MICROCHIP

Regenerative Braking of BLDC Motors

By

Daniel Torres, Applications Engineer

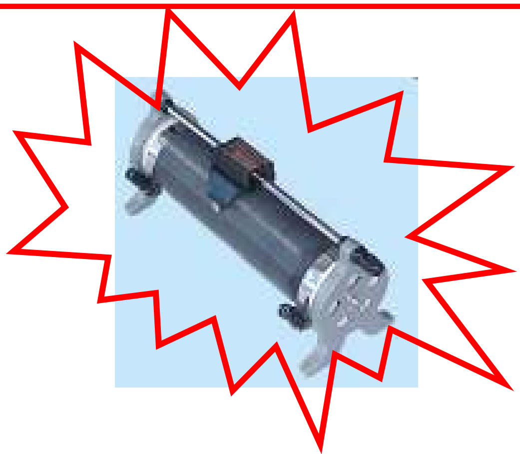
Patrick Heath, Marketing Manager

High-Performance Microcontroller Division

Microchip Technology Inc.

Different electrical braking scheme

Kinetic Energy



Dynamic Braking

OR

Kinetic Energy

Regenerative Braking

Regenerative Brake in BLDC motor

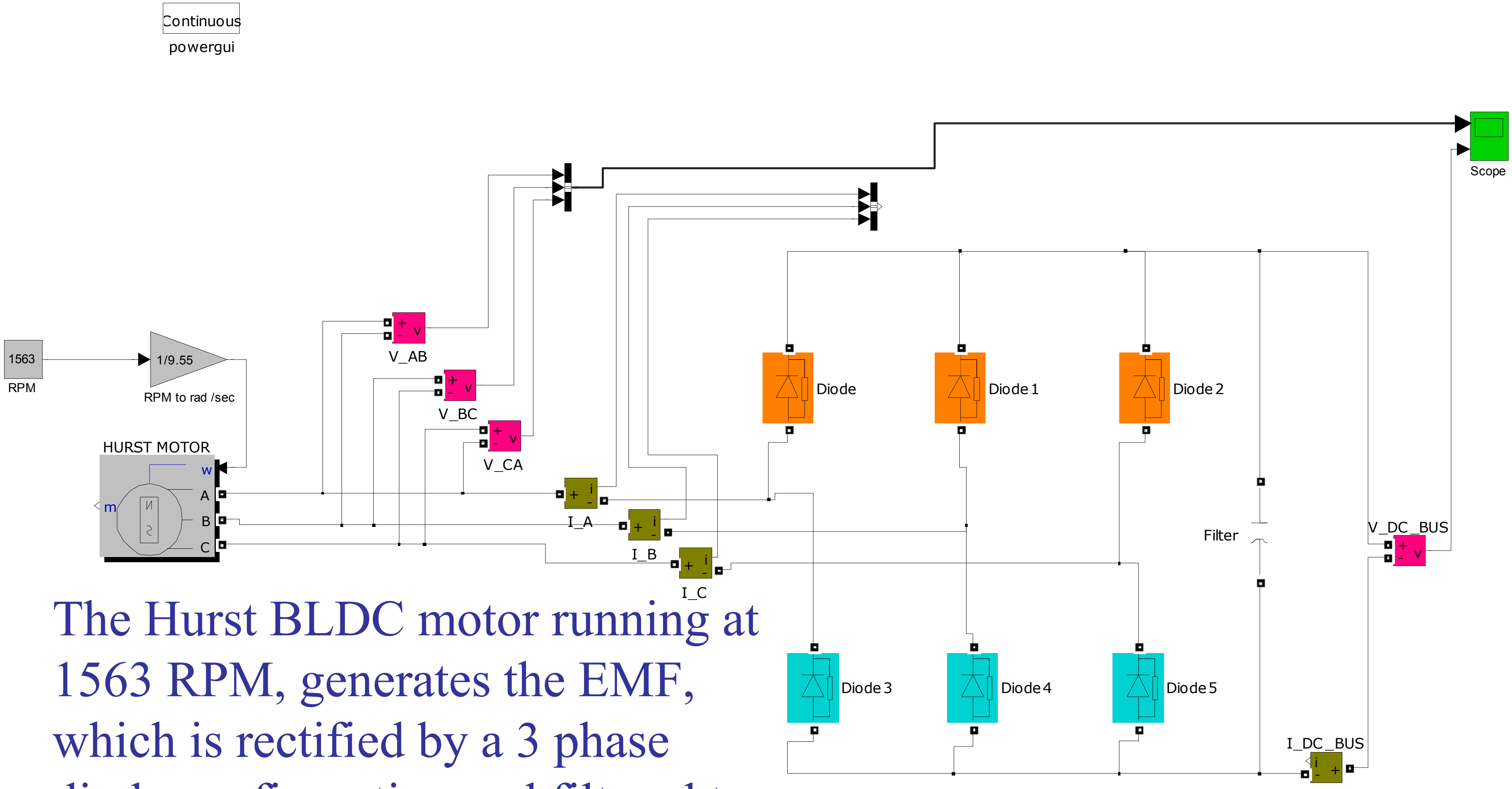
Kinetic Energy

BLDC Hub Motor used in e-bike application

While braking, energy is stored in the battery

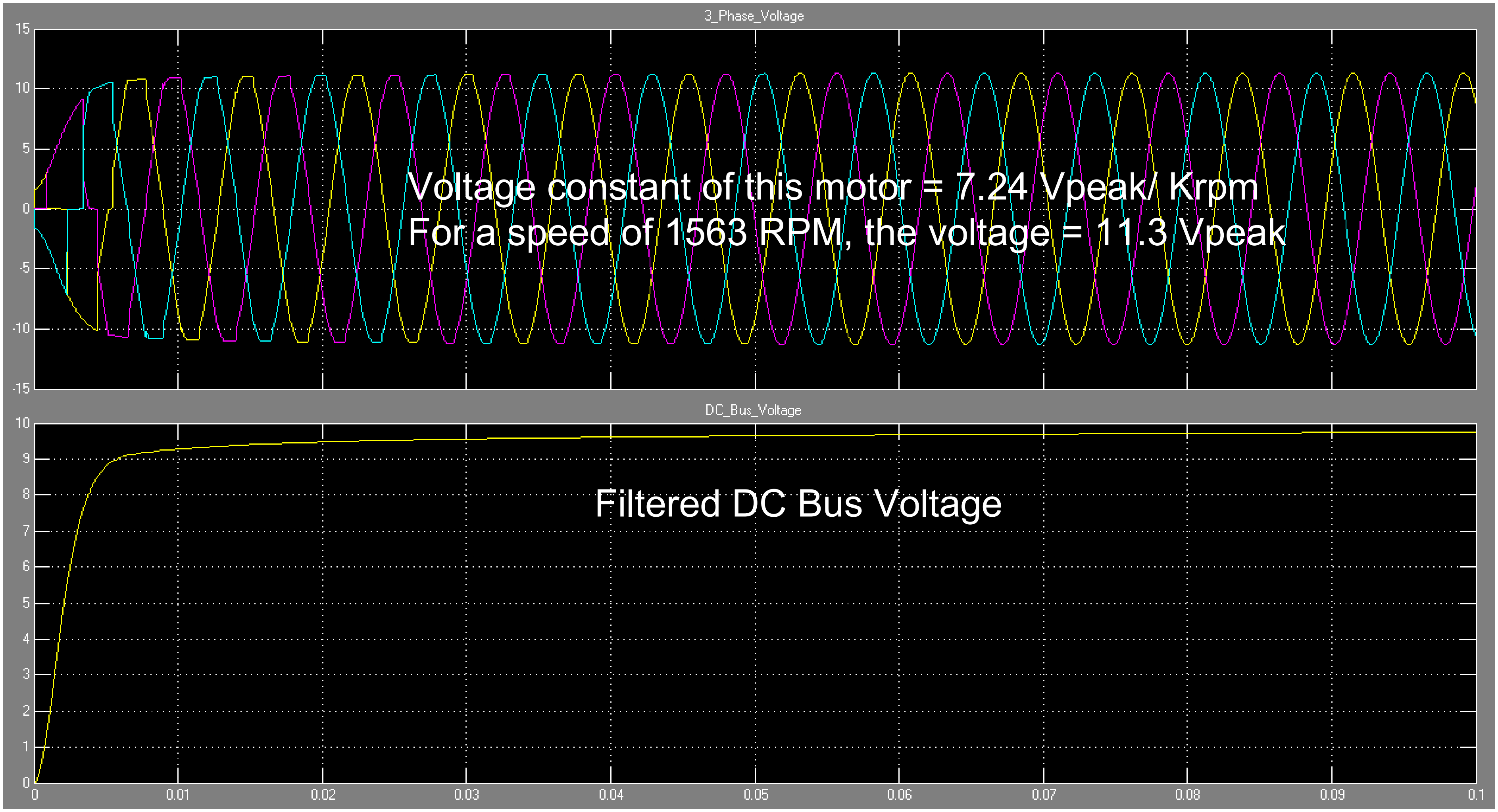
Regenerative braking stores energy back into the battery, while increasing the life of friction pads on brake shoe. However, to bring the bike to a complete stop, the mechanical brakes are required.

Configuration of a 3-Phase Rectifier using Simulink



The Hurst BLDC motor running at 1563 RPM, generates the EMF, which is rectified by a 3 phase diode configuration and filtered to DC to charge the battery.

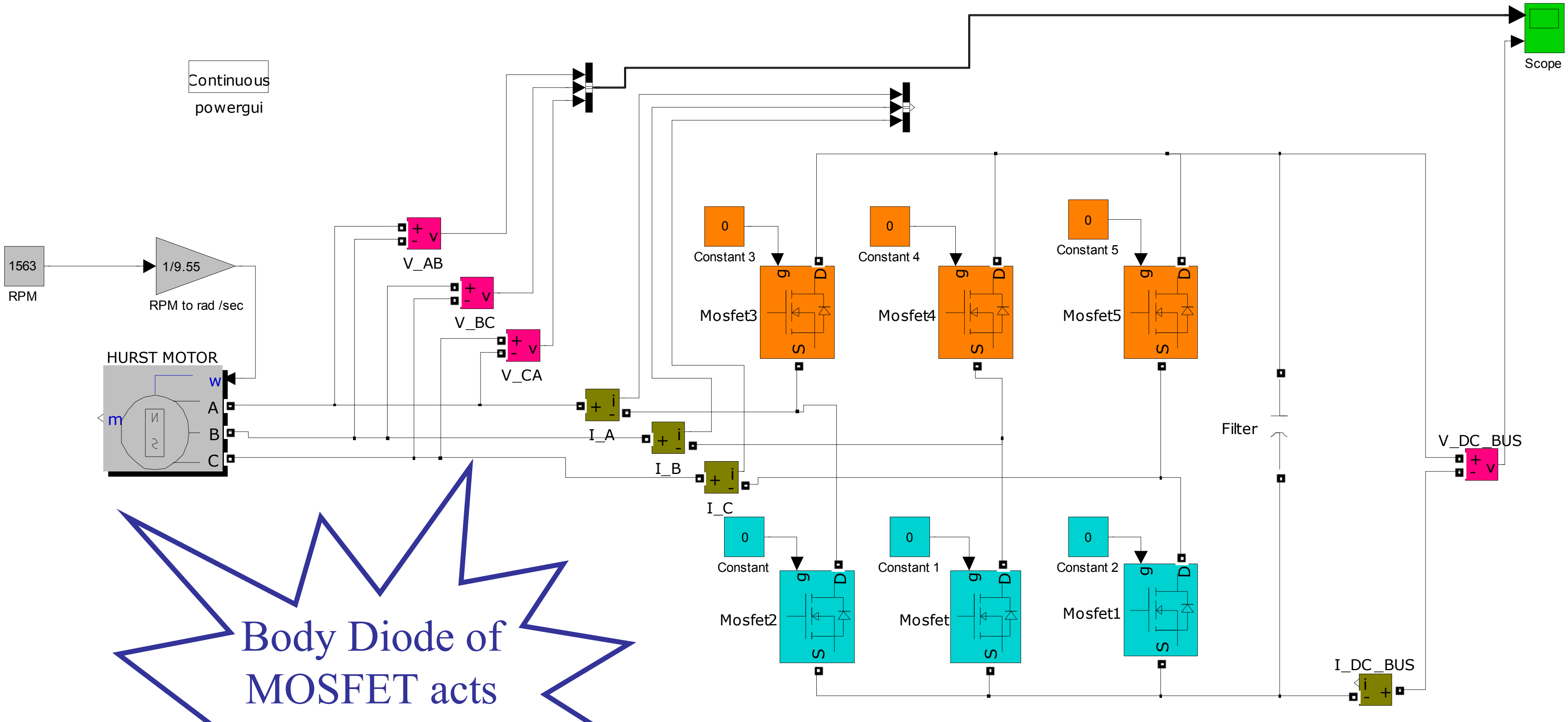
3-Phase Rectifier Simulation Results



Voltage constant of this motor = 7.24 Vpeak/ Krpm
For a speed of 1563 RPM, the voltage = 11.3 Vpeak

Filtered DC Bus Voltage

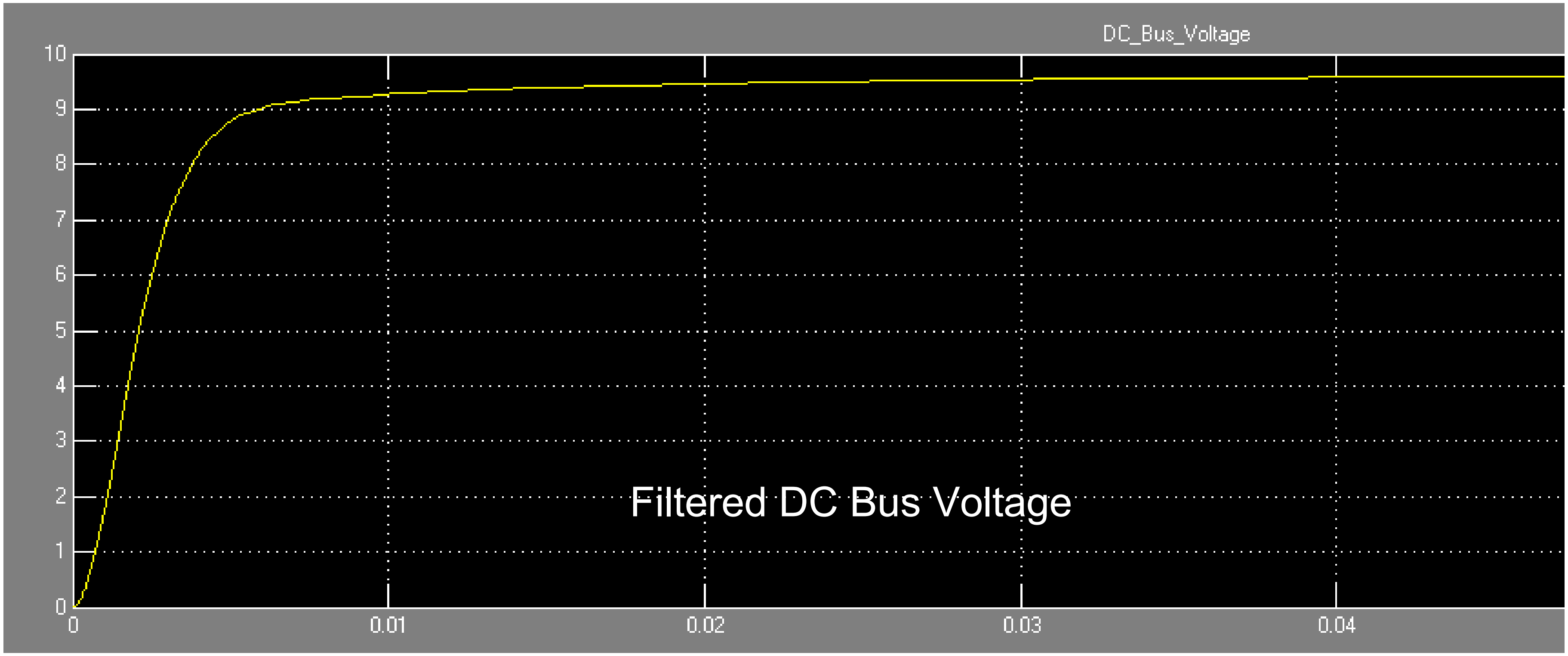
MOSFET Bridge as a 3-Phase Rectifier (using Simulink)



Body Diode of MOSFET acts as rectifier

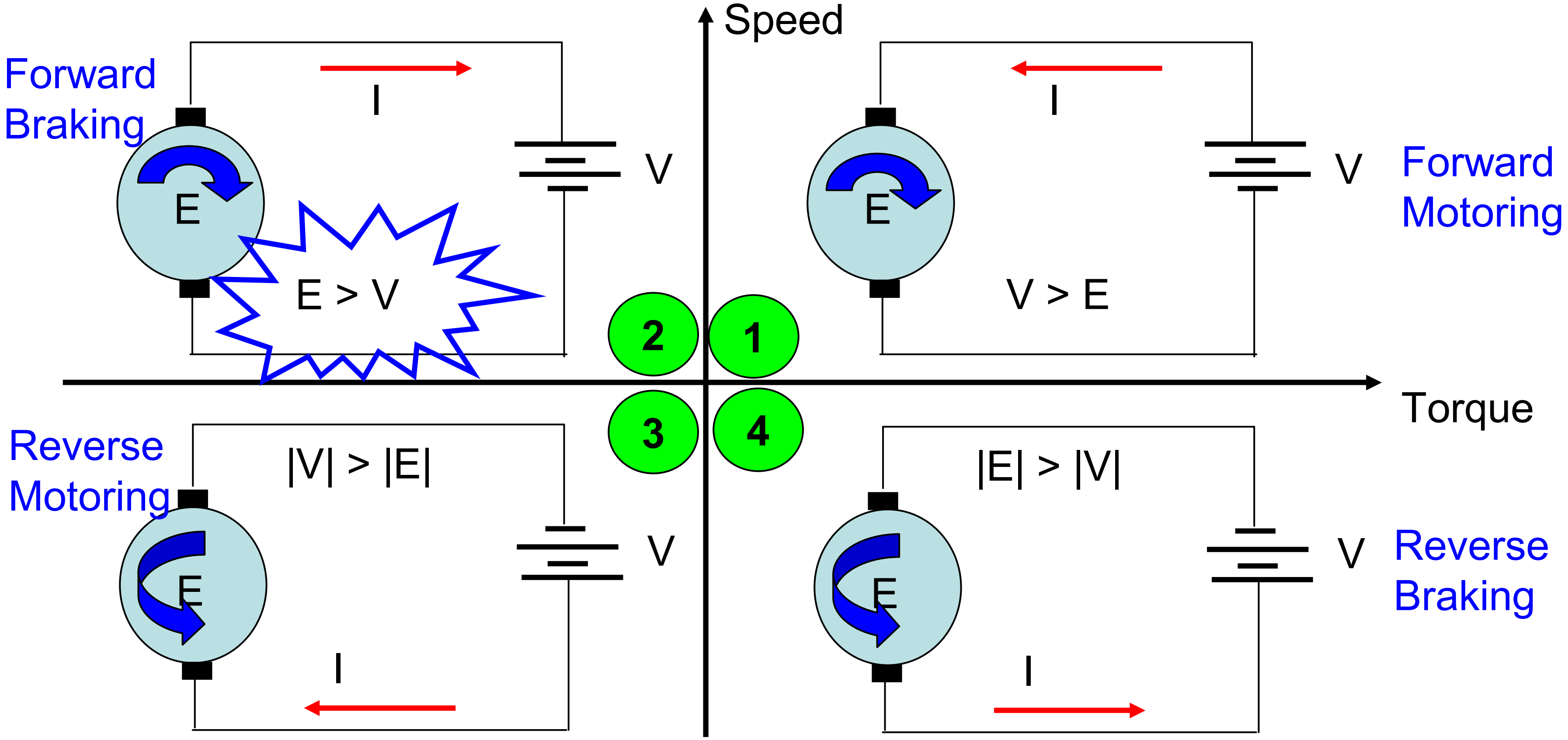
All MOSFETs are turned OFF

3-Phase MOSFET Bridge Rectifier Simulation Results



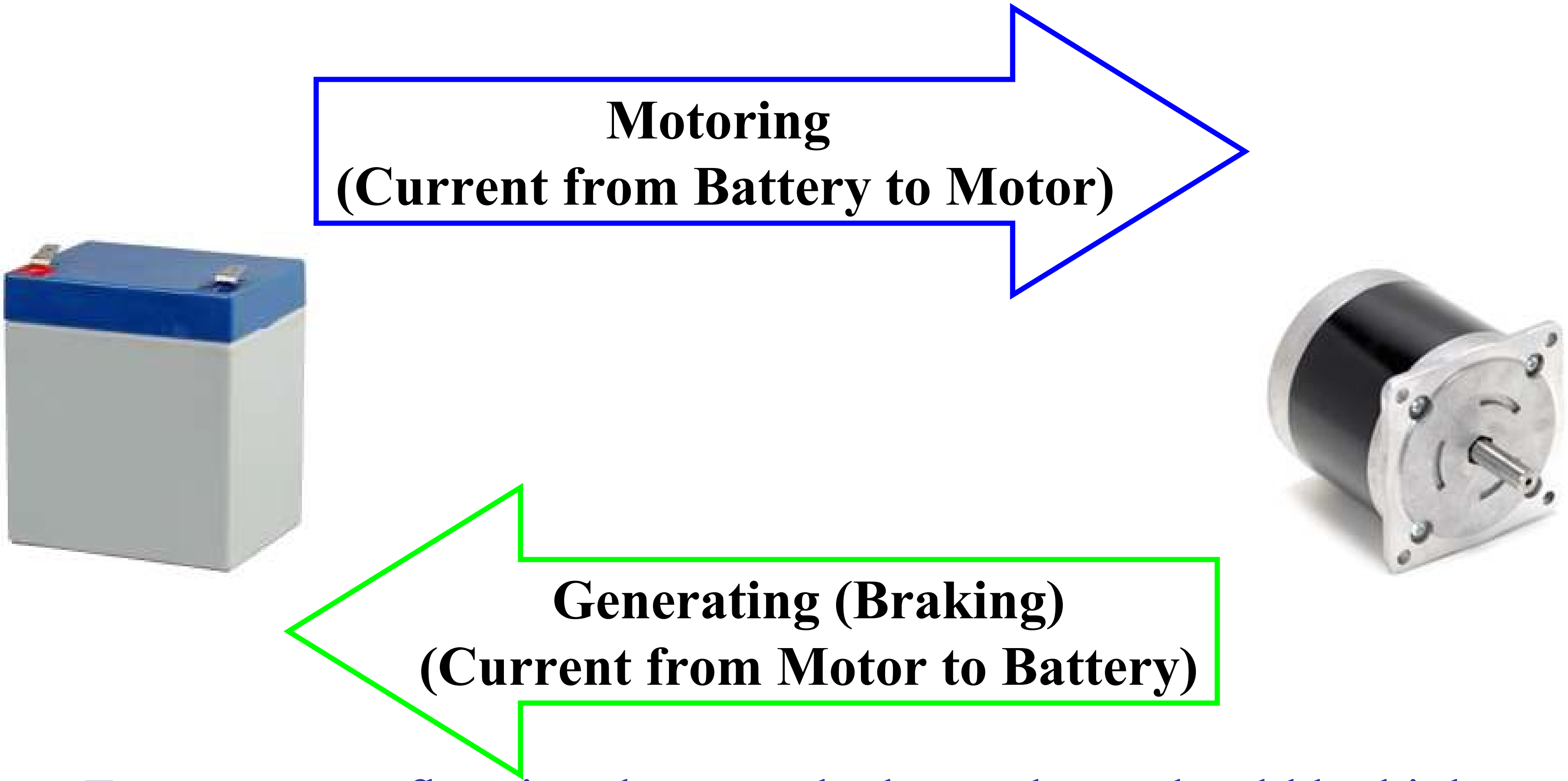
The DC bus voltage results for the 3-phase MOSFET bridge are similar to the rectified 3-phase diode circuit.

4-Quadrant Motor Operation



For a BLDC motor to operate in 2nd quadrant, the value of the back EMF generated by the BLDC motor should be greater than the battery voltage (DC bus voltage). This ensures that the direction of the current reverses, while the motor still runs in the forward direction.

Energy Flow

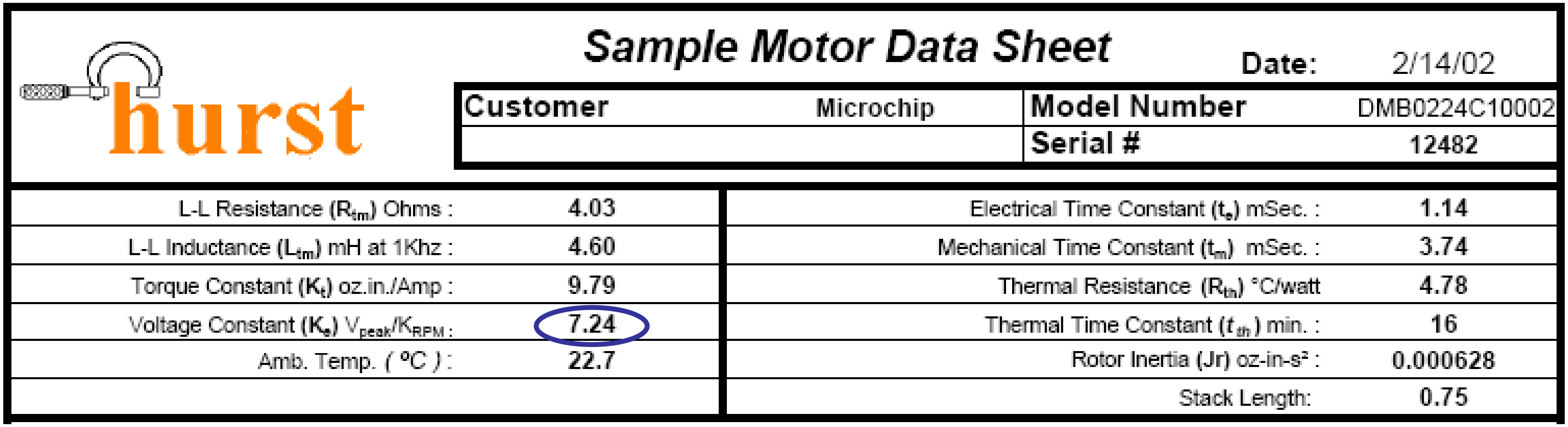


Motoring
(Current from Battery to Motor)

Generating (Braking)
(Current from Motor to Battery)

For current to flow into battery, the bus voltage should be higher than the battery terminal voltage. Hence we have to boost the voltage developed from motor higher than the battery.

Limitation of a Direct Connection



hurst

Sample Motor Data Sheet

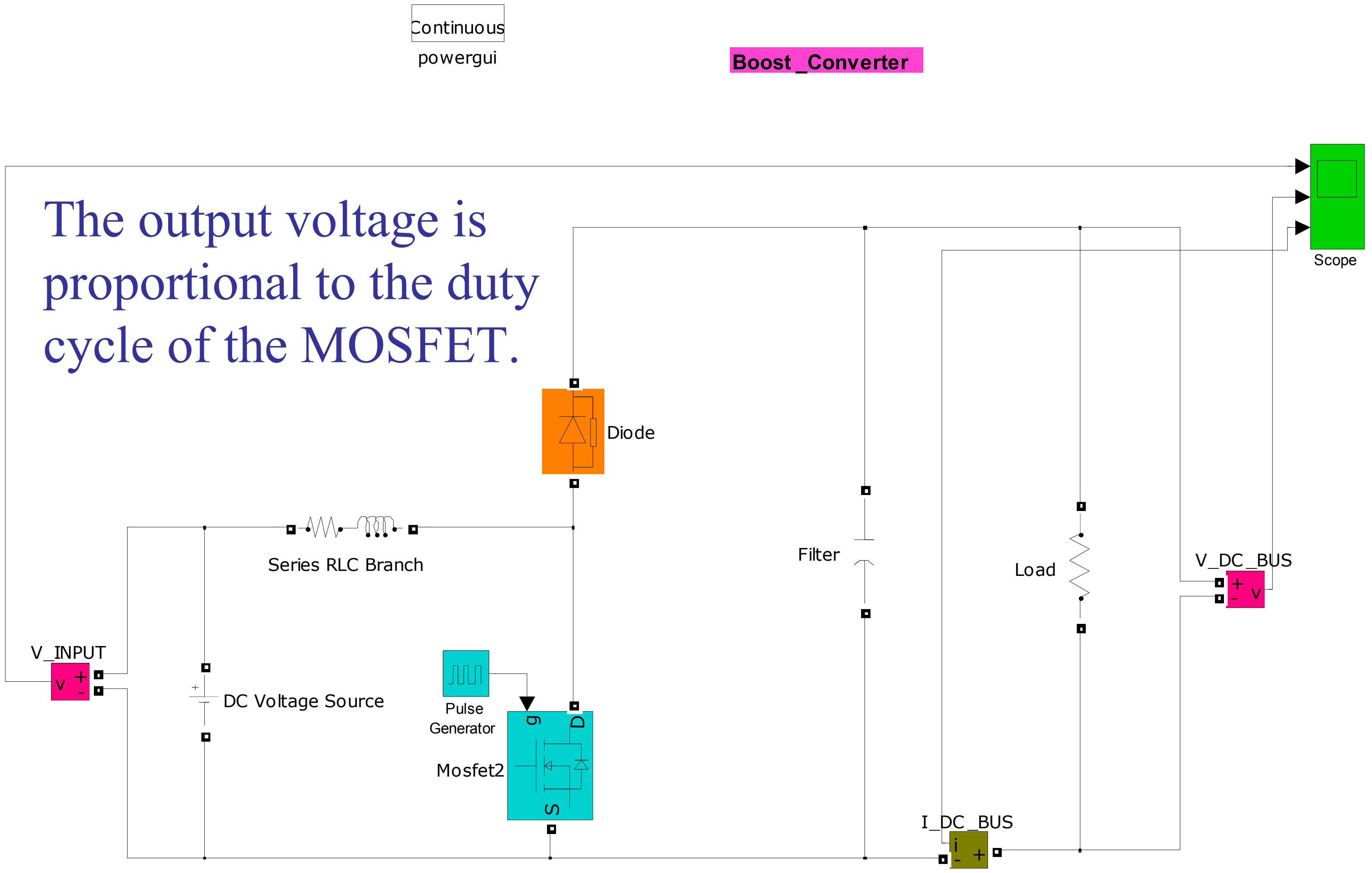
Date: 2/14/02

Customer	Microchip	**Model Number**	DMB0224C10002
		Serial #	12482

L-L Resistance (R_{lm}) Ohms :	4.03	Electrical Time Constant (t_e) mSec. :	1.14
L-L Inductance (L_{lm}) mH at 1Khz :	4.60	Mechanical Time Constant (t_m) mSec. :	3.74
Torque Constant (K_t) oz.in./Amp :	9.79	Thermal Resistance (R_{th}) °C/watt	4.78
Voltage Constant (K_e) V_{peak}/K_{RPM} :	7.24	Thermal Time Constant (t_{th}) min. :	16
Amb. Temp. (°C) :	22.7	Rotor Inertia (Jr) oz-in-s² :	0.000628
		Stack Length:	0.75

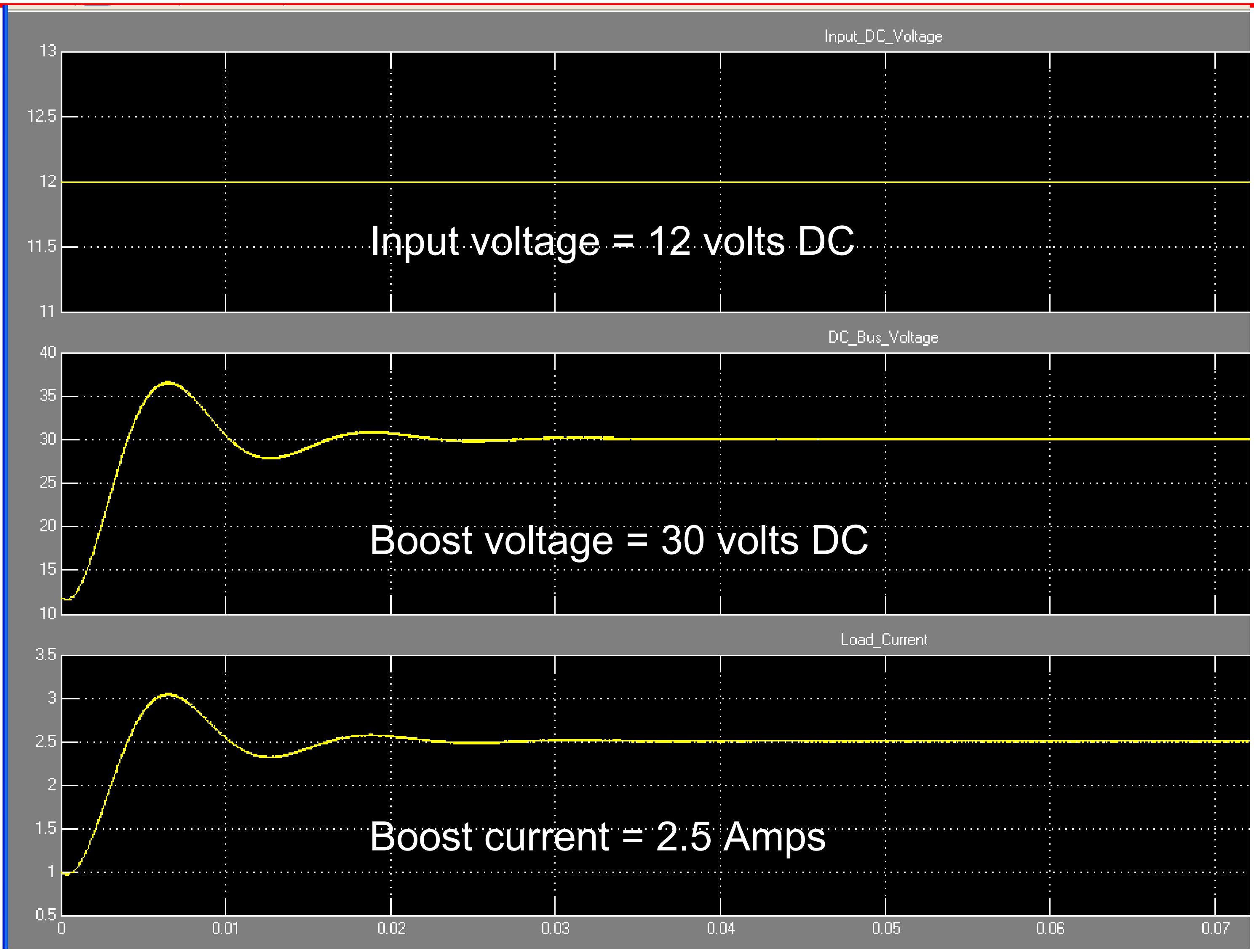
Since this motor is rated for 24-Volts, the battery terminal voltage would be 24-Volts. To generate 24-Volts from the motor (or higher voltage), the motor should run at a speed of 3,400 RPM or higher. Hence we have to figure out ways to boost the back EMF generated by the motor so that even at lower speeds, the motor can work as brake.

Simple Boost Converter (using Simulink)



The output voltage is proportional to the duty cycle of the MOSFET.

Simple Boost Converter Simulation Results

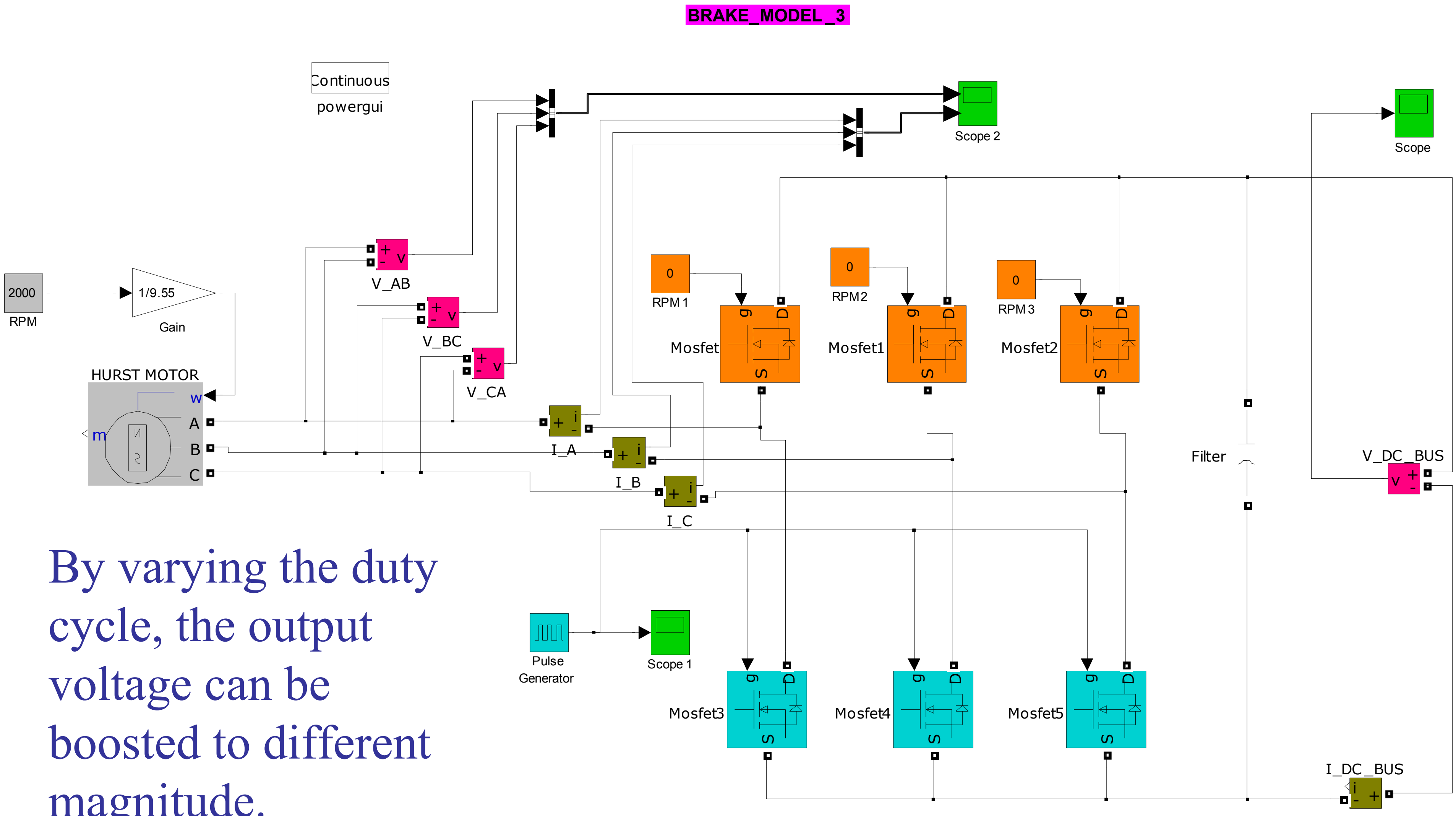


Input voltage = 12 volts DC

Boost voltage = 30 volts DC

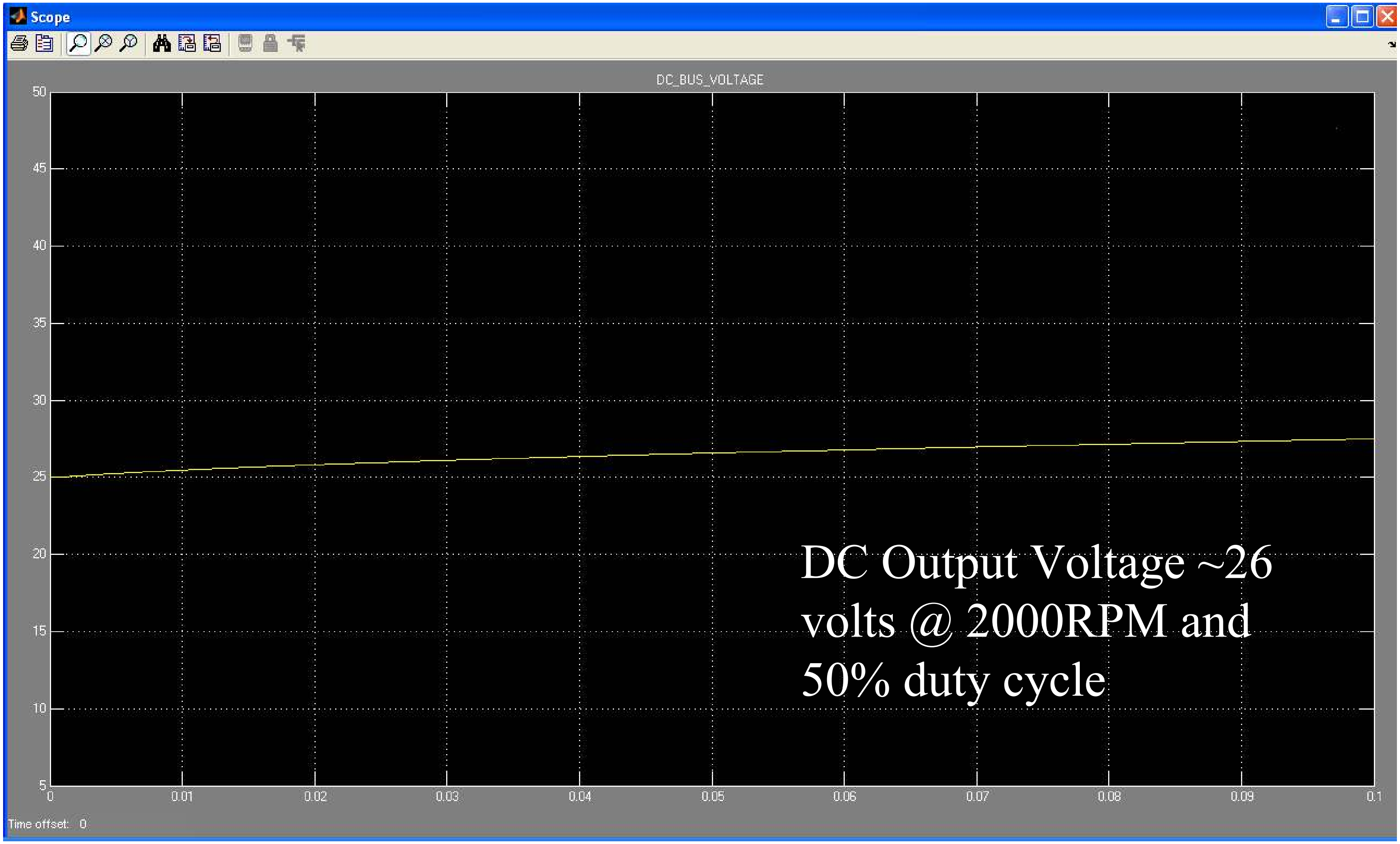
Boost current = 2.5 Amps

Boost Converter Based on a 3-phase MOSFET Bridge



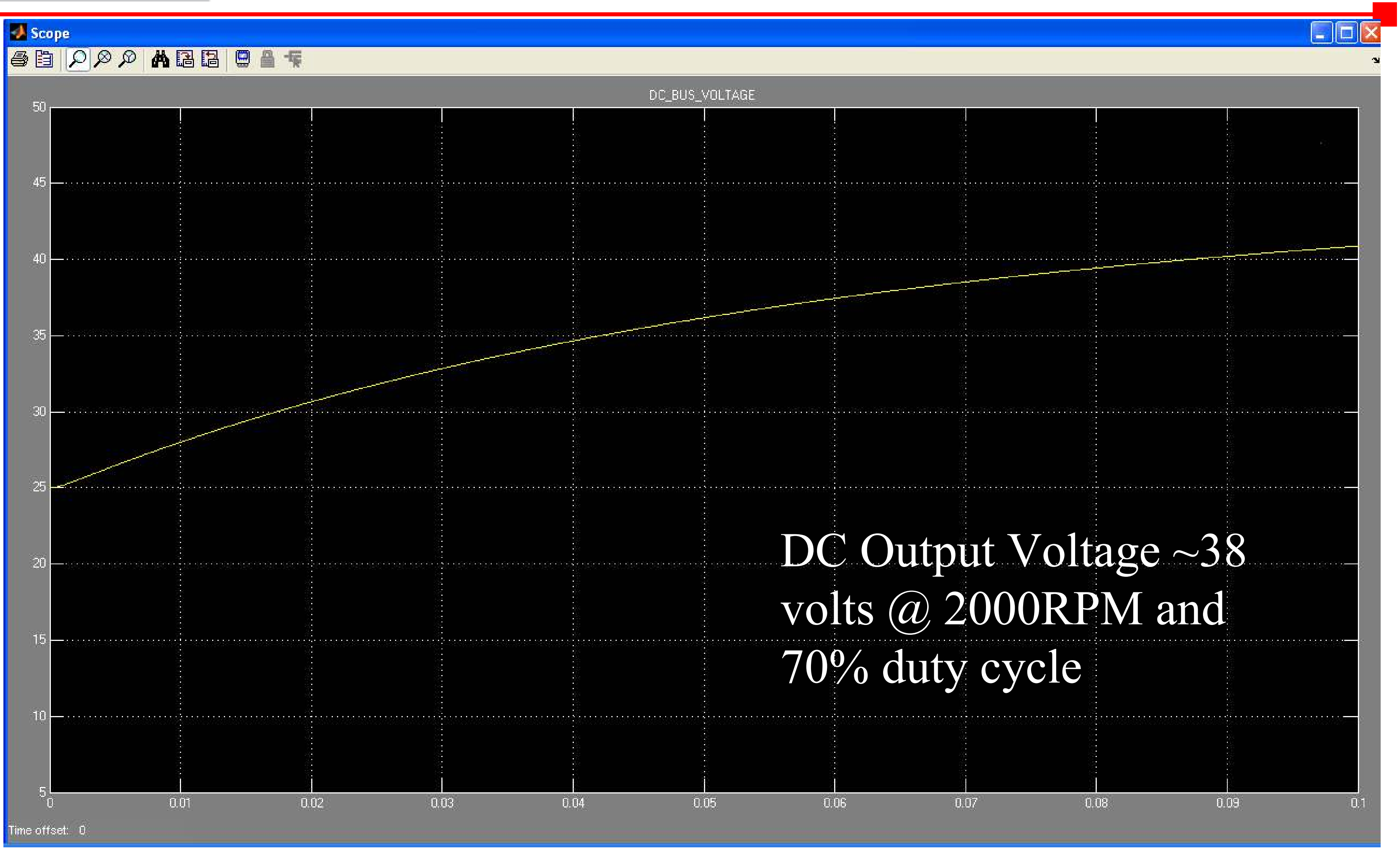
By varying the duty cycle, the output voltage can be boosted to different magnitude.

Boost Converter 3-phase MOSFET Bridge Simulation Results



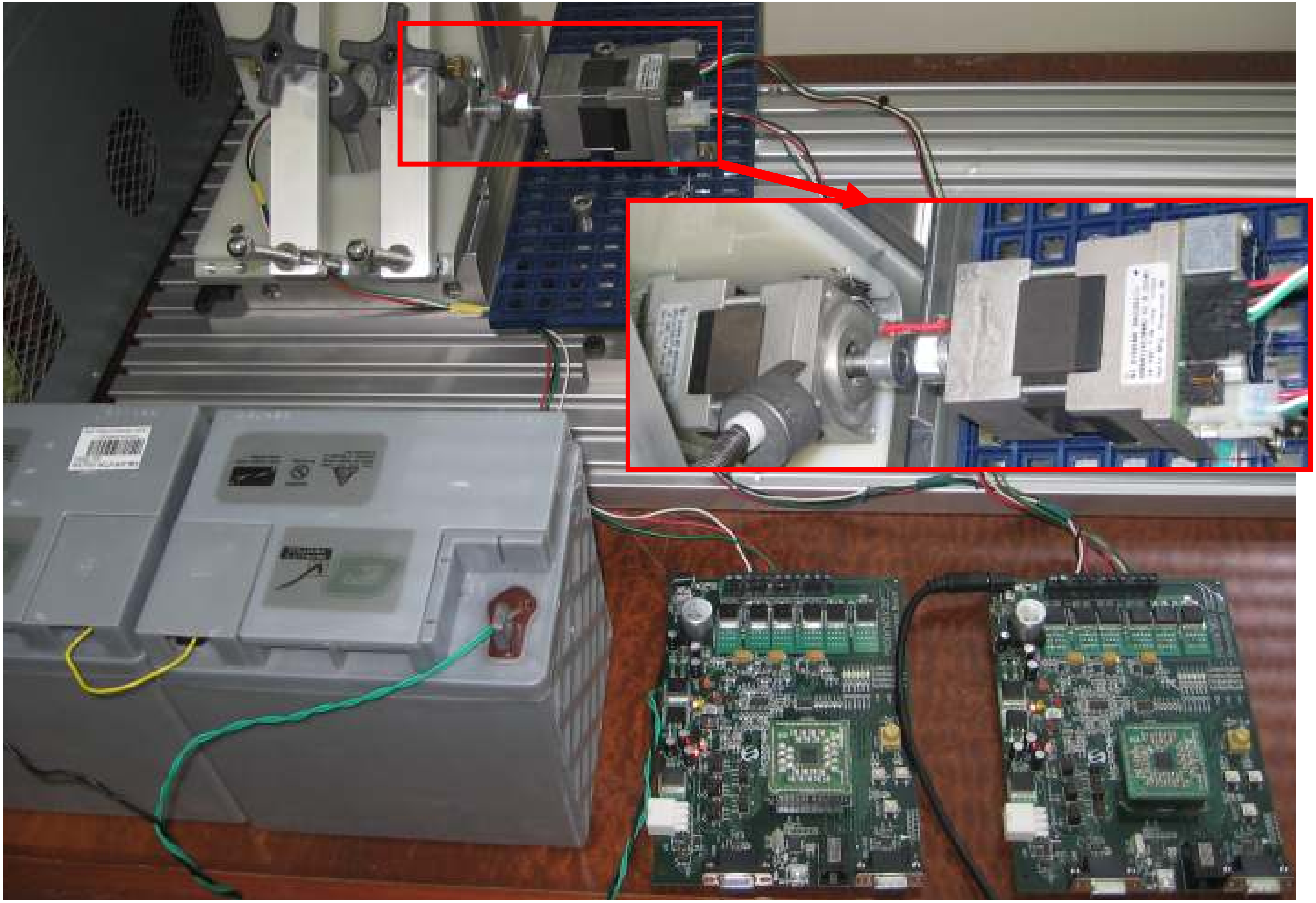
DC Output Voltage ~26 volts @ 2000RPM and 50% duty cycle

Boost Converter 3-phase MOSFET Bridge Simulation Results

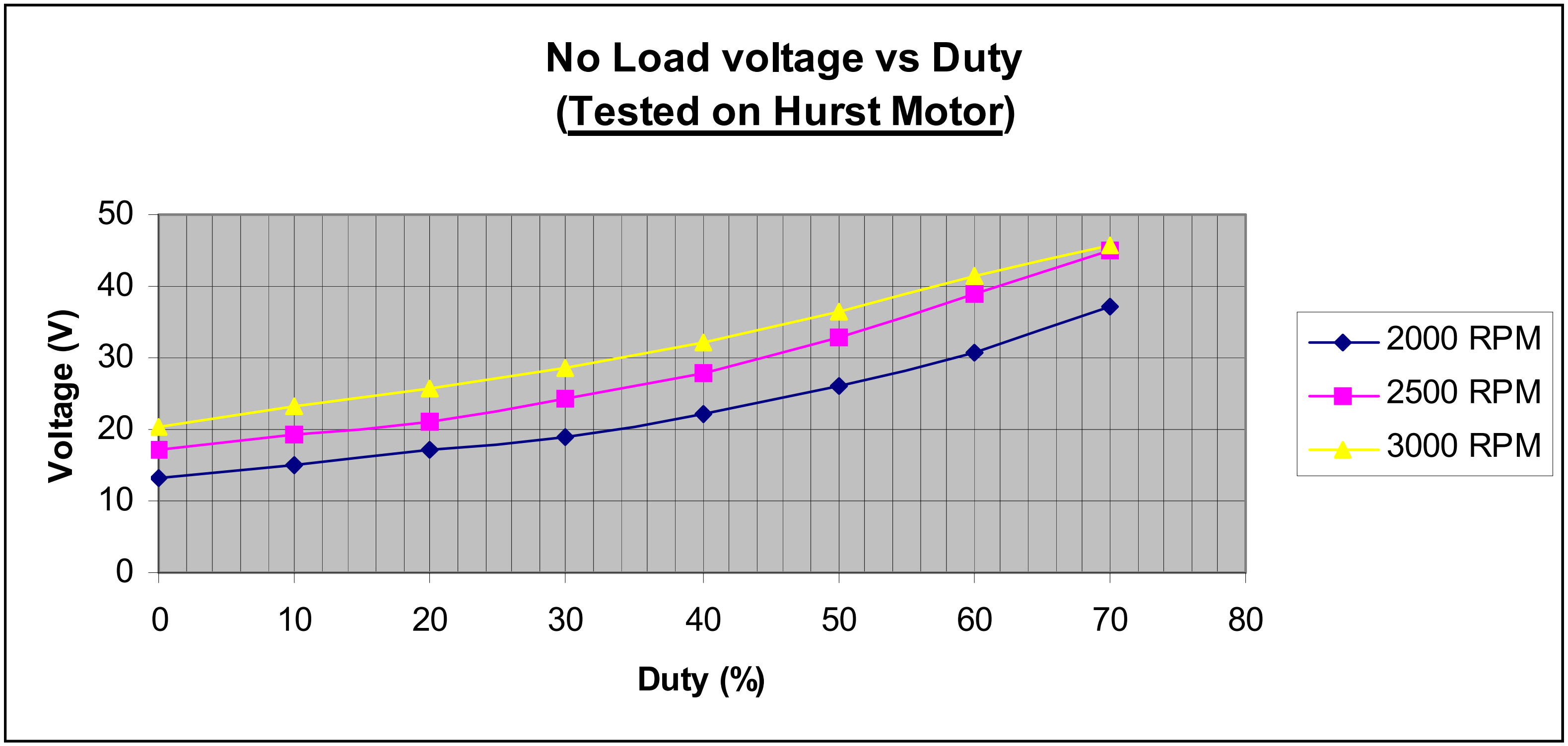


DC Output Voltage ~38 volts @ 2000RPM and 70% duty cycle

Picture of Test Setup



Test Result of Boosted Voltage while running Motor at 2500 RPM



This slide shows the output voltage of the motor after boost, for different speed and duty cycles. The magnitude of the voltage will increase proportional to the shaft speed. Another point evident from the plots is that the output voltage gets boosted proportionally to the duty cycle.

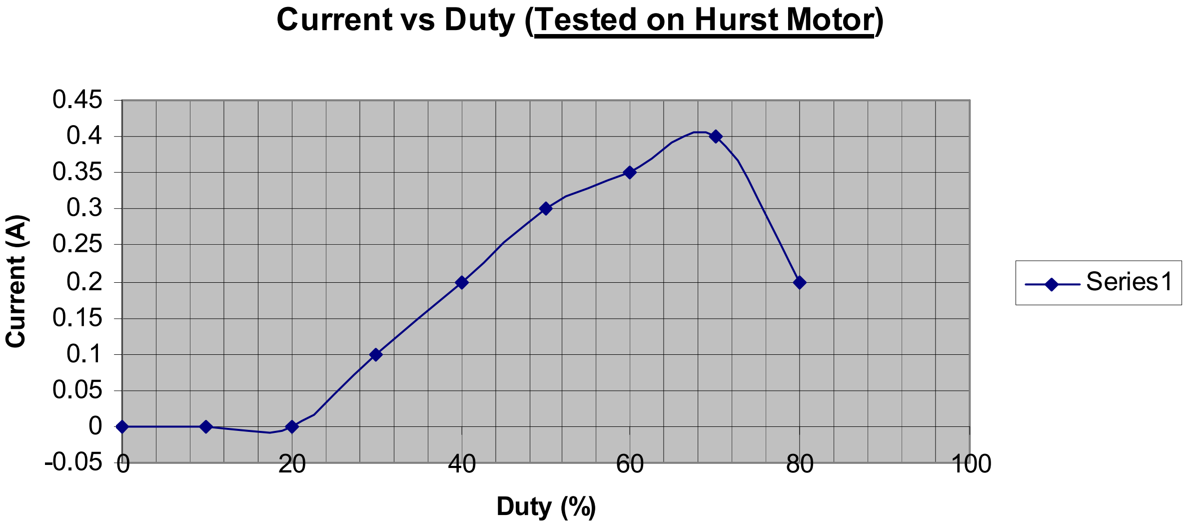
Test Versus Simulation Results at 2000 RPM

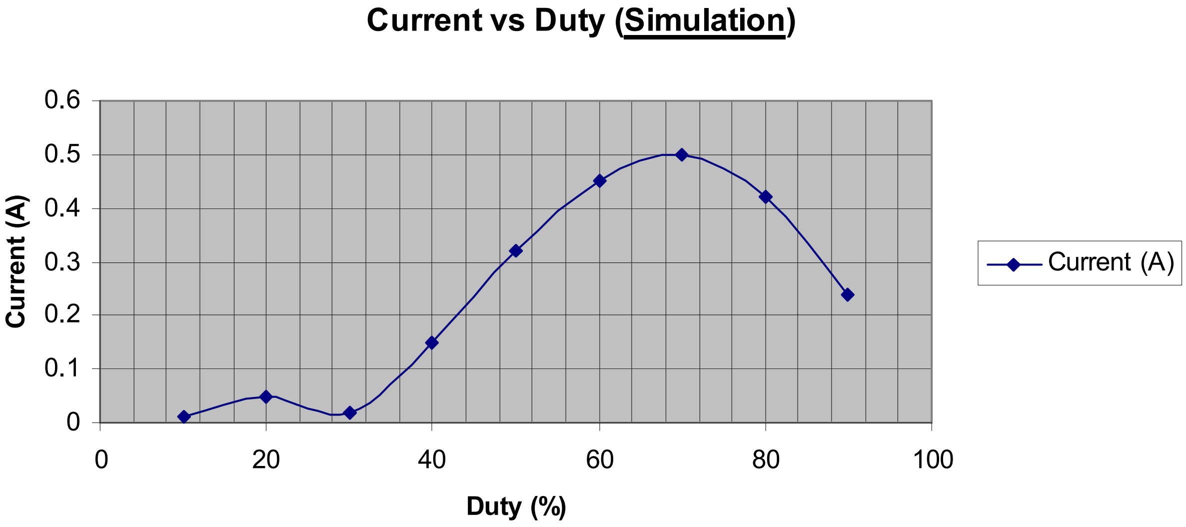
- For low value duty cycles, the boosted voltage is low. Hence no current flows into the battery.

- At around 30% duty cycle, the voltage begins to boost and the current flows into the battery. This is the point where regenerative braking starts.

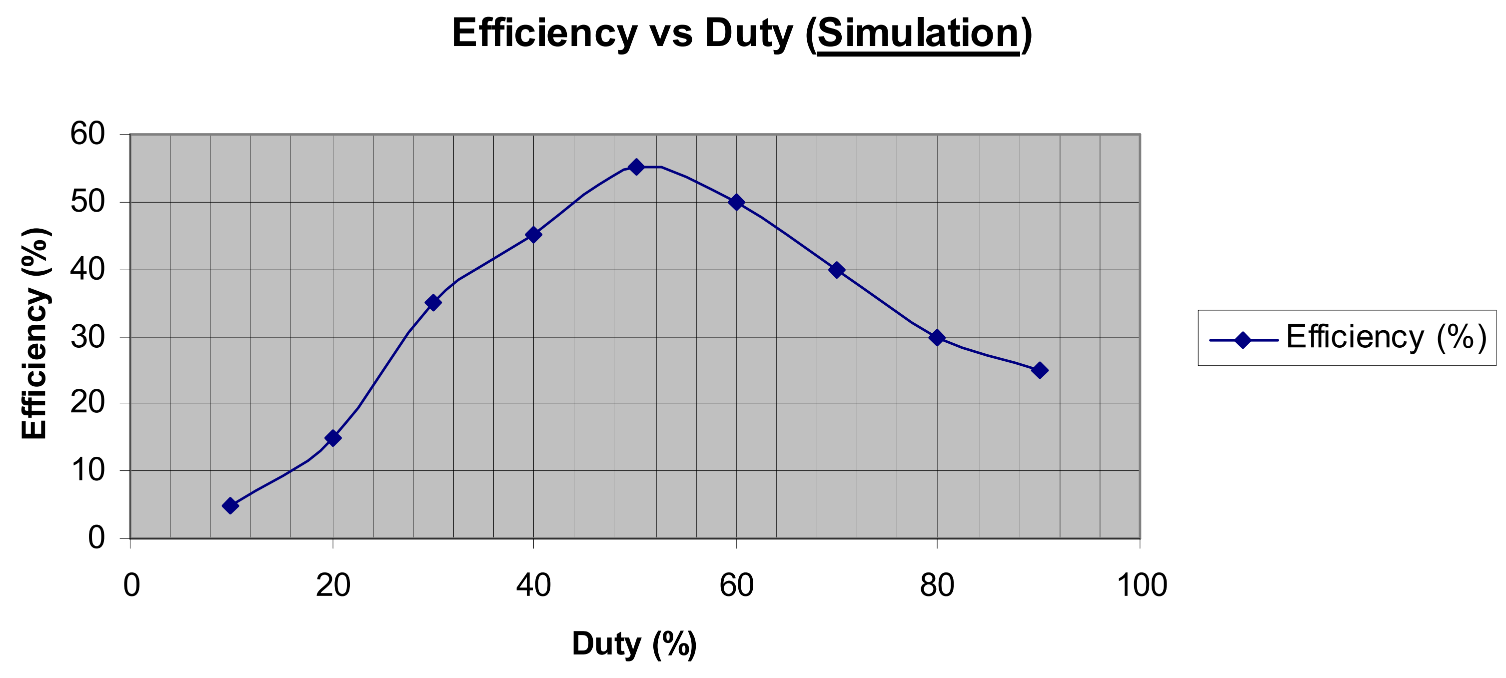
- The peak current from simulation is around 0.5Amps @ 70% duty cycle. This translates to 24V * 0.5 Amps = 12 Watts. Since brake force is proportional to the current, this is the point of maximum brake force.

- Beyond that point, the current starts to fall, mainly because of the motor construction (resistance and inductance drops).


Current vs Duty (Tested on Hurst Motor)


Current vs Duty (Simulation)

Efficiency Simulation Results



This slide shows the efficiency curve of the brake setup, which gives a maximum efficiency of 55% at 50% duty cycle. Since this is a simulated result, the actual figure of efficiency might be lower.

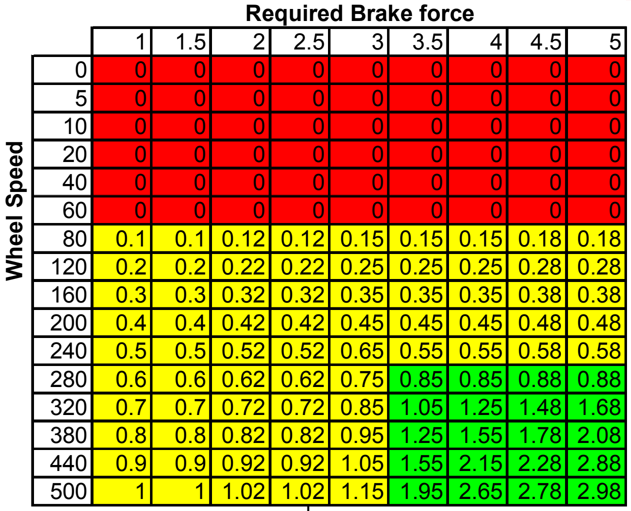
From the plot, it can be seen that the maximum efficiency point and maximum brake force points do not coincide:

- Max brake force @ 70% duty cycle
- Max efficiency @ 50% duty cycle

Hence, the braking algorithm can be designed to operate at either maximum efficiency or at maximum brake force points.

PID Control for Constant Brake Force

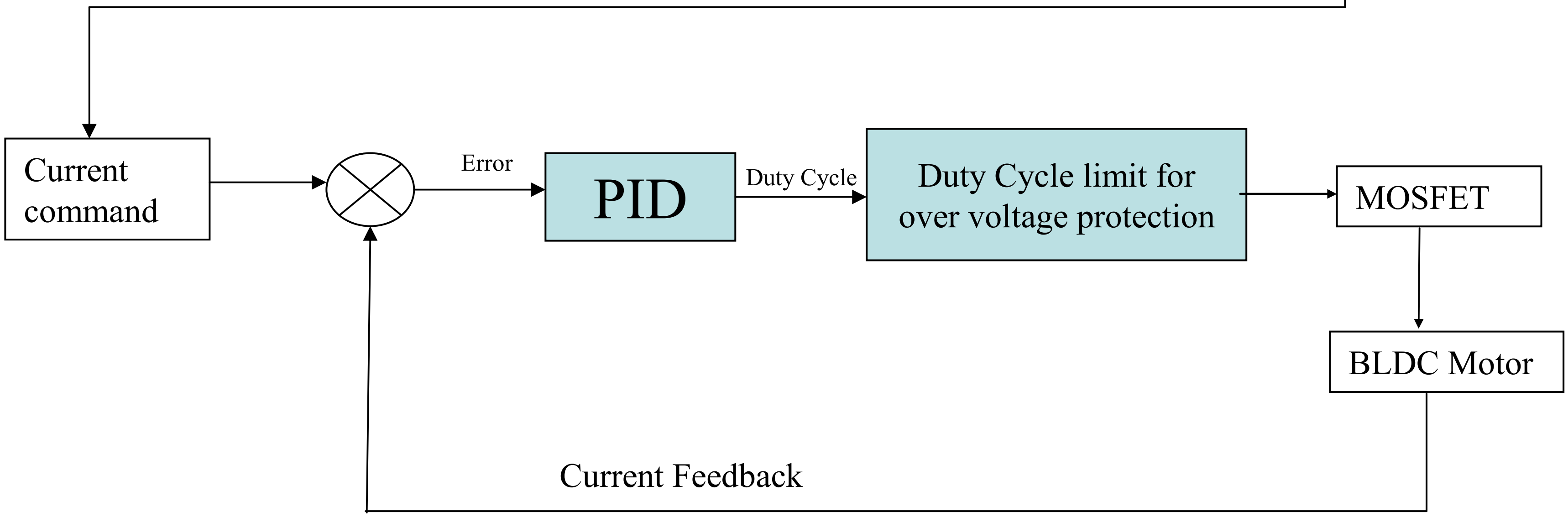
Analog voltage proportional to the required brake force



Required Brake force

Wheel Speed	1	1.5	2	2.5	3	3.5	4	4.5	5
0	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0	0
10	0	0	0	0	0	0	0	0	0
20	0	0	0	0	0	0	0	0	0
40	0	0	0	0	0	0	0	0	0
60	0	0	0	0	0	0	0	0	0
80	0.1	0.1	0.12	0.12	0.15	0.15	0.15	0.18	0.18
120	0.2	0.2	0.22	0.22	0.25	0.25	0.25	0.28	0.28
160	0.3	0.3	0.32	0.32	0.35	0.35	0.35	0.38	0.38
200	0.4	0.4	0.42	0.42	0.45	0.45	0.45	0.48	0.48
240	0.5	0.5	0.52	0.52	0.65	0.55	0.55	0.58	0.58
280	0.6	0.6	0.62	0.62	0.75	0.85	0.85	0.88	0.88
320	0.7	0.7	0.72	0.72	0.85	1.05	1.25	1.48	1.68
380	0.8	0.8	0.82	0.82	0.95	1.25	1.55	1.78	2.08
440	0.9	0.9	0.92	0.92	1.05	1.55	2.15	2.28	2.88
500	1	1	1.02	1.02	1.15	1.95	2.65	2.78	2.98

The PID loop will try to maintain a constant brake force at different motor speeds. Hence the user will get a linear response of brake force.



Current command

Error

PID

Duty Cycle

Duty Cycle limit for over voltage protection

MOSFET

BLDC Motor

Current Feedback

Thank You

Questions?