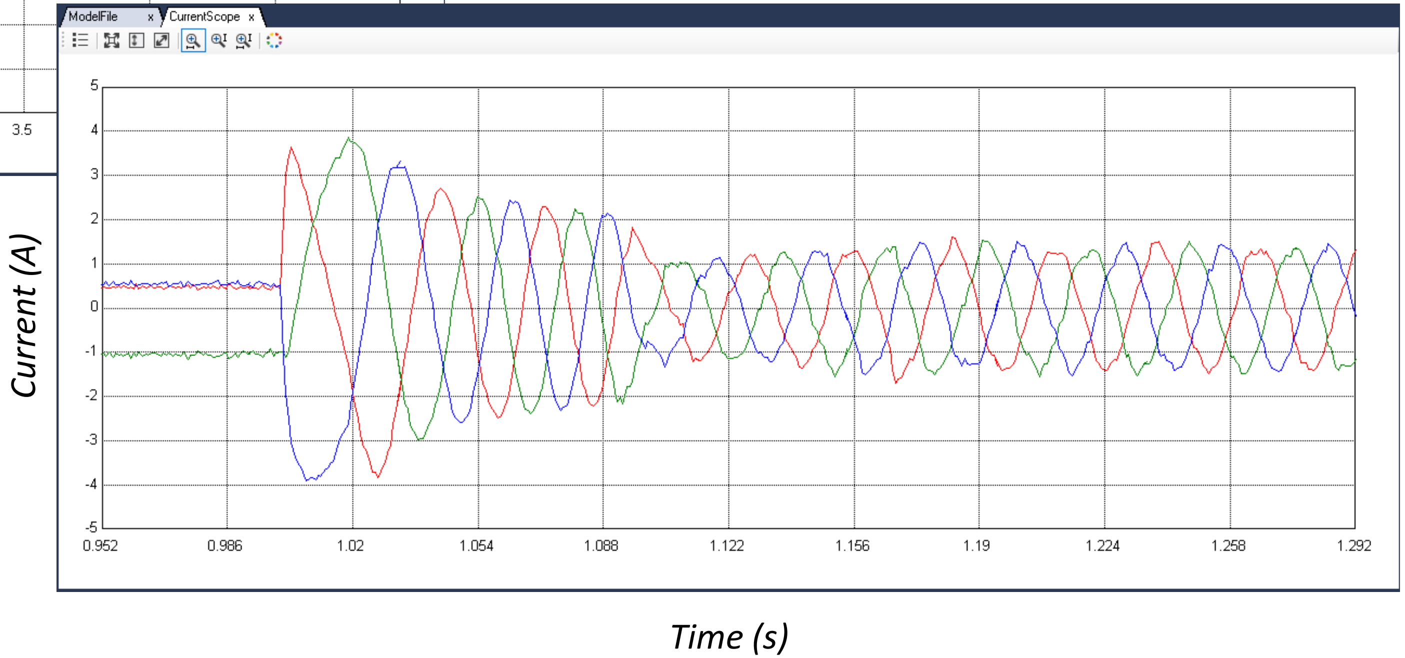


Induction motor real-time vector control results

Induction motor 3ϕ stator current

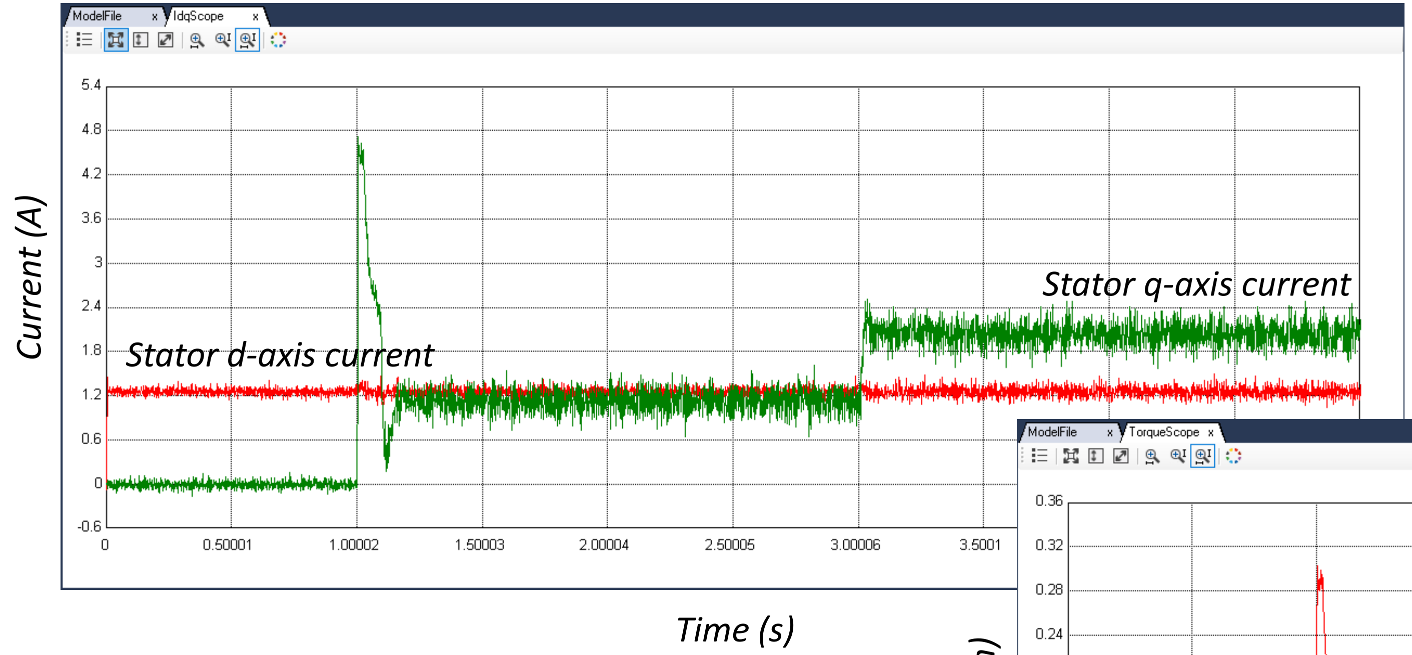


Induction motor 3ϕ stator current (zoomed in)

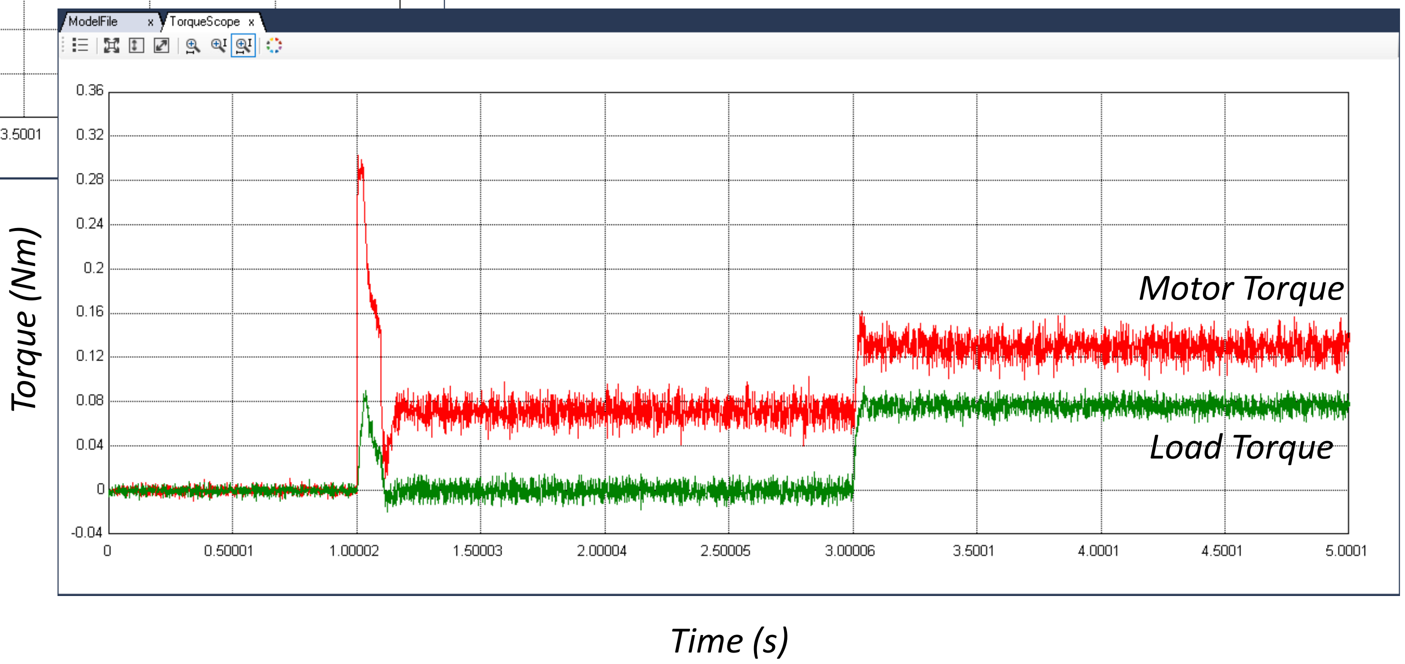


Induction motor real-time vector control results

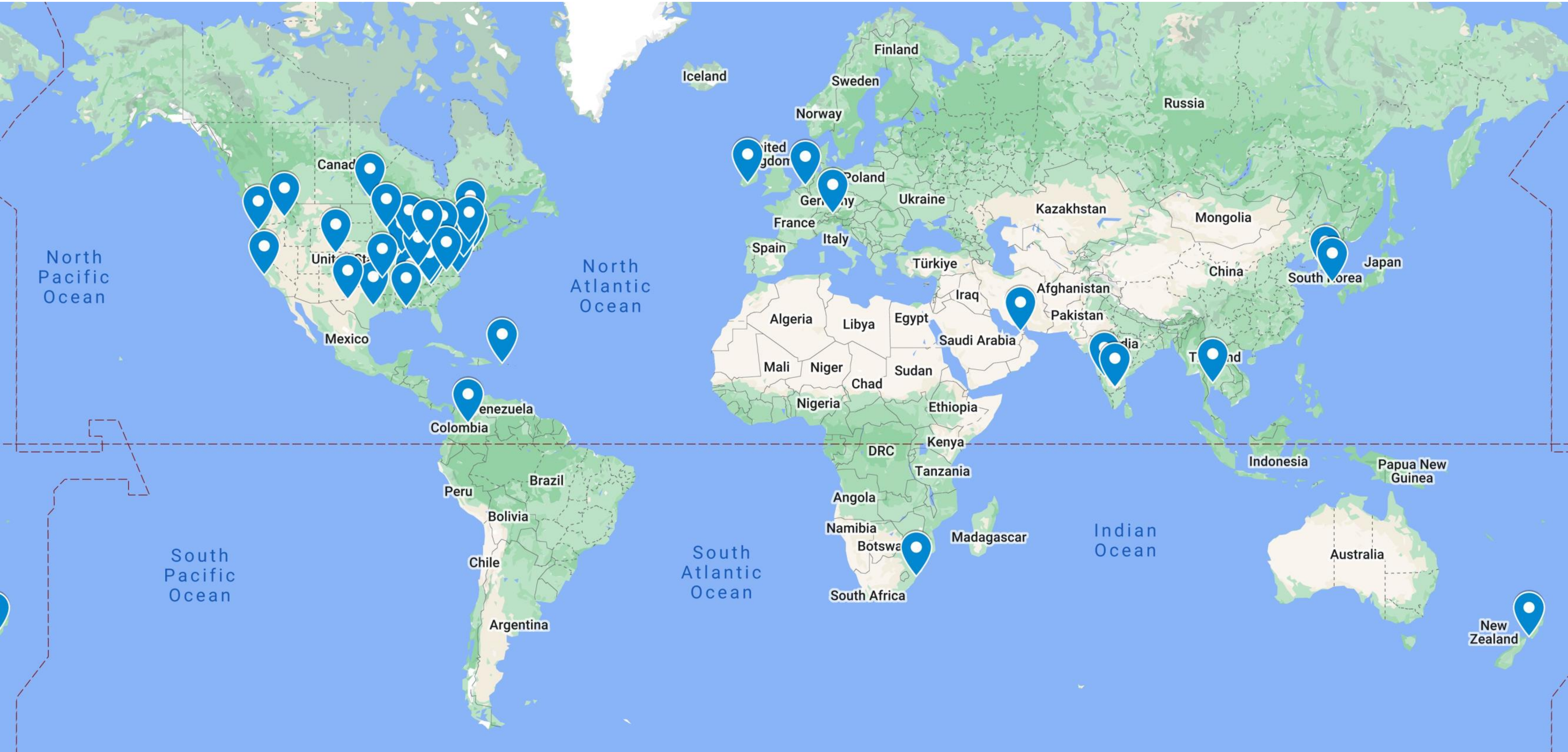
Induction motor stator dq currents



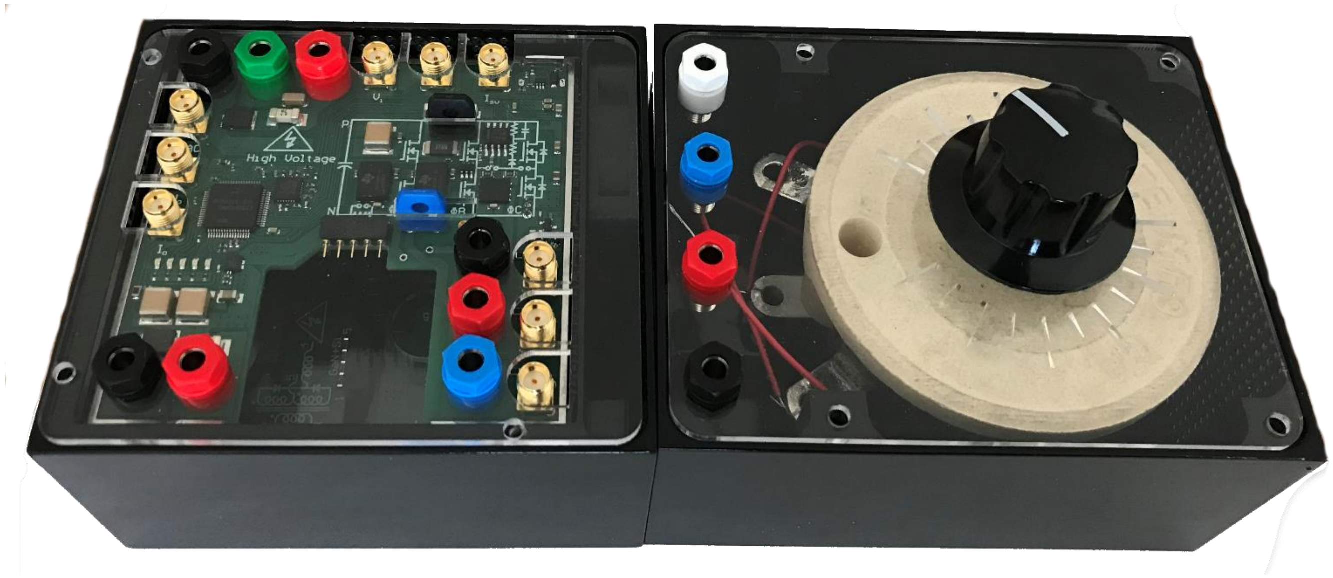
Induction motor torque and load torque



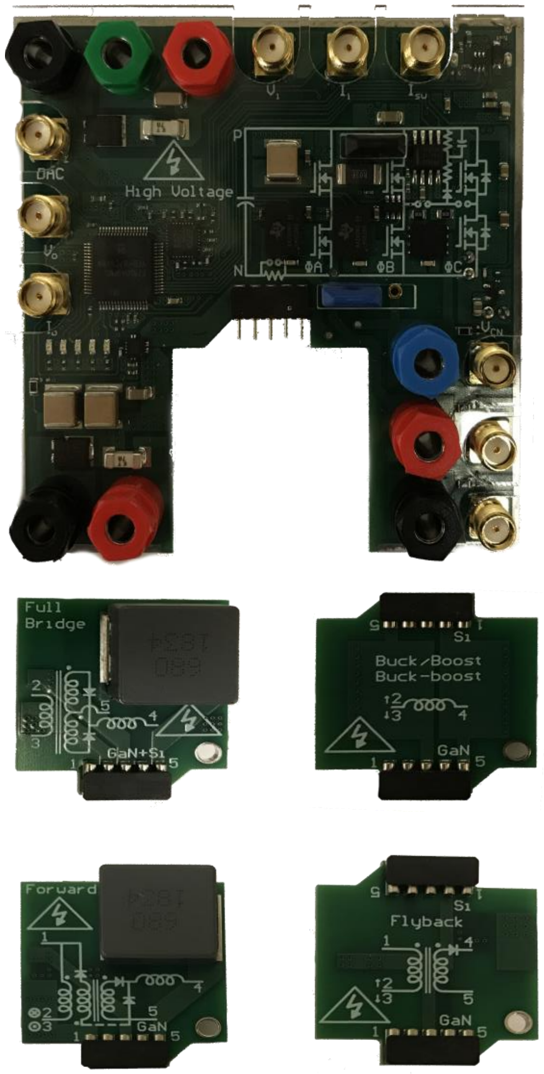
Electric drives lab adoption - Worldwide



WBG based Digitally controlled Power Electronics Lab



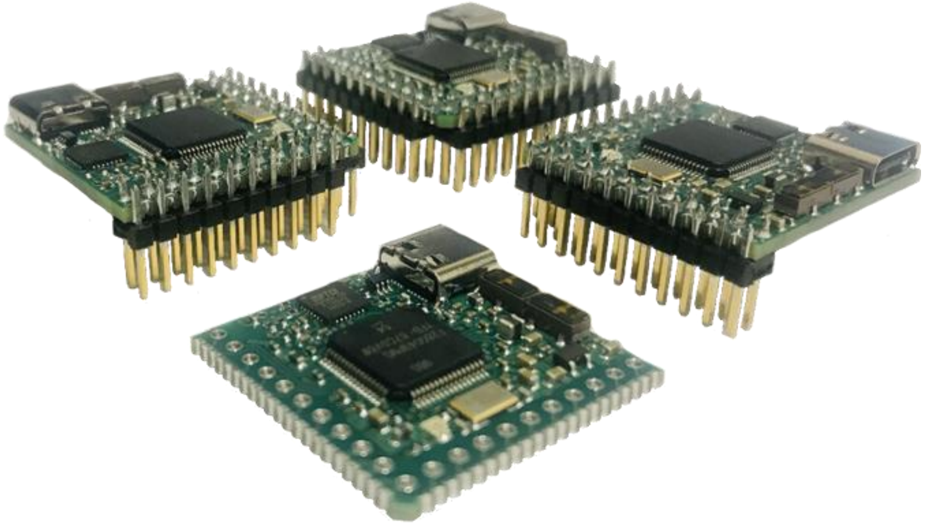
List of Experiments



<u>Power electronics lab (undergraduate level)</u>

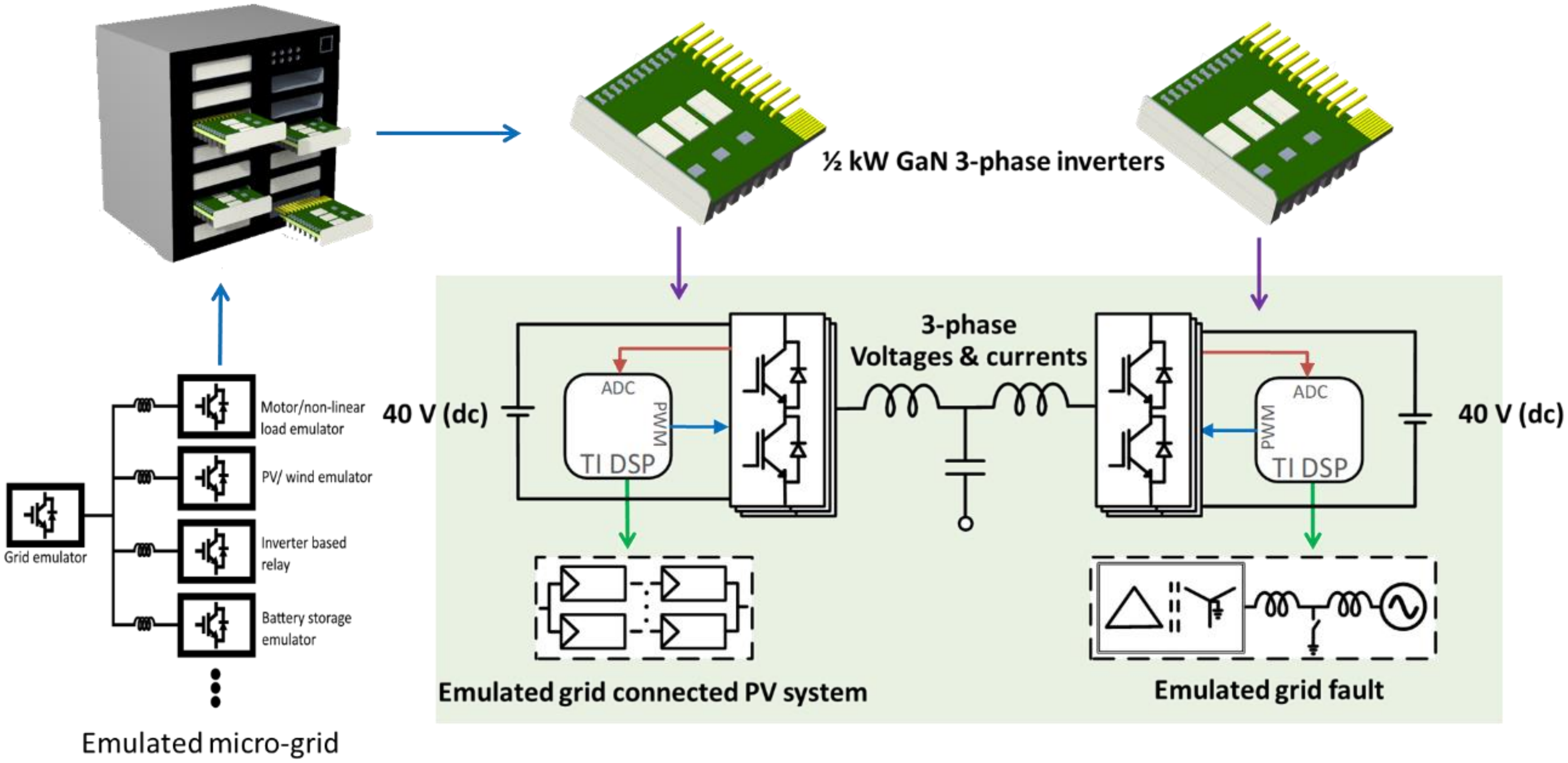
1. Si and GaN power-device characteristics
2. Buck converter
3. Boost converter
4. Buck-boost converter
5. Digital voltage mode control
6. Digital current mode control
7. Flyback converter
8. Forward converter
9. Full-bridge converter
10. Single-phase DC-AC inverter
11. Three-phase DC-AC inverter

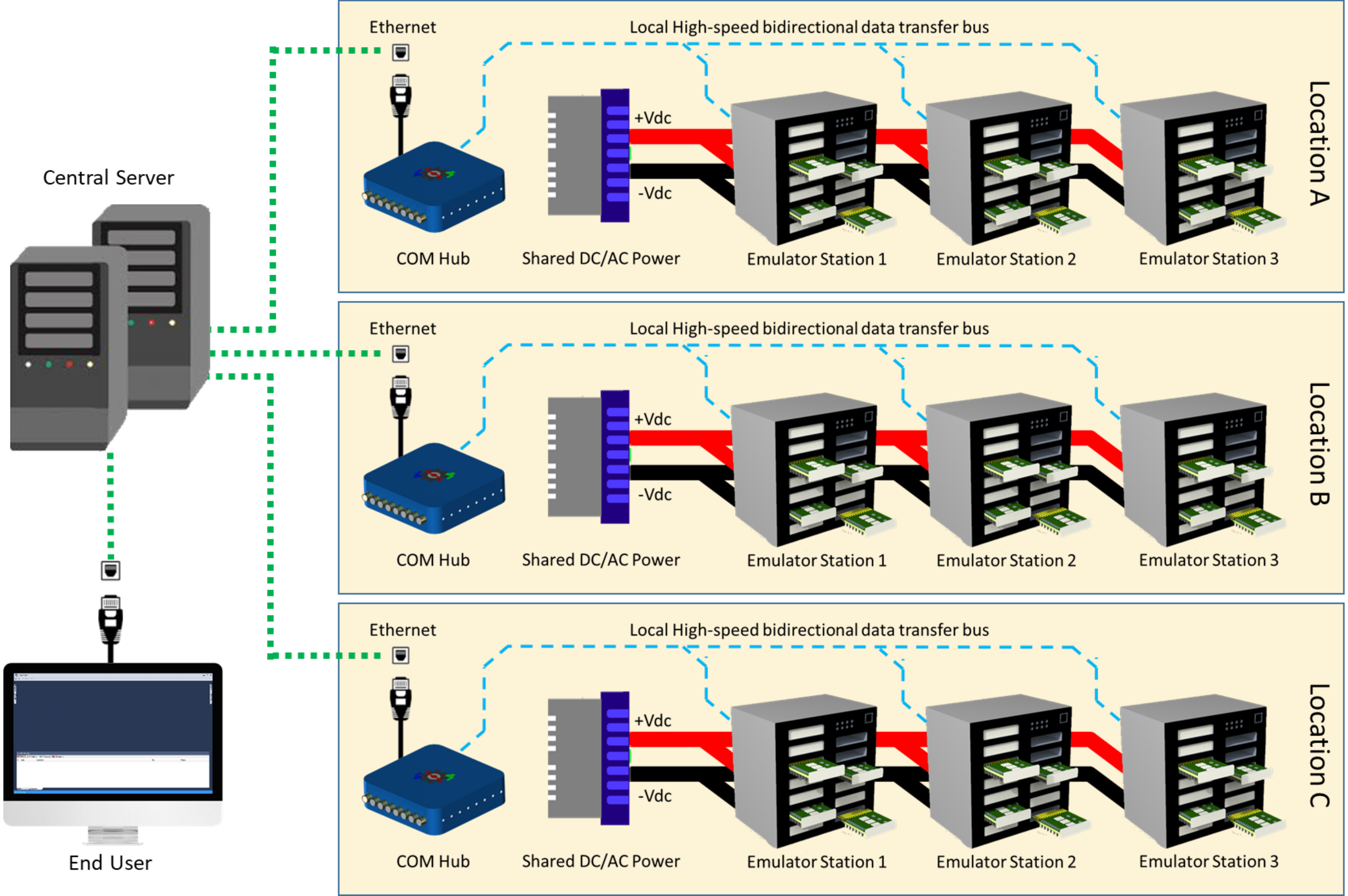
Low-cost general purpose prototyping platform



- Code-free model based design enabled rapid prototyping platform.
- Cost $25 and has similar capability as $9000 dSpace platform.
- Measures 1 x 1 in and can be easily plugged into any real-world control application.
- 100 MHz clock, 16 PWMs, 14 ADCs, 33 GPIOs, 1 SPI/SCI/CAN COM.
- On-board datalogger and programmer that interfaces directly with Workbench.

Emulated Power Systems Lab




Central Server
End User
Ethernet
Local High-speed bidirectional data transfer bus
+Vdc
-Vdc
COM Hub
Shared DC/AC Power
Emulator Station 1
Emulator Station 2
Emulator Station 3
Location A
Ethernet
Local High-speed bidirectional data transfer bus
+Vdc
-Vdc
COM Hub
Shared DC/AC Power
Emulator Station 1
Emulator Station 2
Emulator Station 3
Location B
Ethernet
Local High-speed bidirectional data transfer bus
+Vdc
-Vdc
COM Hub
Shared DC/AC Power
Emulator Station 1
Emulator Station 2
Emulator Station 3
Location C

Acknowledgement

We are greatly indebted for the three grants to the University of Minnesota from the Office of Naval Research (ONR):

a. N00014-22-1-2491 “A Low-Cost Scalable Tabletop Emulator for Shipboard Power System“

b. N00014-19-1-2018 “Developing WBG-Based, Extremely Low-Cost Laboratories for Power Electronics, Motor Drives, and Power System Protection and Relays for National Dissemination”

c. N00014-15-1-2391 “Web-Enabled, Instructor-Taught Online Courses”

These grants allowed the development of the Workbench simulation platform, which is available free-of-cost for educational purposes. These grants also allowed the development of a low-cost hardware laboratory, available from Sciamble Corp (https://sciamble.com) – a University of Minnesota startup.

Thank you