Power Quality Improvements

Some Application: Power Quality Improvement in BLDC Motor Drives

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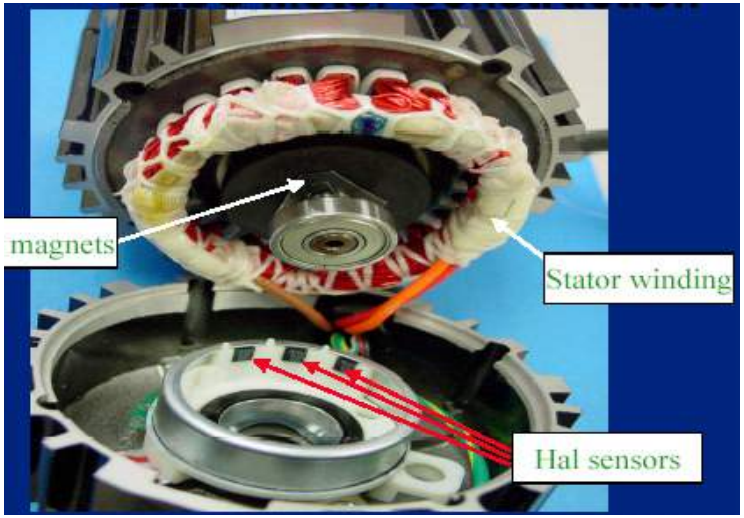
BLDC Motor

- **Brushless DC electric motor** (**BLDC motors**, **BL motors**) also known as **electronically commutated motors** (ECMs, EC motors)
- These are three phase synchronous Motors that are powered by a DC electric source via a VSI (Voltage Source Inverter), which produces an AC electric signal to drive the motor.
- Three phase windings on the stator and permanent magnets on the rotor.
- Rotor position sensing is required for achieving an electronic commutation of BLDC motor via VSI.

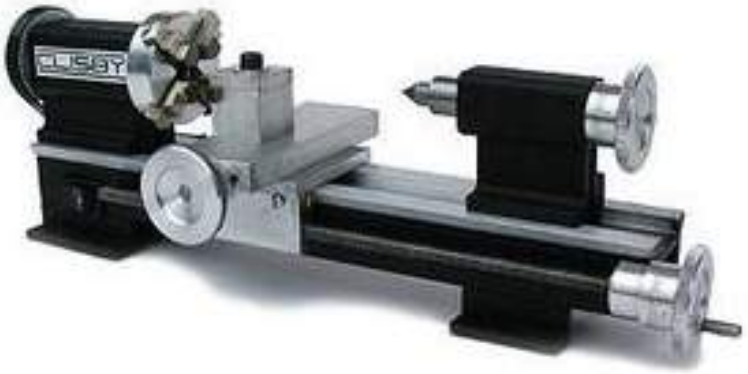


Applications of BLDC Motor : Household Appliances

In Home Appliances ranging from fans, air conditioners, refrigerators, water pumps etc.

Applications of BLDC Motor : Industrial Tools

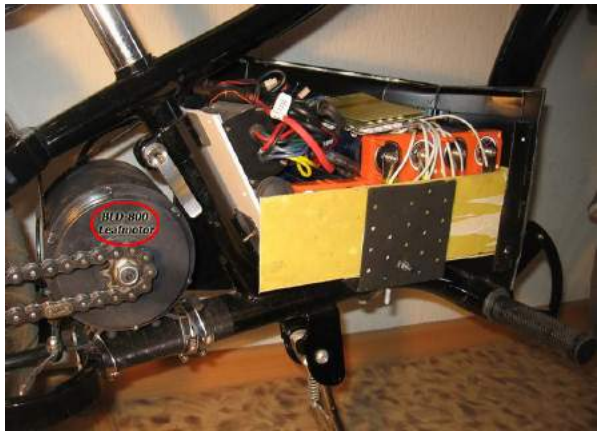
In many industrial tools such as Jig-saw, cutters, grinders, automated drillers, and other rotating machines.



Applications of BLDC Motor : Transportation

In electric vehicles:

Ranging in wide variety of applications from electric bicycle, electric tricycle, scooters, cars etc.

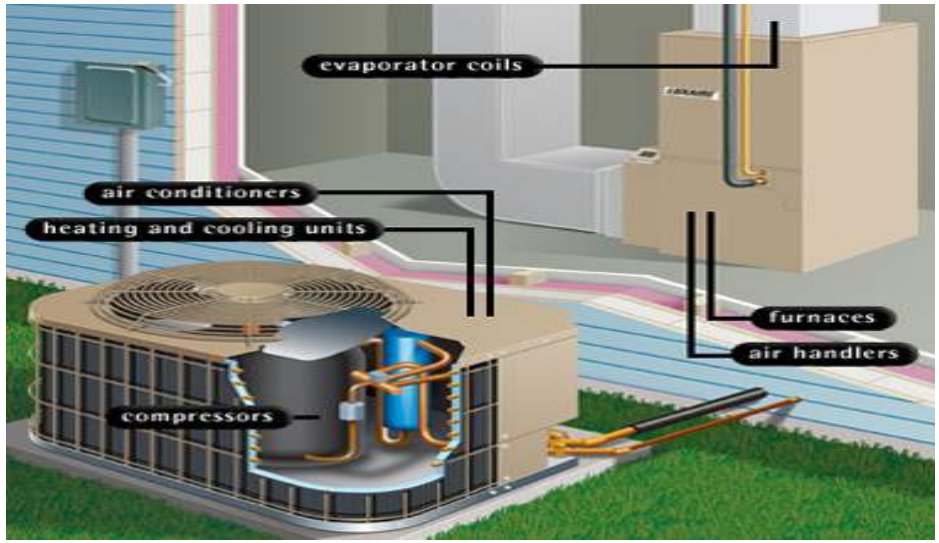


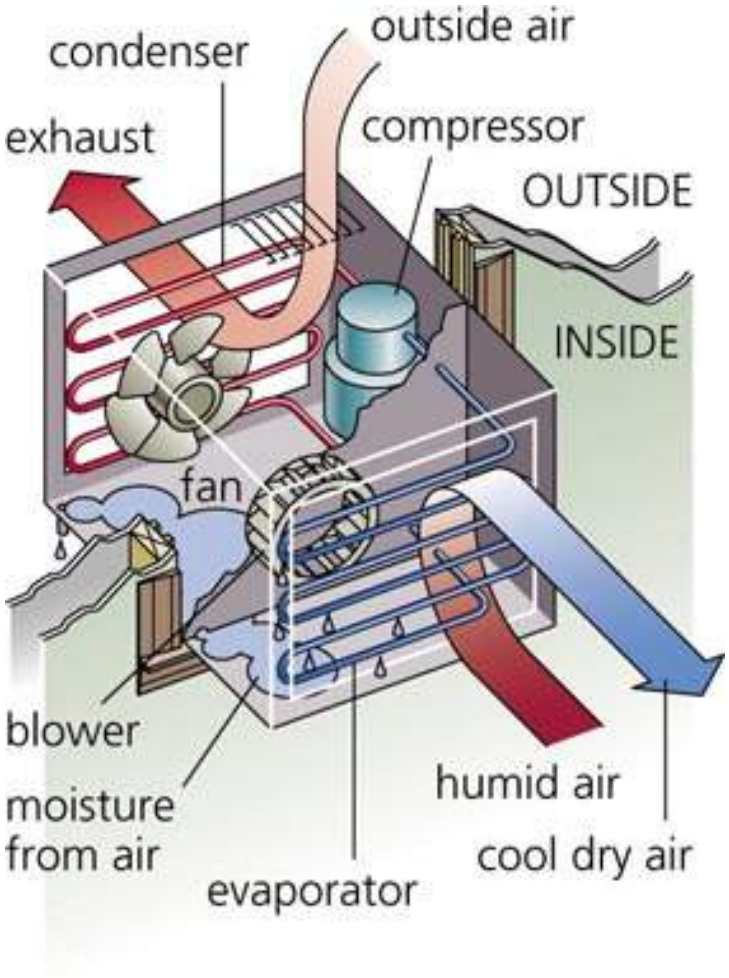
Applications of BLDC Motor : HVAC

In Heating Ventilation

and Air Conditions:

Ranging from wide applications in domestic and industrial purposes

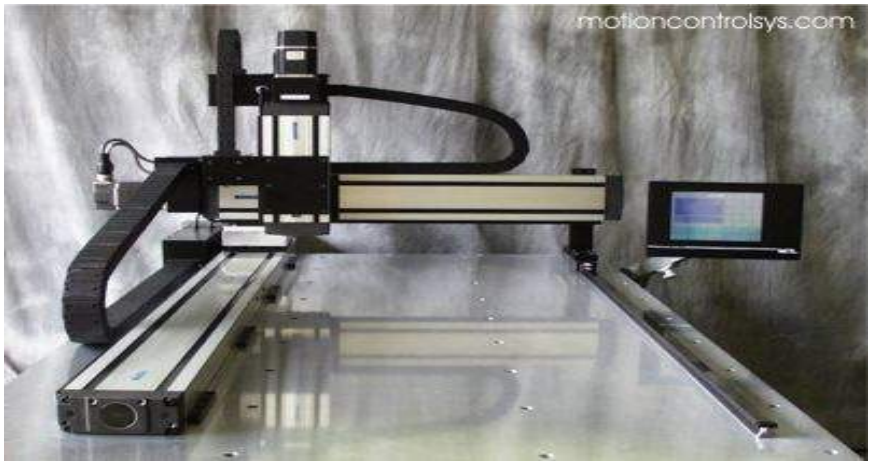




Applications of BLDC Motor : Motion Control System

In Motion Control Systems:

Ranging from wide applications in position control system to servo drive applications.



Control of PMBLDC Motor

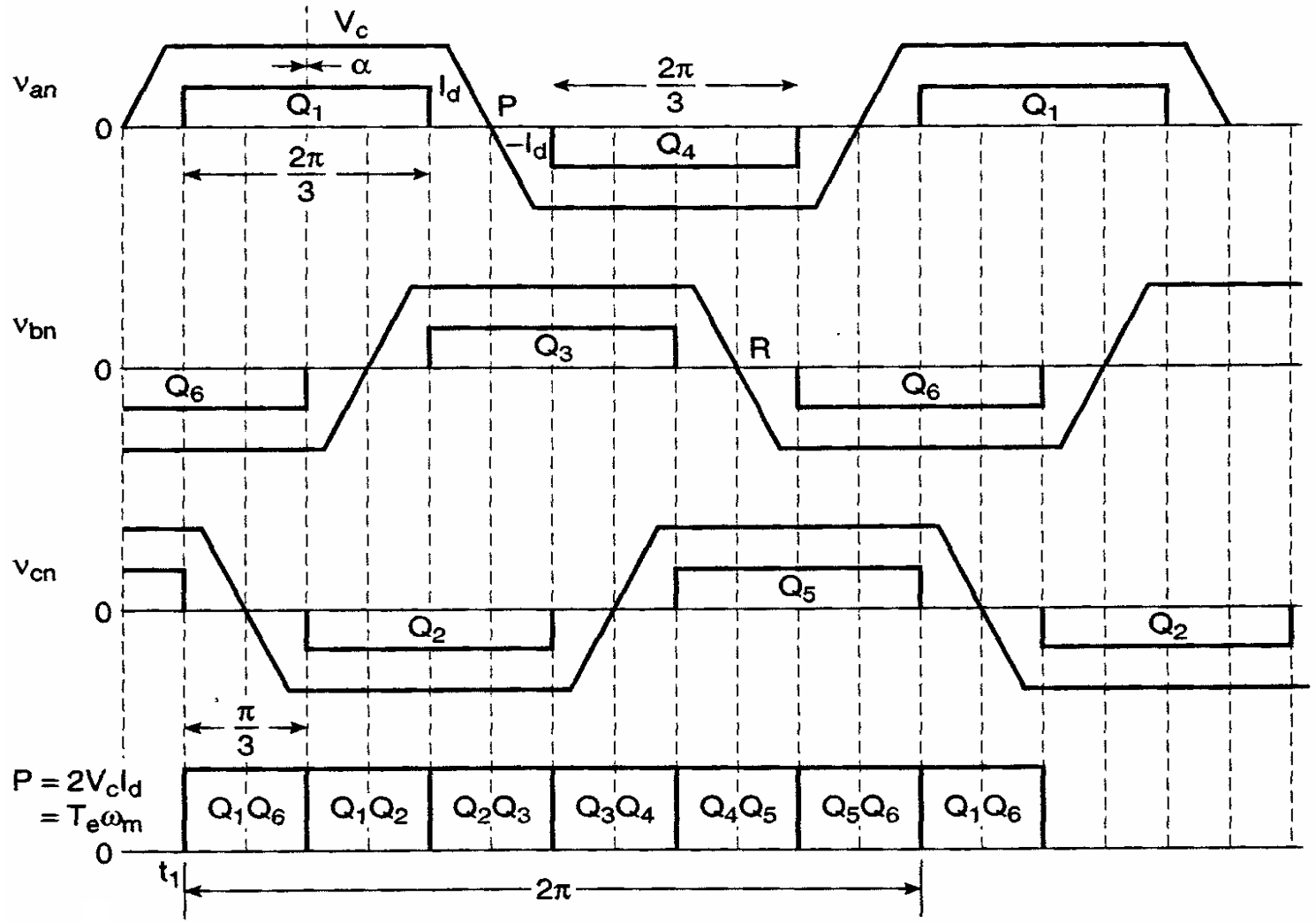
- The control of a PMBLDC Motor requires the information of commutation points only;
- Hall sensors are mostly used to get rotor position;
- The inverter performs the duty of commutator in electronic form;
- The parameter control can be done by voltage control of rectifier;
- The inverter can operate in two modes:
  - 120º conduction mode
  - PWM voltage and current control mode

Control of Brushless DC Motor Drives

- 120º conduction mode
  - The switches Q_1-Q_6 are switched on so that the input dc current I_d is symmetrically located at the center of each phase voltage wave
  - At any instant in time, one switch from the upper group (Q_1,Q_3,Q_5) and one switch from the lower group (Q_2,Q_4,Q_6) are on together;
  - The absolute position sensor is used to ensure the correct timing of the switching/commutation of the devices.

Control of Brushless DC Motor Drives

- 120º conduction mode

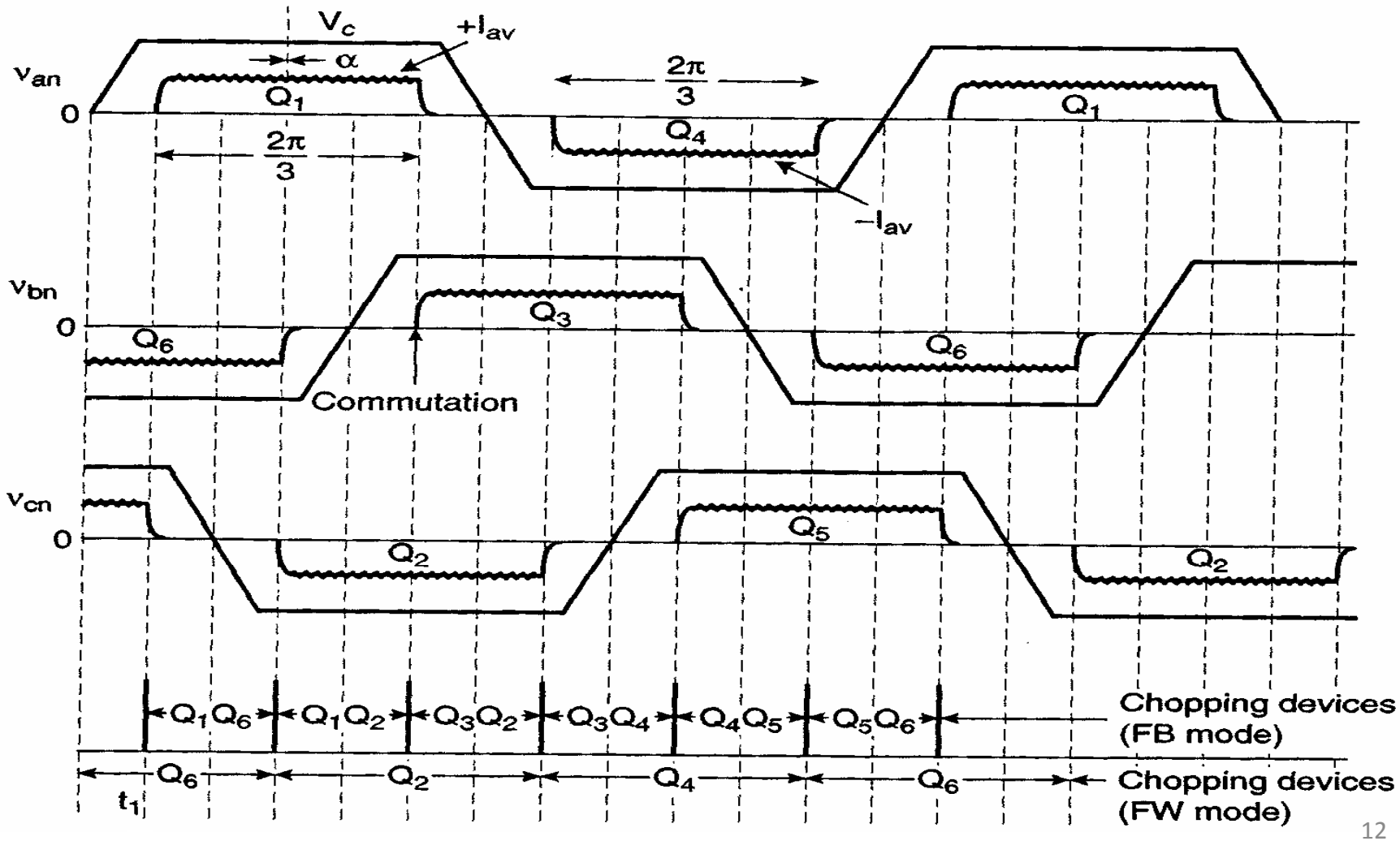


Control of Brushless DC Motor Drives

- PWM voltage and current control mode :
  - In addition to commutation control the inverter controls the current and voltage output of the inverter by operating the PWM in a chopper mode;
  - The average output current and voltage are set by the duty cycle of the switches in the PWM inverter;
  - Varying the duty cycle results in variable average output current/voltage;
  - Two chopping modes can be used : feedback mode and freewheeling mode.

Control of Brushless DC Motor Drives

- PWM voltage and current control mode :



Control of Brushless DC Motor Drives

- PWM voltage and current control mode :

  - In feedback mode, two switches are switched on and off together (e.g. Q_1 and Q_6) whereas in freewheeling mode, the chopping is performed only on one switch at a time.
  - During on time of the switches (considering Q_1 and Q_6 pair), the currents of phases a and b shall increase;
  - However, during the off time of these switches, the currents will decrease through feedback diodes D_3 and D_4.

Control of Brushless DC Motor Drives

- PWM voltage and current control mode:

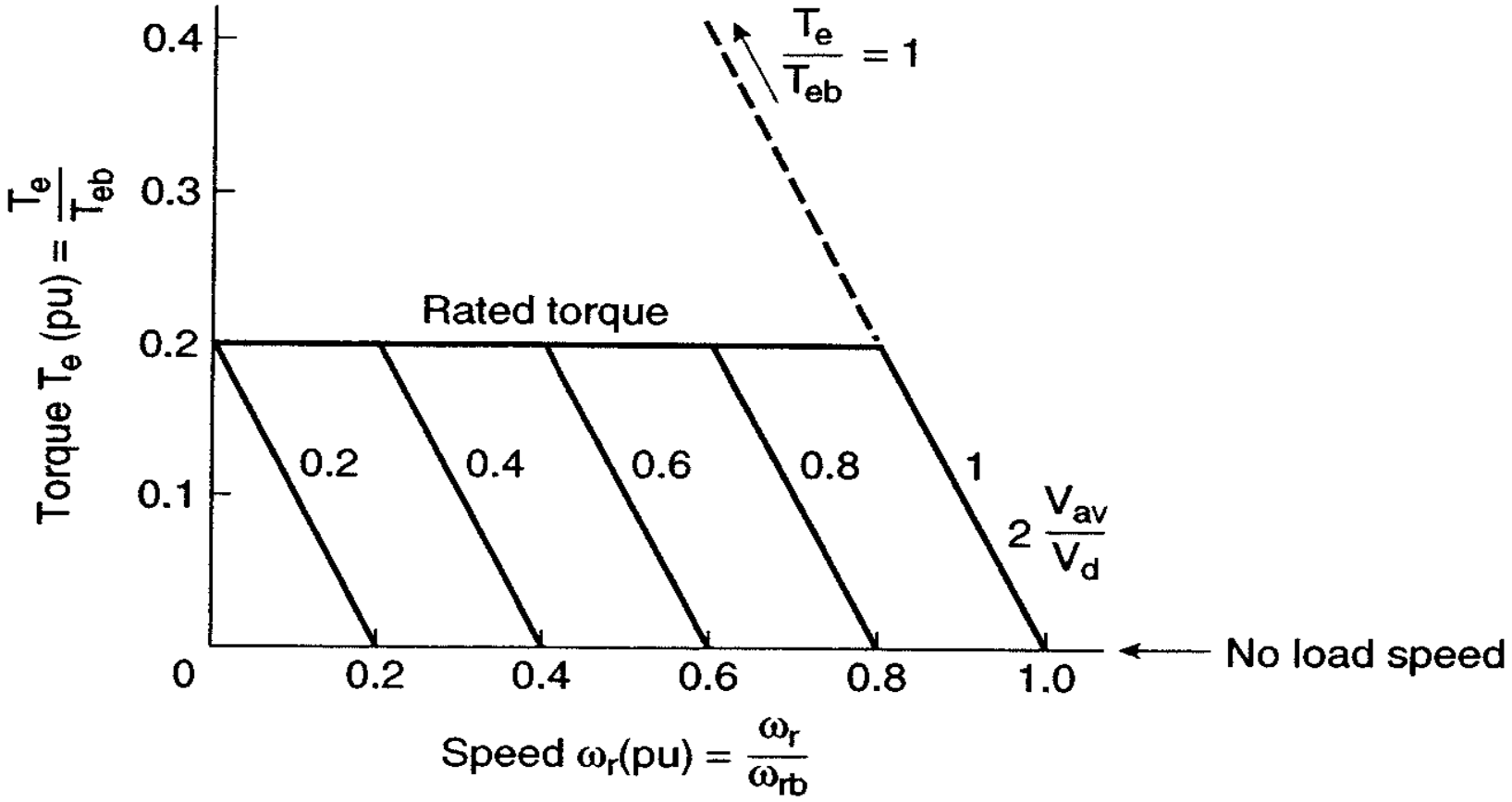
  - The average terminal voltage V_{av} will be determined by the duty cycle of the switches
  - In the freewheeling mode of operation, when Q_6 is turned on V_d is applied across a-b and the current increases.
  - When Q_6 is turned off, freewheeling current flows through Q_1 and D_3 (effectively short-circuiting the motor terminals) and the current decreases (due to the back emf).

Control of Brushless DC Motor Drives

- PWM voltage and current control mode :

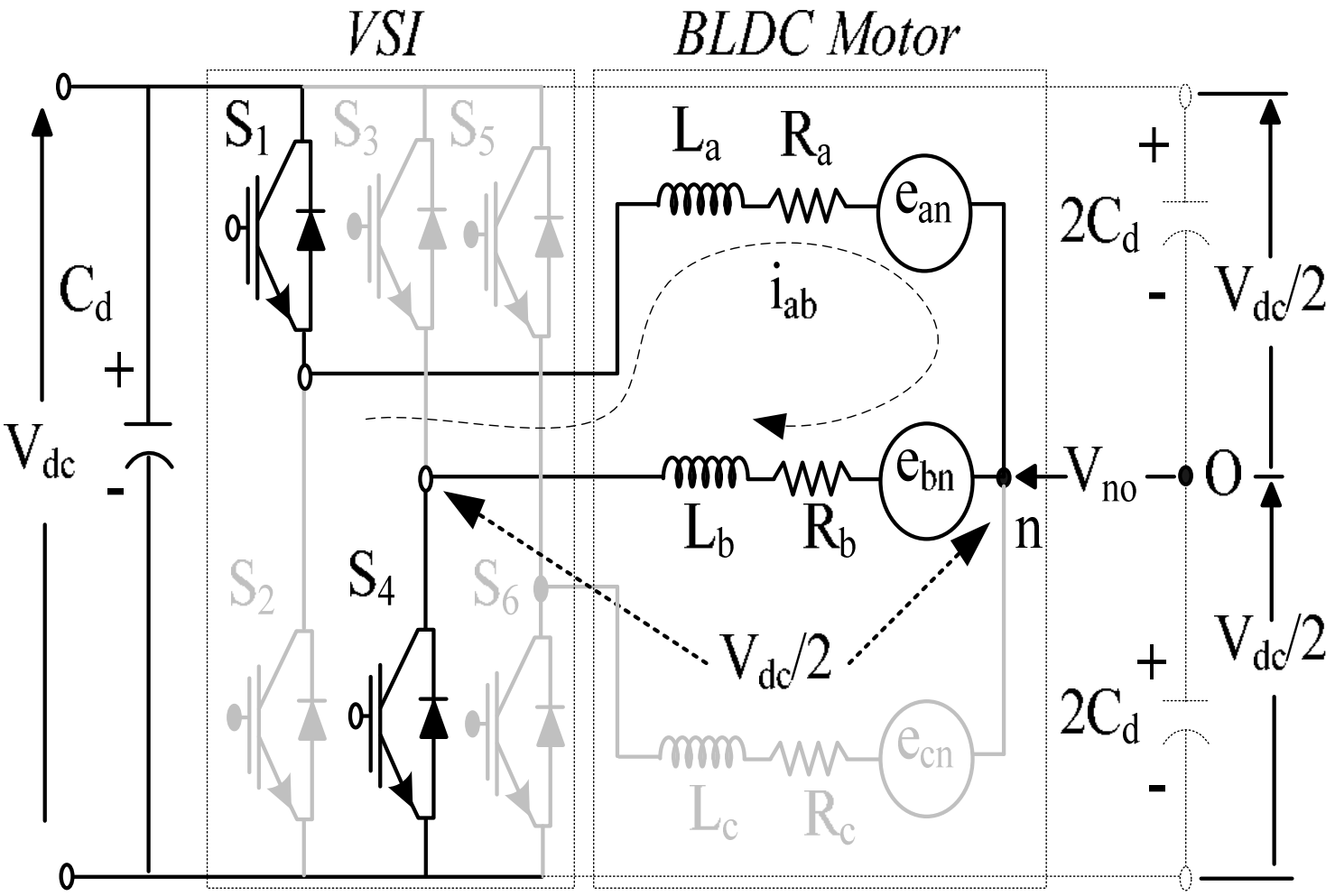
  - The back emf is proportional to rotor speed and is given by: $V_c = K \omega_r$
    where K is the back emf constant and ω_r is the mechanical rotor speed (P/2) ω_e
  - The steady state (dc) circuit equation for any switch combination is: $V_d = 2(R_s I_d + V_c)$
  - The torque expression can be rewritten as:
    $T_e = K P I_d = k_t I_d$ where P is no of poles
  - The base torque is defined as : $T_{base} = k_t I_d \mid I_d = I_{sc}$ where I_{sc} is short circuit current given by $V_d/2R_s$
  - Therefore, base torque $T_{base} = k_t V_d/2R_s$

Normalized Torque-Speed Characteristic of BLDC Motor Drives



The droop in the no-load speed is due to the voltage drop in stator resistance.

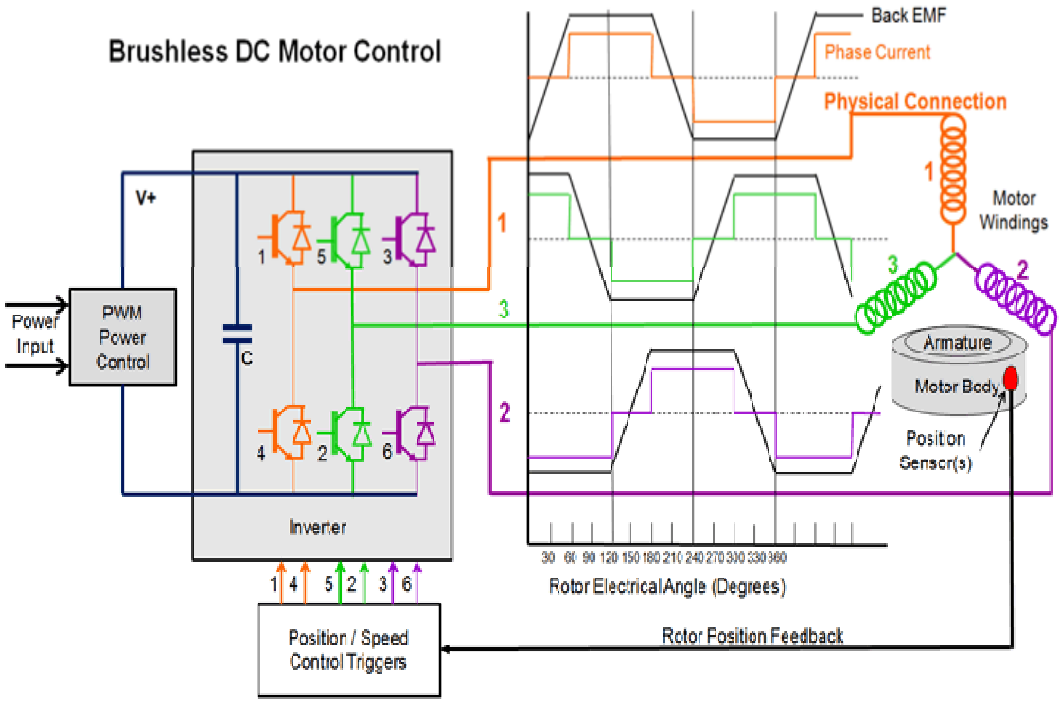
BLDC Motor Drive fed by a VSI



Control of PMBLDC Motor Drives

- Three Hall effect sensors are used to provide the rotor position feedback in the form of three 120º phase shifted square waves (in phase with voltage waves).
- There after a decoder generates six step current waveforms.
- The speed control loop generates I_d^* from the speed reference ω_r^*.
- The reference phase currents are then generated by the decoder.
- Hysteresis current control is used to control the phase currents to track the reference phase currents

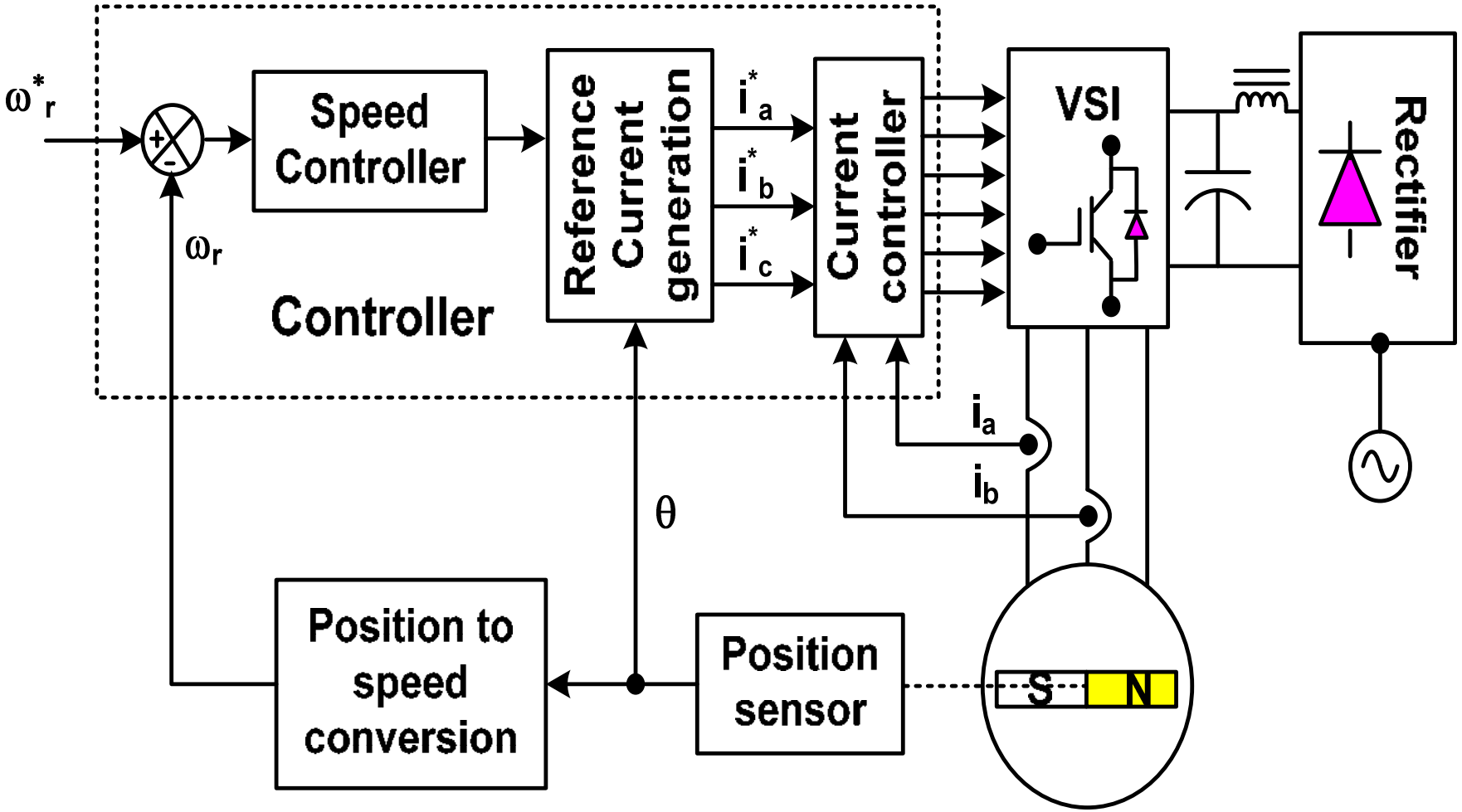
Switching Sequence of BLDC Motor Drives



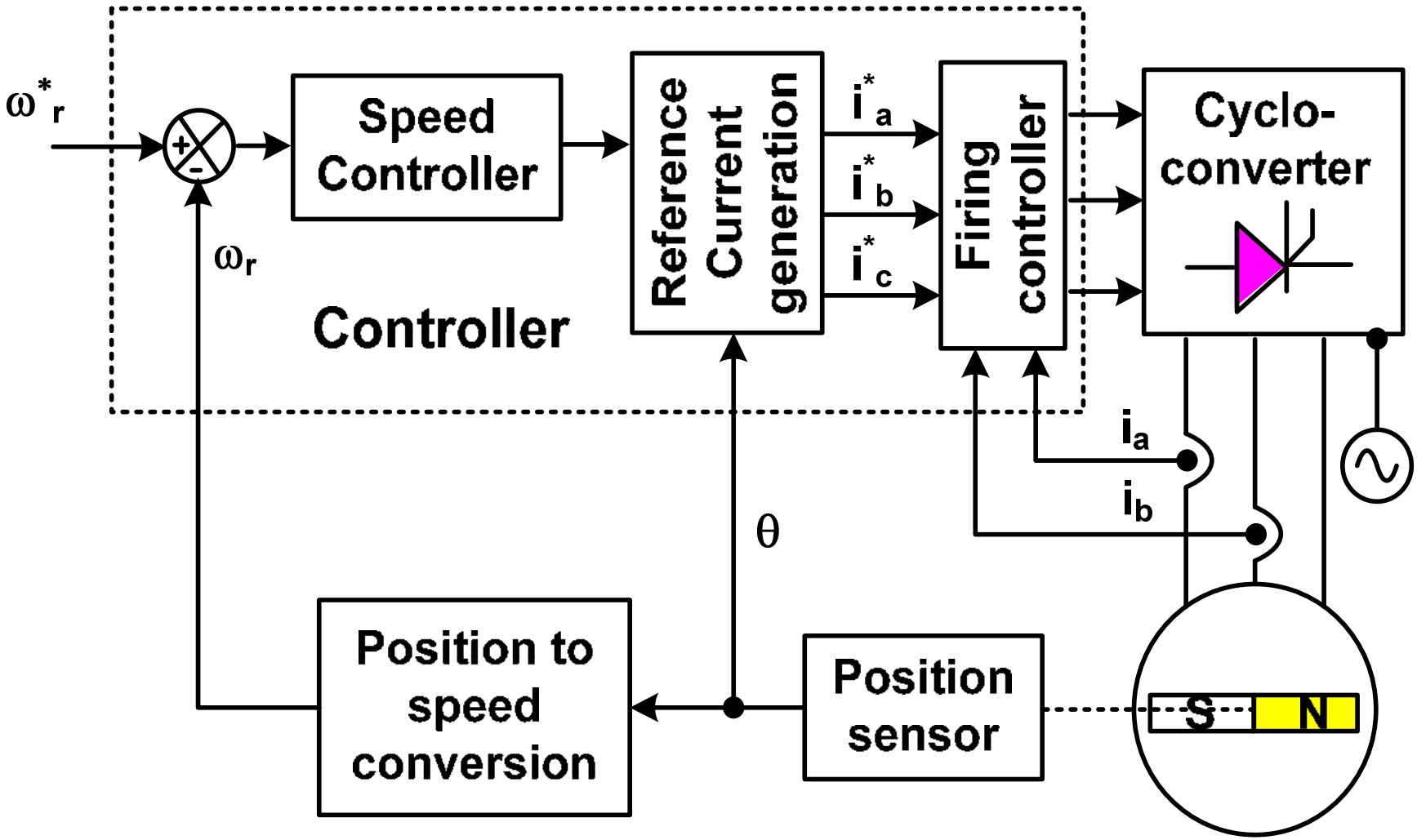
$\theta\,(^0)$	*Hall Signal*			*Switching Sequence*					
	H_a	H_b	H_c	S_1	S_2	S_3	S_4	S_5	S_6
NA	0	0	0	0	0	0	0	0	0
0-60	0	0	1	1	0	0	0	0	1
60-120	0	1	0	0	1	1	0	0	0
120-180	0	1	1	0	0	1	0	0	1
180-240	1	0	0	0	0	0	1	1	0
240-300	1	0	1	1	0	0	1	0	0
300-360	1	1	0	0	1	0	0	1	0
NA	1	1	1	0	0	0	0	0	0

Closed Loop Control of BLDC Motor Drives

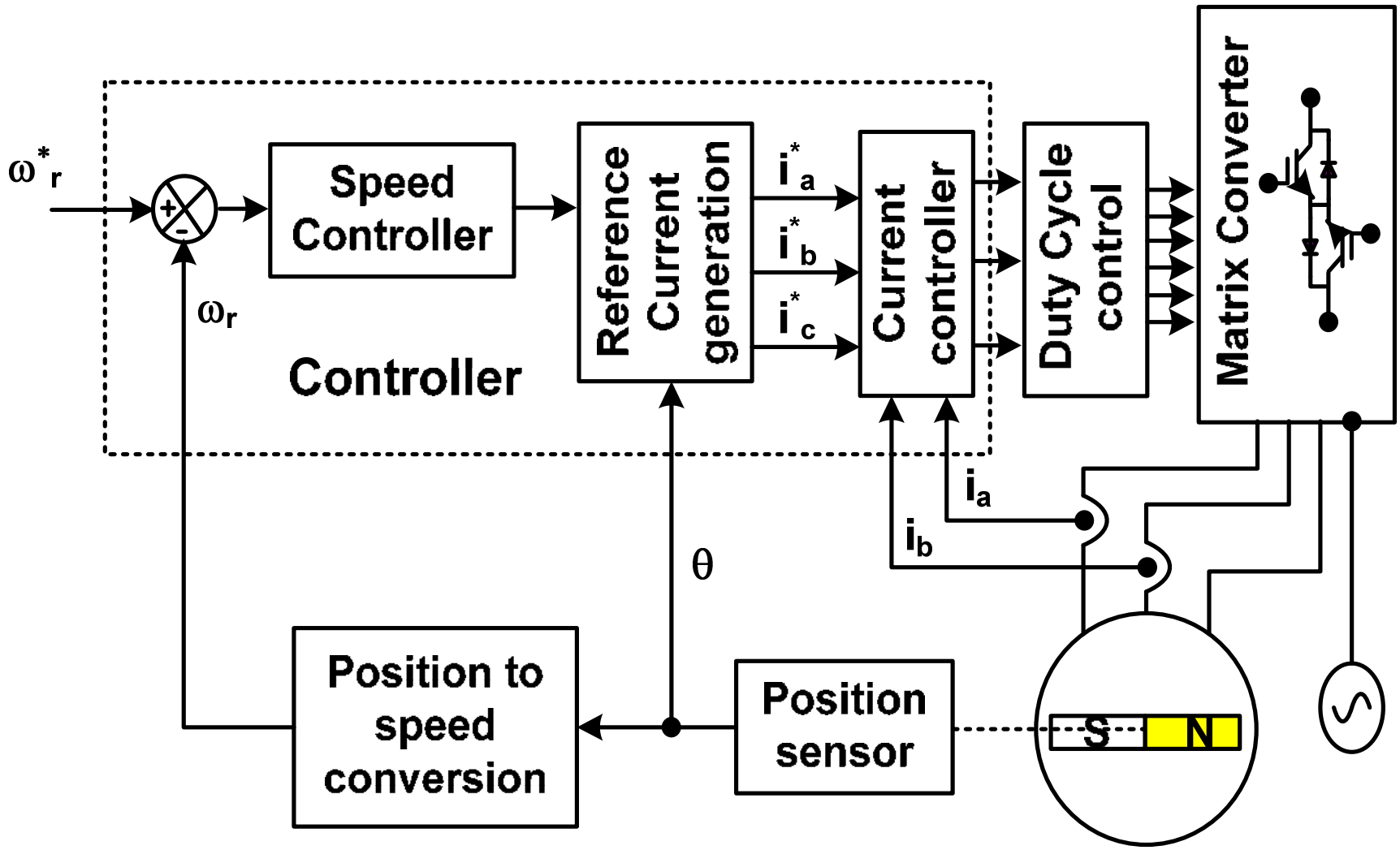
VSI fed BLDC Motor Drive



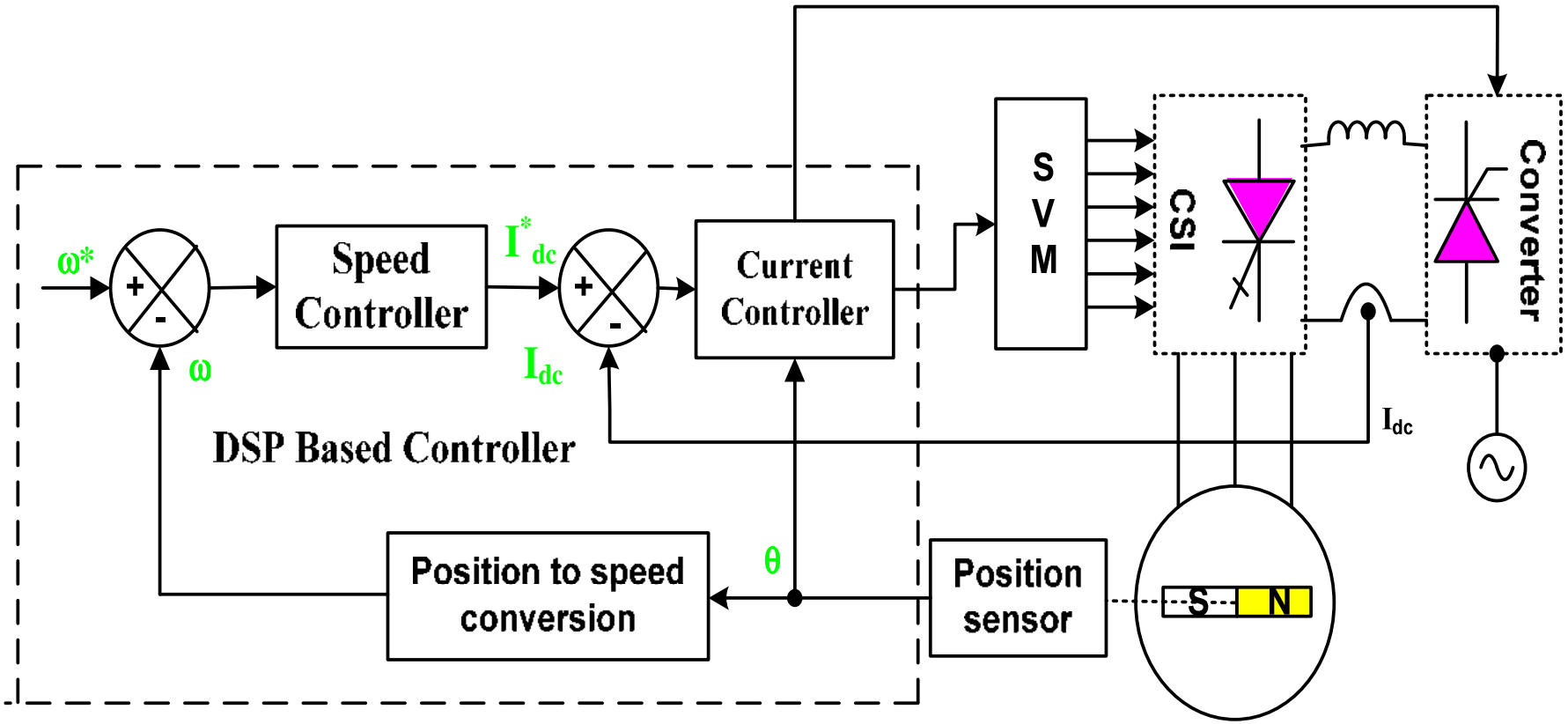
Cycloconverter fed PMBLDCM Drive



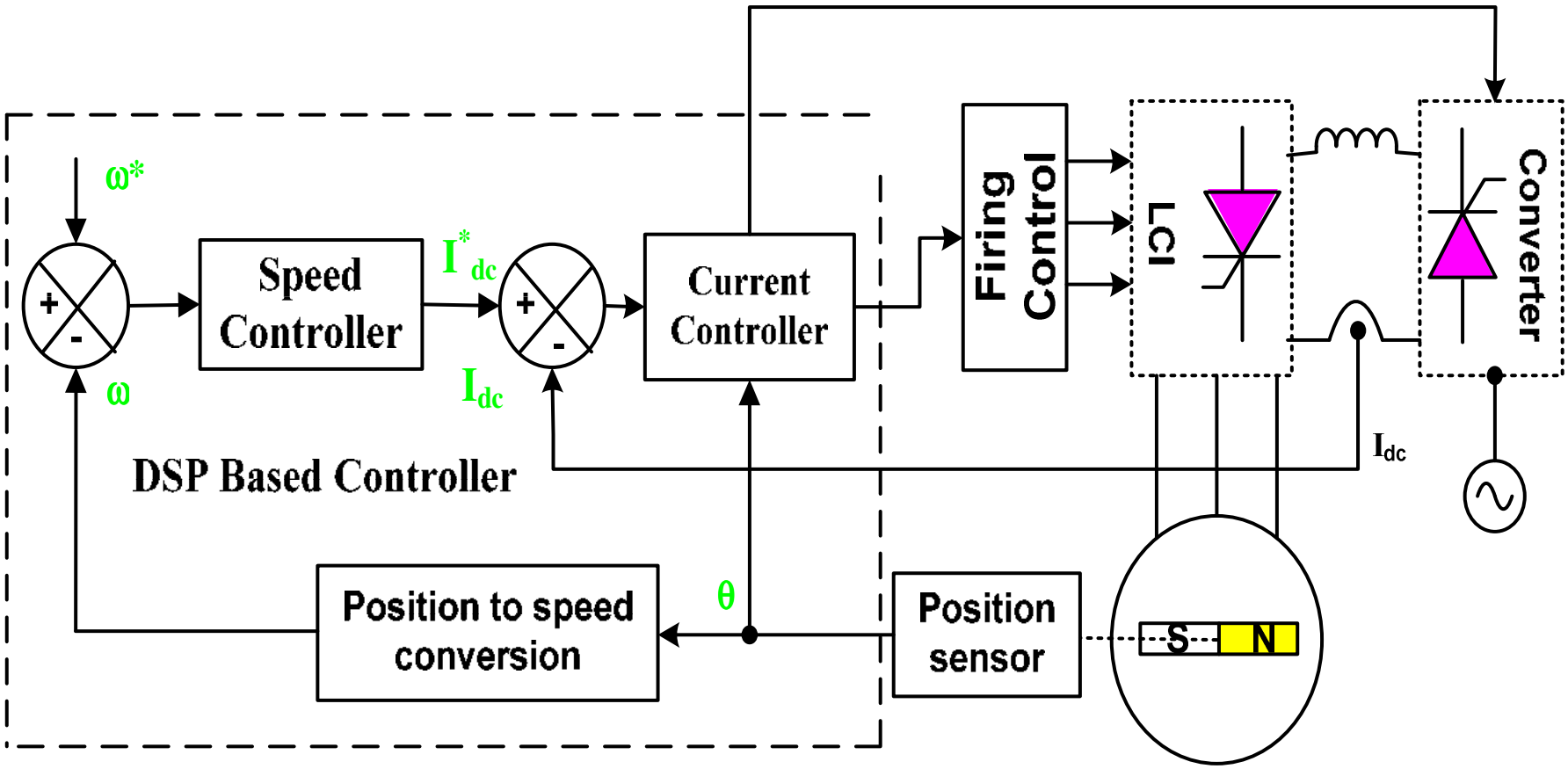
Matrix Converter fed PMBLDCM Drive



CSI fed PMBLDCM Drive

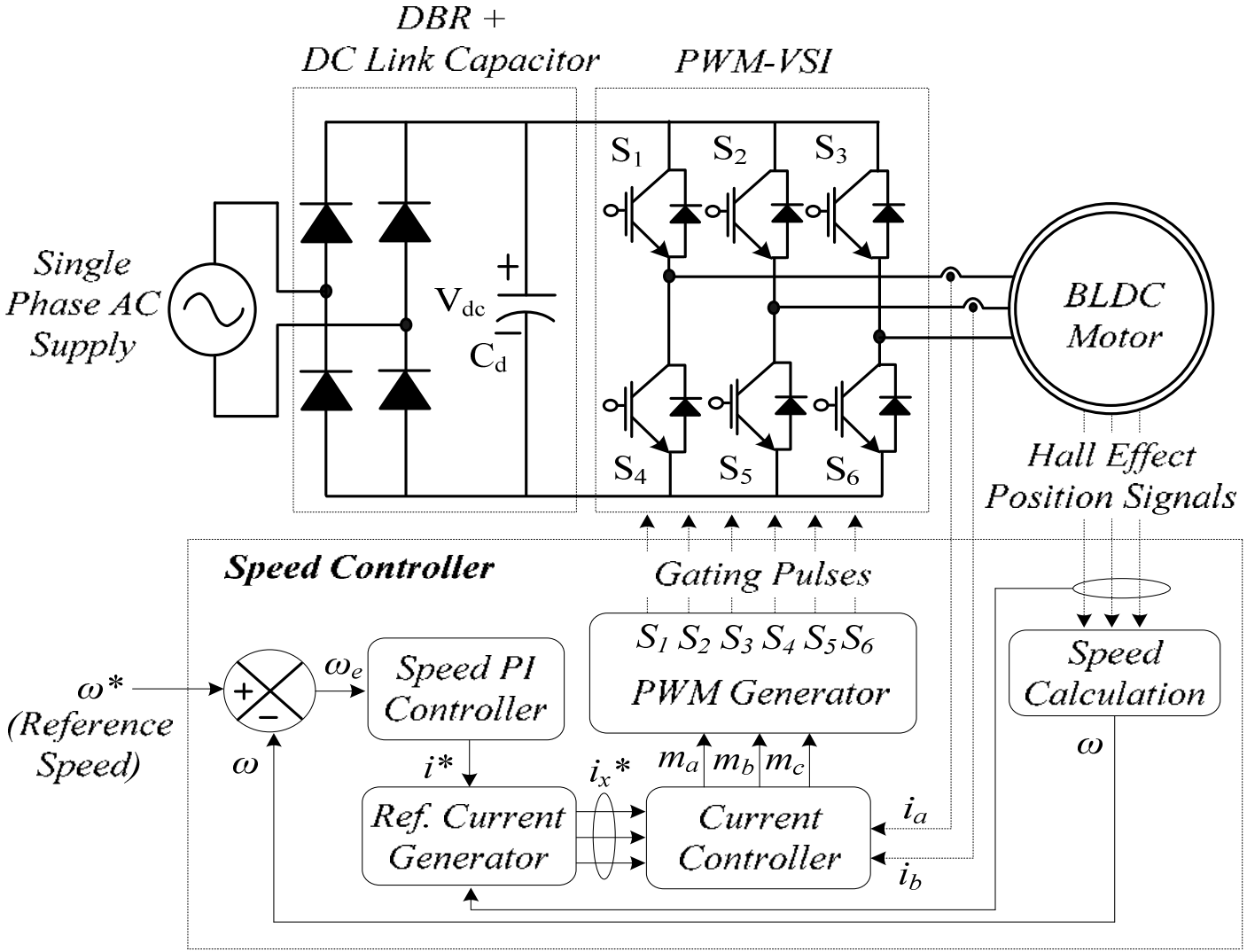


LCI fed PMBLDCM Drive

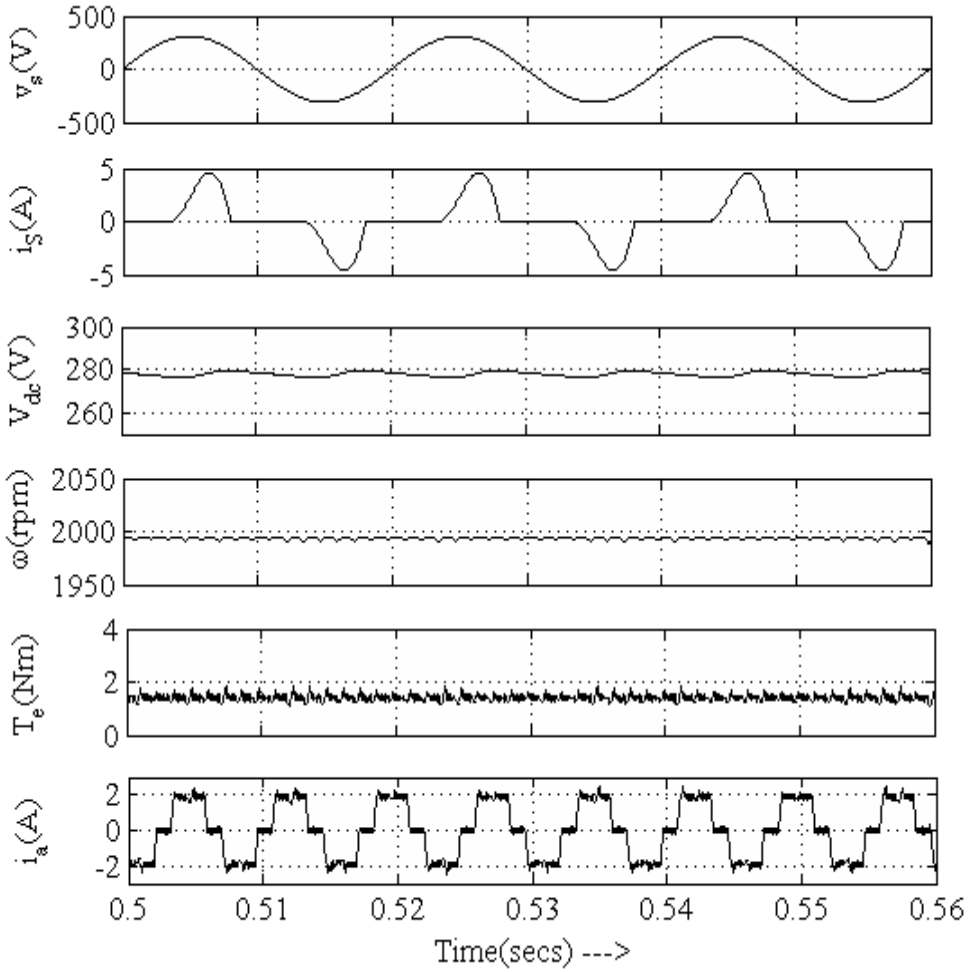


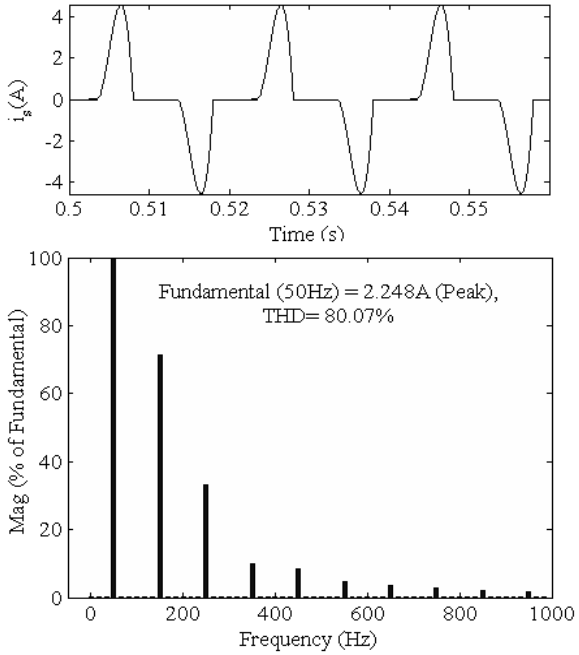
Conventional BLDC Motor Drive and its Power Quality Aspects

Conventional DBR Fed BLDC motor drive with speed control



Steady state performance and harmonic spectra of supply current at AC mains for Conventional Scheme

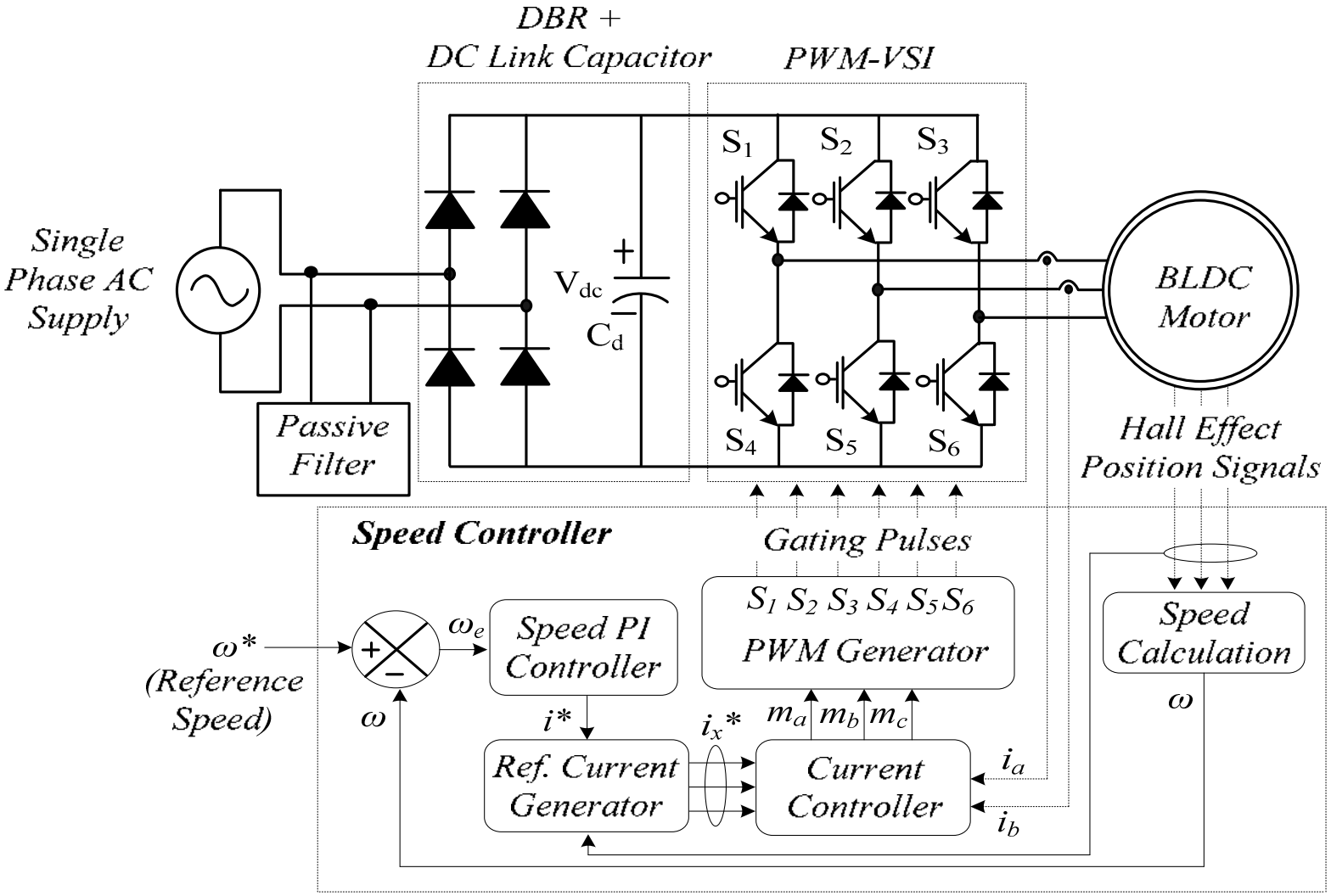




Disadvantages of conventional BLDC motor drive with speed control

- Very high amount of harmonics in the supply current
- THD (Total Harmonic Distortion) of supply current as high as 80% (Not acceptable by IEC 61000-3-2)
- PF (Power Factor) as low as 0.75
- Speed control using a PWM based VSI (Voltage Source Inverter) having high switching losses
- Large number of sensing requirement

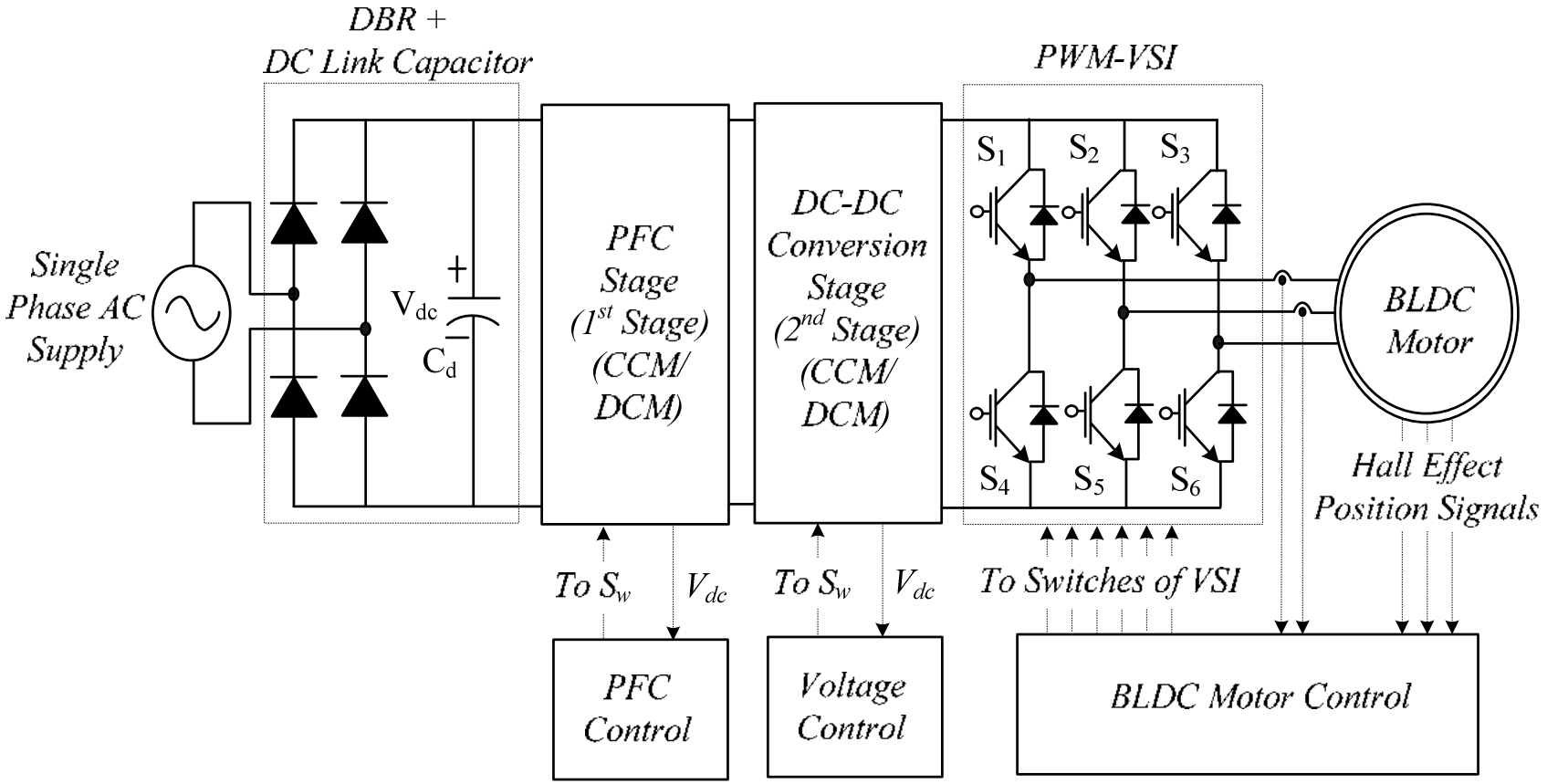
Conventional BLDC motor drive for speed control with passive power factor correction



Disadvantages of a conventional BLDC motor drive with speed control with passive power factor correction

- Bulky inductors in passive filter due to its operation at line frequency (50/60 Hz)
- Problem of high harmonics and low efficiency at light loading conditions
- Speed control using a PWM based VSI (Voltage Source Inverter) having high switching losses
- Large number of sensing requirement

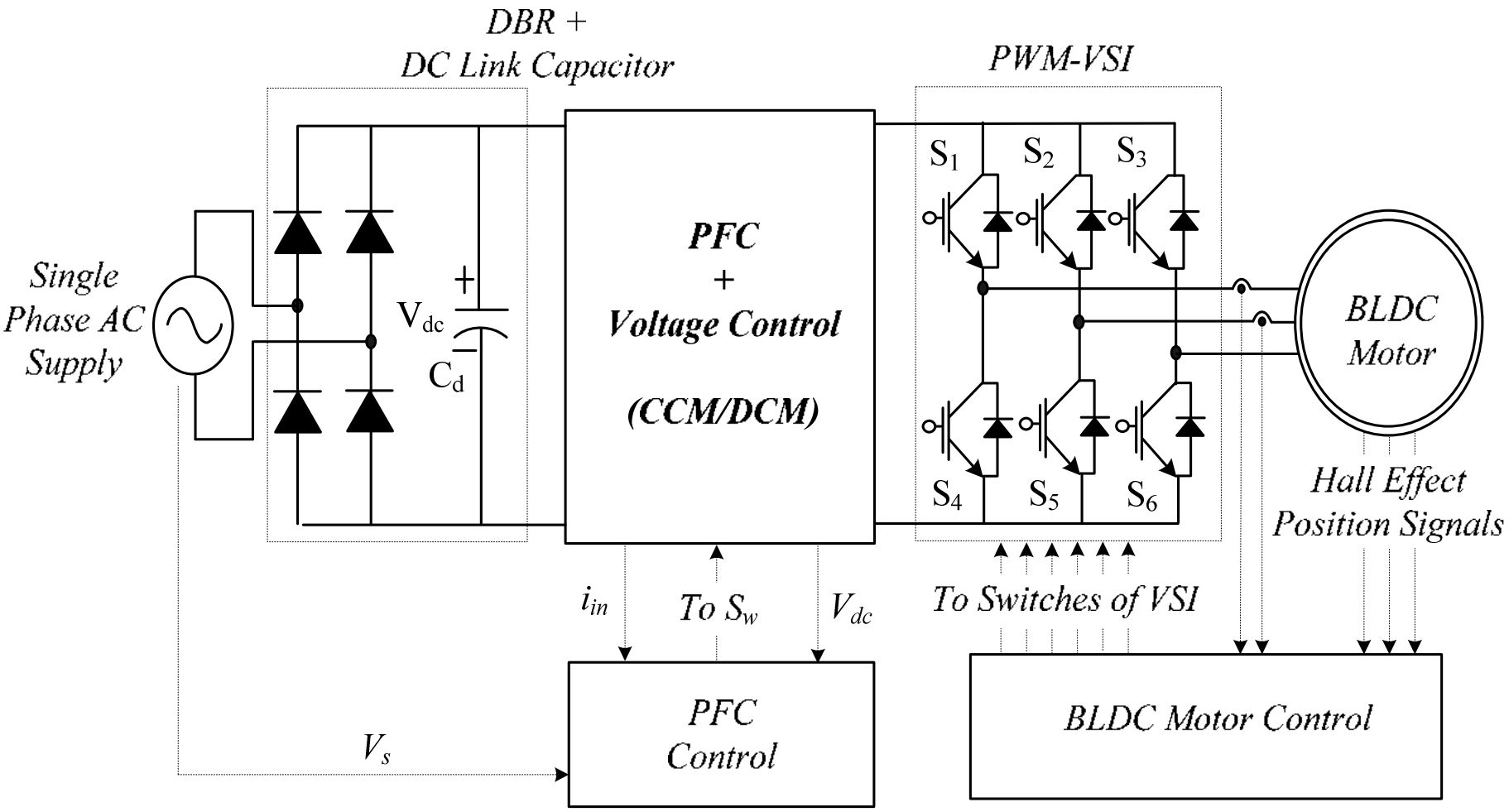
Conventional BLDC motor drive with two stage power conversion (PFC + Voltage Control) speed control



Disadvantages of conventional BLDC motor drive with two stage power conversion (PFC + Voltage Control) speed

- Higher losses in Multi-Stage power conversion
- Higher number of components which leads to higher cost
- Independent control for PFC, voltage control and BLDC motor
- Much higher amount of sensing requirement in two stage of power conversion

A BLDC Motor Fed by a Single Stage power Converter



Single Stage Power Conversion with Speed Control using a Variable DC Link Voltage

- Lower losses in a Single-Stage power conversion
- Less number of components which leads to lower cost
- Speed control by controlling the DC link voltage of VSI
- Fundamental frequency switching of VSI; hence low switching losses
- Very less amount of sensing requirement.

Choice of Mode of Operation of a PFC Converter

CCM
(Continuous Conduction Mode)

Current Multiplier Approach

Require sensing of DC Link Voltage (V_{dc}), Supply Voltage (V_s) and Inductor Current (I_{in})

Lower Stress on PFC Converter Switch

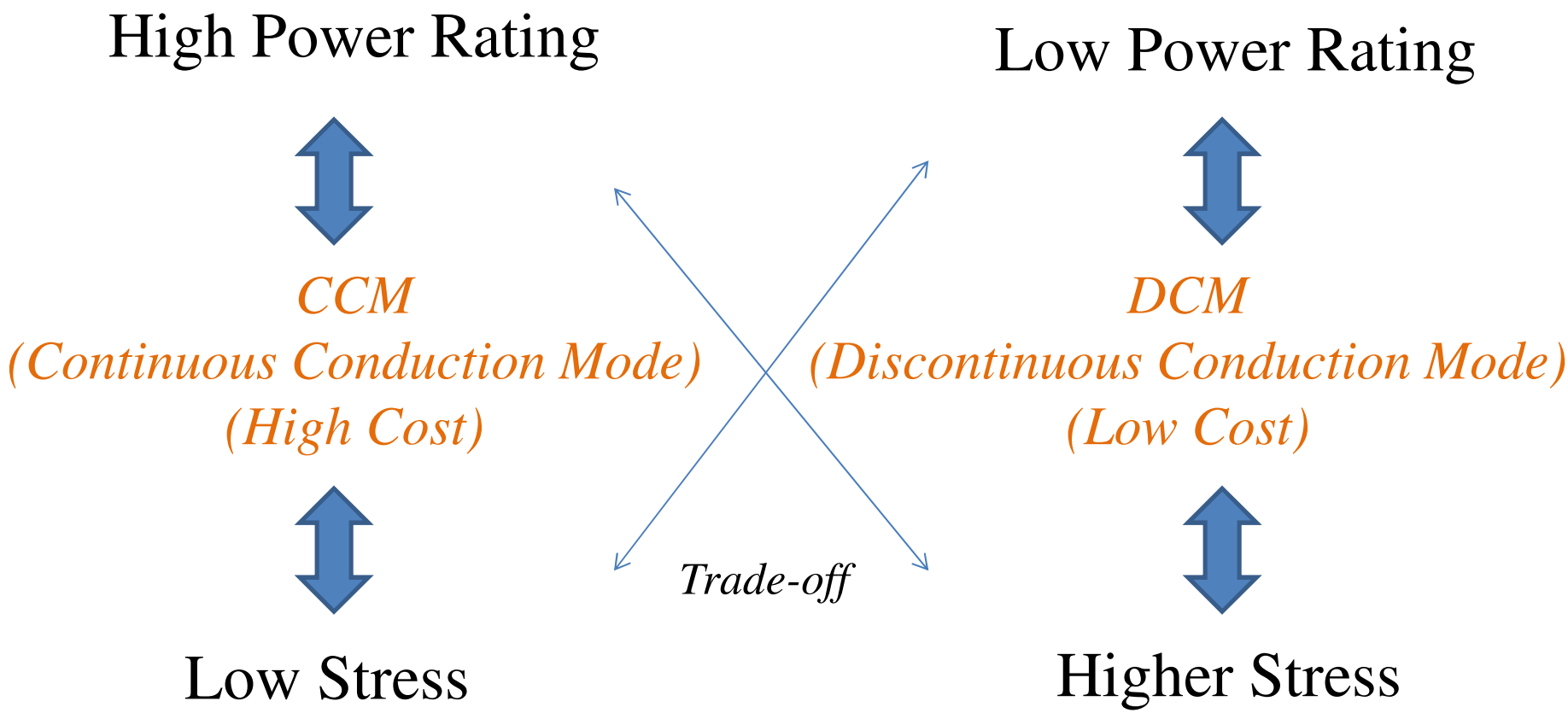
DCM
(Discontinuous Conduction Mode)

Voltage Follower Approach

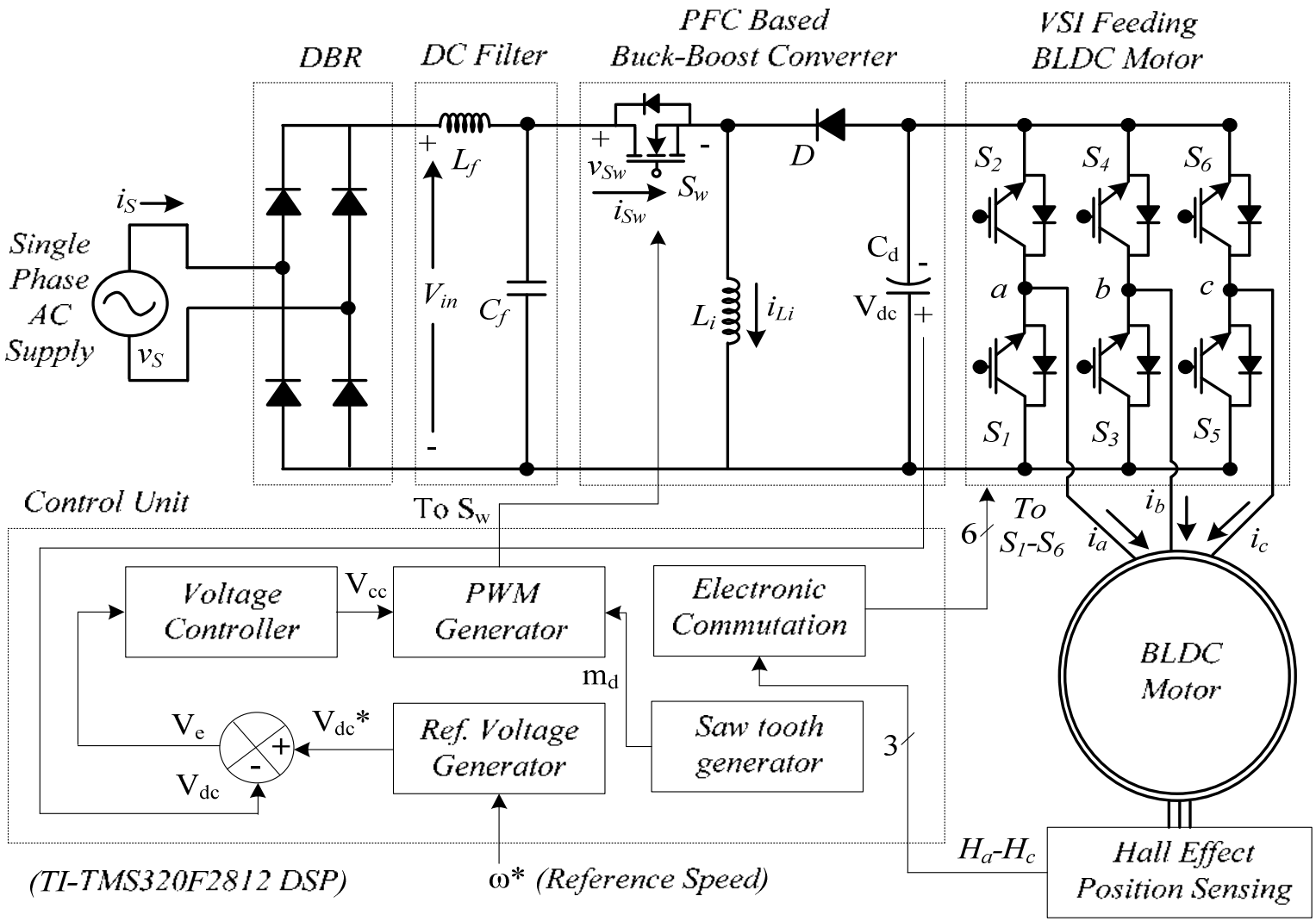
Require sensing of DC Link Voltage (V_{dc}) only. Inherent PFC

Higher Stress on PFC Converter Switch

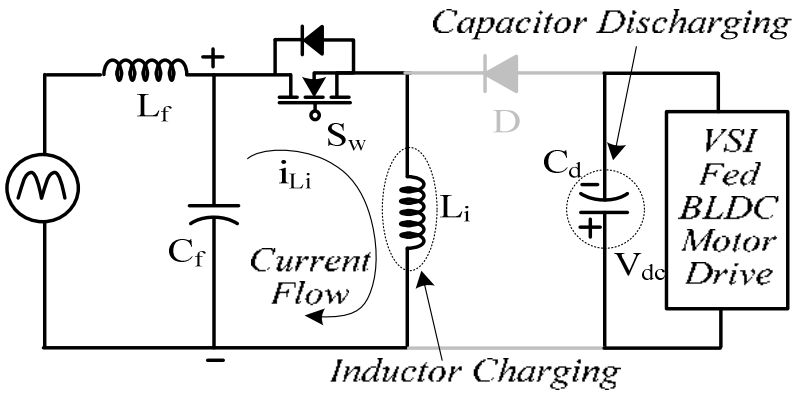
Choice of Mode of Operation of a PFC Converter



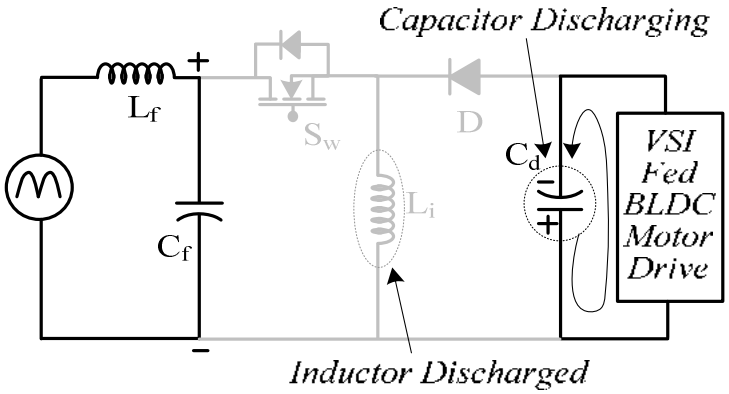
A PFC Based BLDC motor drive using PFC Buck-Boost Converter



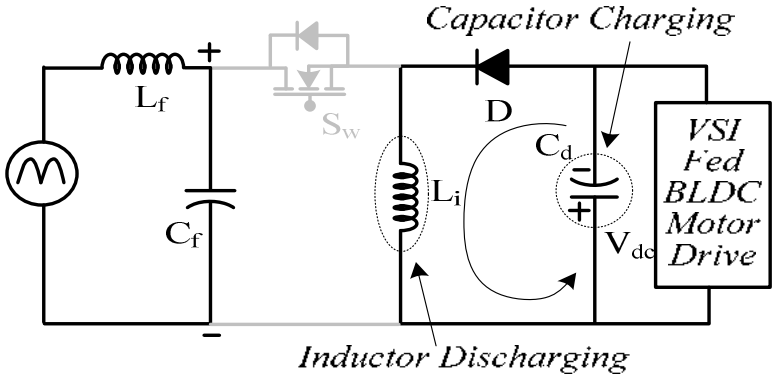
Operation of PFC Buck-Boost Converter



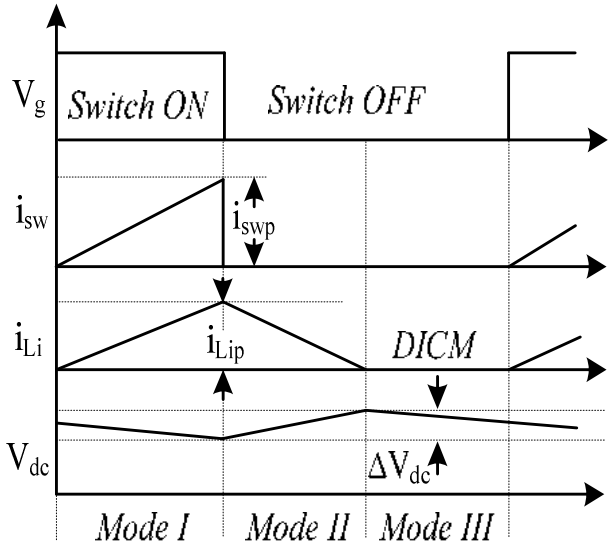
Mode I



Mode III



Mode II



Design of a PFC Buck-Boost Converter

The average input voltage appearing to input of converter

$$V_{in} = \frac{2\sqrt{2}V_s}{\pi}$$

The voltage conversion ratio is given as,

$$V_o = \frac{D}{1-D}V_{in}$$

Inductor Operating in CCM

$$L_i = \frac{V_{in}D}{f_S \Delta i_{Li}}$$

Inductor Operating in DCM

$$L_i << L_{ic} = \frac{R(1-D)^2}{2f_S}$$

DC Link Capacitor Design

$$C_d = \frac{I_d}{2\omega\Delta V_{dc}}$$

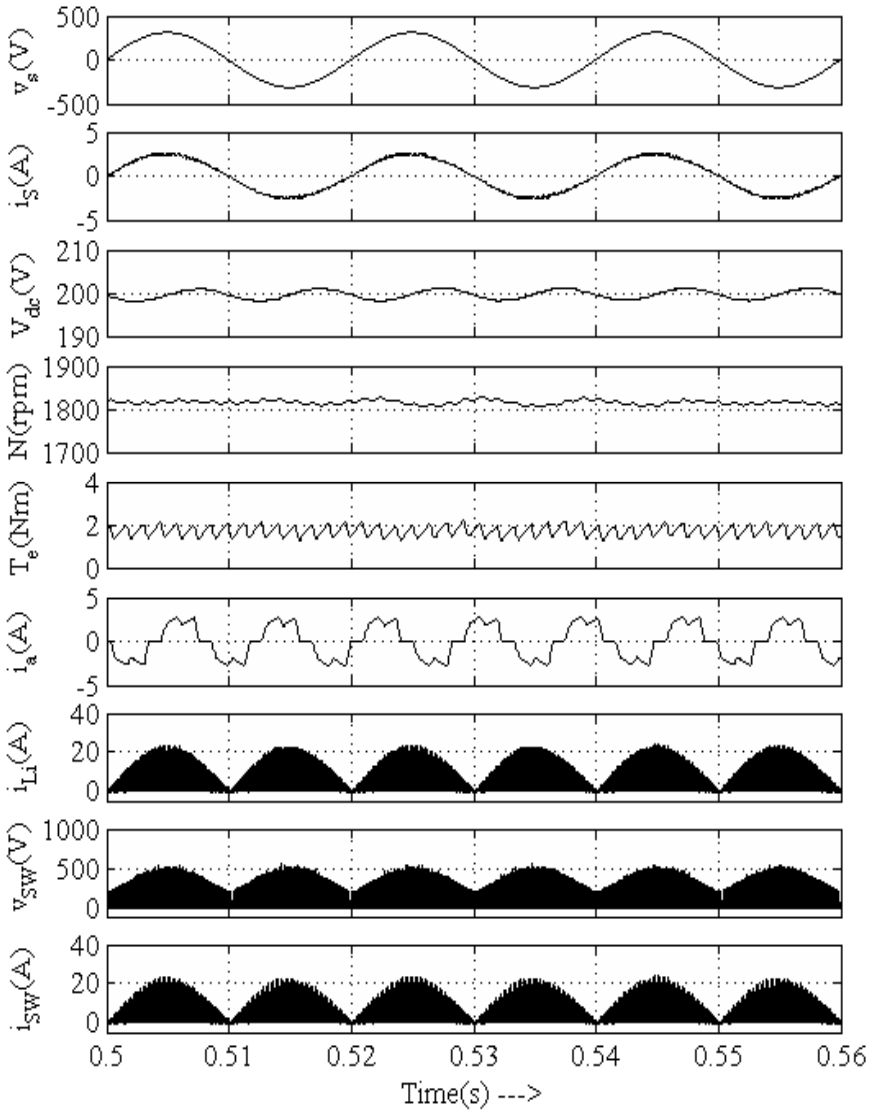
Simulation Results- Steady State Performance

V_s= 220V

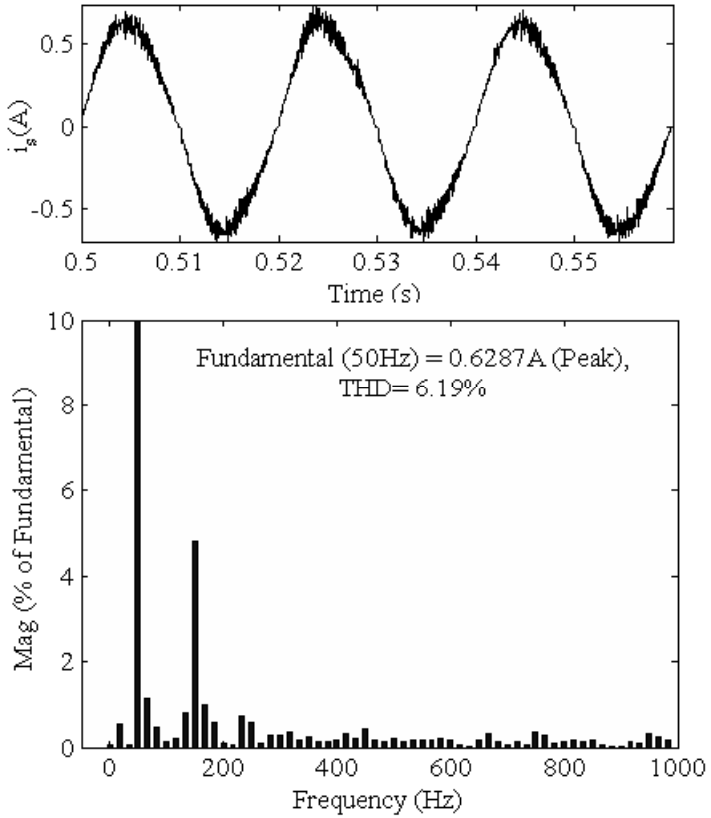
V_{dc}=200V

P_o= 400W

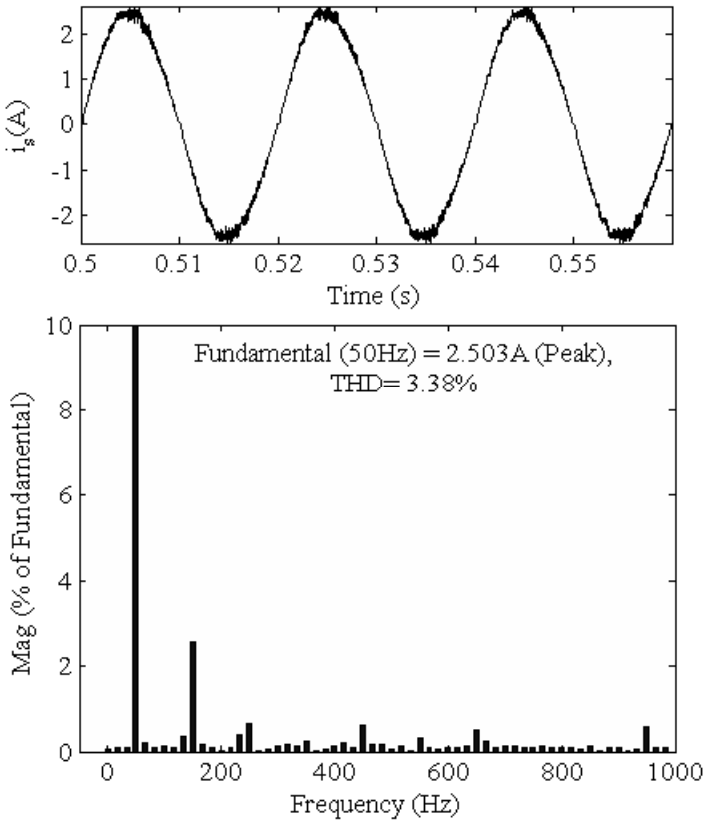
f_S=20kHz



Simulation Results- Harmonic Spectra of supply Current at different value of DC link voltage (Speed Control)

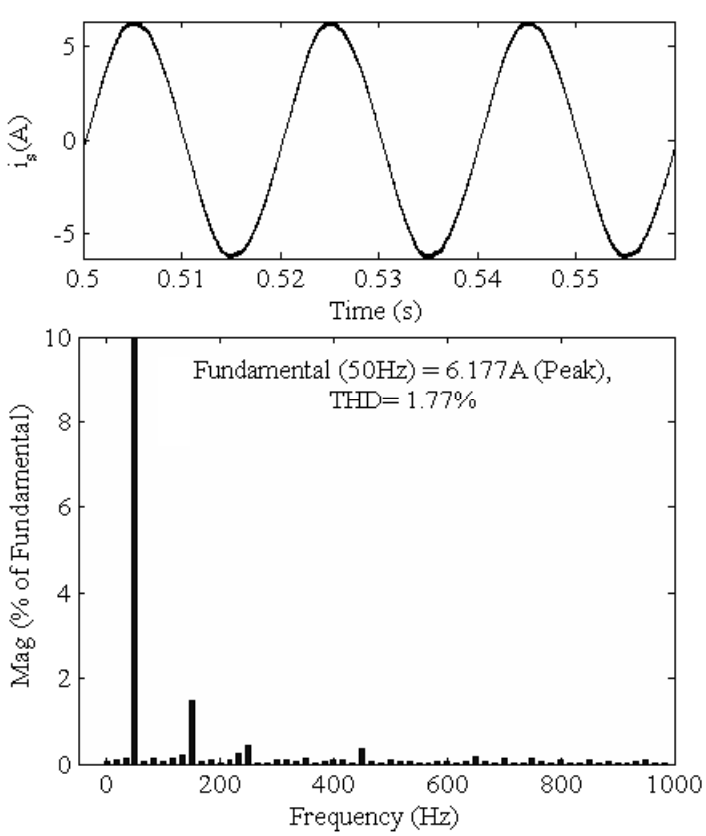


At rated load on BLDC motor with supply voltage as 220V and DC link voltage as 50V

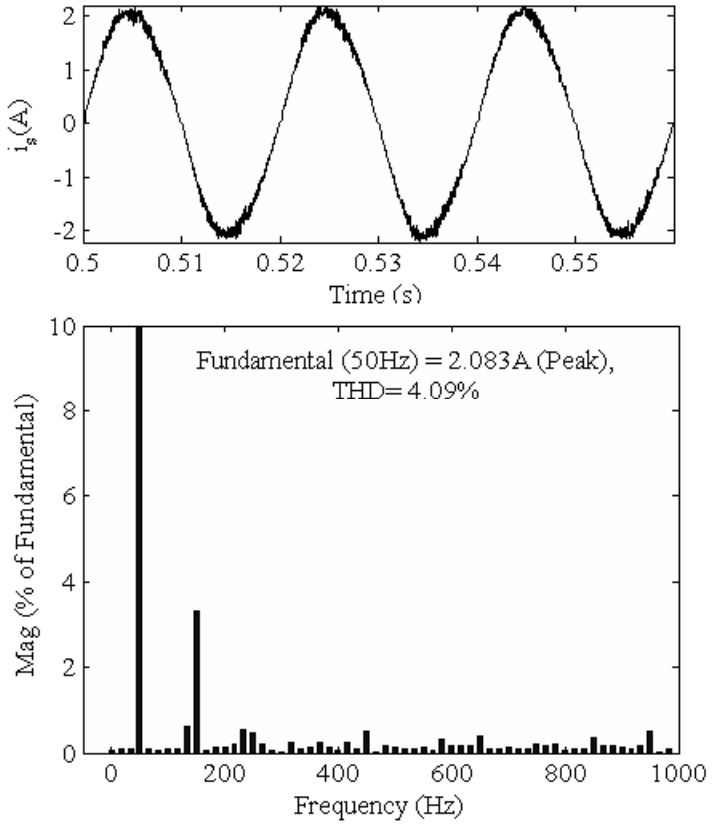


At rated load on BLDC motor with supply voltage as 220V and DC link voltage as 200V

Simulation Results- Harmonic Spectra of supply Current at different value of Supply Voltage (Universal Mains)

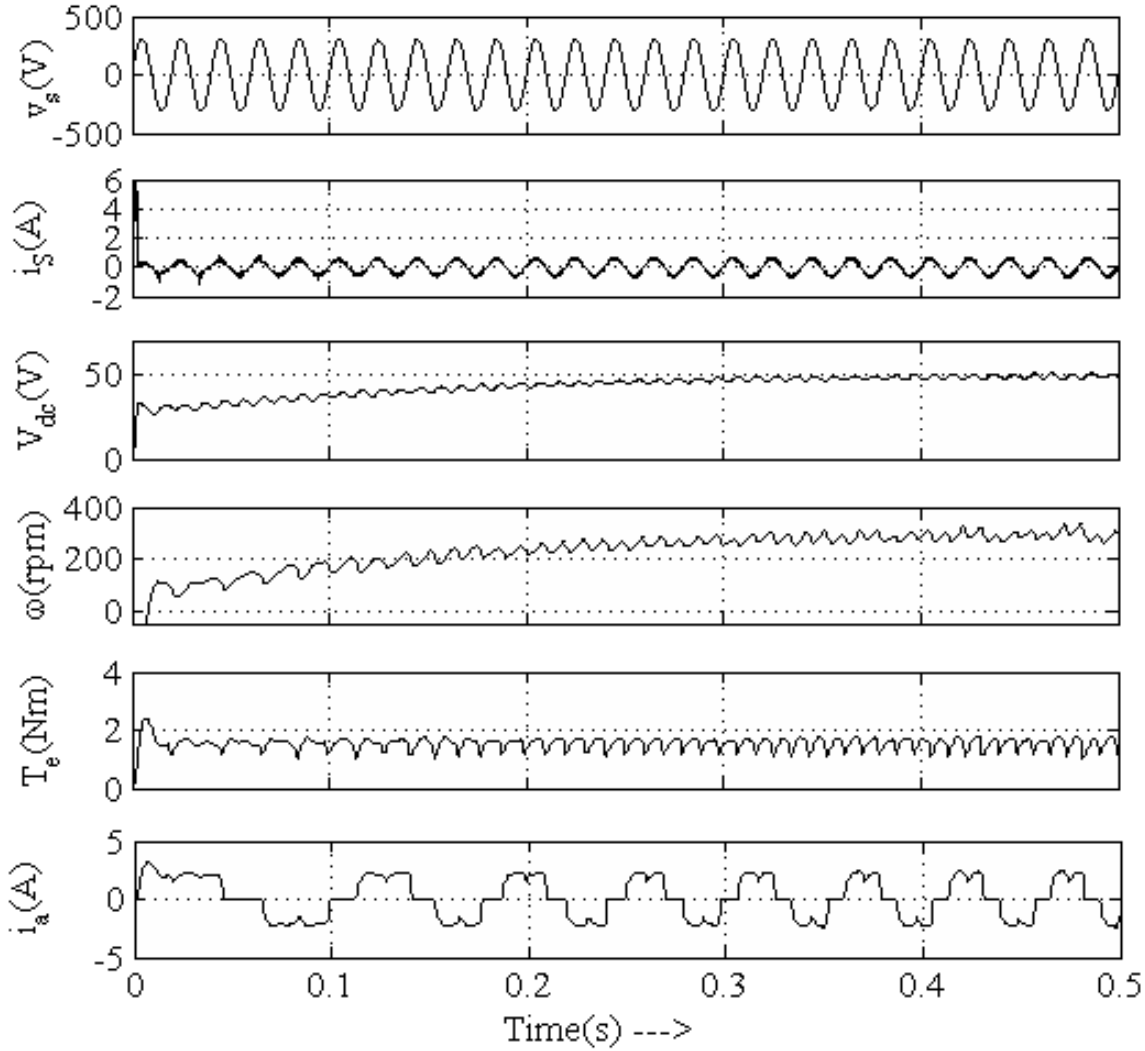


At rated load on BLDC motor with supply voltage as 90V and DC link voltage as 200V

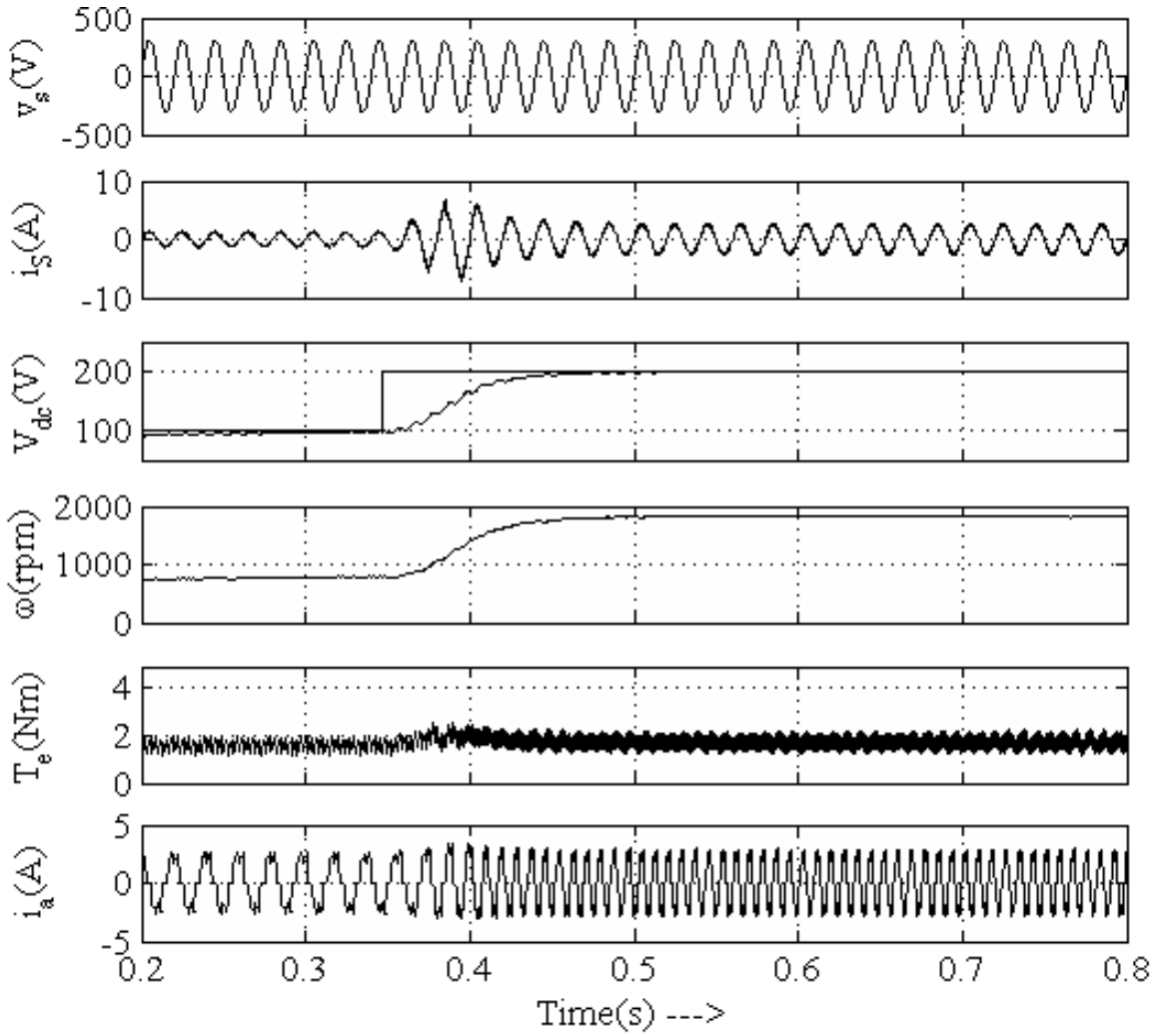


At rated load on BLDC motor with supply voltage as 265V and DC link voltage as 200V

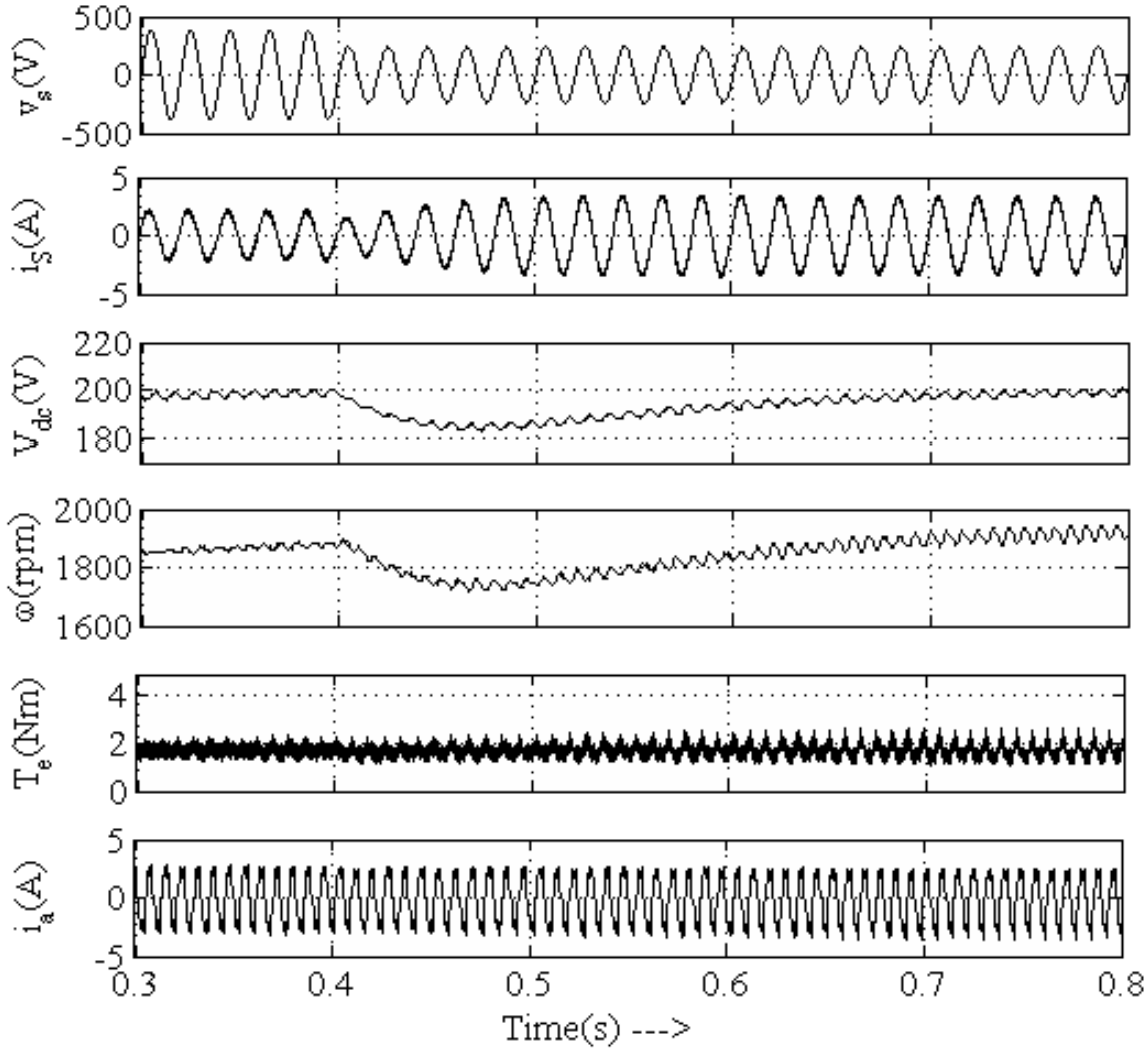
Simulation Results- Dynamic behaviour during starting



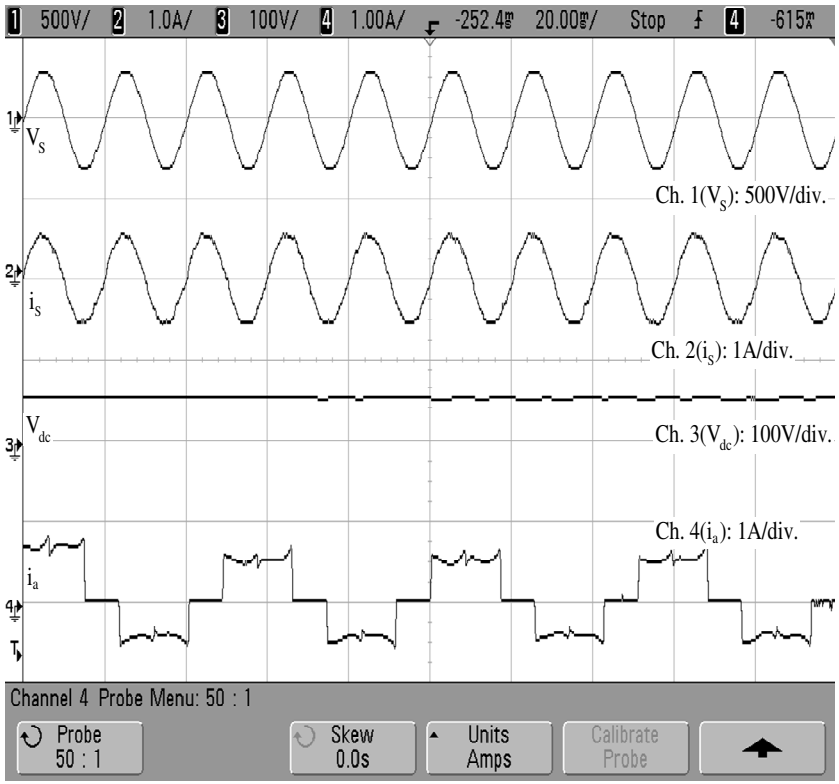
Simulation Results- Dynamic behaviour during Speed Control



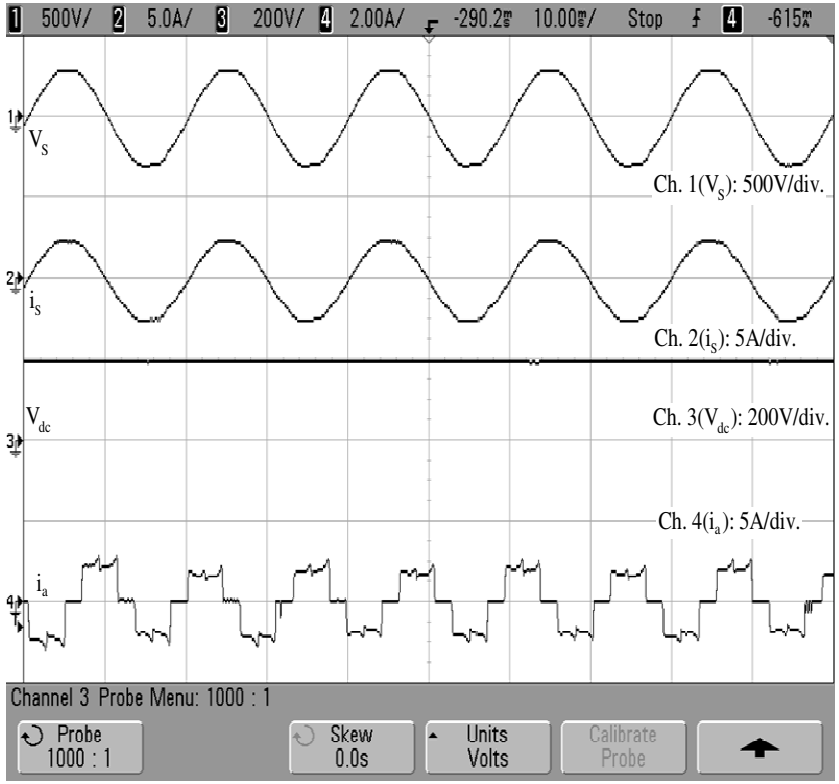
Simulation Results- Dynamic behaviour during supply voltage fluctuation



Experimental Results- Steady state behaviour

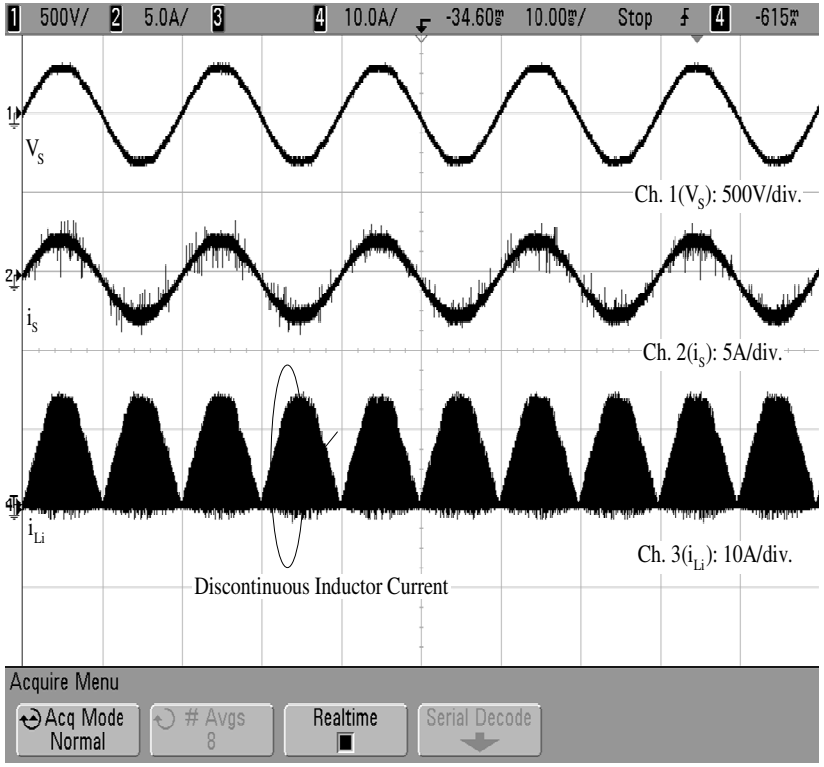


At rated load on BLDC motor with supply voltage as 220V and DC link voltage as 50V

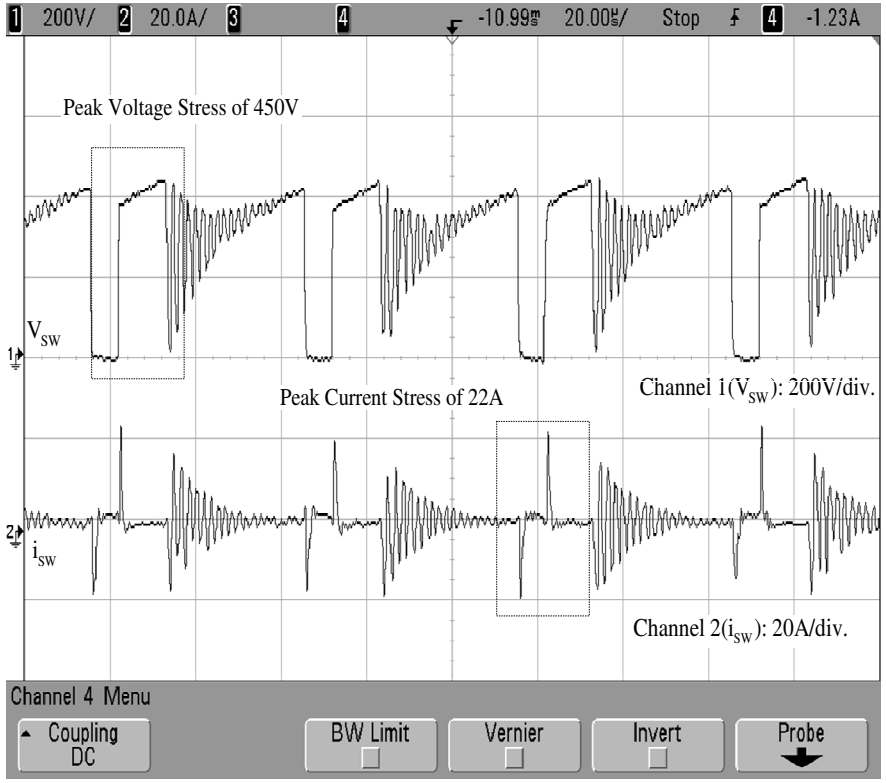


At rated load on BLDC motor with supply voltage as 220V and DC link voltage as 200V

Experimental Results- PFC Operation

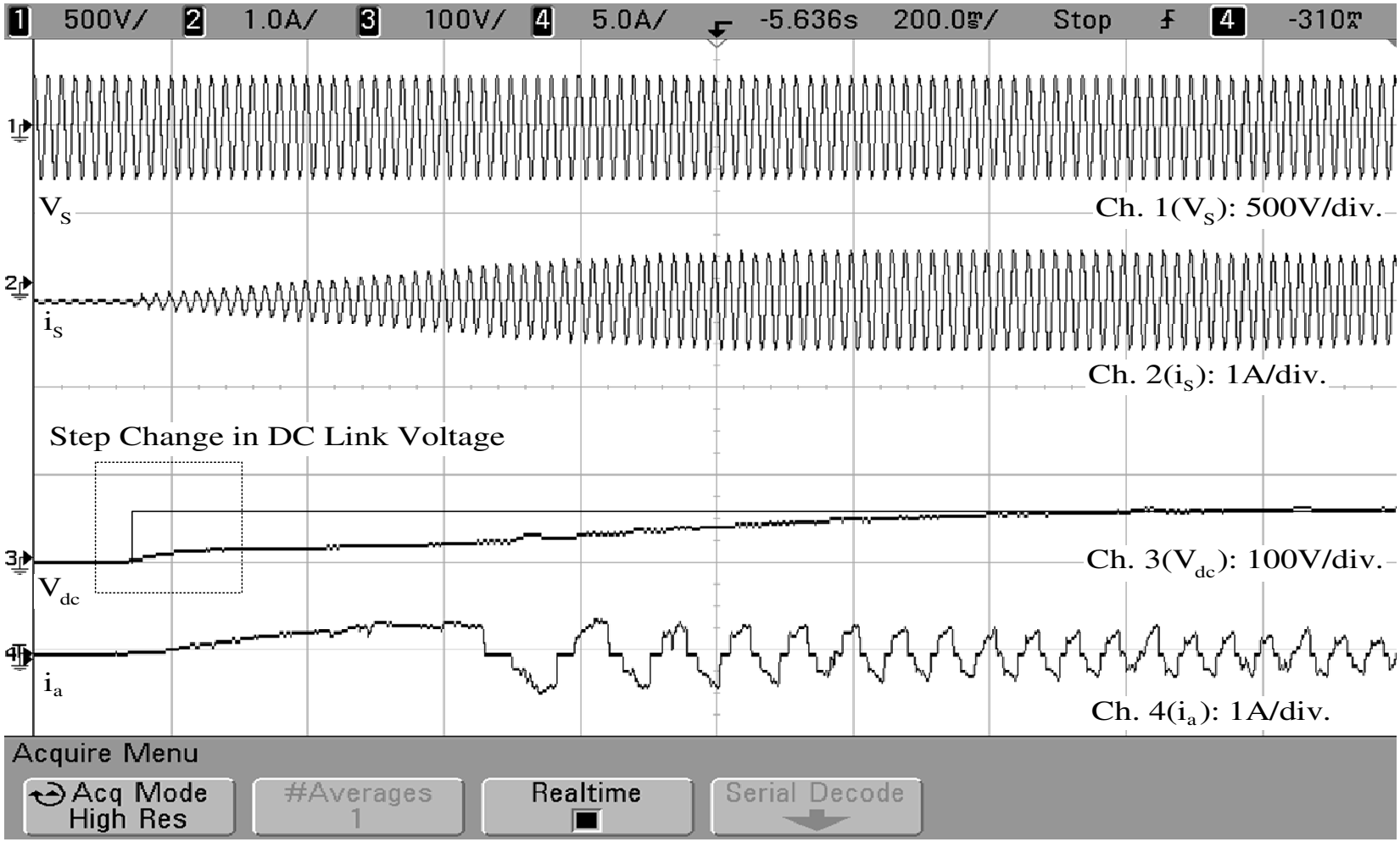


Inductor Current variation with supply voltage and supply current

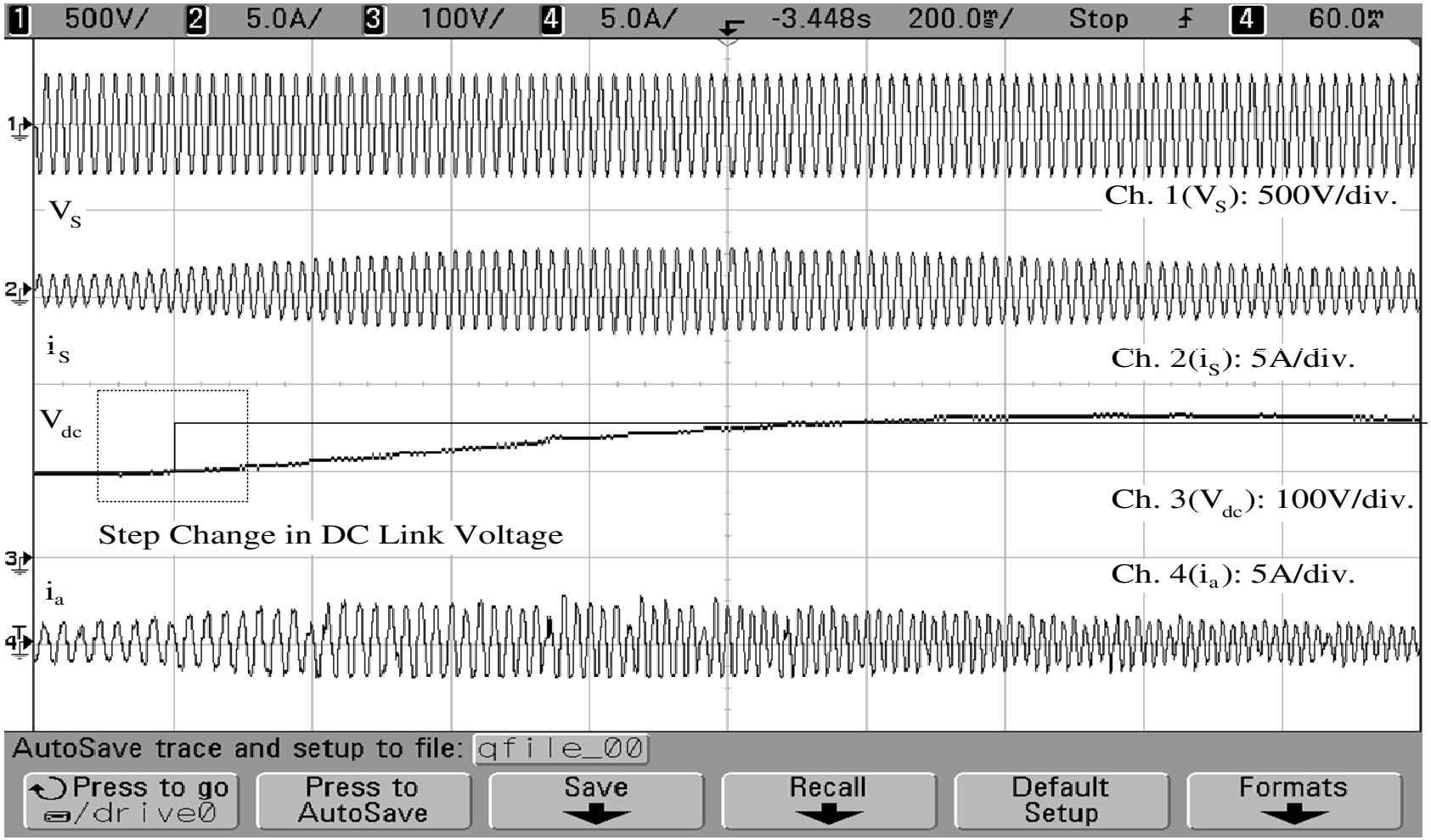


Stresses on Switch of PFC converter

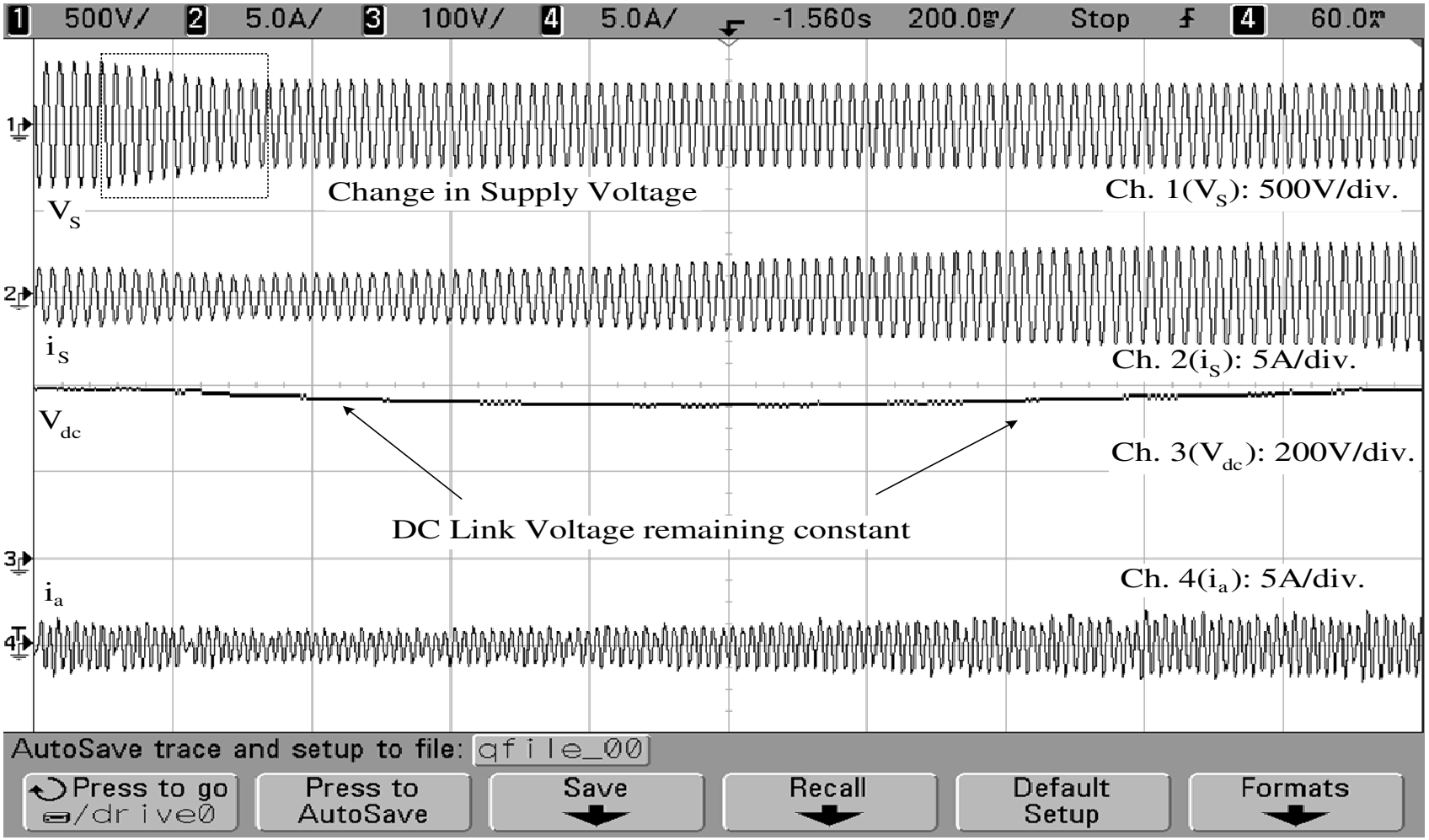
Experimental Results- Dynamic behaviour during starting



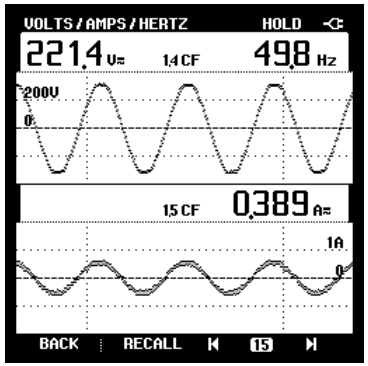
Experimental Results- Dynamic behaviour during speed control

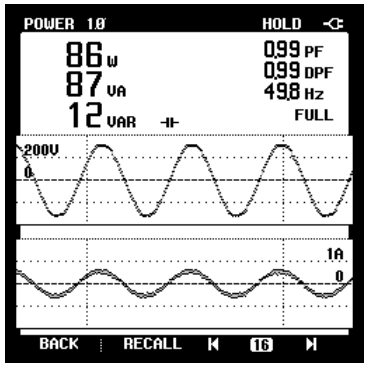


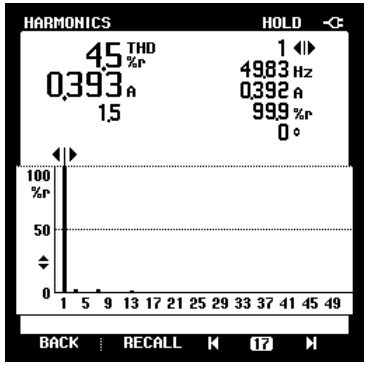
Experimental Results- Dynamic behaviour during supply voltage fluctuation



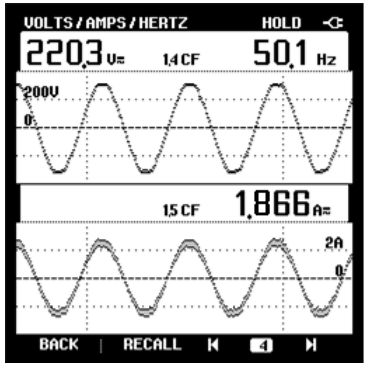
Experimental Results- Power Quality Indices

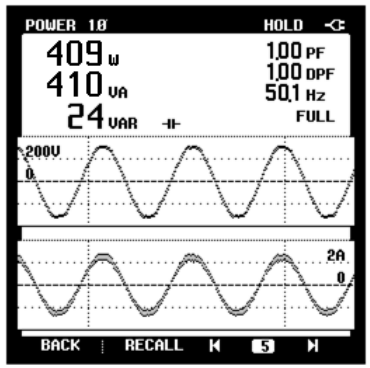


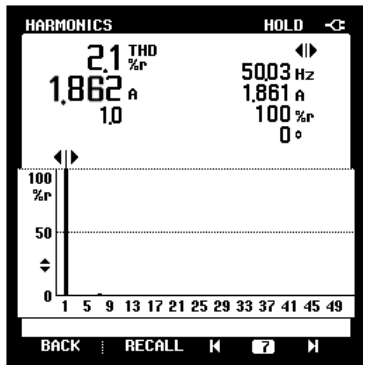




At rated load on BLDC with DC link voltage as 50V and supply voltage as 220V

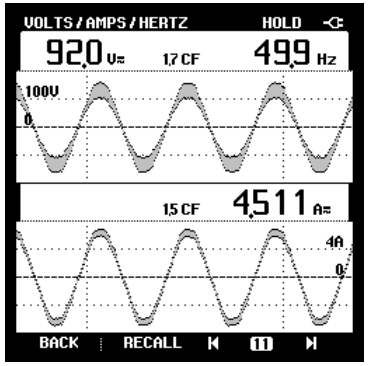


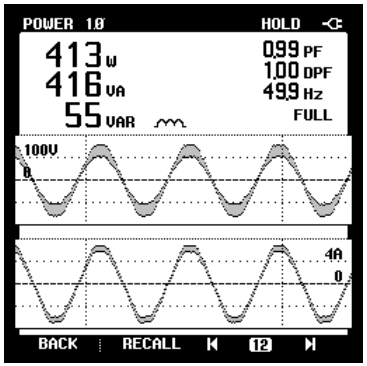


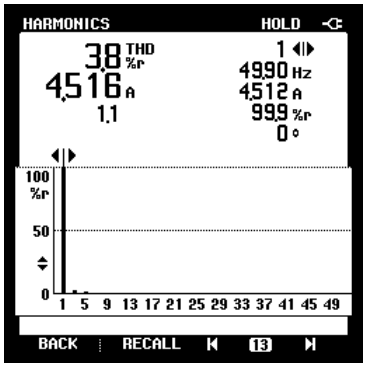


At rated load on BLDC with DC link voltage as 200V and supply voltage as 220V

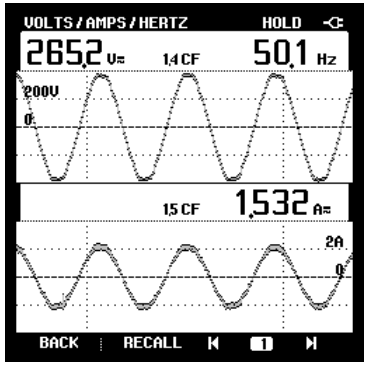
Experimental Results- Power Quality Indices

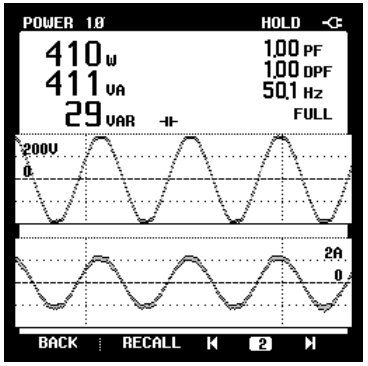


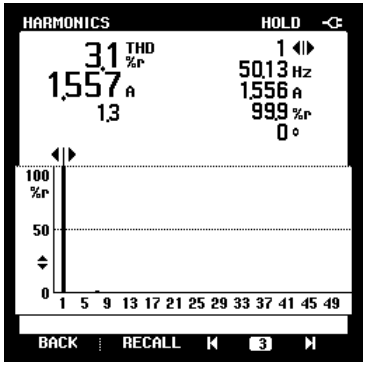




At rated load on BLDC with DC link voltage as 200V and supply voltage as 90V

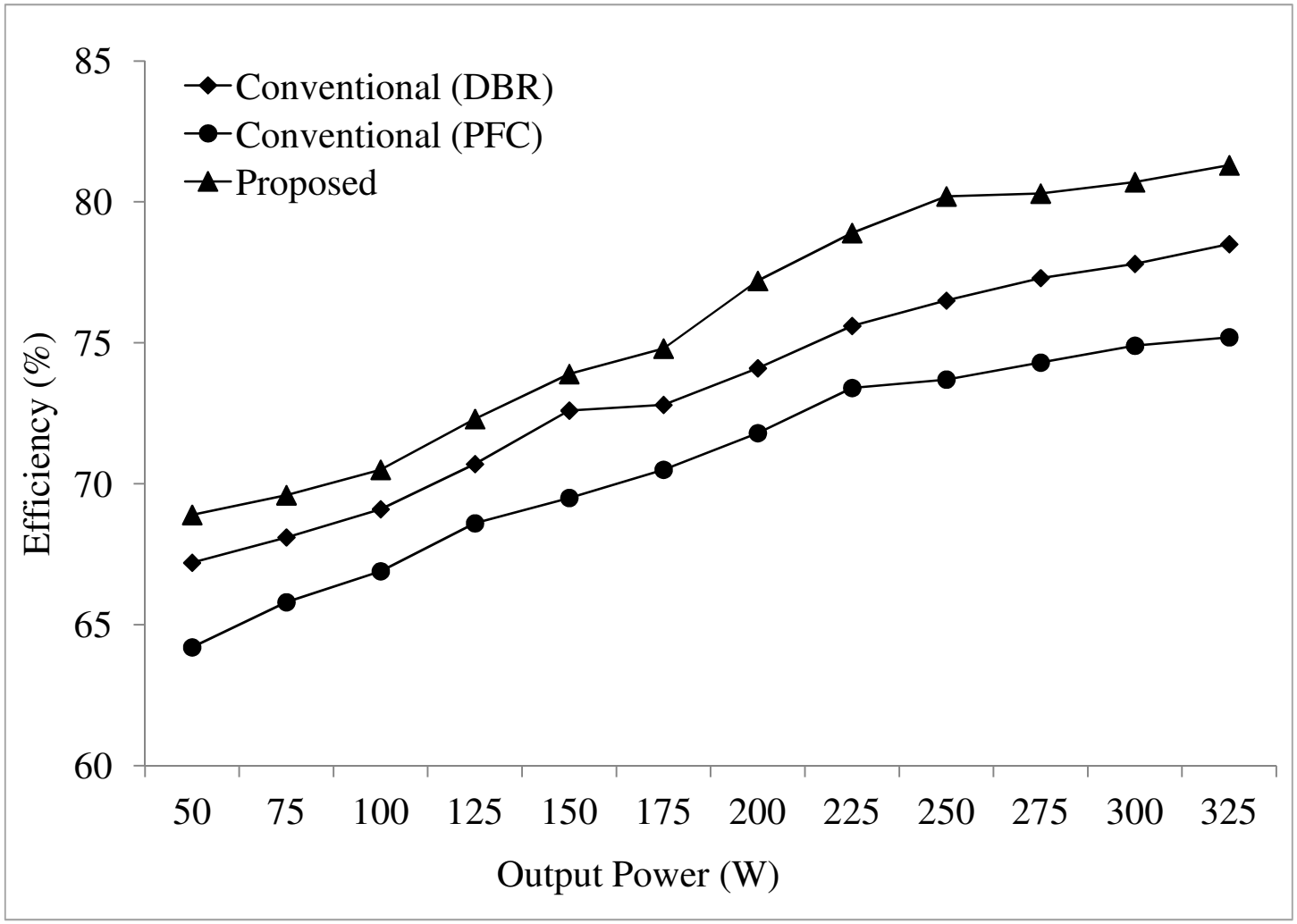




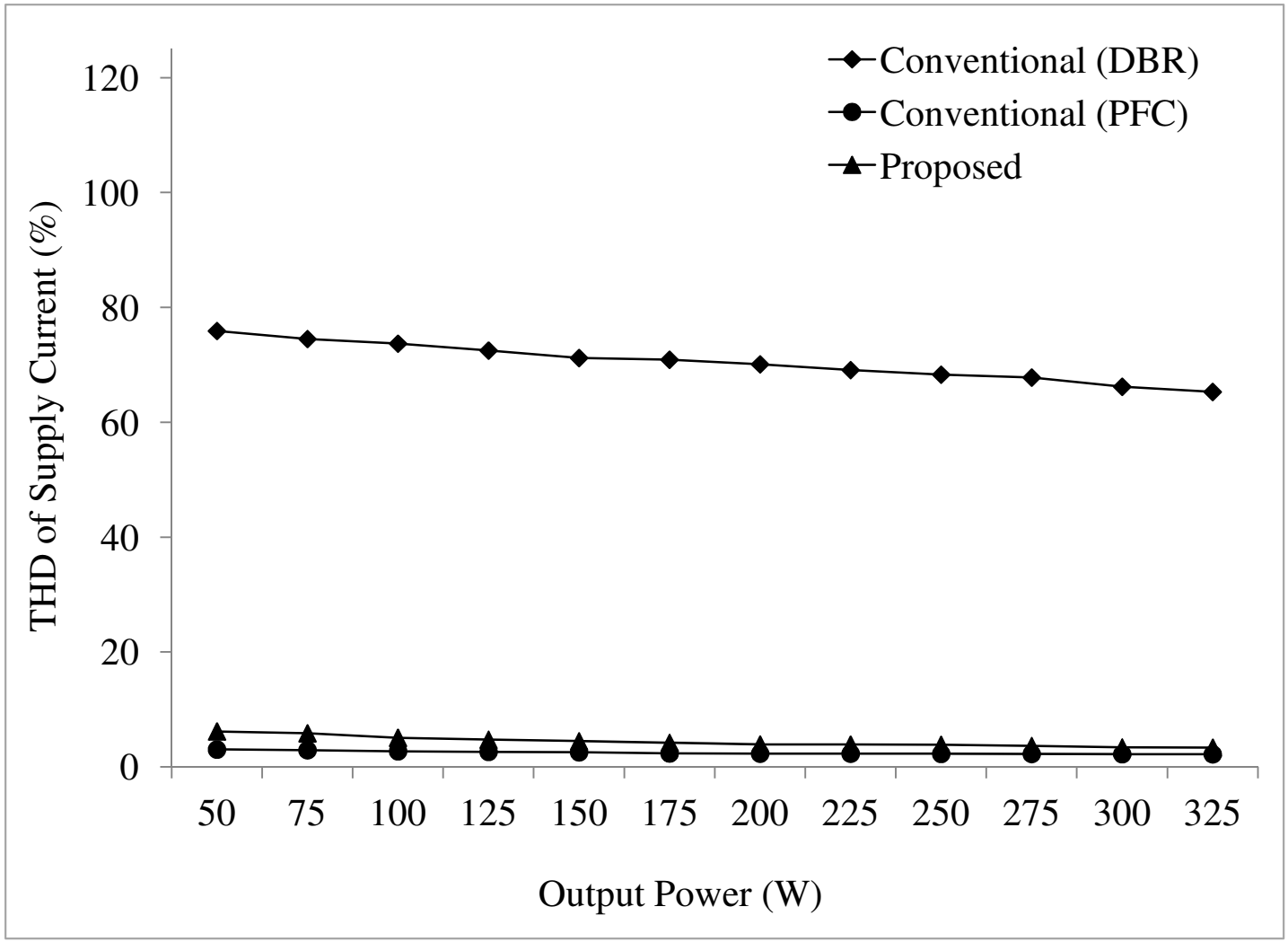


At rated load on BLDC with DC link voltage as 200V and supply voltage as 265V

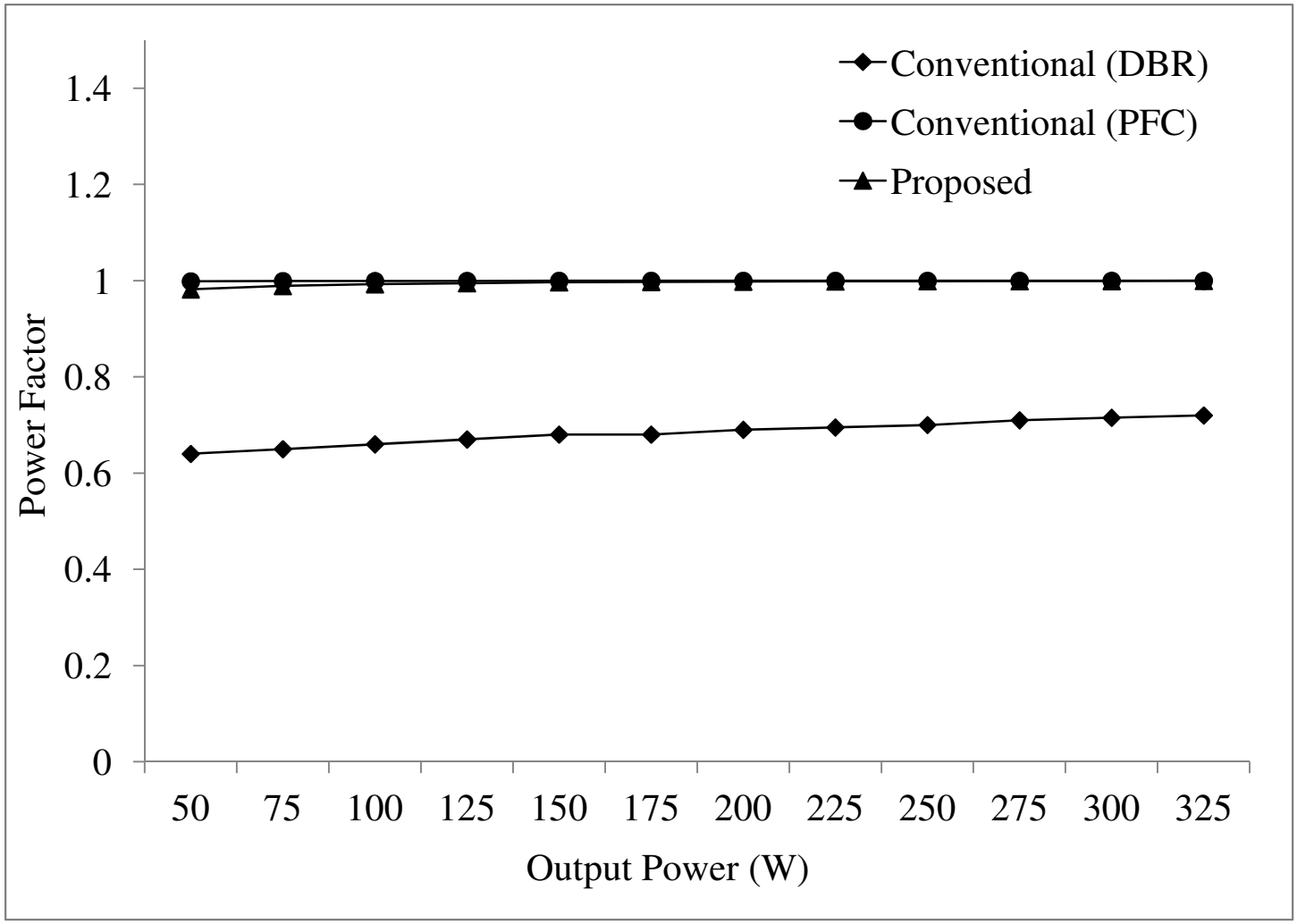
Comparative Analysis- Efficiency



Comparative Analysis- THD of Supply Current



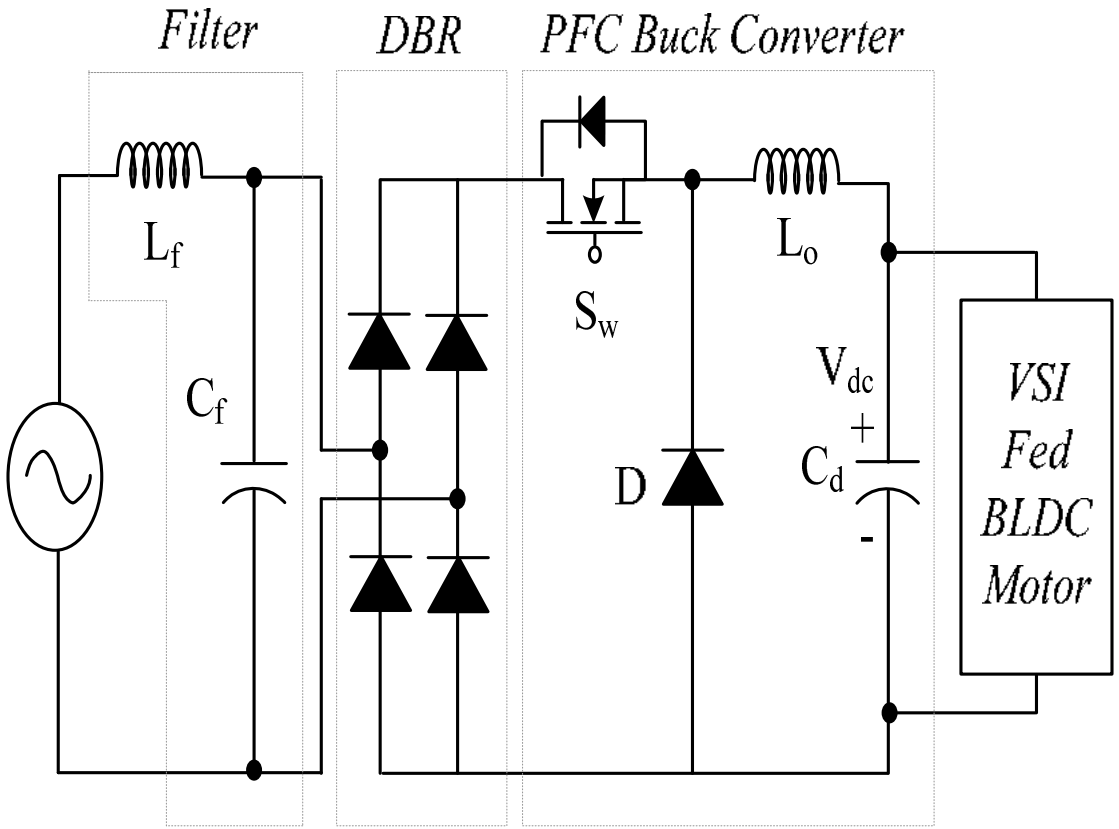
Comparative Analysis- Power Factor



Other Configurations of a PFC Converter Feeding a BLDC Motor Drive

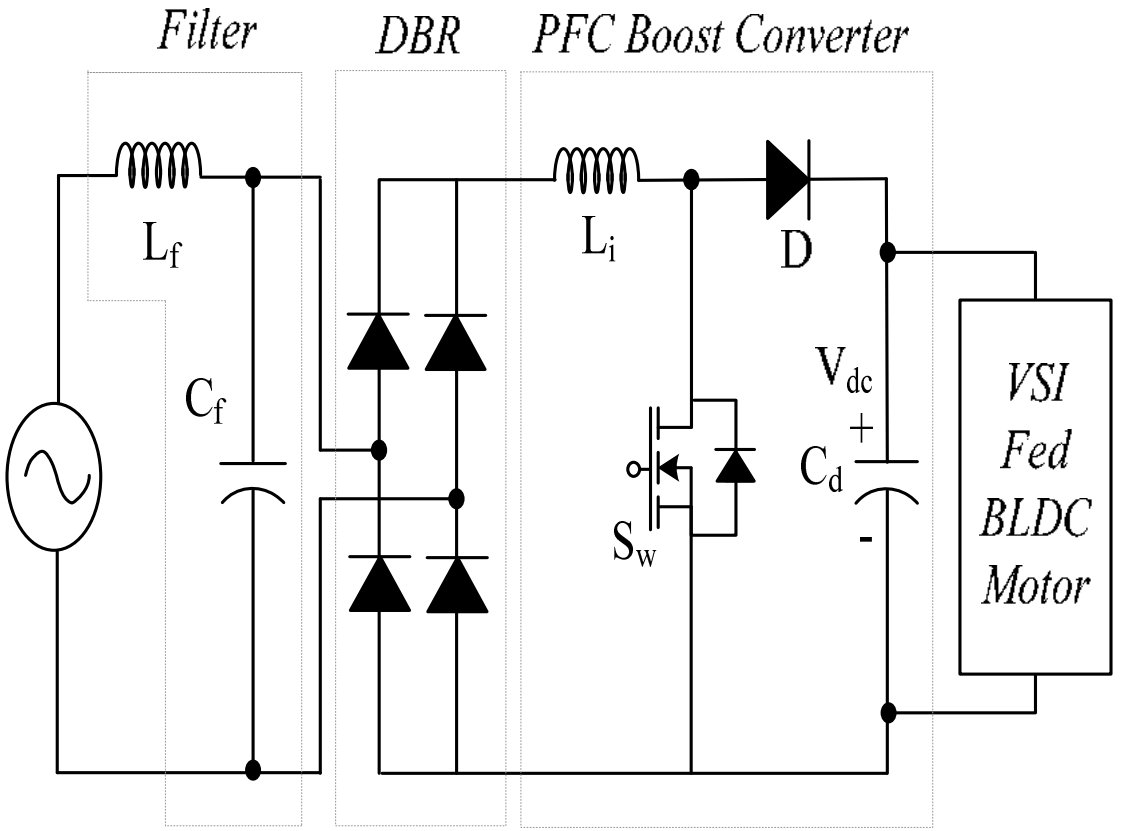
A PFC Based BLDC motor drive using PFC Buck Converter

Have a limited voltage conversion ratio i.e. D<1. Hence voltage control is achieved only for voltage less than the average input voltage.

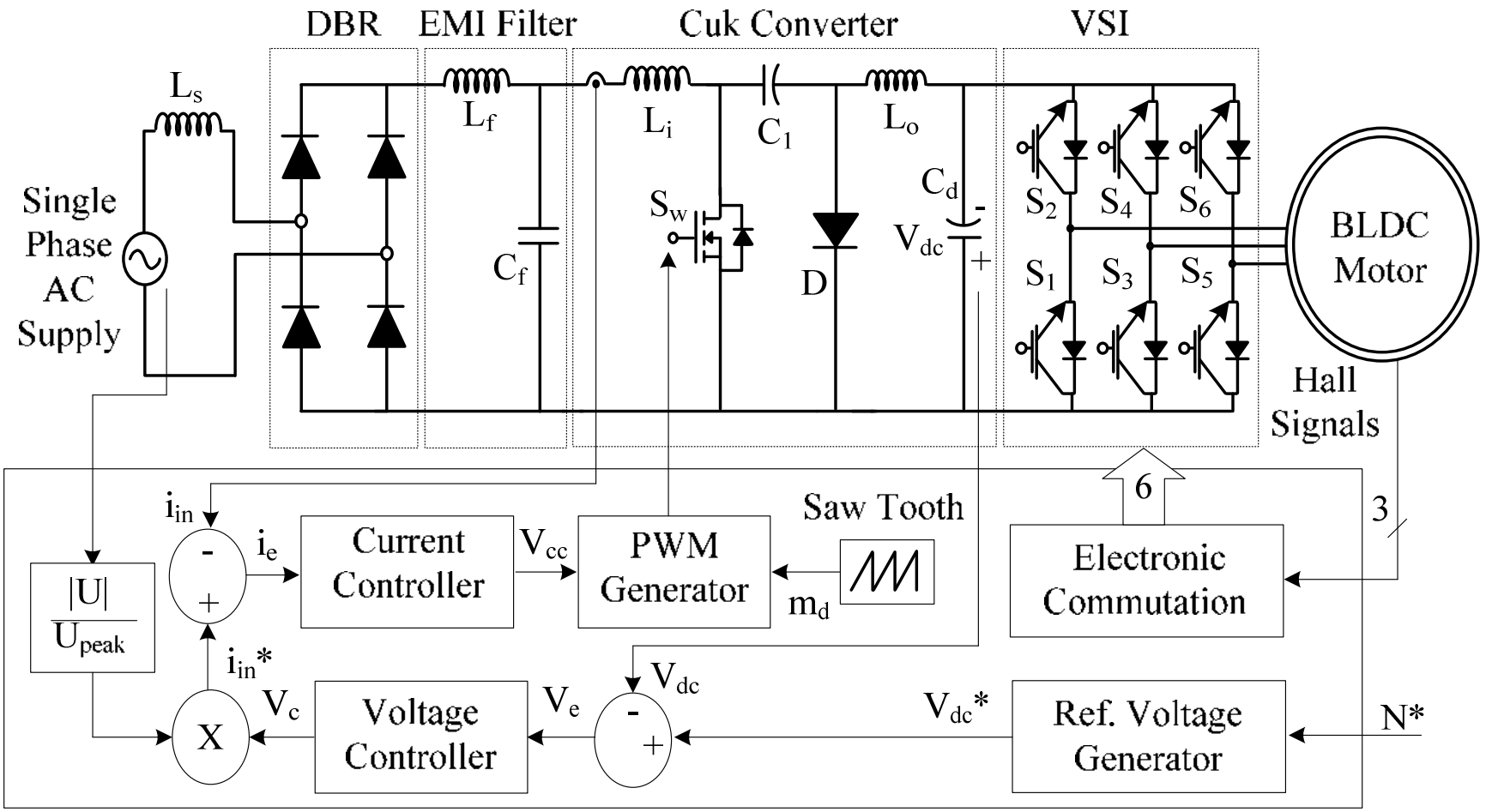


A PFC Based BLDC motor drive using PFC Boost Converter

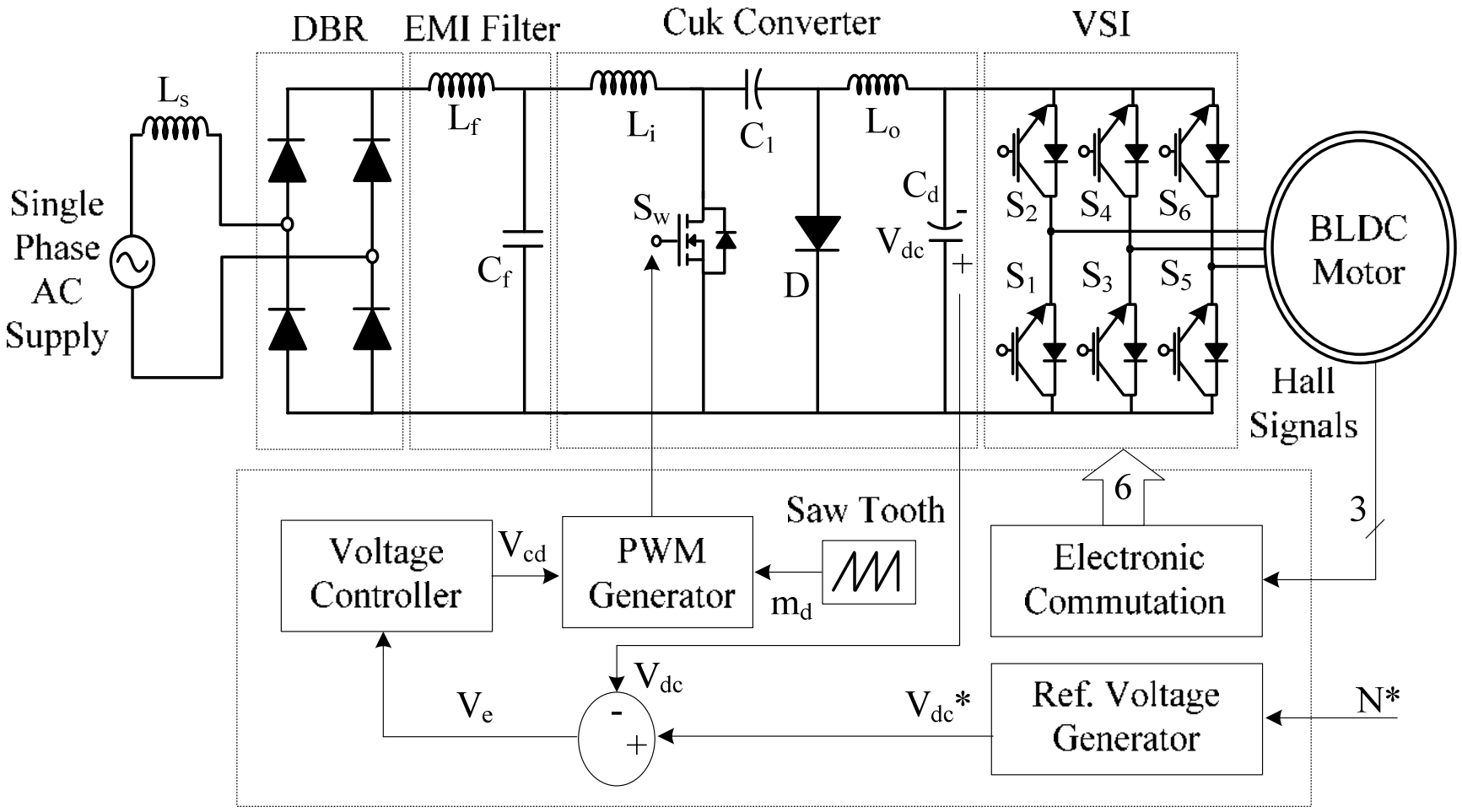
Since the voltage conversion ratio is always greater than 1 (i.e. $V_o > V_{in}$); Hence voltage control is cannot be achieved in this configuration. A PWM based Speed Control is employed.



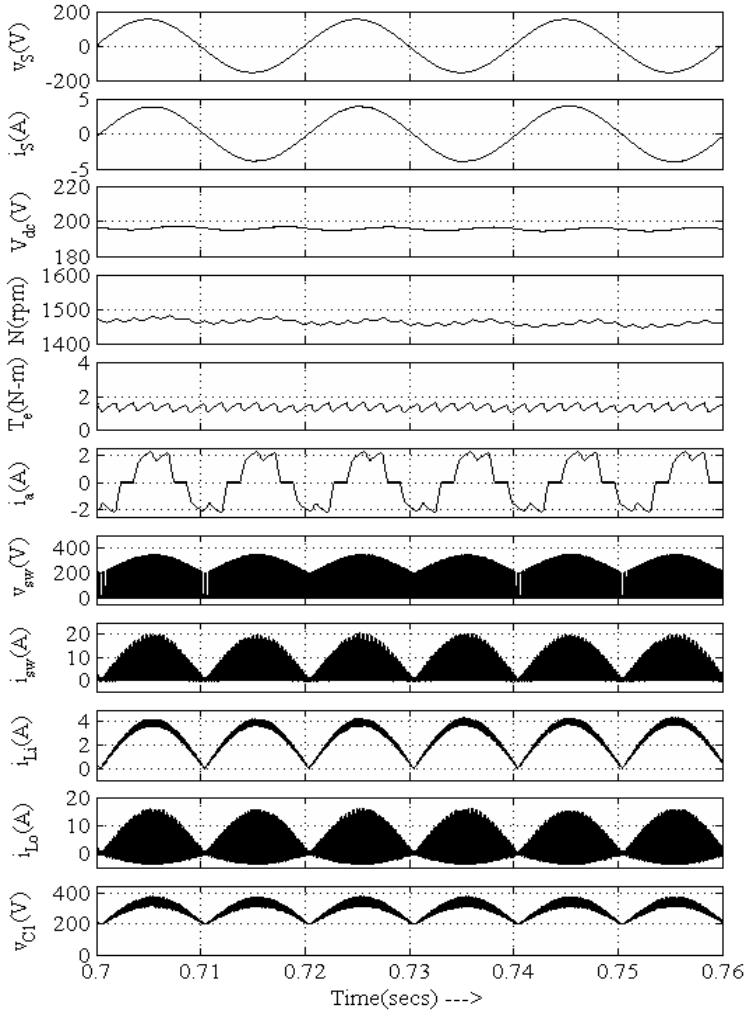
A PFC Based BLDC motor drive using PFC Cuk Converter – CCM Operation

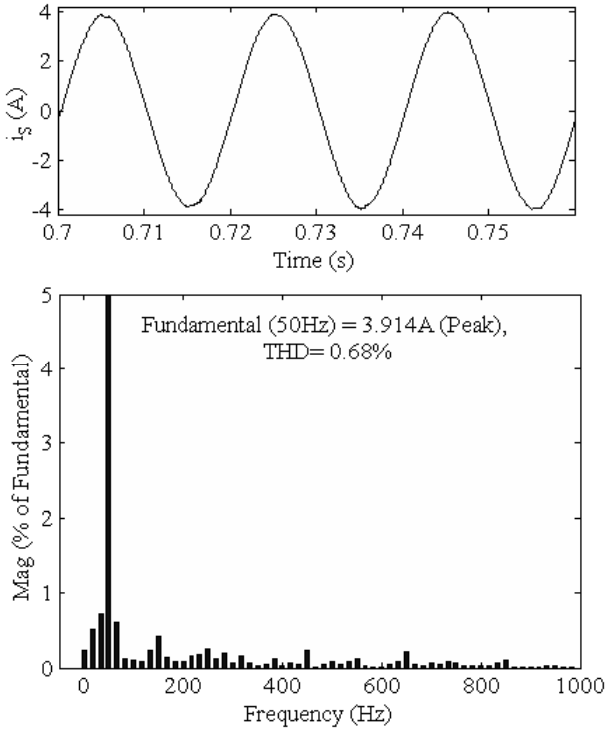


A PFC Based BLDC motor drive using PFC Cuk Converter – DCM Operation



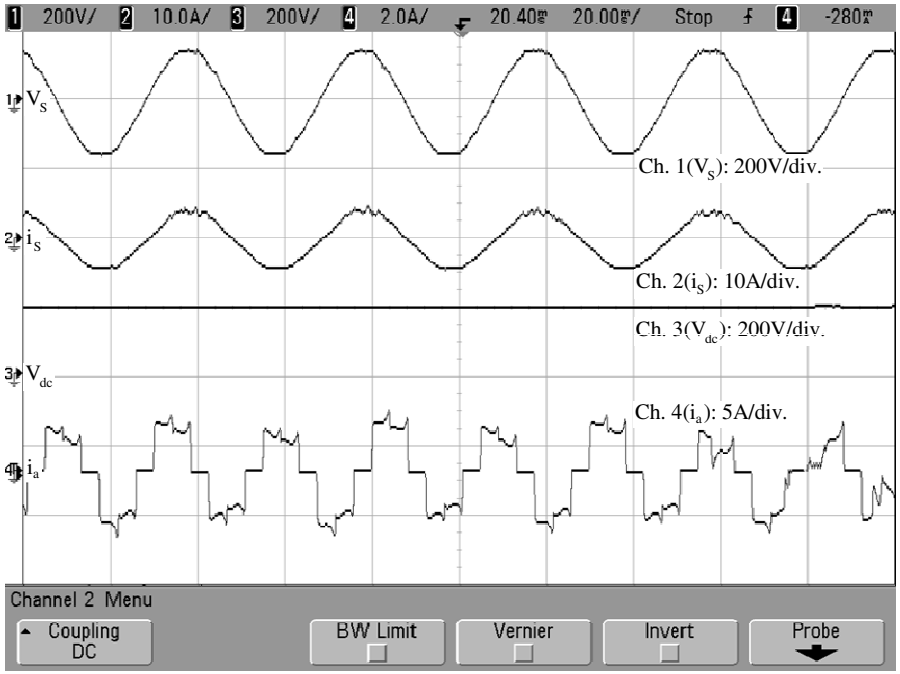
Simulated Results of a PFC Based BLDC motor drive using PFC Cuk Converter – DICM (L_o) Operation

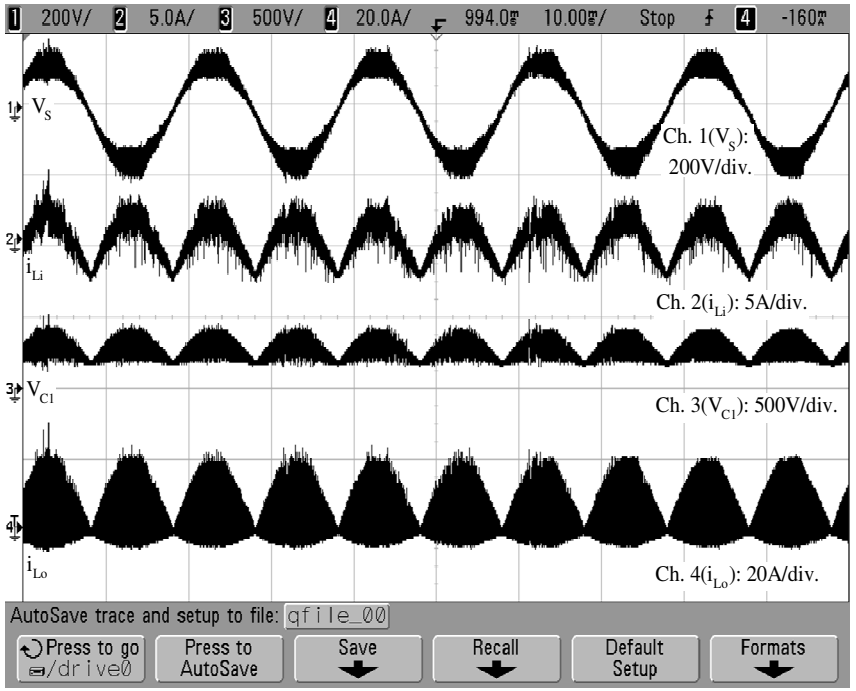




V_s= 220V, V_{dc}=200V, P_o= 400W, f_S=20kHz

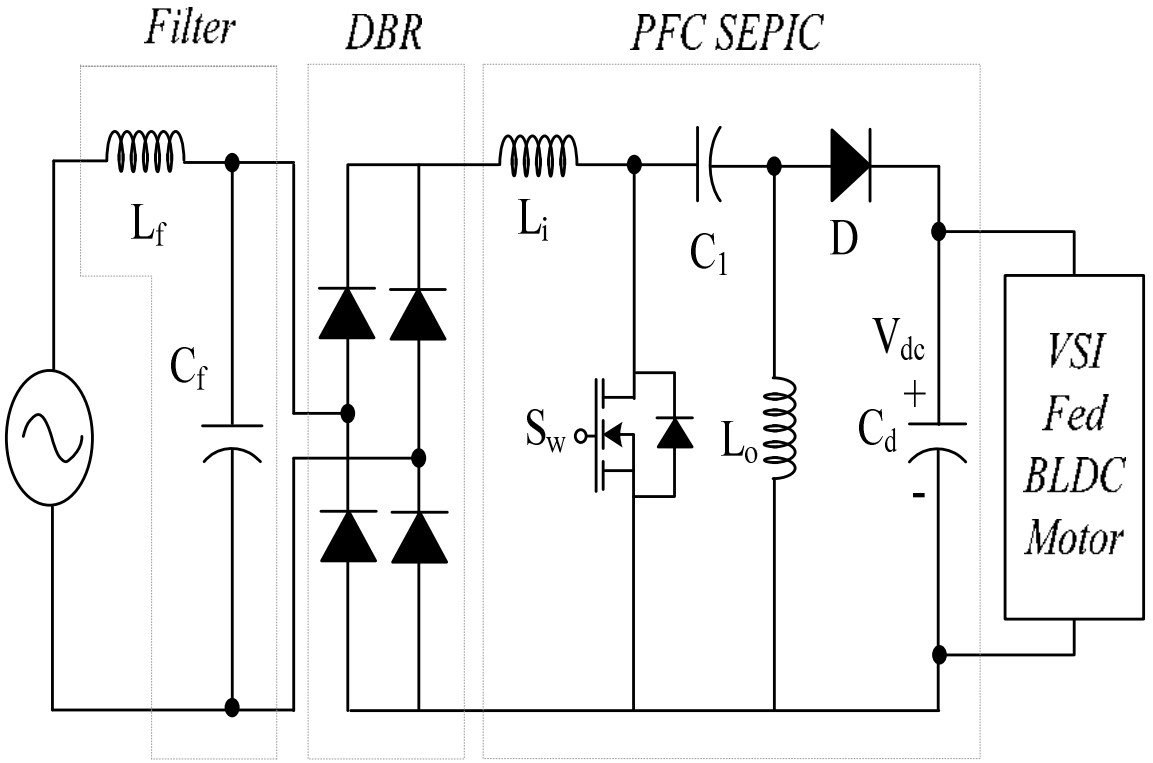
Experimental Results of a PFC Based BLDC motor drive using PFC Cuk Converter – DICM (L_o) Operation





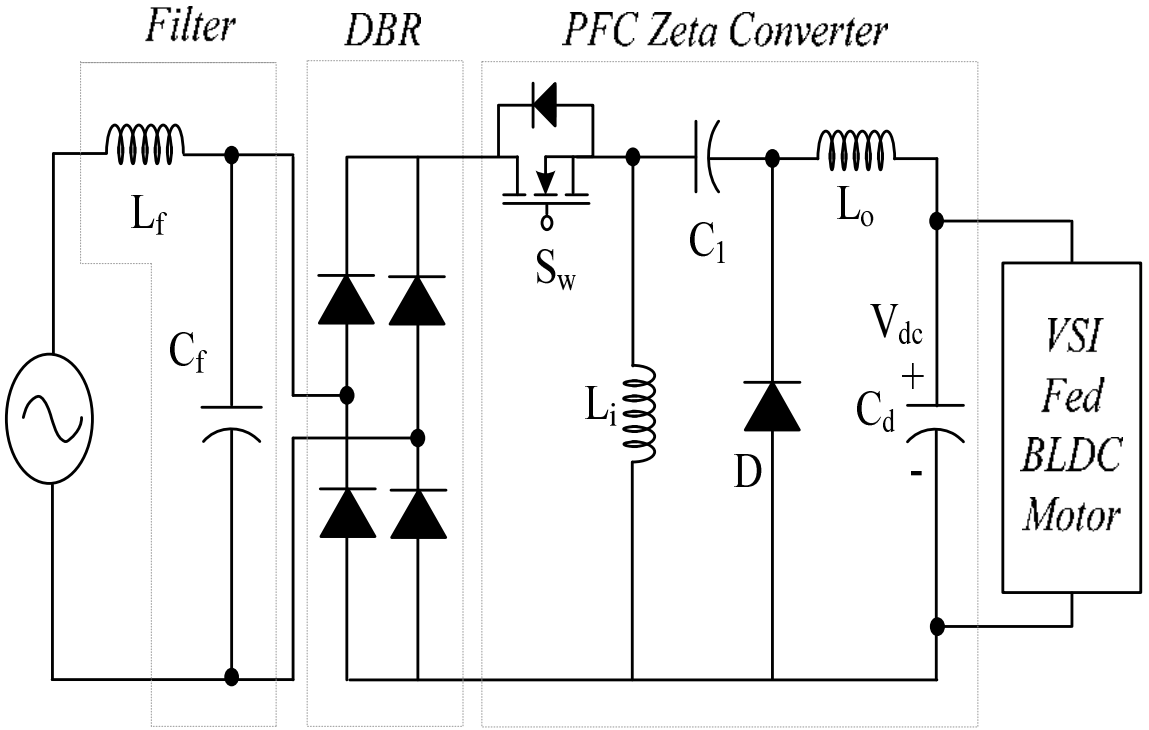
A PFC Based BLDC motor drive using PFC SEPIC Converter

A buck boost configuration which can provide a wide range of voltage conversion i.e. (0<D<1) with positive output polarity. Provides an excellent PFC operation over a wide range of speed control.



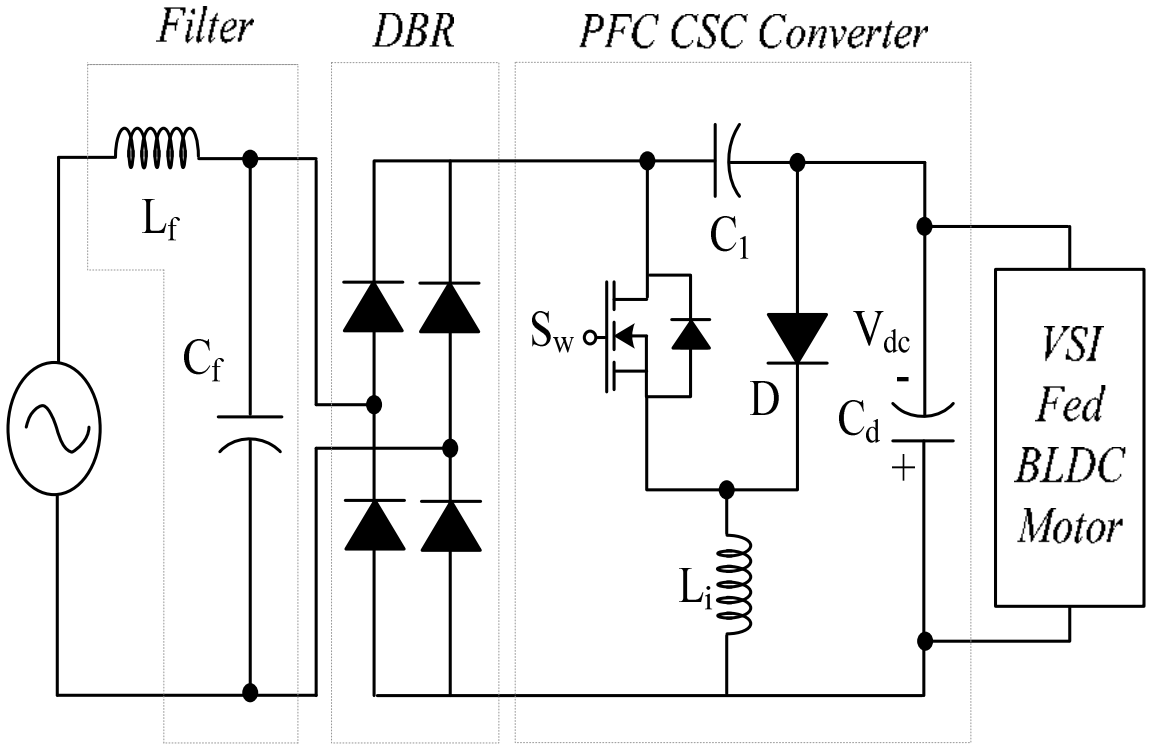
A PFC Based BLDC motor drive using PFC Zeta Converter

A buck boost configuration which can provide a wide range of voltage conversion i.e. (0<D<1) with positive output polarity. Provides an excellent PFC operation over a wide range of speed control.



A PFC Based BLDC motor drive using PFC CSC Converter

A buck boost configuration with reduced number of components.
Negative output polarity.
Provides an excellent PFC operation over a wide range of speed control.



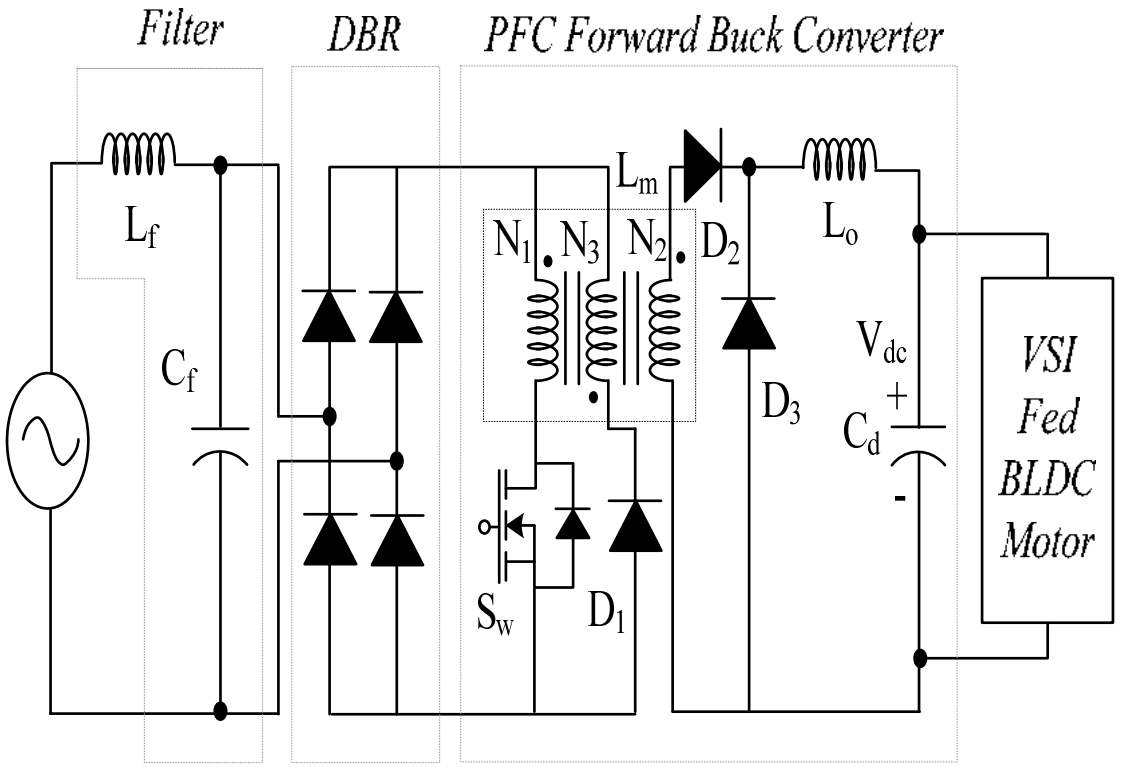
Isolated Configurations of a PFC Converter Feeding a BLDC Motor Drive

Requirement of an Isolation

Household appliances such as refrigerators, washing machines needs isolation to avoid any shock to the personnel's.

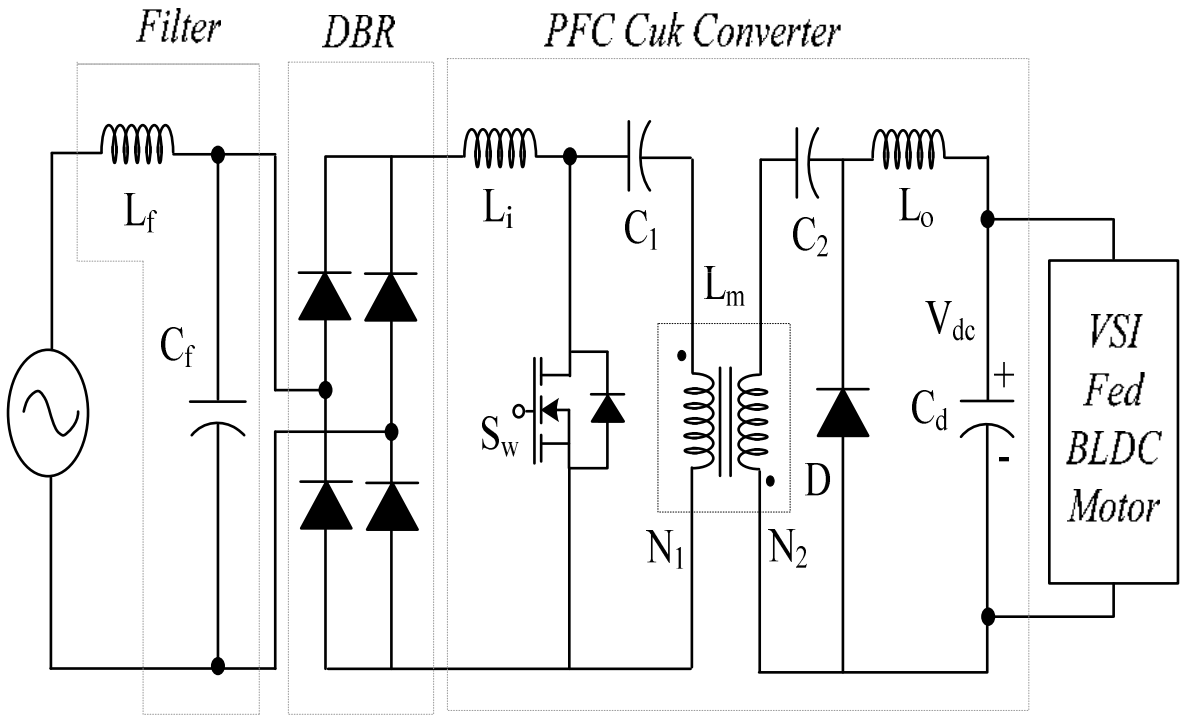
A PFC Based BLDC motor drive using PFC Forward Buck Converter

A buck configuration which can provide a wide range of voltage conversion i.e. (0<D<1) with positive output polarity.



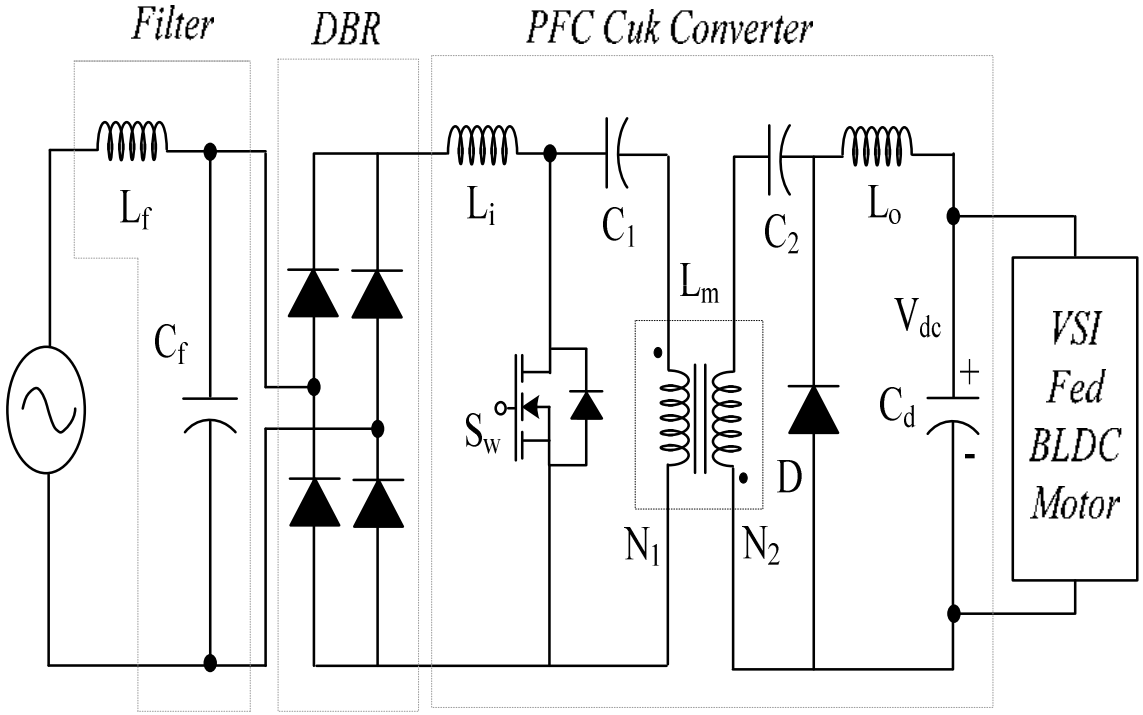
A PFC Based BLDC motor drive using PFC Flyback Converter

A buck boost configuration which can provide a wide range of voltage conversion i.e. (0<D<1) with positive output polarity. Provides an excellent PFC operation over a wide range of speed control.



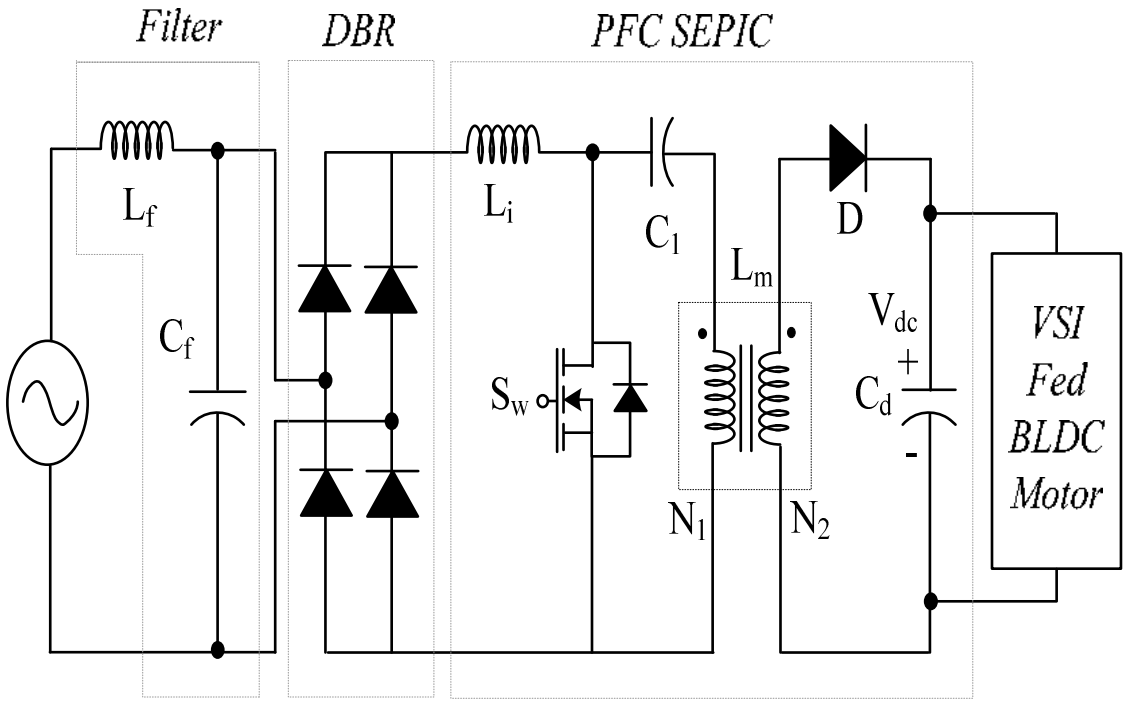
A PFC Based BLDC motor drive using PFC Isolated Cuk Converter

A buck boost configuration which can provide a wide range of voltage conversion i.e. (0<D<1) with positive output polarity. Provides an excellent PFC operation over a wide range of speed control.



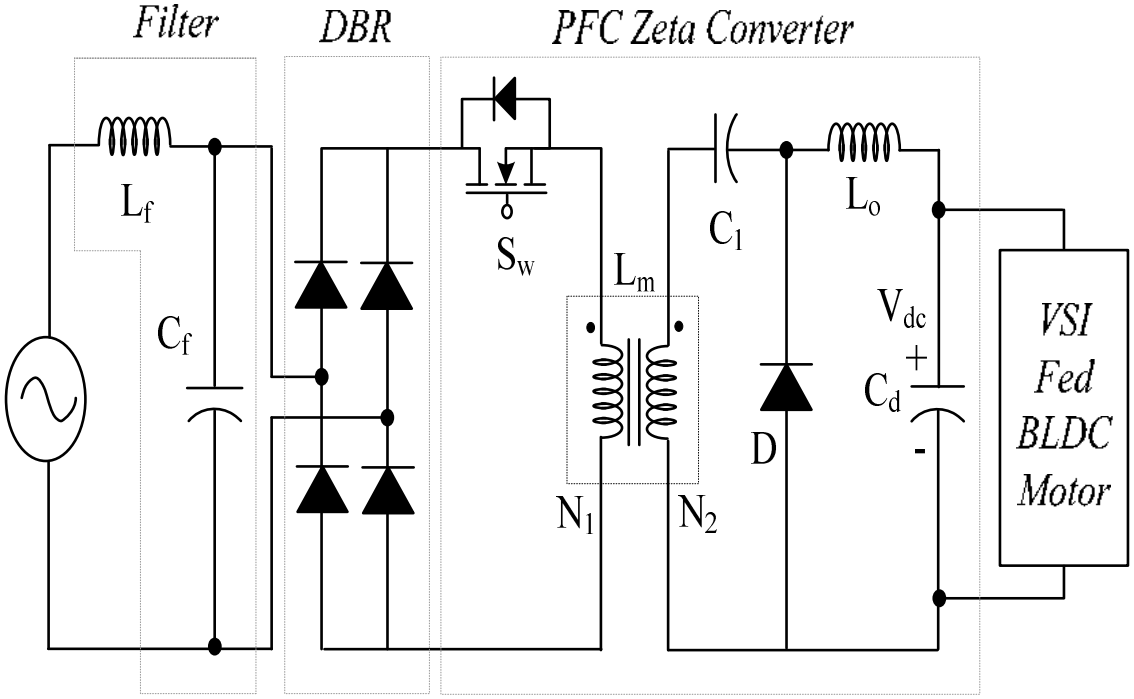
A PFC Based BLDC motor drive using PFC Isolated SEPIC Converter

A buck boost configuration which can provide a wide range of voltage conversion i.e. (0<D<1) with positive output polarity. Provides an excellent PFC operation over a wide range of speed control.



A PFC Based BLDC motor drive using PFC Isolated Zeta Converter

A buck boost configuration which can provide a wide range of voltage conversion i.e. (0<D<1) with positive output polarity. Provides an excellent PFC operation over a wide range of speed control.



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7. J.F. Girgeas, “Permanent Magnets Motor Technology – Design and Applications”,Marcel Dekker,Inc., New York, 1997.
8. P.Pillay and R. Krishnan, “Modeling, Simulation, and Analysis of Permanent Magnets Motor Drives, Part II: The Brushless DC Motor Drive”, IEEE Trans. on Industry Applications, Vol. 25, No. 2, March/April 1989, pp. 274-279.