Design of Brushless DC Motor Driver and Controller

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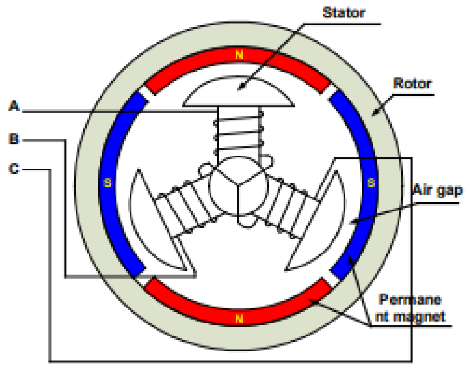
14 April 2020

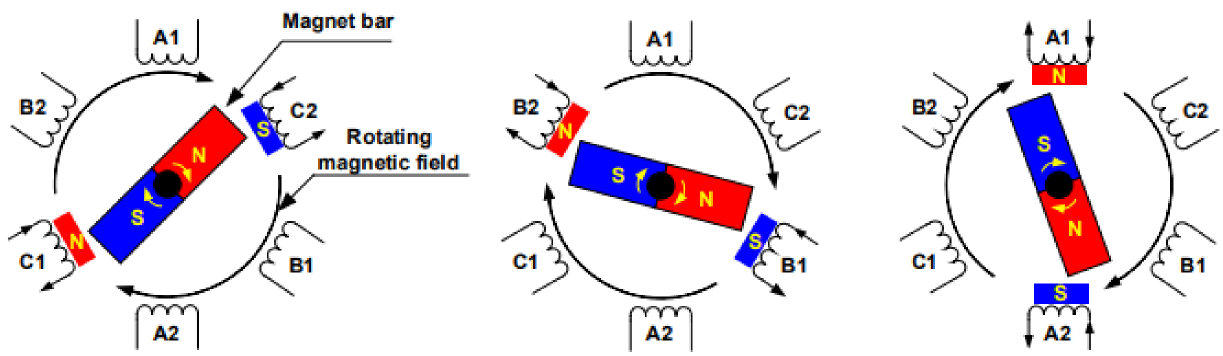
Contents

1. Working of Brushless DC Motor

A brushless DC motor is a permanent magnet synchronous electric motor which is driven by direct current electricity. These motors an indispensable part of modern drive technology, most commonly employed for actuating drives, machine tools, electric propulsion, robotics, computer peripherals and also for electrical power generation. With the development of sensor-less technology besides digital control, these motors have become very effective in terms of total system cost, size and reliability.



Brushless DC motor is driven by electronically controlled commutation. The phase currents are changed at appropriate times to rotate the rotor magnet to desired position. The energization of stator windings produces a magnetic field which attracts or repels the rotor for a short time so that the two magnetic fields align.

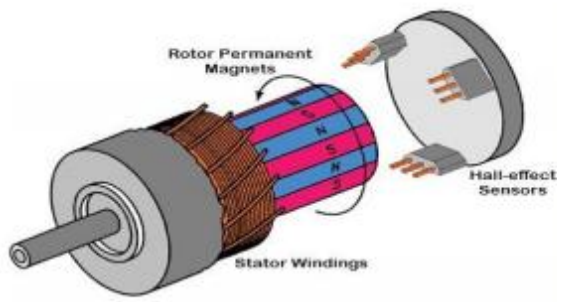


Commutation is achieved by controlling the switches of a three phase bridge.

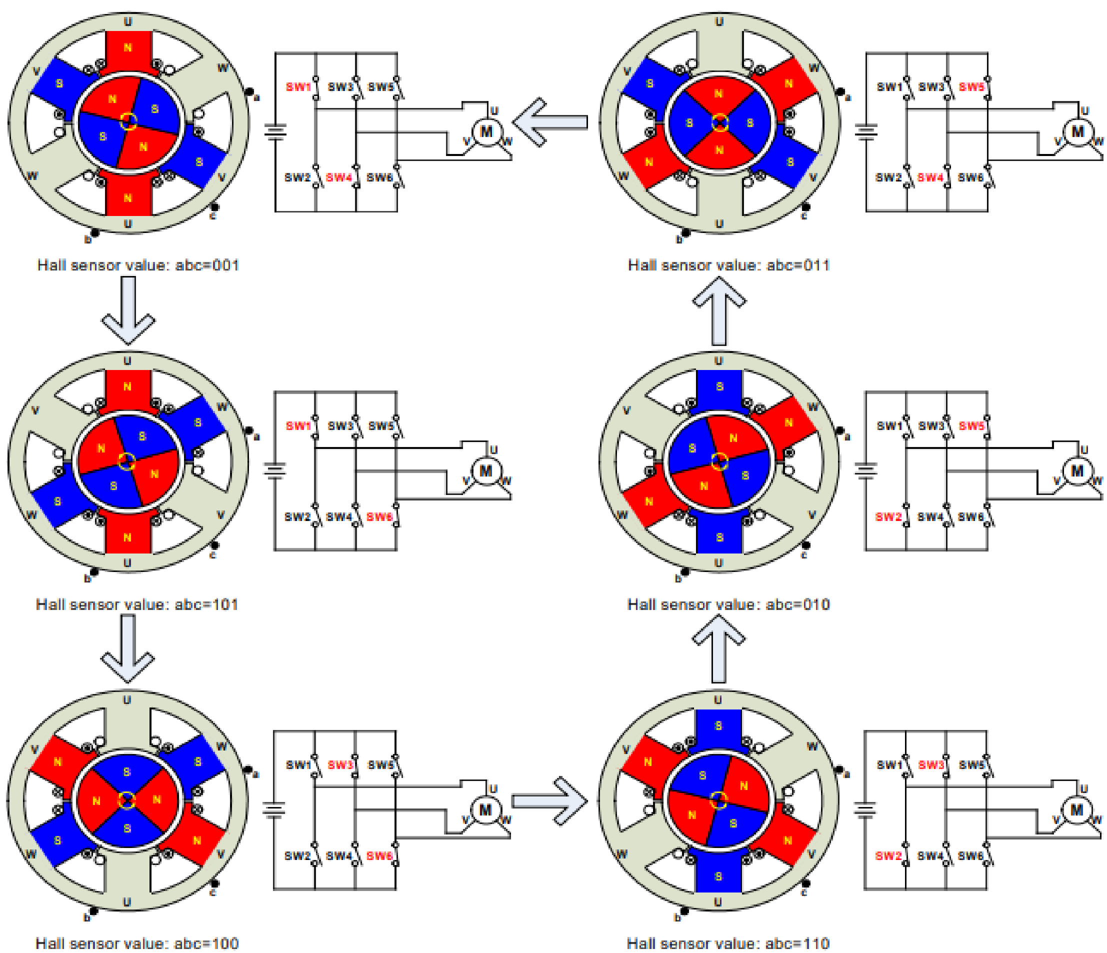
Brushless DC Motor has a high efficiency and power to size ratio. It is capable of generating constant torque even at very high speeds. Moreover, it requires minimal maintenance due to superior thermal performance and absence of commutation brushes.

Feature	Brushless DC Motor	Brushed DC Motor	Induction Motor
Rotor Structure	Field Magnets are made of permanent magnets.	Field Magnets are made of electromagnets.	Field Magnets are made of electromagnets.
Commutation	Electronic Commutation based on rotor position information.	Mechanical brushes and commutator.	Special Starting circuit required.
Efficiency	High. Electronic switches are more efficient than commutator/ brushes arrangement.	Moderate. Rotor Losses reduce efficiency.	Moderate. Rotor Losses reduce efficiency.
Maintenance	Little. No maintenance required for brushes/ commutator.	Periodic. Maintenance required for brushes/ commutator.	Little. No maintenance required for brushes/ commutator.
Thermal Performance	Better. The rotor does not generate heat.	Poor. Both the rotor and stator generate heat.	Moderate. Both the rotor and stator generate heat.
Output Power/ Frame size (Ratio)	High. Modern Permanent Magnet.	Moderate/ Low. Rotor Losses reduce efficiency.	Moderate/ Low. Rotor Losses reduce efficiency.
Speed/ Torque characteristics	Flat.	Moderately Flat.	Nonlinear. Lower Torque at lower speeds.
Dynamic Response	Fast.	Slow.	Slow.
Speed Range	High. No limitation imposed by brushes/ commutator.	Low. Rotor losses increase at high speeds.	Low. The rotor runs at a lower frequency than stator by slip frequency and slip increases with load.
Electric Noise	Low.	High. Sparking occurs at brushes.	Low.
Lifetime	Long.	Short.	Moderate.
Self-Starting	No. Synchronous operation. Controller is always required for variable speed.	Yes. Controller is only required for variable speed	Yes. Starting circuit is always required for starting.
Direction Reversal	Reversing the switching sequence.	Reversing the terminal voltage.	Changing two phases of motor input.
System Cost	High. The controller is expensive.	Low.	Low.

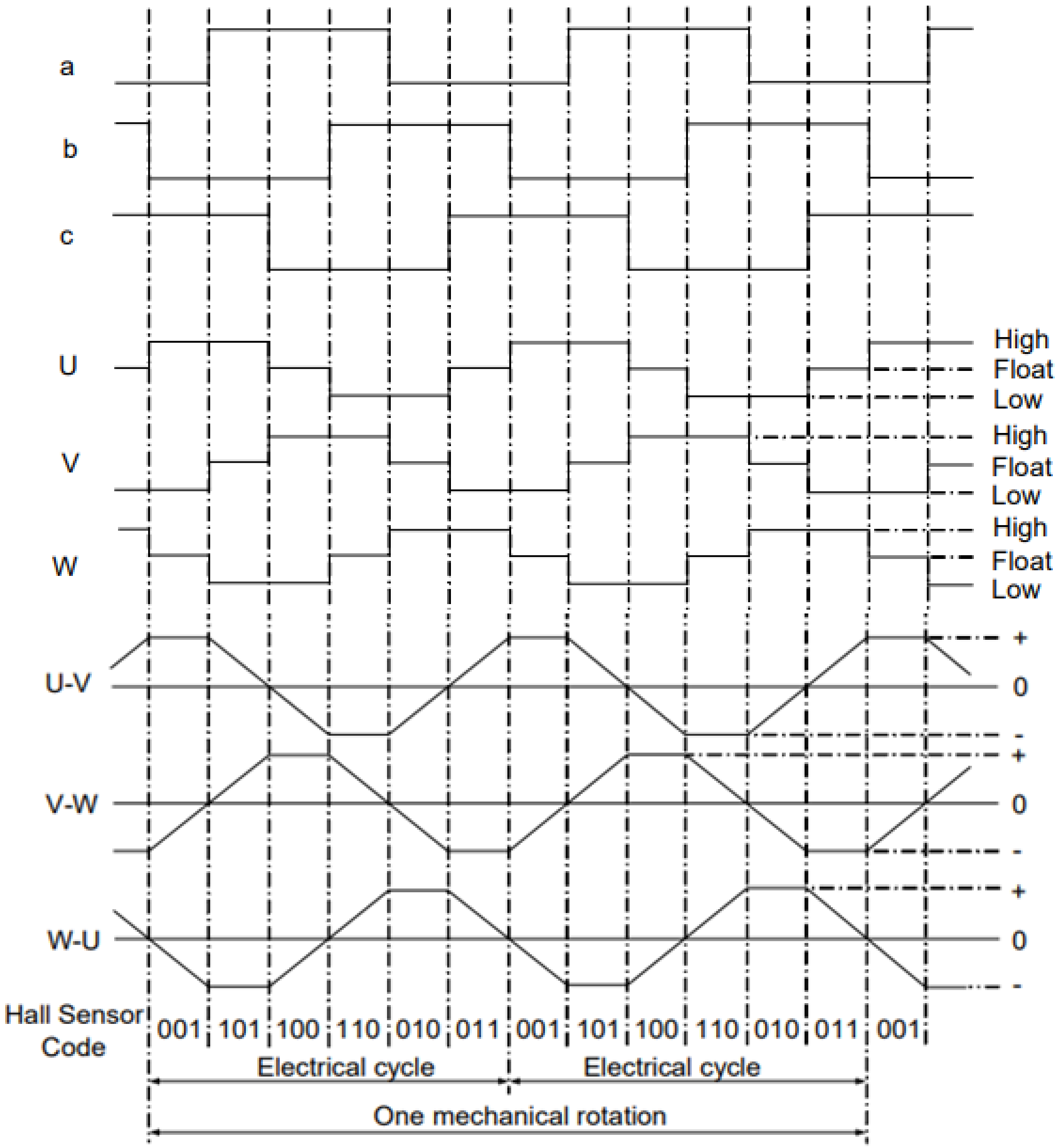
The commutation is achieved based on the inputs of Hall sensors attached around the rotor.



The Hall sensor inputs are used to control the 3-phase bridge switches and the voltages applied to the stator windings.



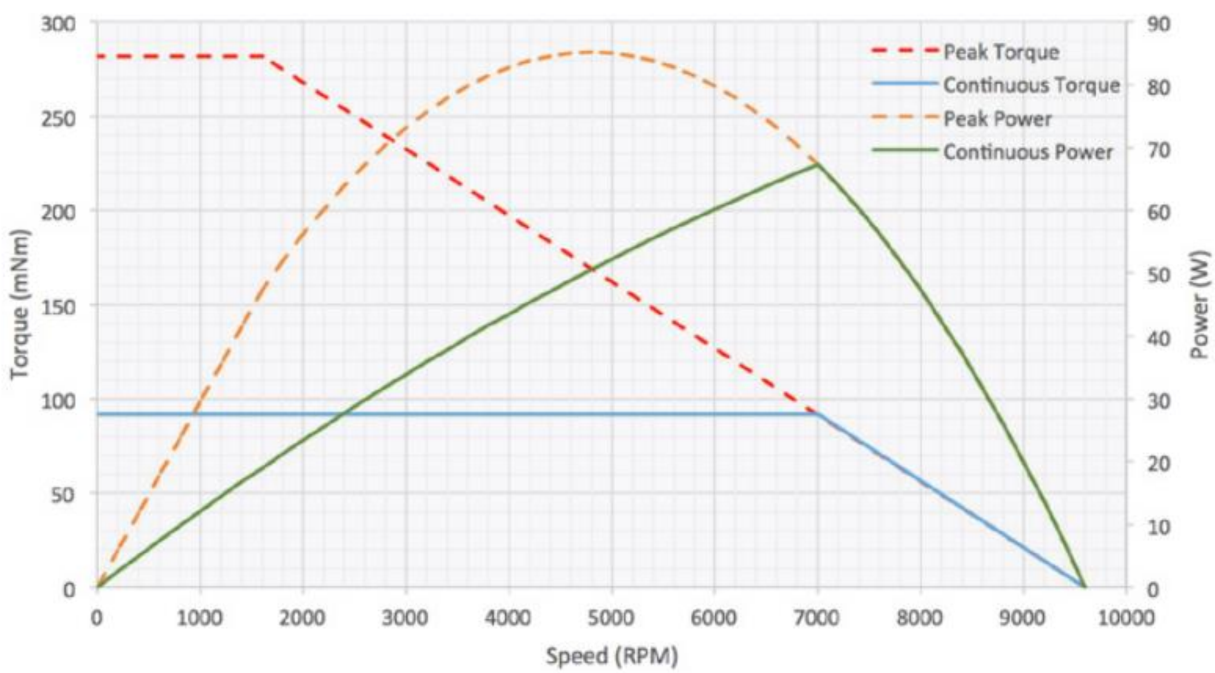
The resulting variation of Hall Sensor signals, Phase voltages and Line-Line voltages is shown below for one mechanical rotation.



The motor properties of sample BLDC Motors is given in tabular form below.

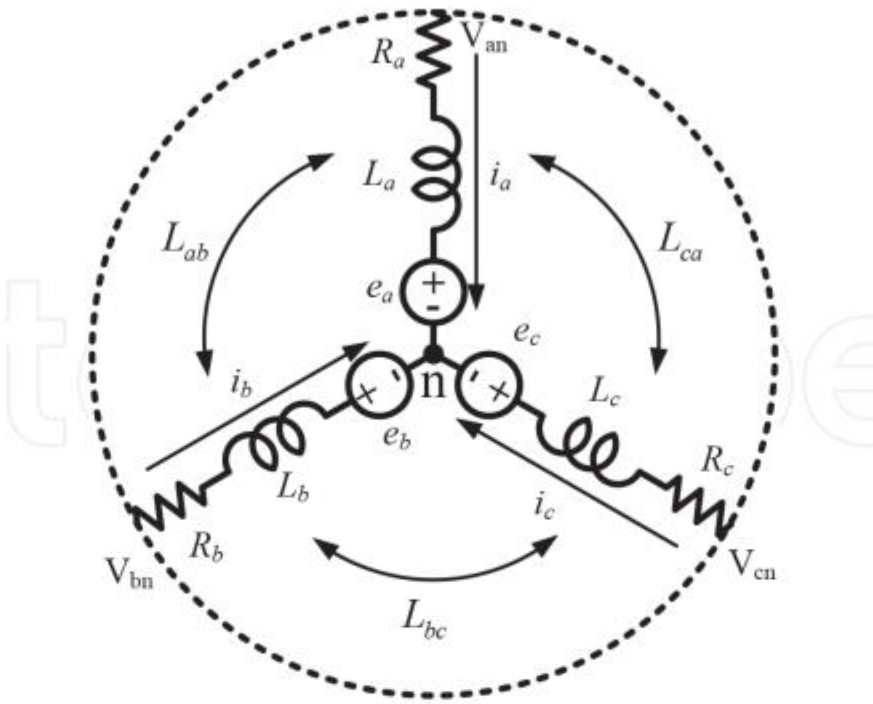
	Units	RPX32-090			RPX32-150		
Continuous Stall Torque*	mNm	90			150		
Peak Torque	mNm	282			438		
Motor Constant	nMn/√Watt	24.01			35.31		
Elec. Time Constant	msec	0.6			0.62		
Mech. Time Constant	msec	1.35			1.15		
Rotor Inertia	gm.cm^2	8.0			11.1		
Thermal Resistance	C/Watt	5.2			4.1		
Weight	g	150.0			260.0		
		V12	**V24**	**V48**	**V12**	**V24**	**V48**
Design Voltage	Volts	12	24	48	12	24	48
Cont. Stall Current	Amps	6.5	4.0	2.0	12.0	6.5	3.5
Peak Current	Amps	18.0	12.0	8.0	30.0	20.0	11.0
Voltage Constant ± 10%	V/rad/sec	0.015	0.023	0.048	0.016	0.022	0.045
Torque Constant ±10%	mNm/amp	12.2	23.5	47.9	11.5	22.0	45.0
Resistance ±10%	Ohms	0.22	0.96	3.68	0.113	0.48	1.67
Inductance ±30%	mH	0.193	0.6	2.3	0.1255	0.3	1.0

The Torque and Power characteristics are shown in graphical form below.



2. Modeling of Brushless DC Motor

The equivalent motor electrical circuit is given below.



The motor equations are:

$$\begin{bmatrix} V_{an} \\ V_{bn} \\ V_{cn} \end{bmatrix} = \begin{bmatrix} R_s & 0 & 0 \\ 0 & R_s & 0 \\ 0 & 0 & R_s \end{bmatrix} \begin{bmatrix} i_{as} \\ i_{bs} \\ i_{cs} \end{bmatrix} + \frac{d}{dt} \begin{bmatrix} L_{aa} & L_{ab} & L_{ac} \\ L_{ba} & L_{bb} & L_{bc} \\ L_{ca} & L_{cb} & L_{cc} \end{bmatrix} \begin{bmatrix} i_{as} \\ i_{bs} \\ i_{cs} \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix}$$

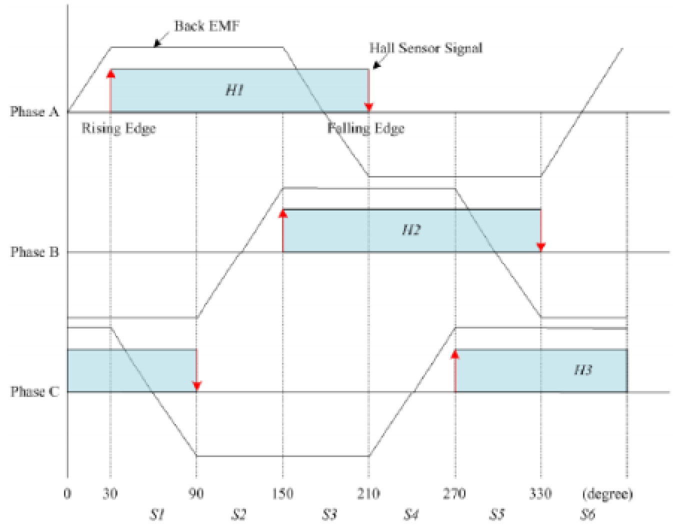
$$e_a = \frac{k_e}{2} \omega_m F(\theta_e)$$

$$e_b = \frac{k_e}{2} \omega_m F(\theta_e - \frac{2\pi}{3})$$

$$e_c = \frac{k_e}{2} \omega_m F(\theta_e + \frac{2\pi}{3})$$

$$F(\theta_e) = \begin{cases} 1 & 0 \le \theta_e \le \frac{2\pi}{3} \\ 1 - \frac{6}{\pi}\left(\theta_e - \frac{2\pi}{3}\right) & \frac{2\pi}{3} \le \theta_e \le \pi \\ -1 & \pi \le \theta_e \le \frac{5\pi}{3} \\ -1 + \frac{6}{\pi}\left(\theta_e - \frac{5\pi}{3}\right) & \frac{5\pi}{3} \le \theta_e \le 2\pi \end{cases}$$

The Hall sensor signals and Back EMF waveforms are shown in the graphs below.



The Hall Signals are represented by

$$HALL_a = H(\theta_e)$$

$$HALL_b = H(\theta_e - \frac{2\pi}{3})$$

$$HALL_c = H(\theta_e + \frac{2\pi}{3})$$

$$H(\theta_e) = \begin{cases} 0 & 0 \le \theta_e \le \frac{\pi}{6} \\ 1 & \frac{\pi}{6} \le \theta_e \le \frac{7\pi}{6} \\ 0 & \frac{7\pi}{6} \le \theta_e \le 2\pi \end{cases}$$

The Mechanical System Equations are,

$$T_e \omega_m = \begin{bmatrix} e_a & e_b & e_c \end{bmatrix} \begin{bmatrix} i_{as} \\ i_{bs} \\ i_{cs} \end{bmatrix}$$

$$T_e - T_L = B\omega_m + J\frac{d\omega_m}{dt}$$

$$\omega_r = \frac{P}{2}\omega_m$$

For a balanced system,

$$i_{as} + i_{bs} + i_{cs} = 0$$

$$\begin{bmatrix} V_{an} \\ V_{bn} \\ V_{cn} \end{bmatrix} = \begin{bmatrix} R_s & 0 & 0 \\ 0 & R_s & 0 \\ 0 & 0 & R_s \end{bmatrix} \begin{bmatrix} i_{as} \\ i_{bs} \\ i_{cs} \end{bmatrix} + \frac{d}{dt} \begin{bmatrix} L_s & 0 & 0 \\ 0 & L_s & 0 \\ 0 & 0 & L_s \end{bmatrix} \begin{bmatrix} i_{as} \\ i_{bs} \\ i_{cs} \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix}$$

In steady state,

$$T_e = K_t i_{as}$$

$$T_e - T_L = B\omega_m$$

The $\alpha\beta$-axis model of the motor can be obtained by decomposing the voltage, current and flux linkage space-vectors into their corresponding α-axis and β-axis components.

$$\begin{bmatrix} x_\alpha \\ x_\beta \end{bmatrix} = \frac{2}{3}\begin{bmatrix} cos\theta & \cos(\theta - \frac{2\pi}{3}) & \cos(\theta - \frac{4\pi}{3}) \\ -sin\theta & -\sin(\theta - \frac{2\pi}{3}) & -\sin(\theta - \frac{4\pi}{3}) \end{bmatrix}\begin{bmatrix} x_a \\ x_b \\ x_c \end{bmatrix}$$

If the α-axis is aligned with the a-axis, $\theta = 0$

$$\begin{bmatrix} x_\alpha \\ x_\beta \end{bmatrix} = \frac{2}{3}\begin{bmatrix} 1 & \frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix}\begin{bmatrix} x_a \\ x_b \\ x_c \end{bmatrix}$$

The dq-axis rotating reference frame is derived by substituting θ = $\omega_r t$:

$$\begin{bmatrix} x_d \\ x_q \end{bmatrix} = \frac{2}{3}\begin{bmatrix} cos(\omega_r t) & \cos(\omega_r t - \frac{2\pi}{3}) & \cos(\omega_r t - \frac{4\pi}{3}) \\ -\sin(\omega_r t) & -\sin(\omega_r t - \frac{2\pi}{3}) & -\sin(\omega_r t - \frac{4\pi}{3}) \end{bmatrix}\begin{bmatrix} x_a \\ x_b \\ x_c \end{bmatrix}$$

The dq-axis model of the motor can be obtained by decomposing the voltage, current and flux linkage space-vectors into their corresponding d-axis and q-axis components.

$$\begin{bmatrix} v_d \\ v_q \end{bmatrix} = \left[T_{abc/dq}\right]\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix}$$

$$\begin{bmatrix} i_{ds} \\ i_{qs} \end{bmatrix} = \left[T_{abc/dq}\right]\begin{bmatrix} i_{as} \\ i_{bs} \\ i_{cs} \end{bmatrix}$$

$$\begin{bmatrix} \lambda_{ds} \\ \lambda_{qs} \end{bmatrix} = \left[T_{abc/dq}\right]\begin{bmatrix} \lambda_{as} \\ \lambda_{bs} \\ \lambda_{cs} \end{bmatrix}$$

The resulting dq-axis model equations are:

1. Flux Linkage Equations:

$$\lambda_f = Rotor\ Permanent\ Magnet\ Flux$$

$$\lambda_s = \sqrt{\lambda_{ds}^2 + \lambda_{qs}^2} = Stator\ Flux$$

$$\begin{bmatrix} \lambda_{ds} \\ \lambda_{qs} \end{bmatrix} = \begin{bmatrix} L_s + L_{dm} & 0 \\ 0 & L_s + L_{qm} \end{bmatrix} \begin{bmatrix} i_{ds} \\ i_{qs} \end{bmatrix} + \begin{bmatrix} \lambda_f \\ 0 \end{bmatrix}$$

2. Voltage Equations

$$\begin{bmatrix} v_d \\ v_q \end{bmatrix} = \begin{bmatrix} R_s & 0 \\ 0 & R_s \end{bmatrix} \begin{bmatrix} i_{ds} \\ i_{qs} \end{bmatrix} + \frac{d}{dt} \begin{bmatrix} \lambda_{ds} \\ \lambda_{qs} \end{bmatrix} + \omega_r \begin{bmatrix} -\lambda_{qs} \\ \lambda_{ds} \end{bmatrix}$$

3. Torque Equation

$$T_e = \frac{3P}{4} \left(i_{qs}\lambda_f + \left((L_s + L_{dm}) - (L_s + L_{qm}) \right) i_{ds} i_{qs} \right)$$

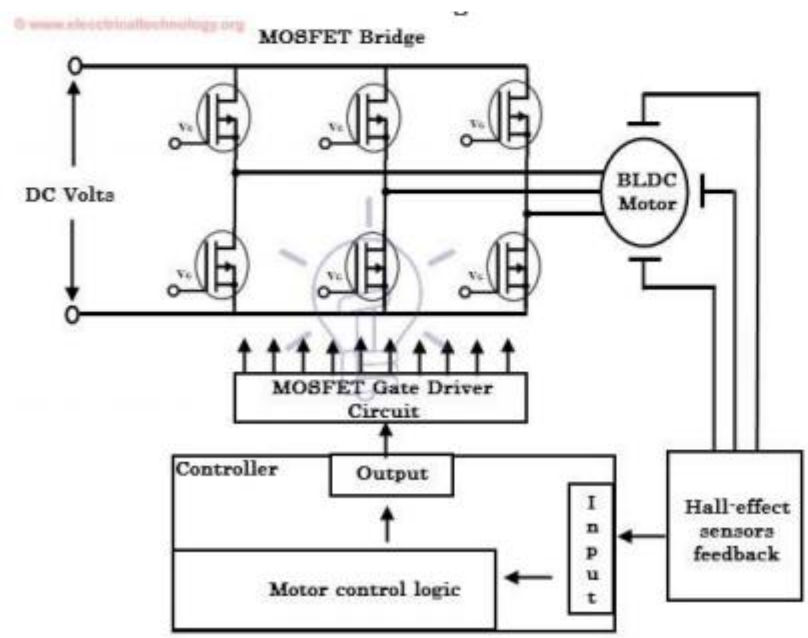
$$T_e = \frac{3P}{4} \left(i_{qs}\lambda_f + (L_d - L_q) i_{ds} i_{qs} \right)$$

For balanced system, Maximum Torque Operation is achieved when

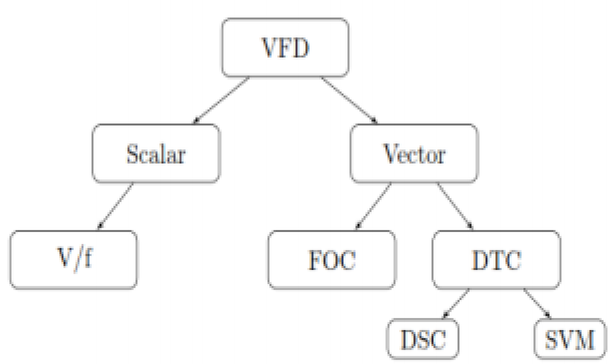
$$T_e = \frac{3P}{4} \left(i_{qs}\lambda_f \right)$$

3. Design of Brushless DC Motor Controller

The purpose of Brushless DC motor controller is to drive the motor. It may also control the motor speed, torque or current. The controller requires the information of rotor position to decide the switching sequence for the Bridge of Electronic switches.



The Motor controllers can be classified as Scalar or Vector Controllers. Scalar Control relies on adjustment of stator voltage or frequency to keep the stator flux constant. Vector control techniques include Field Oriented Control and Direct Torque Control. These schemes will be discussed in the next section



The plant model for the Brushless DC motor is

$$V_{abc} = Ri_{abc} + sLi_{abc} + e_{abc}(\theta_e)$$

$$T_e - T_L = B\omega_m + Js\omega_m$$

$$T_e = \frac{3P}{4}\left(i_{qs}\lambda_f\right)$$

The current controller can be designed to adjust the average stator voltage applied across stator windings. This can be achieved using a Pulse Width Modulation technique. Before this, the currents must be sensed using current sensors and a low pass filter.

$$G_{LPF} = \frac{1}{1 + sT_i}$$

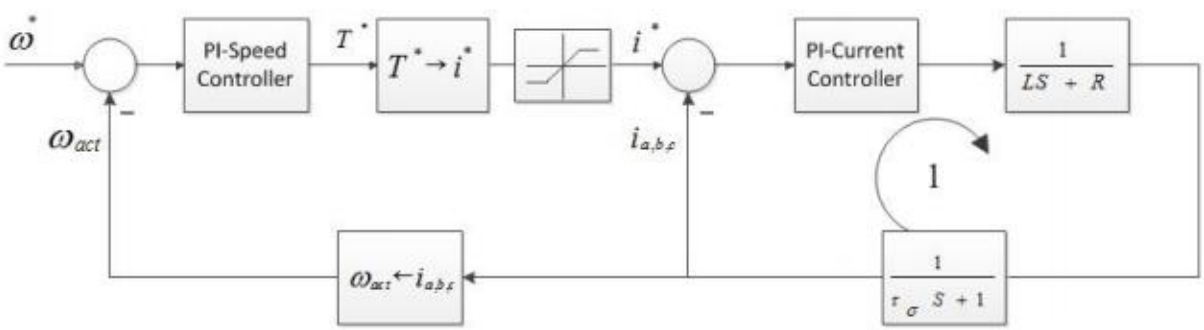
The current controller can be realized using a PI controller to track current reference and generate correction voltage command.

$$G_i(s) = k_{Pi} + \frac{k_{Ii}}{s}$$

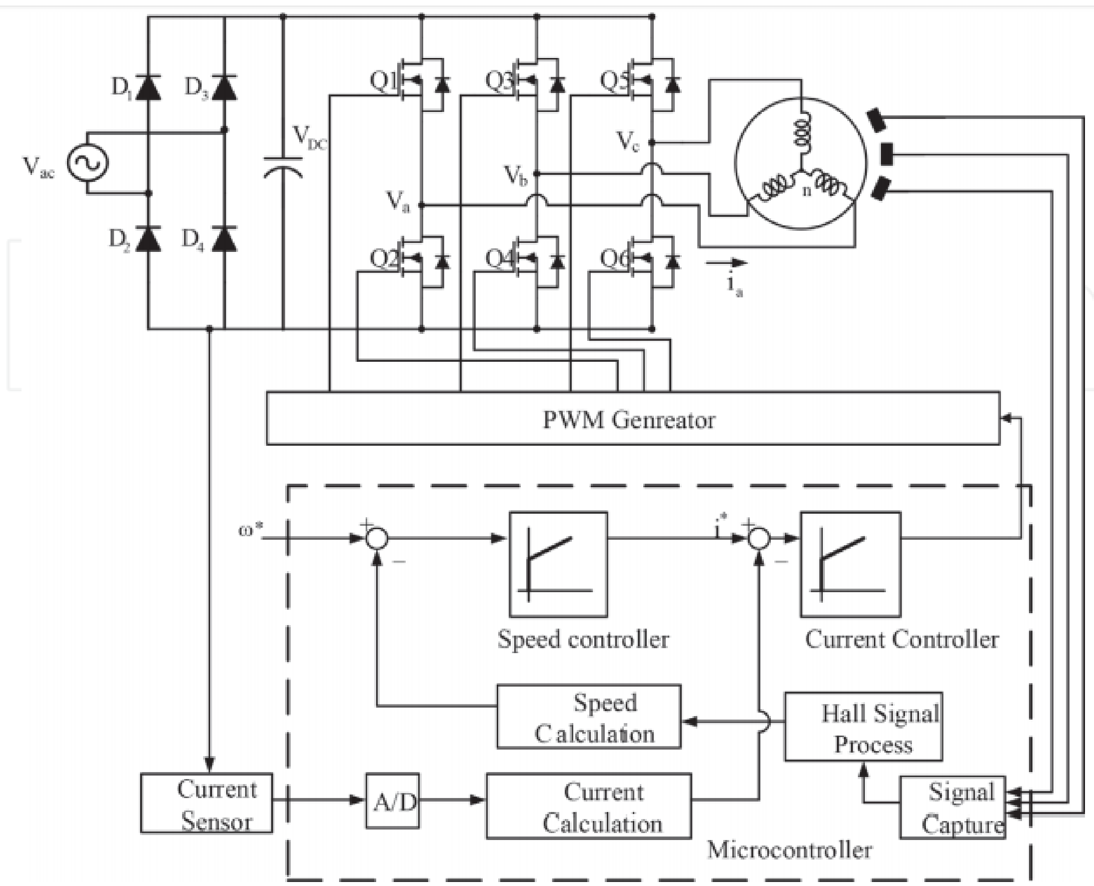
A speed controller can be designed to track a speed reference. It works by comparing the motor speed with the reference speed. The error is passed through a PI speed controller.

$$G_s(s) = k_{Ps} + \frac{k_{Is}}{s}$$

The controller generates a Torque/ current reference for the cascaded current controller. The complete cascaded controller is shown below.



The complete system for speed control of Brushless DC Motor is shown below.



D1
D3
D2
D4
Vac
VDC
Q1
Q3
Q5
Q2
Q4
Q6
Va
Vb
Vc
n
ia
PWM Genreator
ω*
i*
Speed controller
Current Controller
Speed Calculation
Hall Signal Process
Current Sensor
A/D
Current Calculation
Signal Capture
Microcontroller

3.1. Direct Torque Control

The Electromagnetic Torque of Brushless DC Motor can be expressed as

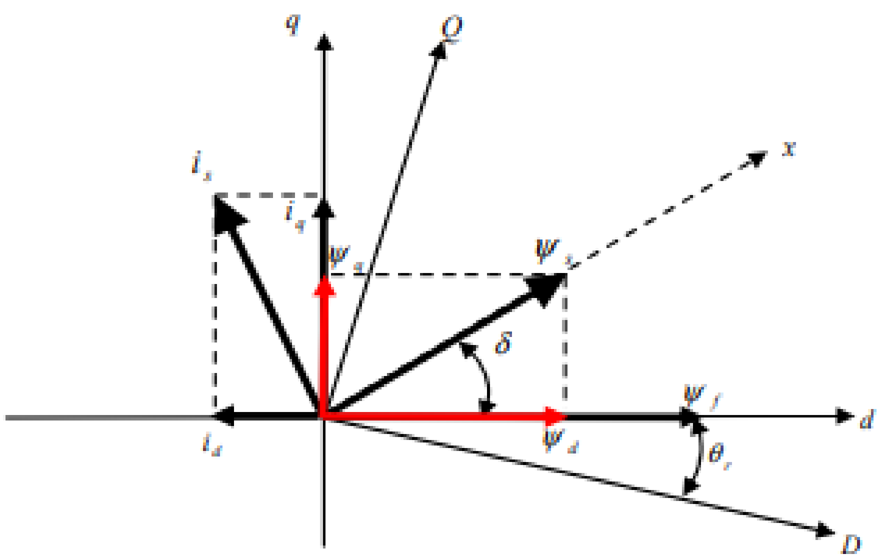
$$T_e = \frac{3P}{4L_{ds}L_{qs}} |\lambda_s| [2\lambda_f L_{qs} sin\delta - |\lambda_s| (L_{qs} - L_{ds}) \, sin2\delta]$$

The first component of Torque results from field excitation. It is responsible for driving the load hence it must be maximized by controlling the stator flux λ_s, or the sine of angle between stator flux and rotor flux $sin\delta$. This is the basis of Direct Torque Control.

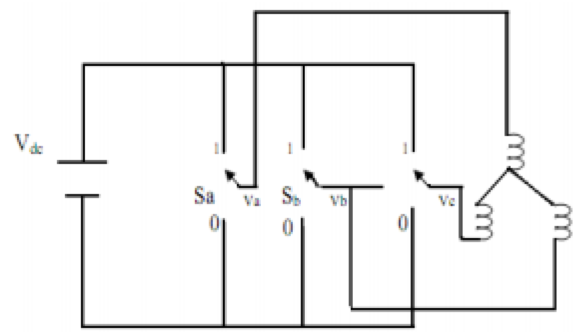
$$T_{ed} = \frac{3P}{4L_{ds}L_{qs}} |\lambda_s| [2\lambda_f L_{qs} sin\delta]$$

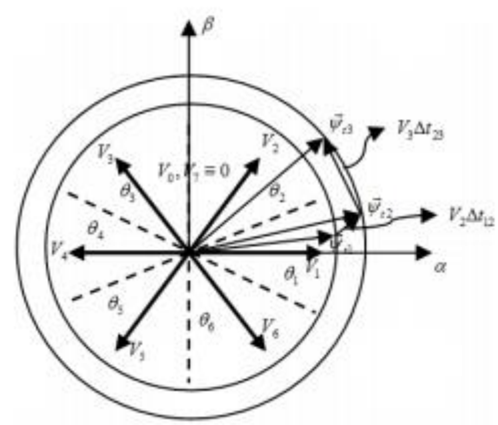
The second component is responsible for producing pulsating reluctance torque which results in wastage of energy. For this reason, the second component of Torque must be zero by ensuring $L_{qs} = L_{ds}$ (non-salient motor) or $i_{ds} = 0$.

$$T_{eq} = \frac{3P}{4L_{ds}L_{qs}} |\lambda_f| [-|\lambda_s| (L_{qs} - L_{ds}) \, sin2\delta]$$



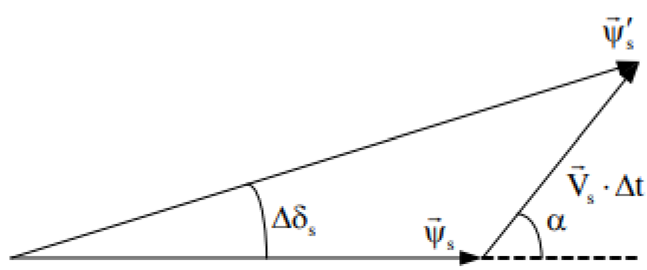
The Direct Torque Controller works by changing the stator flux λ_s, or the sine of angle between stator flux and rotor flux $sin\delta$. This is achieved by applying the appropriate stator voltage vector to correct the stator flux.



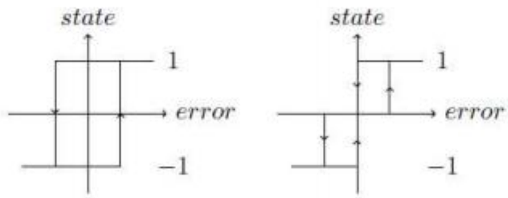


The resultant stator flux is approximately

$$\overrightarrow{\Psi_s'} = \overrightarrow{\Psi_s} + \overrightarrow{V_s}.\Delta t - \overrightarrow{\iota_s}.R_s.\Delta t \approx \overrightarrow{\Psi_s} + \overrightarrow{V_s}.\Delta t$$



The Controller works by comparing stator flux and torque to their reference values. A hysteresis comparator generates correction commands to tweak the stator flux by application of correction voltage.

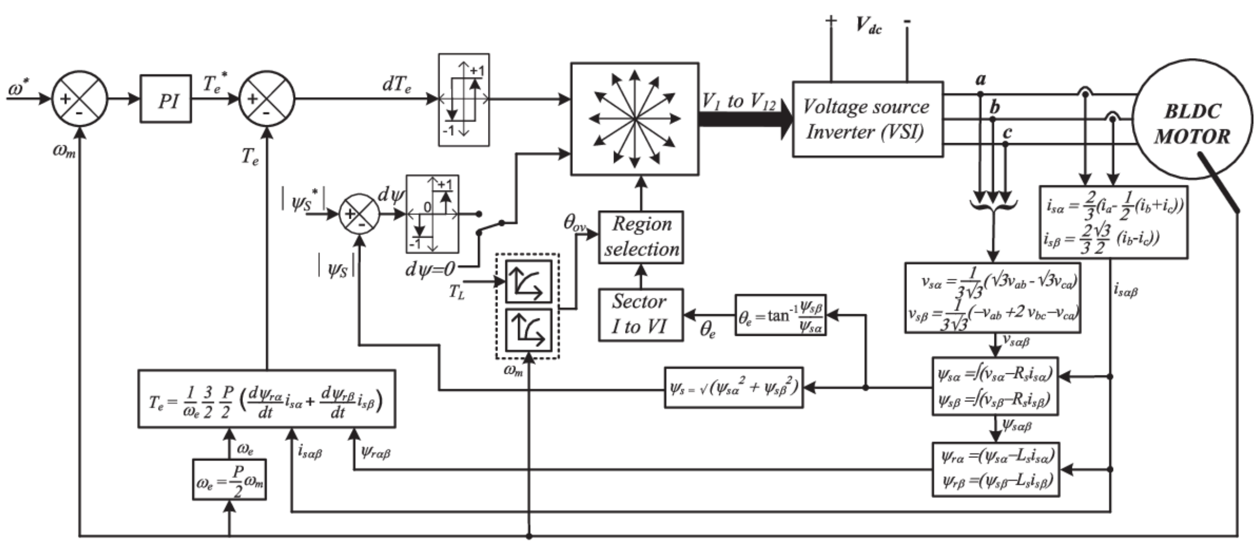


(a) Flux: two level (b) Torque: three level

Correction voltage command depends on the voltage sector of Stator voltage. The commands are stored in a switching table to make the process efficient and fast. Usually a switching frequency of 10kHz is chosen.

Flux φ	Torque τ	θ - Section (stator flux linkage position)					
		θ_1	θ_2	θ_3	θ_4	θ_5	θ_6
	τ=1	V_2(110)	V_3(010)	V_4(011)	V_5(001)	V_6(101)	V_1(100)
φ=1	τ=0	V_7(111)	V_0(111)	V_7(111)	V_0(111)	V_7(111)	V_0(111)
	τ=-1	V_6(101)	V_1(100)	V_2(110)	V_3(010)	V_4(011)	V_5(001)
	τ=1	V_3(010)	V_4(011)	V_5(001)	V_6(101)	V_1(100)	V_2(110)
φ =0	τ=0	V_0(111)	V_7(111)	V_0(111)	V_7(111)	V_0(111)	V_7(111)
	τ=-1	V_5(001)	V_6(101)	V_1(100)	V_2(110)	V_3(010)	V_4(011)

The overall block diagram for Direct Torque Control is given below.



3.2. Field Oriented Control

The Electromagnetic Torque of Brushless DC Motor can be expressed as

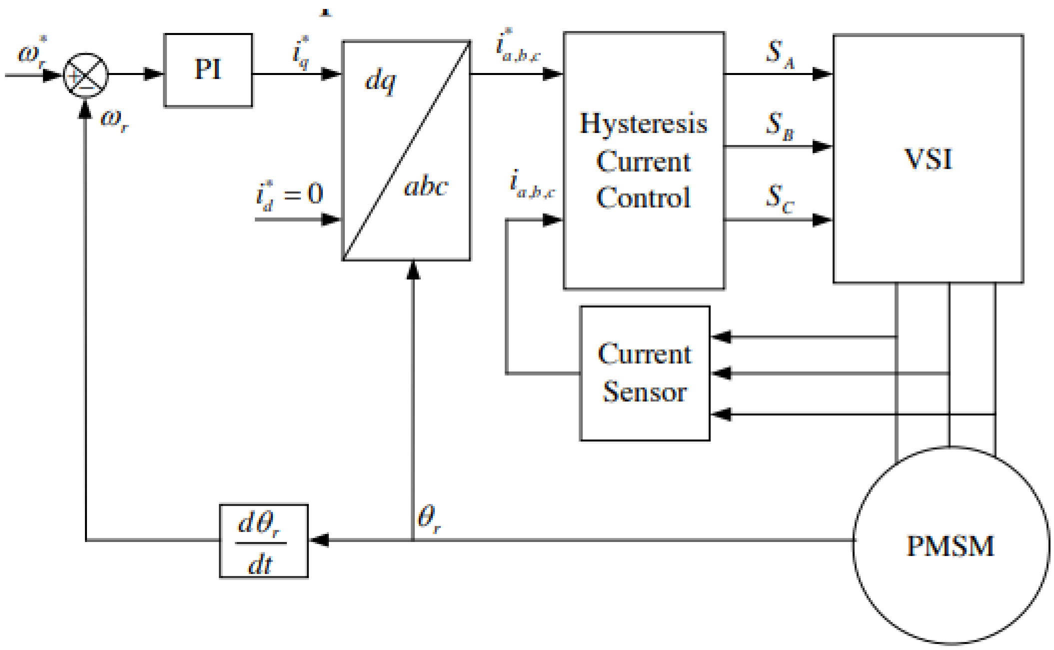
$$T_e = \frac{3P}{4}\left(i_{qs}\lambda_f + \left(L_{ds} - L_{qs}\right)i_{ds}i_{qs}\right)$$

The first component of Torque results from field excitation. It is responsible for driving the load hence it must be maximized by controlling the quadrature component of stator current i_{qs}. This is the basis of Field Oriented Control.

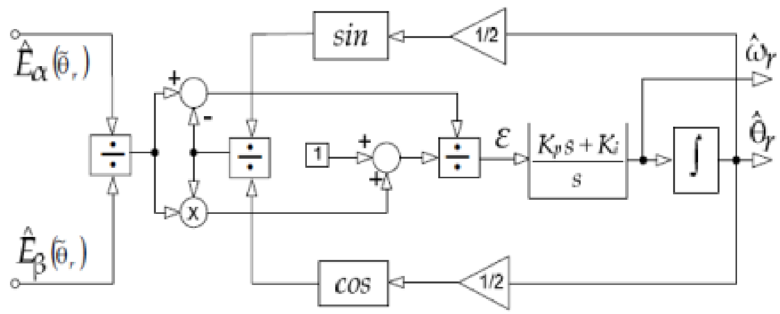
$$T_e = \frac{3P}{4}\left(i_{qs}\lambda_f\right)$$

The second component is responsible for producing reluctance torque which results in wastage of energy. For this reason, the second component of Torque must be zero by ensuring $L_{qs} = L_{ds}$ (non-salient motor) or $i_{ds} = 0$.

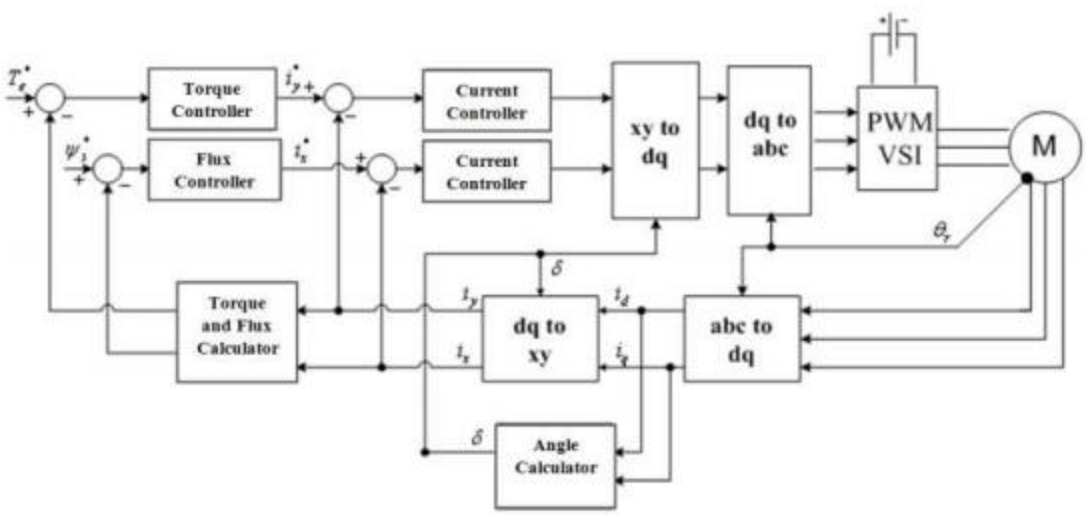
$$T_{eq} = \frac{3P}{4}\left[\left(L_{ds} - L_{qs}\right)i_{ds}i_{qs}\right]$$



The abc/dq and dq/abc reference frame transformations require the measurement of rotor angle/ speed. A speed sensor can be used for this purpose. A Phase Locked Loop can also be used to track the motor speed using Hall Sensor signals.



The Field Oriented Controller can be used for the direct control of Torque and stator flux. Separate Controllers must be designed as shown below.



Field Oriented Control requires complex computations because it involves system transformations. It also needs the sensor position unlike Direct Torque Controller. Ultimately, Field Oriented Control is more precise and complex, much slower and more sensitive to sensor errors and parameter variation as compared to Direct Torque Control.

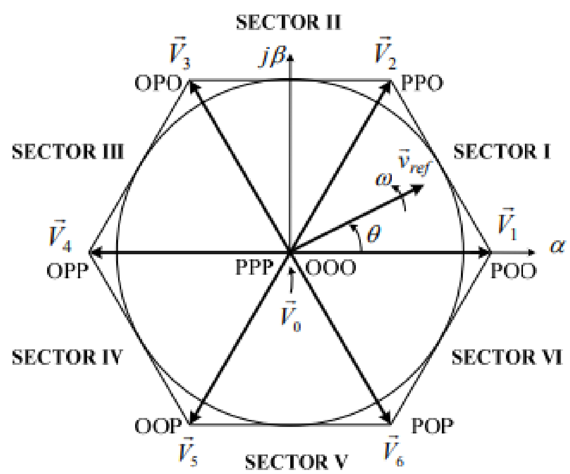
Method / Index	FOC	DTC
System Transformation	need	no need
Voltage Modulation	need	no need
Calculation Value	high	low
Sensivity To Parameter Changes	yes	no
Sensor Position	need	no need

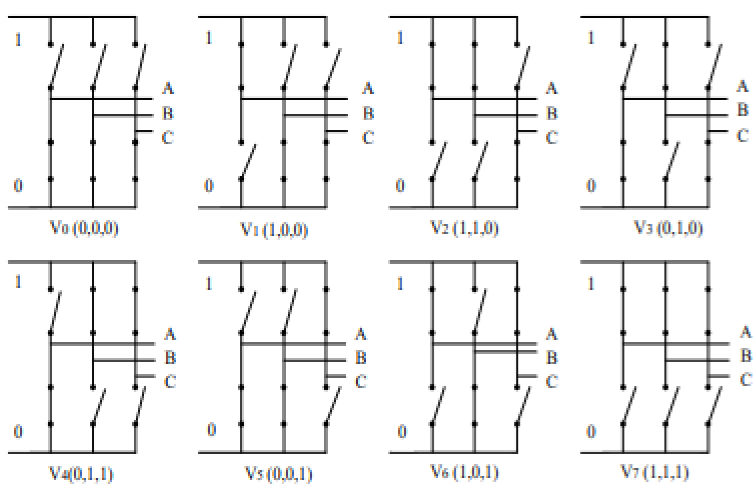
3.3. Space Vector PWM

Space vector modulation (SVM) is a real-time modulation technique widely used for digital control of voltage source inverters. The operating status of the switches in the two-level inverter can be represented by switching states. The switching state 'P' denotes that the upper switch in an inverter leg is on and the inverter terminal voltage is positive (+Vdc) while 'O' indicates that the inverter terminal voltage is zero due to the conduction of the lower switch.

Switching State	Leg *a*			Leg *b*			Leg *c*		
	S_1	S_4	v_{aN}	S_3	S_6	v_{bN}	S_5	S_2	v_{cN}
P	On	Off	V_{dc}	On	Off	V_{dc}	On	Off	V_{dc}
O	Off	On	0	Off	On	0	Off	On	0

There are eight possible combinations of switching states in the two-level inverter. Among the eight switching states, [PPP] and [OOO] are zero states and the others are active states.





The active and zero switching states can be represented by active and zero space vectors, respectively in the αβ reference frame. The space vector diagram below represents the six active vectors which form a regular hexagon with six equal sectors (I to VI). The zero vector V0 lies on the center of the hexagon.

$$\overrightarrow{\mathrm{V_k}} = \frac{2}{3} V_{dc} e^{j(k-1)\frac{\pi}{3}}$$

where k represents the sector.

For a given magnitude and position, $\overrightarrow{\mathrm{v_{ref}}}$ can be synthesized by three nearby stationary vectors (OOO, POO and PPO in sector 1), based on which the switching states of the inverter can be selected, and gate signals for the active switches can be generated. When $\overrightarrow{\mathrm{v_{ref}}}$ passes through sectors one by one, different sets of switches will be turned on or off. As a result, when $\overrightarrow{\mathrm{v_{ref}}}$ rotates one revolution in space, the inverter output voltage varies one cycle over time.

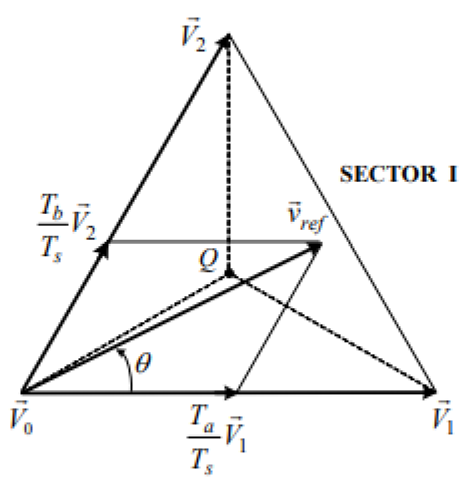
$$\overrightarrow{v_{ref}} = v_{ref} e^{j\theta}$$

$$v_{ref} = \sqrt{v_\alpha^2 + v_\beta^2}$$

$$\theta = \tan^{-1} \frac{v_\beta}{v_\alpha}$$

The inverter output frequency corresponds to the rotating speed of $\overrightarrow{\mathrm{v_{ref}}}$ while its output voltage can be adjusted by the modulation index:

$$\mathrm{m_a} = \frac{\sqrt{3} v_{ref}}{V_{dc}}$$



The dwell time for the stationary vectors represents the duty-cycle time of the chosen switches during a sampling period Ts. The dwell time calculation is based on 'volt-second balancing' principle, that is, the product of the reference voltage $\overrightarrow{\mathrm{v_{ref}}}$ and sampling period Ts equals the sum of the voltage multiplied by the time interval of chosen space vectors. Assuming that the sampling period Ts is sufficiently small, the reference vector ref v r can be considered constant during Ts. Under this assumption, $\overrightarrow{\mathrm{v_{ref}}}$ can be approximated by two adjacent active vectors and one zero vector. Ta , Tb and T0 are the dwell times for the vectors $\overrightarrow{v_1}$, $\overrightarrow{v_2}$ and $\overrightarrow{v_0}$, respectively:

$$\begin{cases} T_a = \dfrac{\sqrt{3}T_s v_{ref}}{V_{dc}} \sin(\dfrac{\pi}{3} - \theta) \\ T_b = \dfrac{\sqrt{3}T_s v_{ref}}{V_{dc}} \sin(\theta) \\ T_0 = T_s - T_a - T_b \end{cases} \qquad 0 \le \theta < \frac{\pi}{3}$$

When $\overrightarrow{v_{ref}}$ is in other sectors, a multiple of π 3/ is subtracted from the actual angular displacement θ such that the modified angle θ ′ falls into the range between zero and π 3/ for use in the equation, that is,

$$\theta' = \theta - (k-1)\frac{\pi}{3} \qquad \text{for } 0 \le \theta' < \frac{\pi}{3}$$

where k = 1, 2, …6 for sectors I, II, …, VI, respectively. For example, when $\overrightarrow{v_{ref}}$ is in sector II, the calculated dwell times Ta, Tb and T0 are for vectors $\overrightarrow{v_2}$, $\overrightarrow{v_3}$ and $\overrightarrow{v_0}$ respectively.

With the space vectors selected and their dwell times calculated, the next step is to arrange switching sequence. In general, the switching sequence design for a given $\overrightarrow{v_{ref}}$ is not unique, but it should satisfy the following two requirements for the minimization of the device switching frequency:

a) The transition from one switching state to the next involves only two switches in the same inverter leg, one being switched on and the other switched off;

b) The transition for ref v r moving from one sector in the space vector diagram to the next requires no or minimum number of switching.

The optimized seven segment switching sequence is given in the table below.

Sector	**Switching Segment**						
	1	2	3	4	5	6	7
I	$\vec{V}_0$	$\vec{V}_1$	$\vec{V}_2$	$\vec{V}_0$	$\vec{V}_2$	$\vec{V}_1$	$\vec{V}_0$
	OOO	POO	PPO	PPP	PPO	POO	OOO
II	$\vec{V}_0$	$\vec{V}_3$	$\vec{V}_2$	$\vec{V}_0$	$\vec{V}_2$	$\vec{V}_3$	$\vec{V}_0$
	OOO	OPO	PPO	PPP	PPO	OPO	OOO
III	$\vec{V}_0$	$\vec{V}_3$	$\vec{V}_4$	$\vec{V}_0$	$\vec{V}_4$	$\vec{V}_3$	$\vec{V}_0$
	OOO	OPO	OPP	PPP	OPP	OPO	OOO
IV	$\vec{V}_0$	$\vec{V}_5$	$\vec{V}_4$	$\vec{V}_0$	$\vec{V}_4$	$\vec{V}_5$	$\vec{V}_0$
	OOO	OOP	OPP	PPP	OPP	OOP	OOO
V	$\vec{V}_0$	$\vec{V}_5$	$\vec{V}_6$	$\vec{V}_0$	$\vec{V}_6$	$\vec{V}_5$	$\vec{V}_0$
	OOO	OOP	POP	PPP	POP	OOP	OOO
VI	$\vec{V}_0$	$\vec{V}_1$	$\vec{V}_6$	$\vec{V}_0$	$\vec{V}_6$	$\vec{V}_1$	$\vec{V}_0$
	OOO	POO	POP	PPP	POP	POO	OOO

The switching commands are stored in a switching table to make the process efficient and fast.

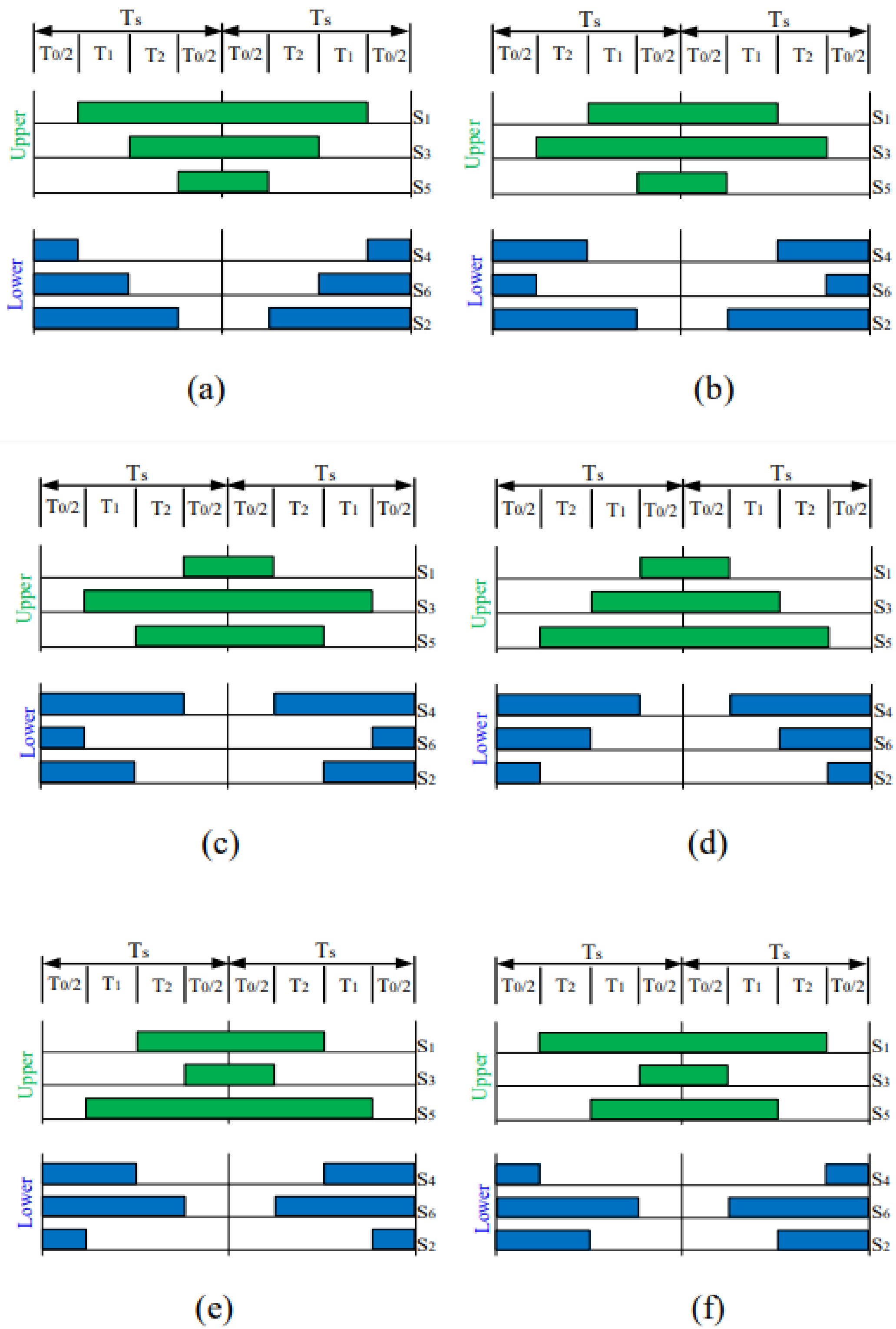
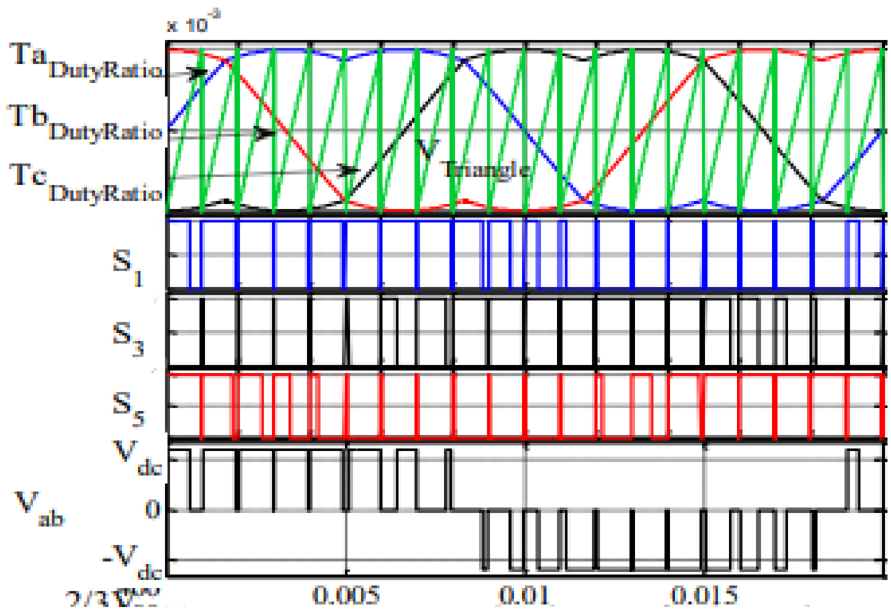


Figure 10: SVPWM switching patterns in (a) sector 1, (b)sector 2, (c) sector 3, (d) sector 4, (e) sector 5, and (f) sector 6

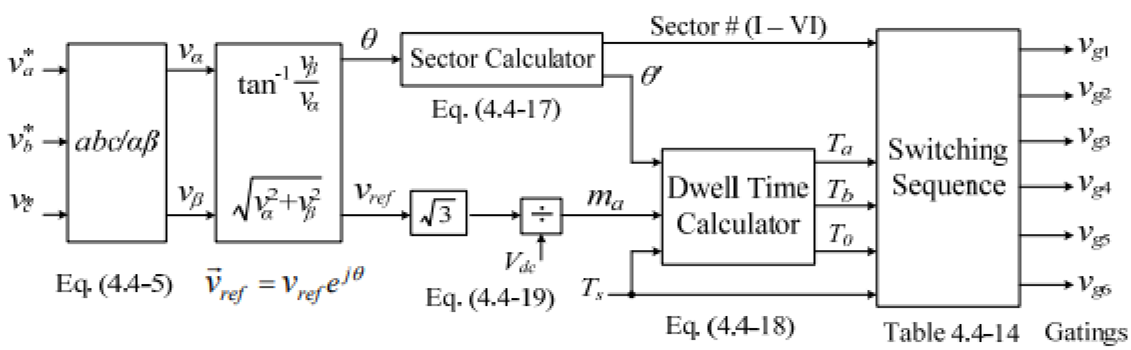
The resulting stator voltages for the eight sectors are shown in the table below.

Voltage vectors	Switching vectors			Line to neutral voltage			Line to line voltage		
	S_1	S_3	S_5	V_{an}	V_{bn}	V_{cn}	V_{ab}	V_{bc}	V_{ca}
V_0	0	0	0	0	0	0	0	0	0
V_1	1	0	0	$2/3\,V_{dc}$	$-1/3\,V_{dc}$	$-1/3\,V_{dc}$	V_{dc}	0	$-V_{dc}$
V_2	1	1	0	$1/3\,V_{dc}$	$1/3\,V_{dc}$	$-2/3\,V_{dc}$	0	V_{dc}	$-V_{dc}$
V_3	0	1	0	$-1/3\,V_{dc}$	$2/3\,V_{dc}$	$-1/3\,V_{dc}$	$-V_{dc}$	V_{dc}	0
V_4	0	1	1	$-2/3\,V_{dc}$	$1/3\,V_{dc}$	$1/3\,V_{dc}$	$-V_{dc}$	0	V_{dc}
V_5	0	0	1	$-1/3\,V_{dc}$	$-1/3\,V_{dc}$	$2/3\,V_{dc}$	0	$-V_{dc}$	V_{dc}
V_6	1	0	1	$1/3\,V_{dc}$	$-2/3\,V_{dc}$	$1/3\,V_{dc}$	V_{dc}	$-V_{dc}$	0
V_7	1	1	1	0	0	0	0	0	0

The results are presented in graphical form below.

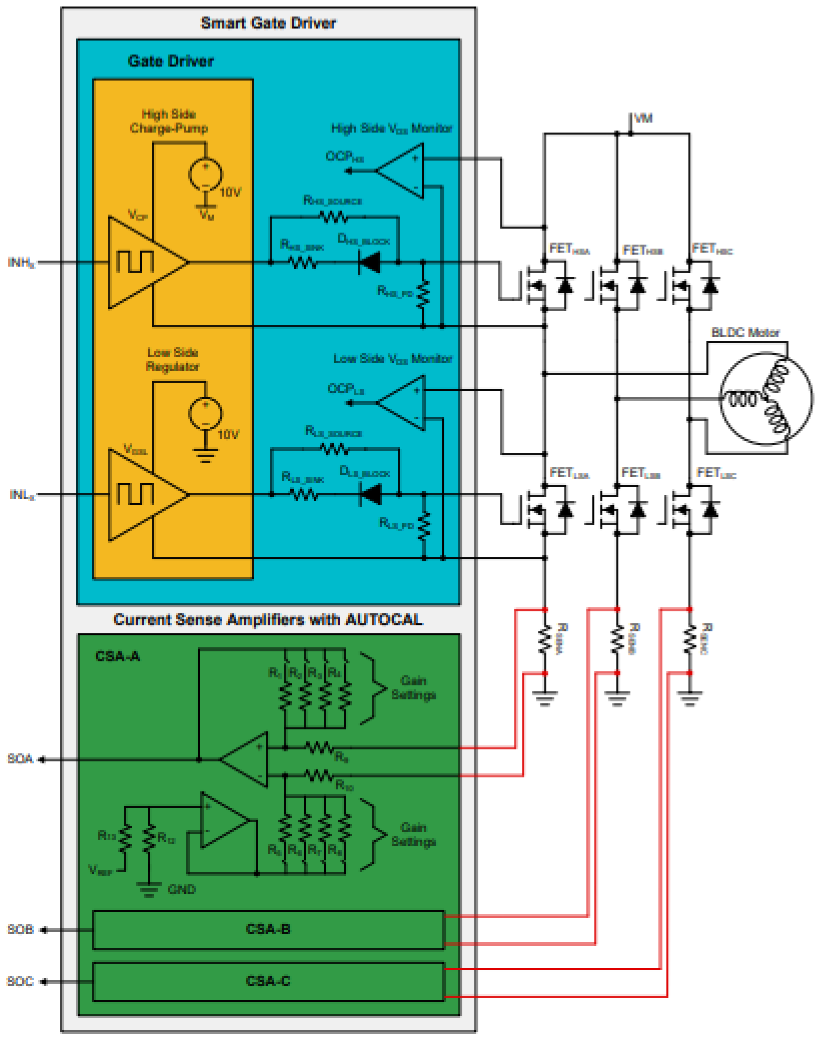


The overall Space Vector Modulation block diagram is given below.



3.4. Safety and Protection of Devices

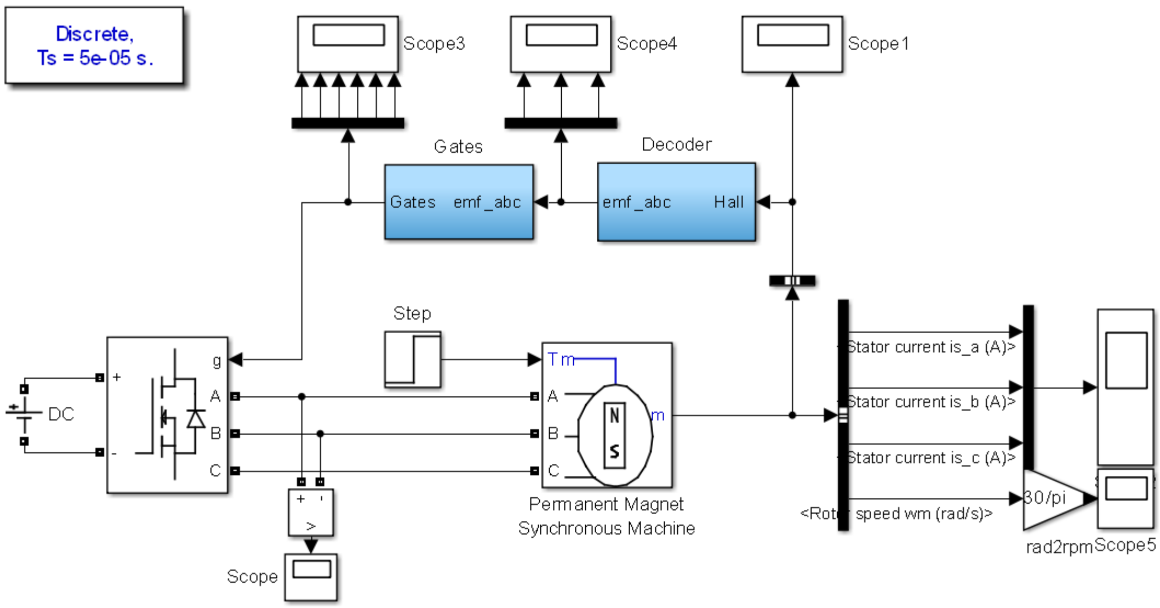
In order to ensure safe and reliable operation of electronic switches and Brushless DC Motor, the switch voltages and currents must be sensed using special circuitry. Controllers must be designed to cause shutdown when necessary. The overall protection system containing sensors and amplifiers is shown below.



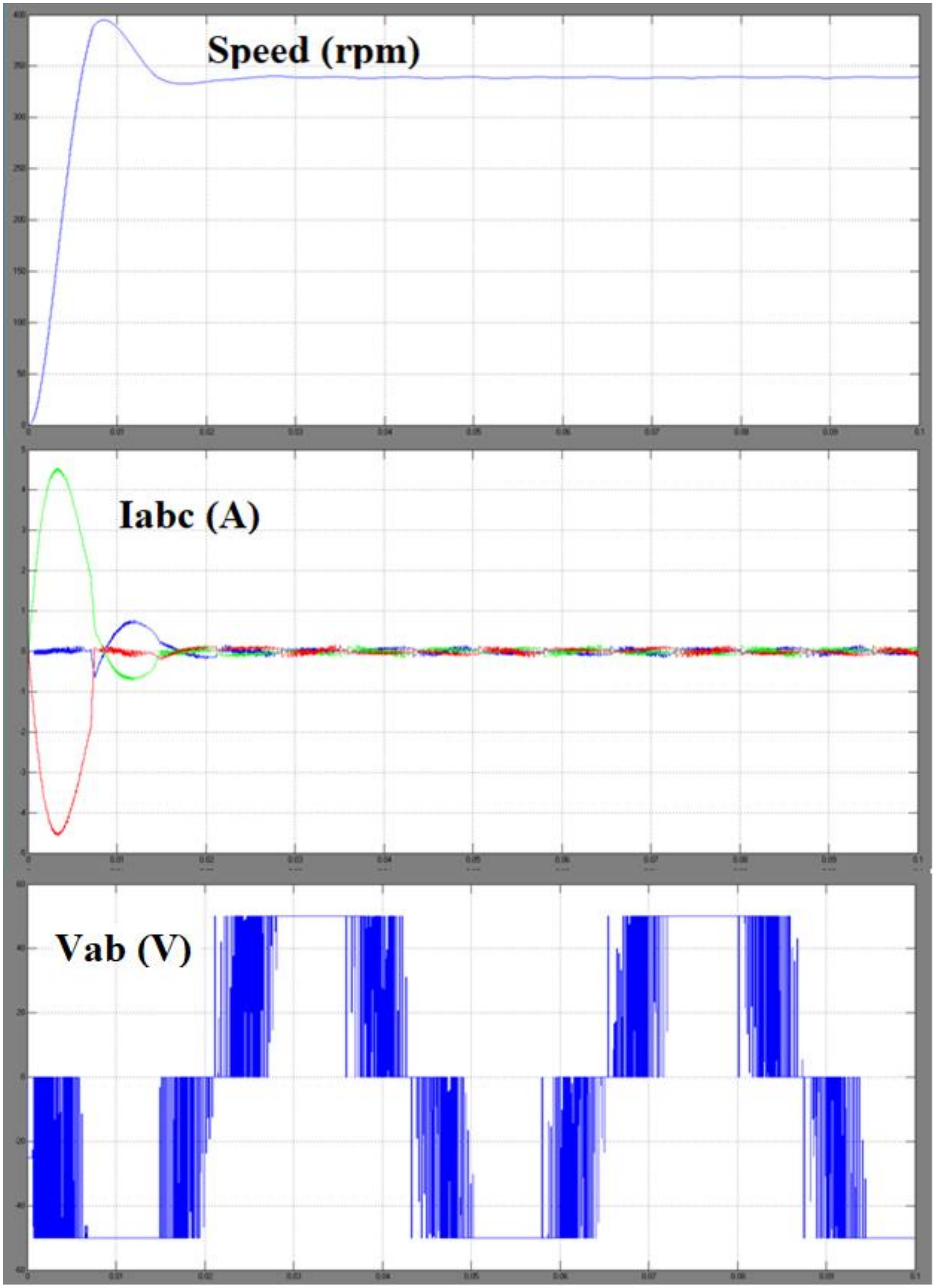
3.5. Open Loop Control

The open loop controller drives the Brushless DC motor by electronically controlled commutation. The phase currents are changed at appropriate times to rotate the rotor magnet to desired position. The energization of stator windings produces a magnetic field which attracts or repels the rotor for a short time so that the two magnetic fields align.

The Simulink model for the simulation is shown below.

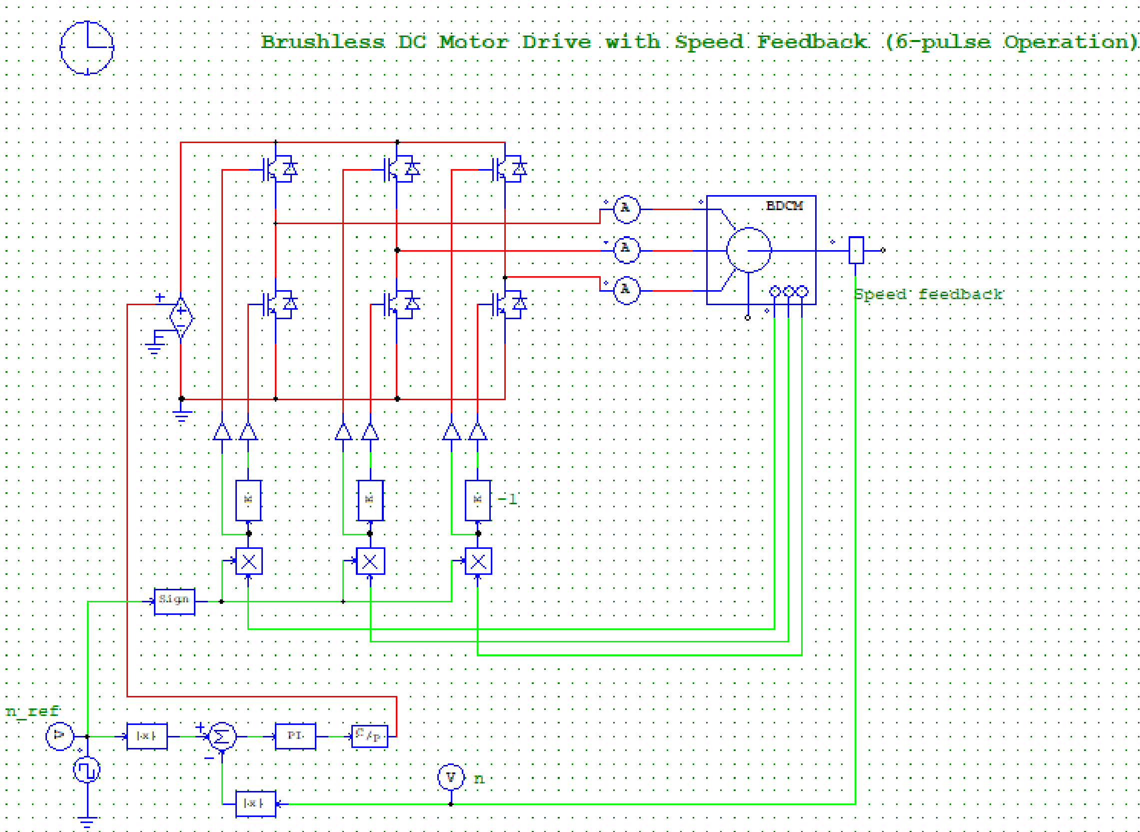


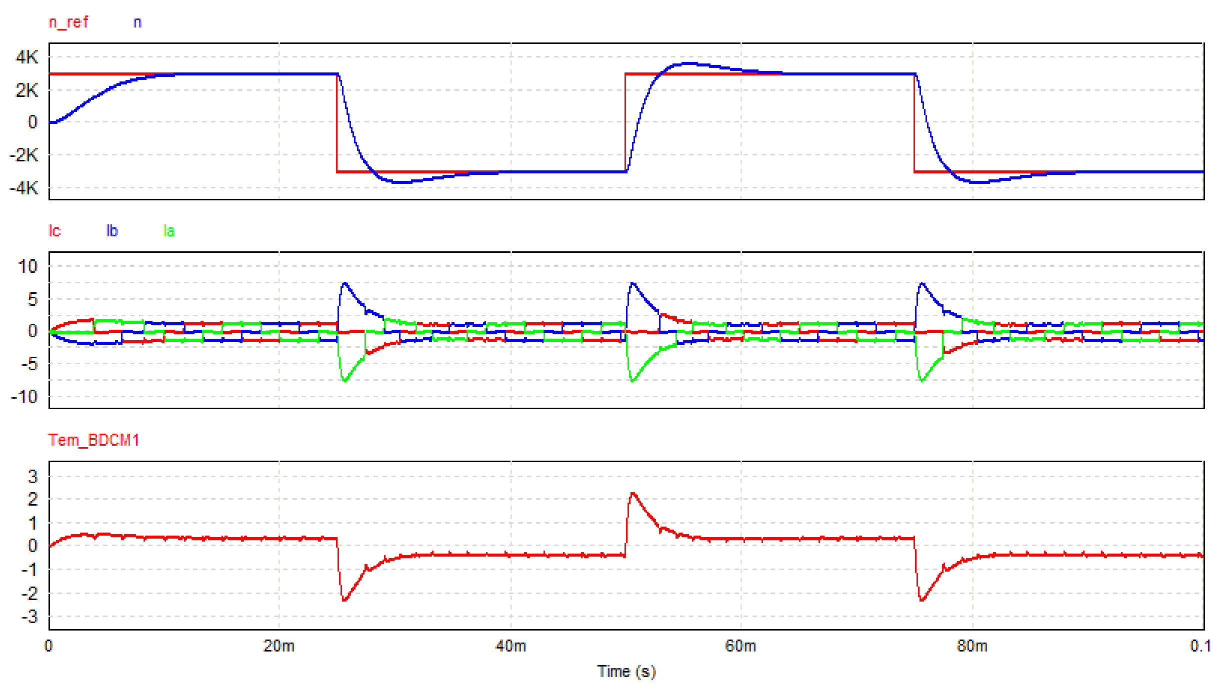
The motor speed, currents and line-line voltage are shown below.



3.6. Speed Control

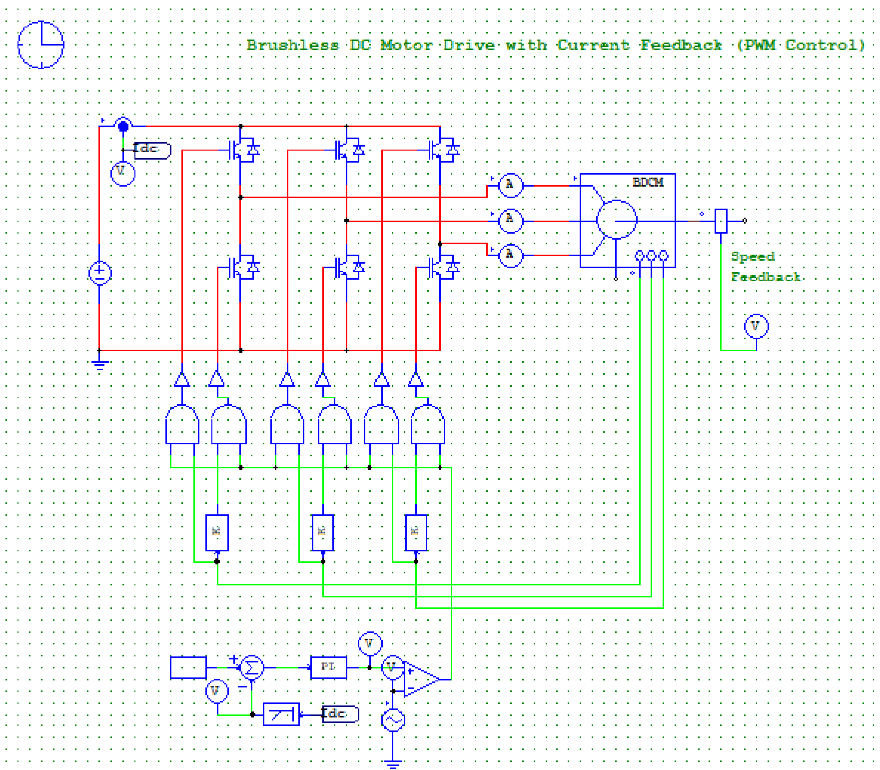
The PSIM model for Speed Control is shown below. The Speed, currents and Torque are plotted also.

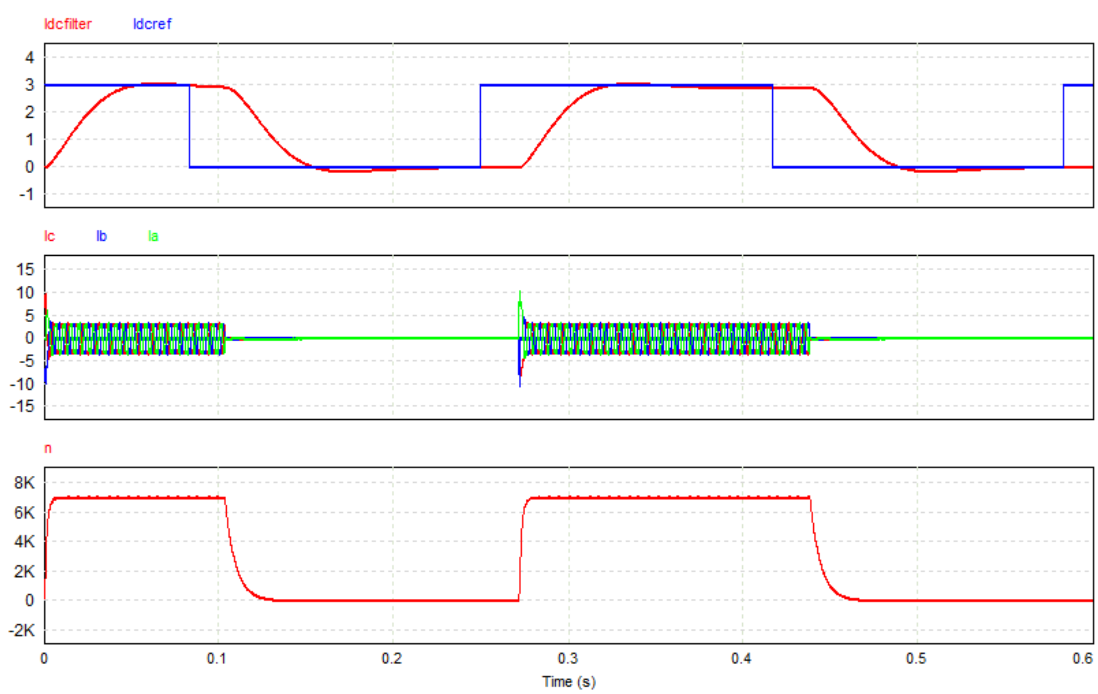




3.7. Current Control

The PSIM model for Current Control is shown below. The DC currents, phase currents and Speed are plotted also.

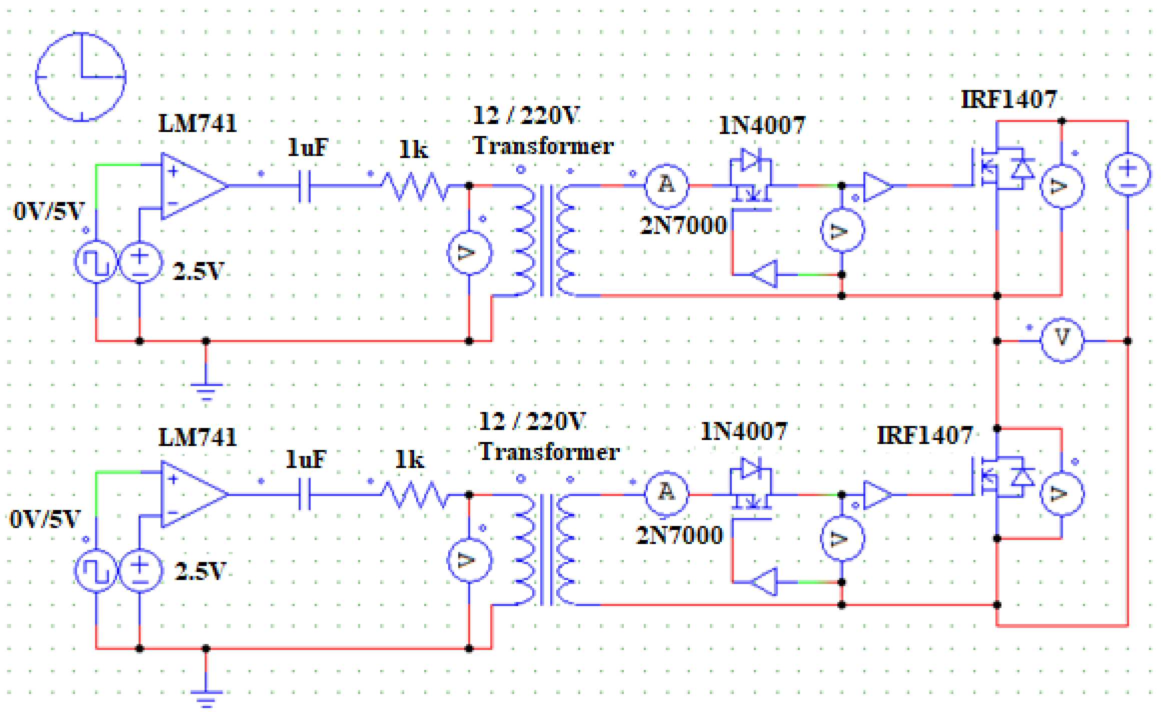


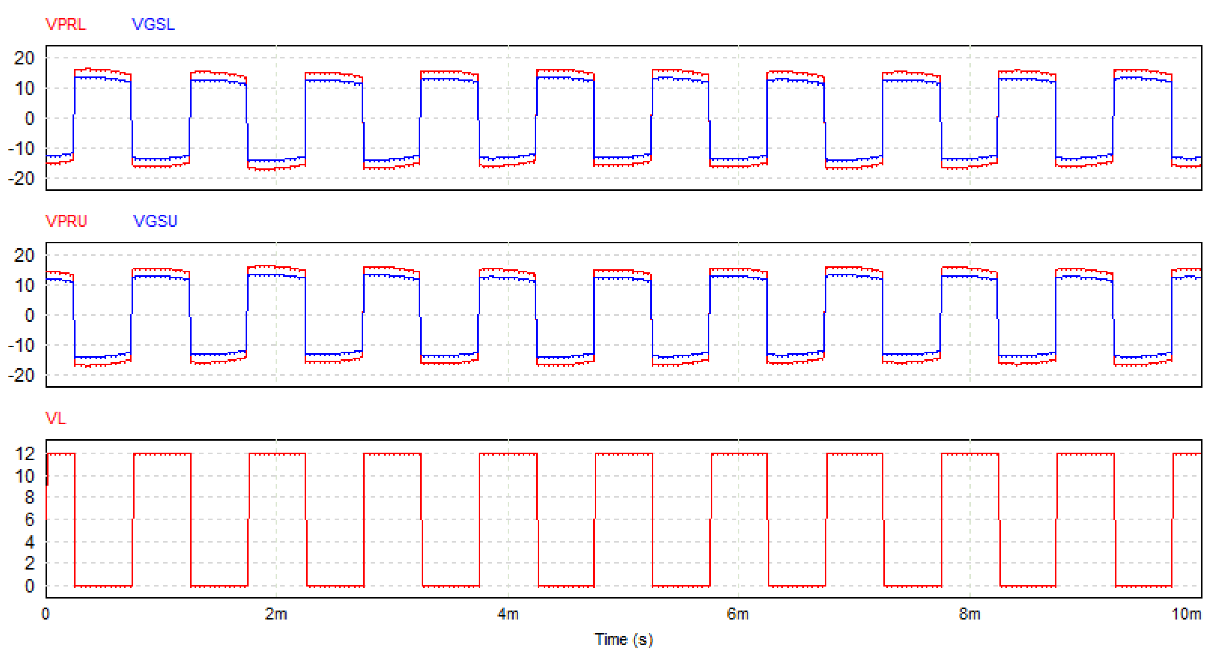


4. Progress

4.1. Inverter with Transformer Isolation

The PSIM model for Inverter with Transformer Isolation is shown below. The primary winding voltages, Main MOSFET Gate-Source voltages and Phase voltage are plotted below.





Arduino Code for Inverter

```
double frequency = 2500.0; //Set frequency in Hertz
double delayTime = (1000000.0 / (frequency * 2.0));//Half Period in microseconds
void setup()
{
pinMode(2, OUTPUT);
pinMode(3, OUTPUT);
pinMode(4, OUTPUT);
pinMode(5, OUTPUT);
pinMode(6, OUTPUT);
pinMode(7, OUTPUT);
pinMode(8, OUTPUT);
pinMode(9, OUTPUT);
pinMode(10, OUTPUT);
pinMode(11, OUTPUT);
pinMode(12, OUTPUT);
pinMode(13, OUTPUT);

digitalWrite(2, HIGH);
digitalWrite(3, HIGH);
digitalWrite(4, HIGH);
digitalWrite(5, HIGH);
digitalWrite(6, HIGH);
digitalWrite(7, HIGH);
}
void loop()
{
digitalWrite(8, LOW);
digitalWrite(9, HIGH);
delayMicroseconds(delayTime/3);
digitalWrite(12, HIGH);
digitalWrite(13, LOW);
delayMicroseconds(delayTime/3);
digitalWrite(10, LOW);
digitalWrite(11, HIGH);
delayMicroseconds(delayTime/3);
digitalWrite(8, HIGH);
digitalWrite(9, LOW);
delayMicroseconds(delayTime/3);
digitalWrite(12, LOW);
digitalWrite(13, HIGH);
delayMicroseconds(delayTime/3);
digitalWrite(10, HIGH);
digitalWrite(11, LOW);
delayMicroseconds(delayTime/3);
}
```

4.2. Inverter with Optical Isolation