REGENERATIVE BRAKING IN BLDC MOTOR

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TOPICS

- Physics behind the BLDC working
- Regenerative braking strategies

MOTOR CONSTRUCTION

- Surface Mounted PMSM’s
- Provides highest air gap flux density as it faces the air gap directly without any other medium in between
- Fairly low reluctance variation between direct and quadrature axis, hence little variation in d and q inductances
- Sinusoidal PMSM type, lesser torque ripple as opposed to the trapezoidal ones

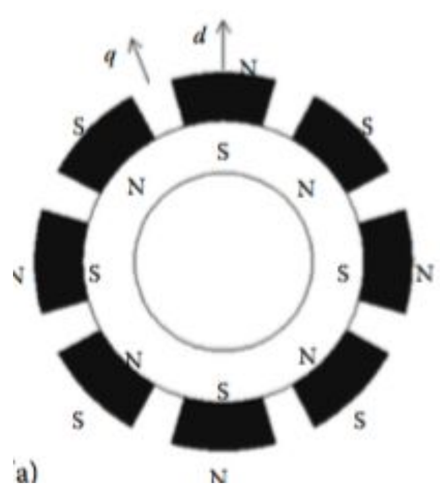
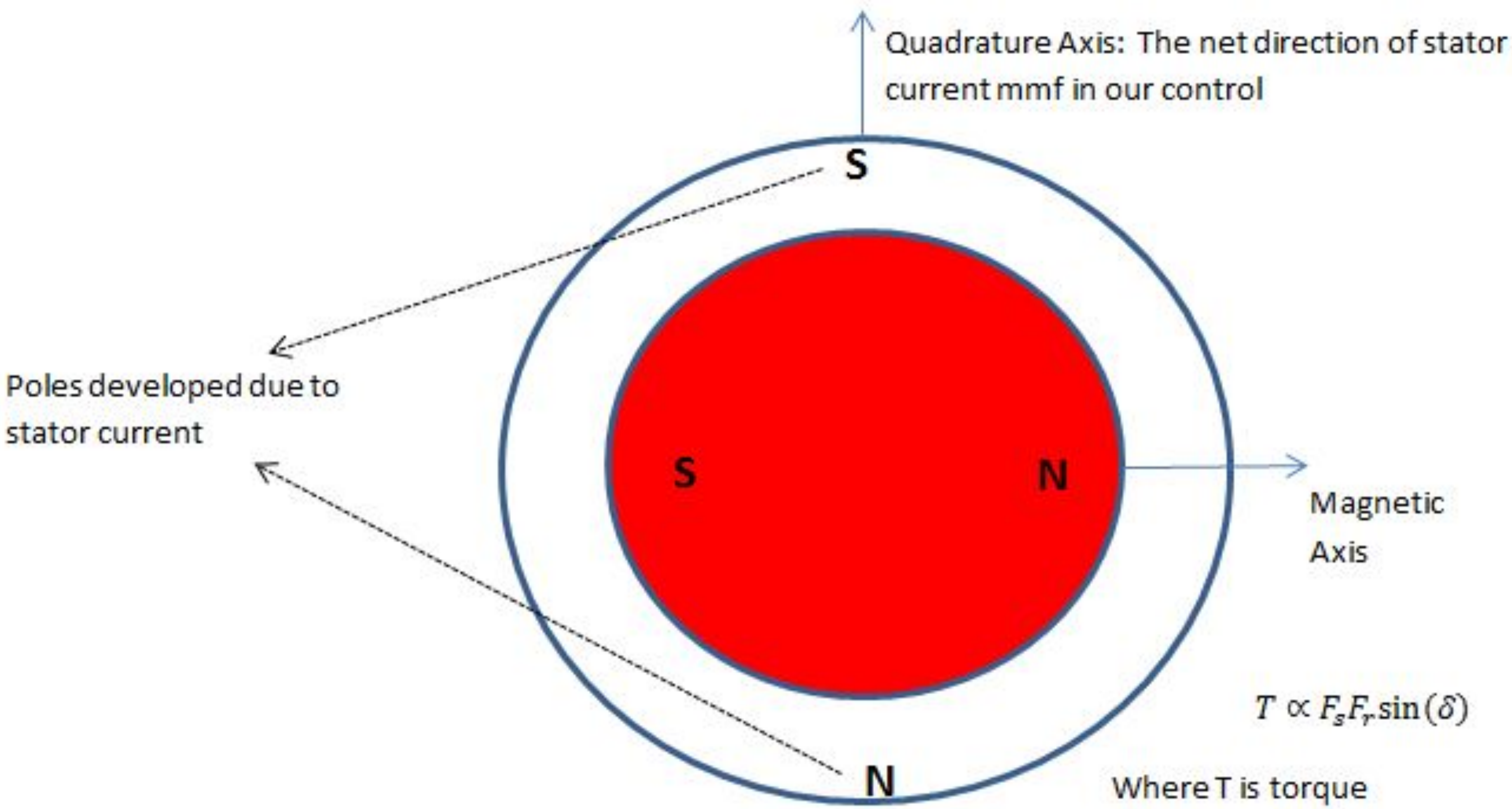


Fig.1[1]

Governing Principle

The basic principle behind running of BLDC motors



$$T \propto F_s F_r \sin(\delta)$$

Where T is torque

F_s / F_r Is mmf due to stator/ rotor

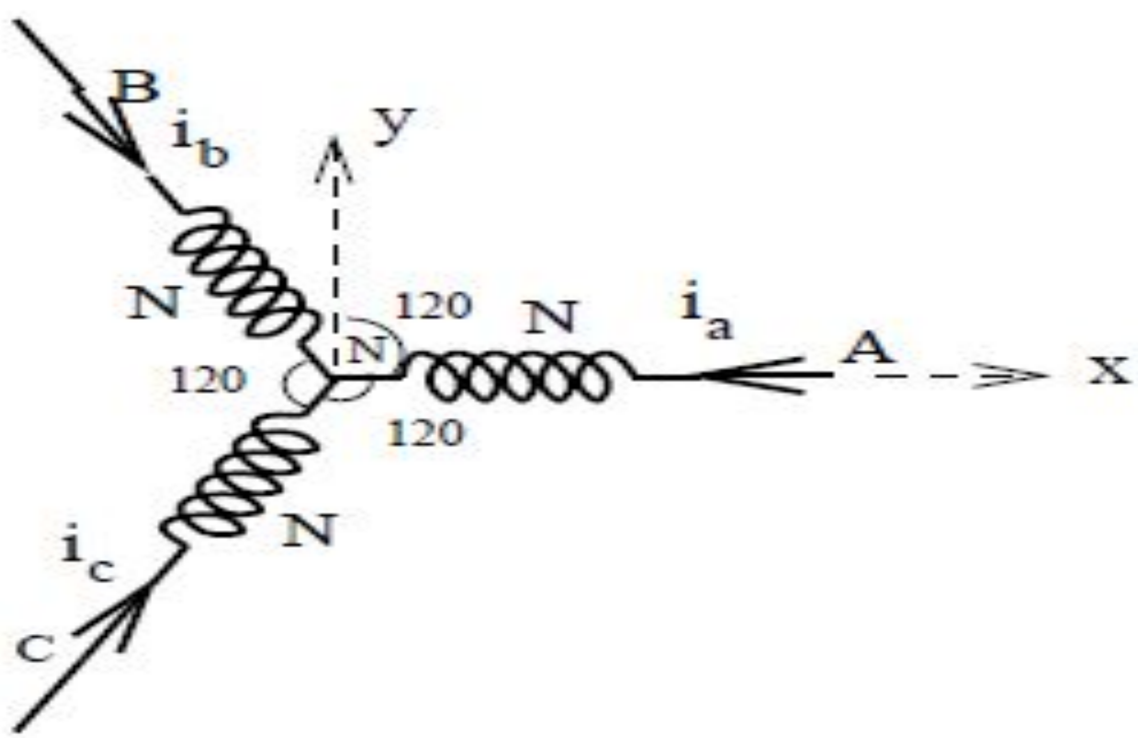
δ is angle between mmf of rotor and stator (90° in our case)

Fig.2

GOVERNING PRINCIPLE

We need a rotating stator mmf, but how to achieve that?

- This is accomplished by using three coils A, B and C of N turns each, displaced in space by 120 degrees and connected to a balanced 3 phase system as shown below



$i_a = I \sin(\omega_s t)$ $\quad$ $i_b = I \sin(\omega_s t + 120^o)$ $\quad$ $i_c = I \sin(\omega_s t + 240^o)$

Fig.3

Contd.

- This is variation of current in coils is achieved using 3 phase H-Bridge which connects to three phases of BLDC motor

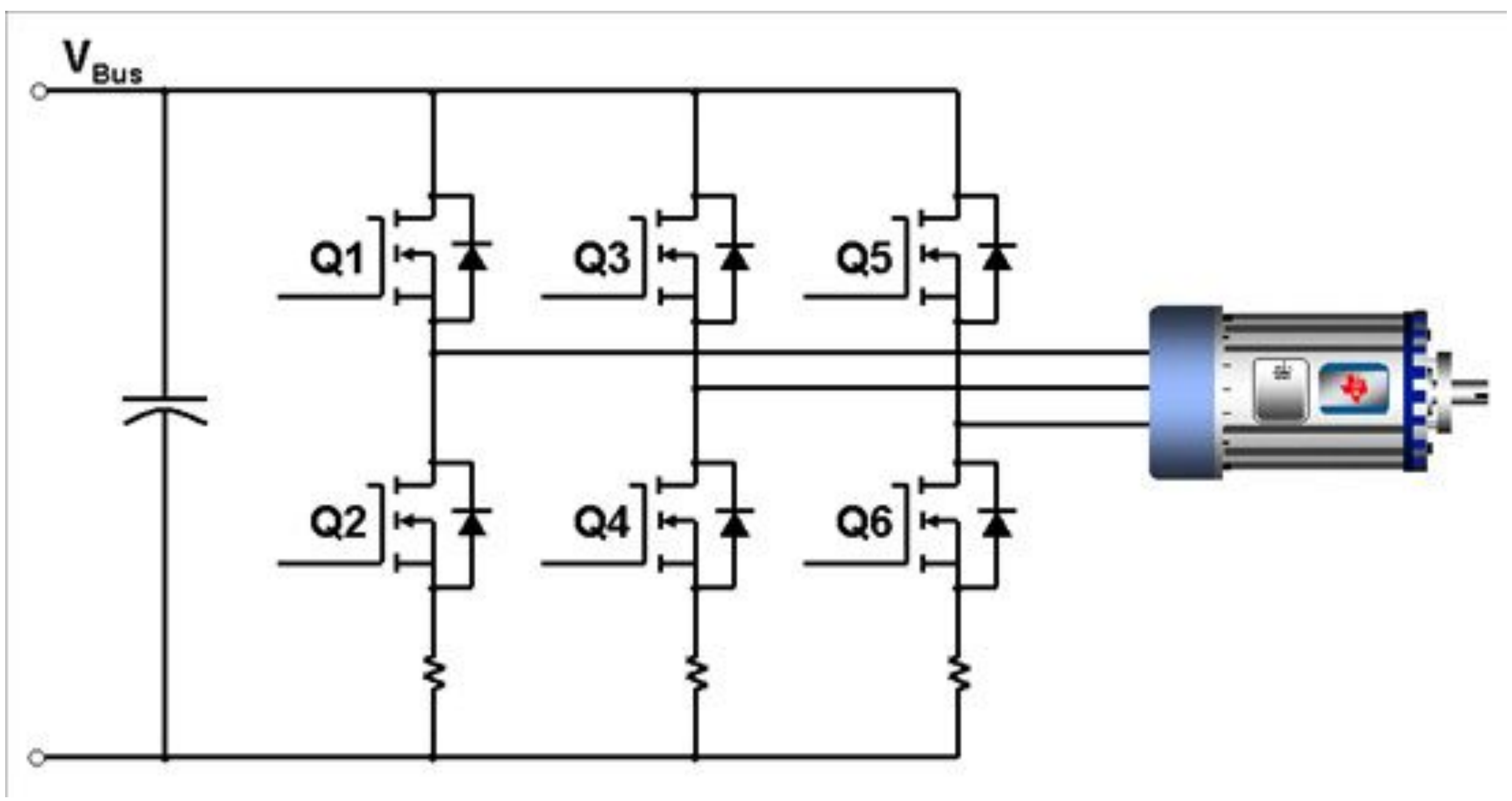


Fig.4

Simple Commutation Sequence

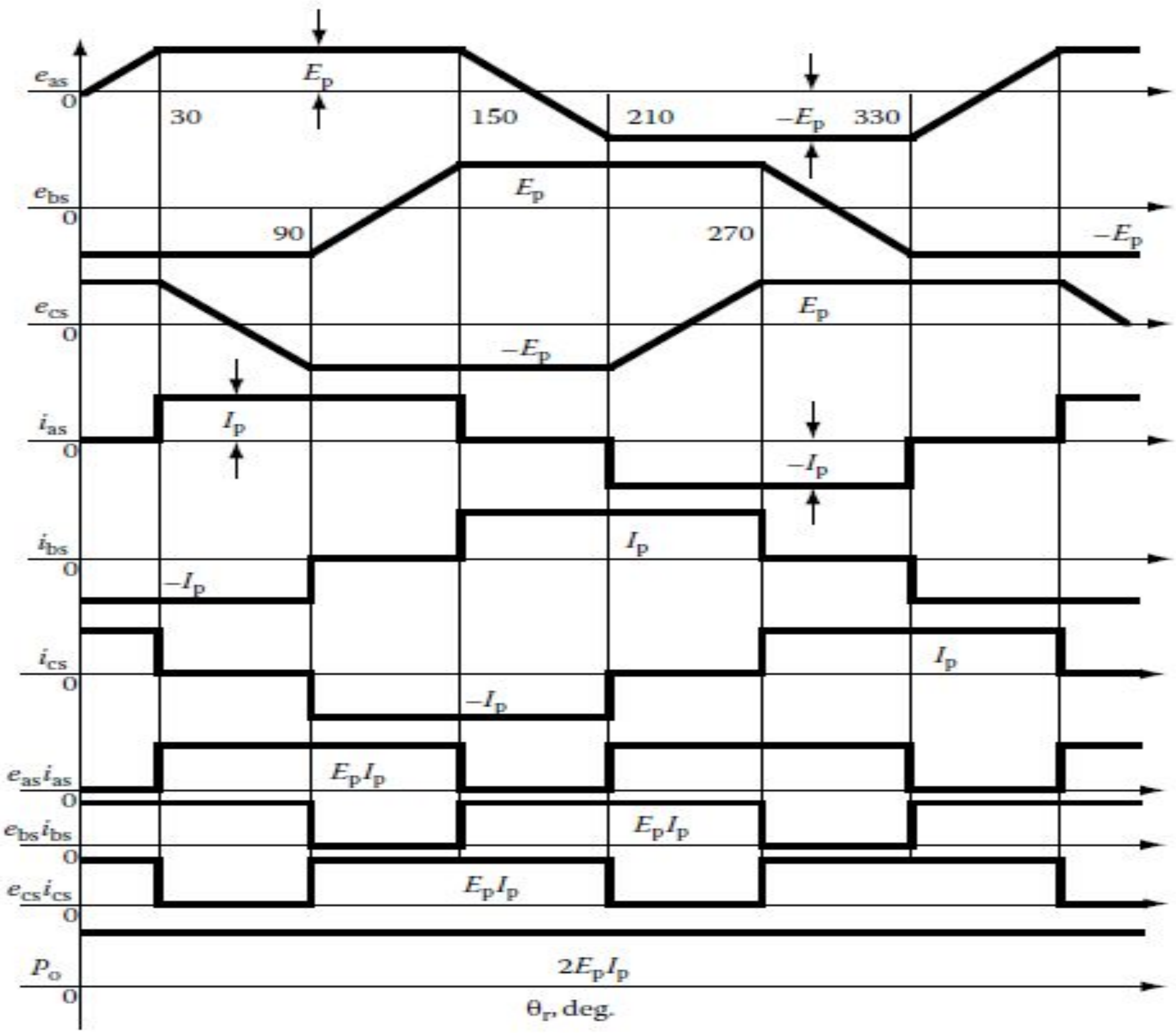


Fig.5

- Following figure shows back emf profile in three coils of bldc motors and corresponding currents in those phases.
- The idea is to connect the phase having +ve emf to positive terminal of battery while that having negative emf to negative terminal of the battery.

Transformation from stator frame to rotor frame

Stator frame of Reference

$$v_{qs} = R_q i_{qs} + p\lambda_{qs}$$
$$v_{ds} = R_d i_{ds} + p\lambda_{ds}$$

$$\lambda_{qs} = L_{qq} i_{qs} + L_{qd} i_{ds} + \lambda_{af} \sin(\theta_r)$$
$$\lambda_{ds} = L_{dq} i_{qs} + L_{dd} i_{ds} + \lambda_{af} \cos(\theta_r)$$

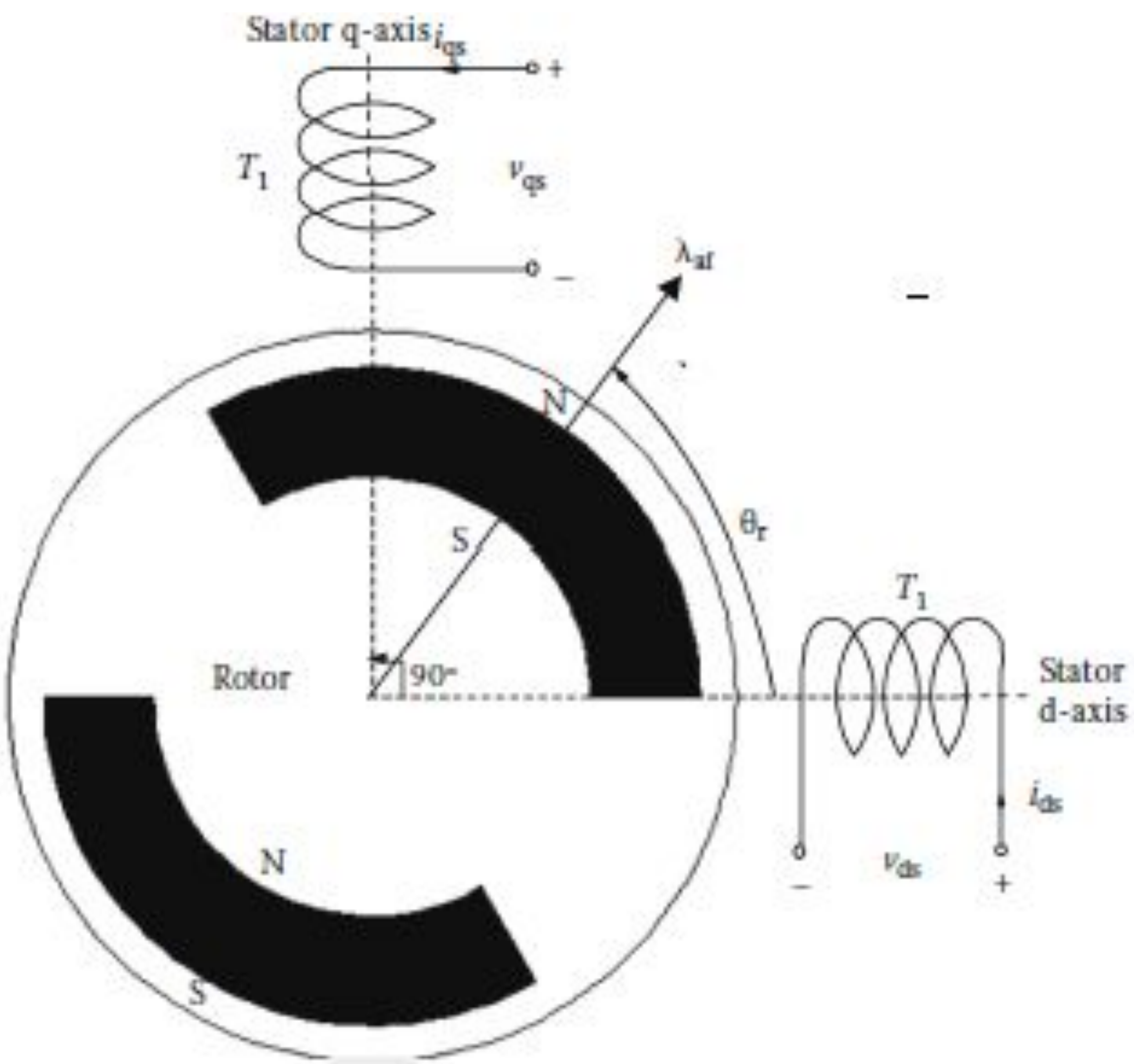


Fig.6[1]

Contd.

- Analysing the system in a frame with rotating speed equal to that of supply voltage, dynamics equations gets simplified
- Since relative angular speed between supply voltage and reference frame is zero, sinusoidal quantities appear as DC quantities.

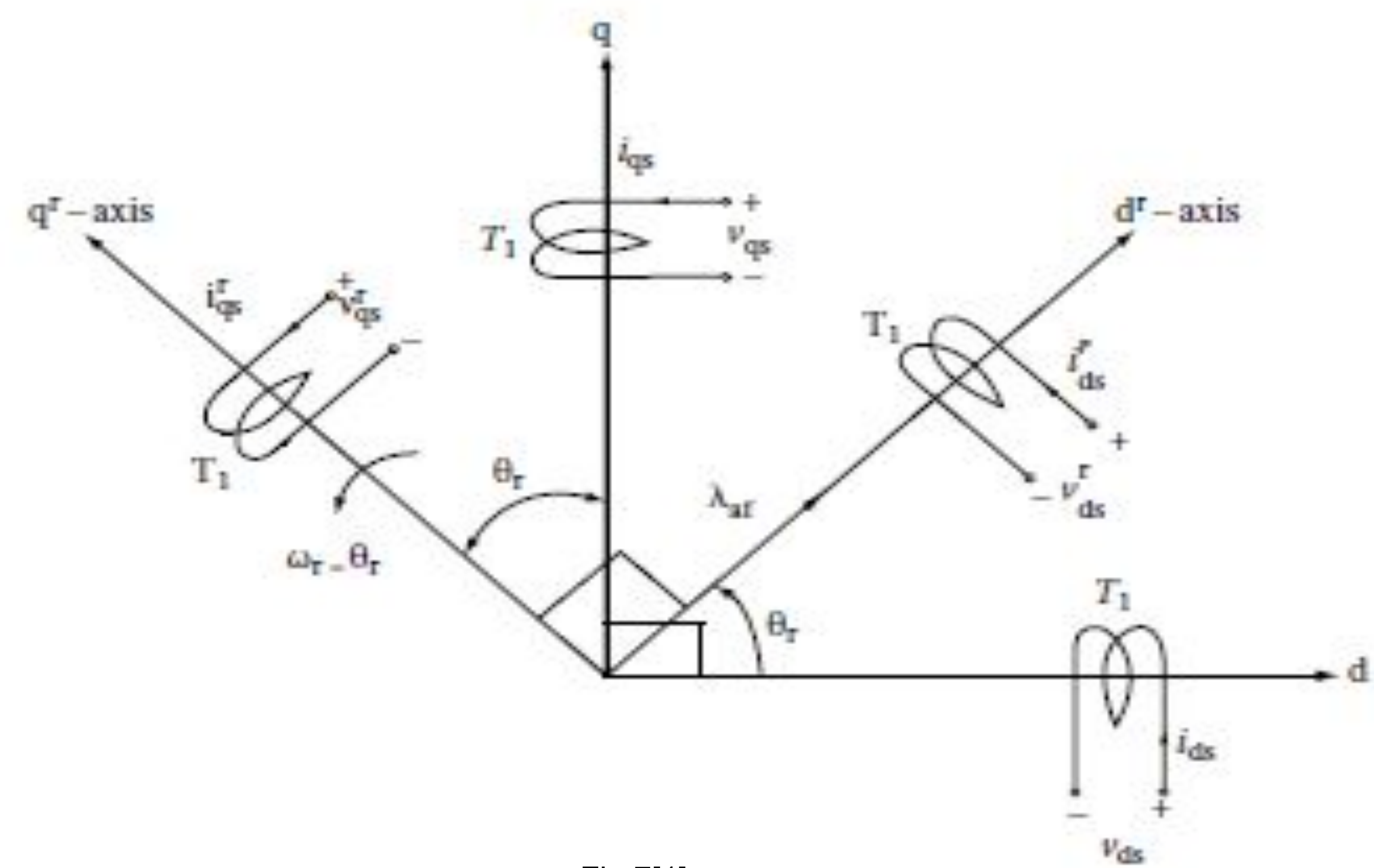


Fig.7[1]

Contd.

$$\begin{bmatrix} v_{qs}^{r} \\ v_{ds}^{r} \end{bmatrix} = \begin{bmatrix} R_s + L_q p & \omega_r L_d \\ -\omega_r L_q & R_s + L_d p \end{bmatrix} \begin{bmatrix} i_{qs}^{r} \\ i_{ds}^{r} \end{bmatrix} + \begin{bmatrix} \omega_r \lambda_{af} \\ 0 \end{bmatrix}$$

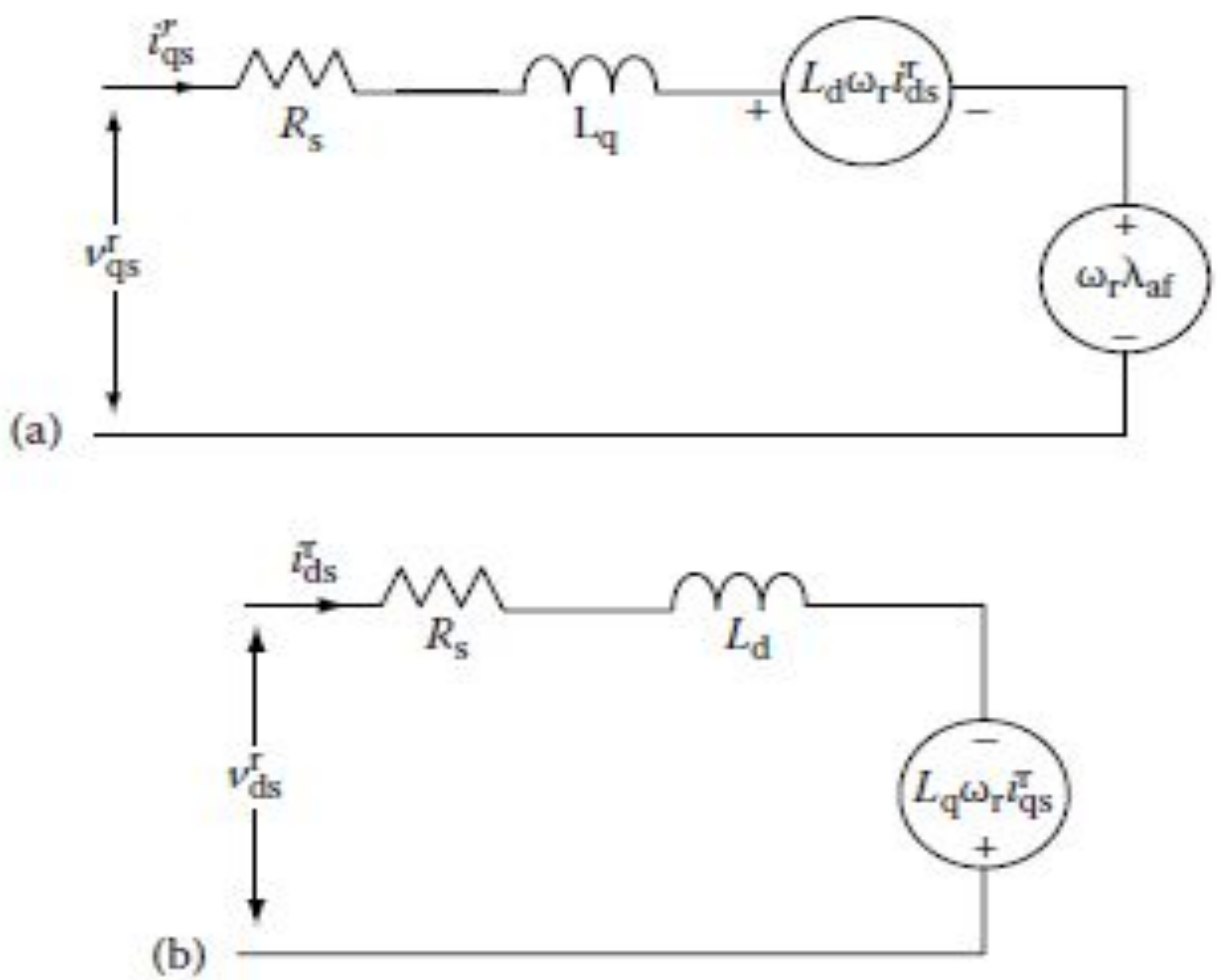


Fig.7[1]

- The equations in rotor frame

STRATEGY-1

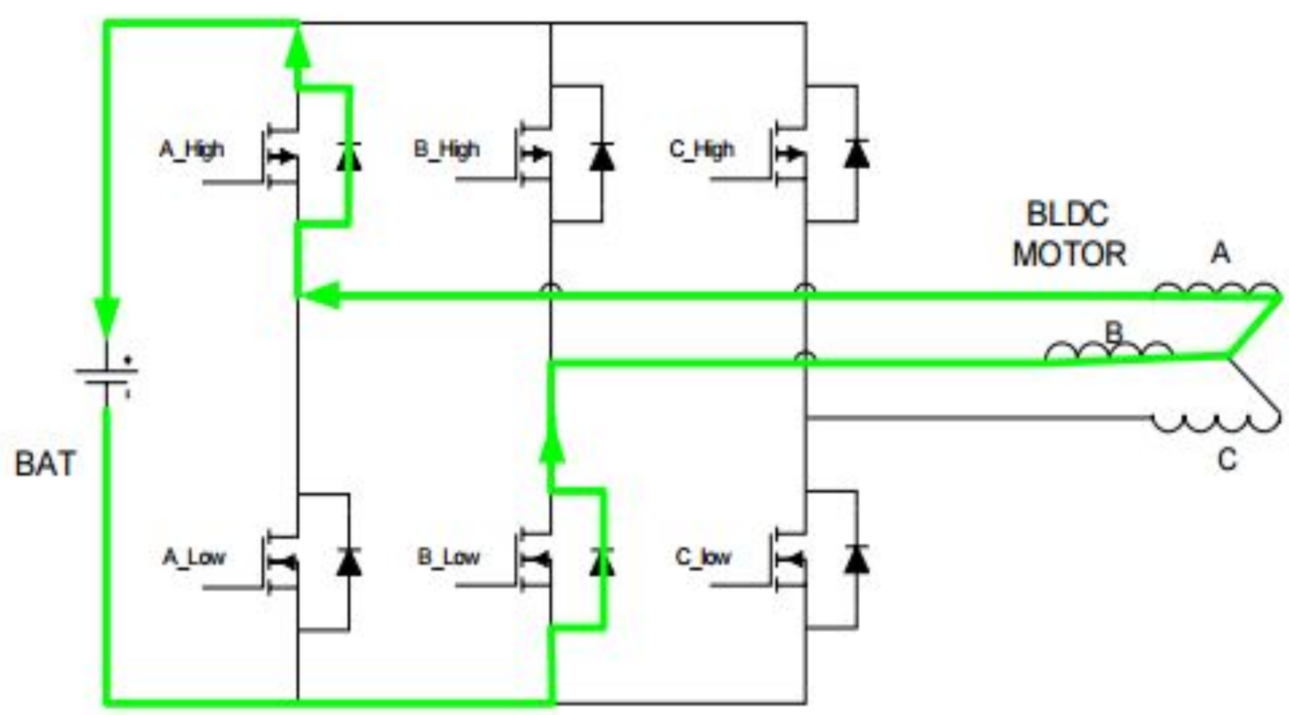


Fig.7[2]

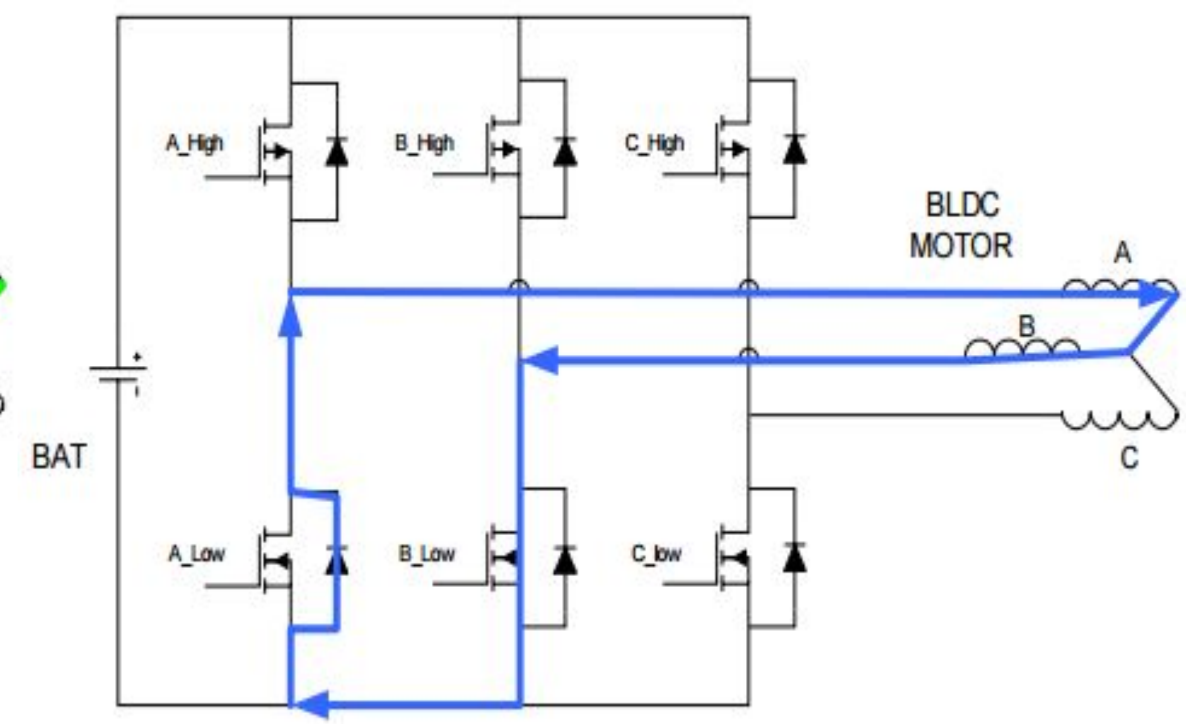


Fig.8[2]

- In the first figure, the circuit is in regen-mode feeding power back to the battery
- In second figure, the circuit is in coasting mode during which current free-wheels across mosfets and free-wheeling diodes.
- The PWM duty cycle decides the relative weights of two modes

STRATEGY-1

- Only three power devices at the low bridge arm are switched on and off at a controlled duty cycle
- Other devices at high arm are turned off permanently during regen
- The position of the rotor was estimated using the FAST estimator provided by TI

position \ Transistor	A1	A4	B3	B6	C5	C2
30-90	−	+	−	−	−	−
90-150	−	+	−	−	−	−
150-210	−	−	−	+	−	−
210-270	−	−	−	+	−	−
270-330	−	−	−	−	−	+
330-360	−	−	−	−	−	+
360-30	−	−	−	−	−	+

Note: "+" indicates working, "−" indicates stop.

Fig.9[3]

STRATEGY-1 (WHY IS COASTING NEEDED?)

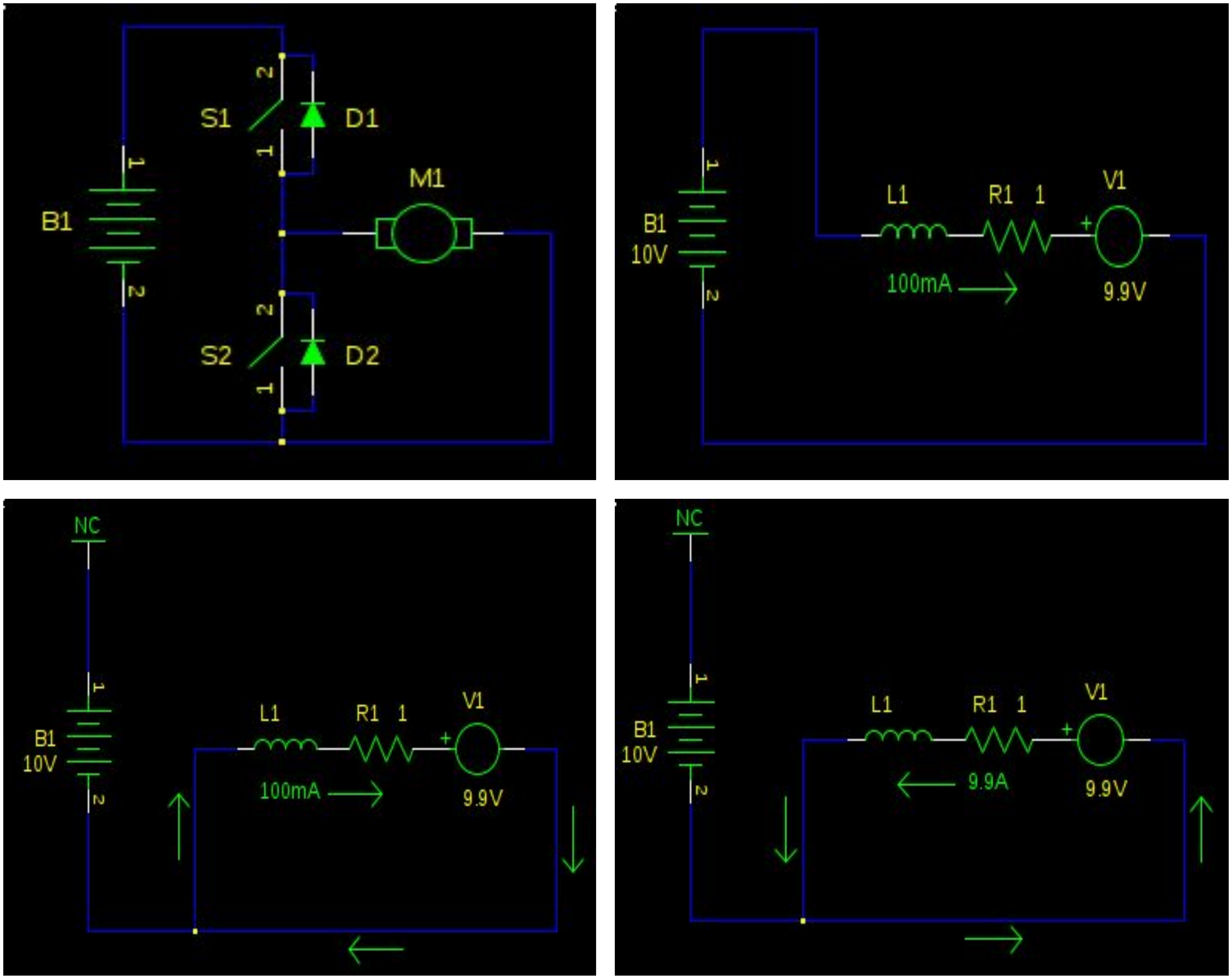


Fig.10[4]

STRATEGY-1 (WHY IS COASTING NEEDED?)

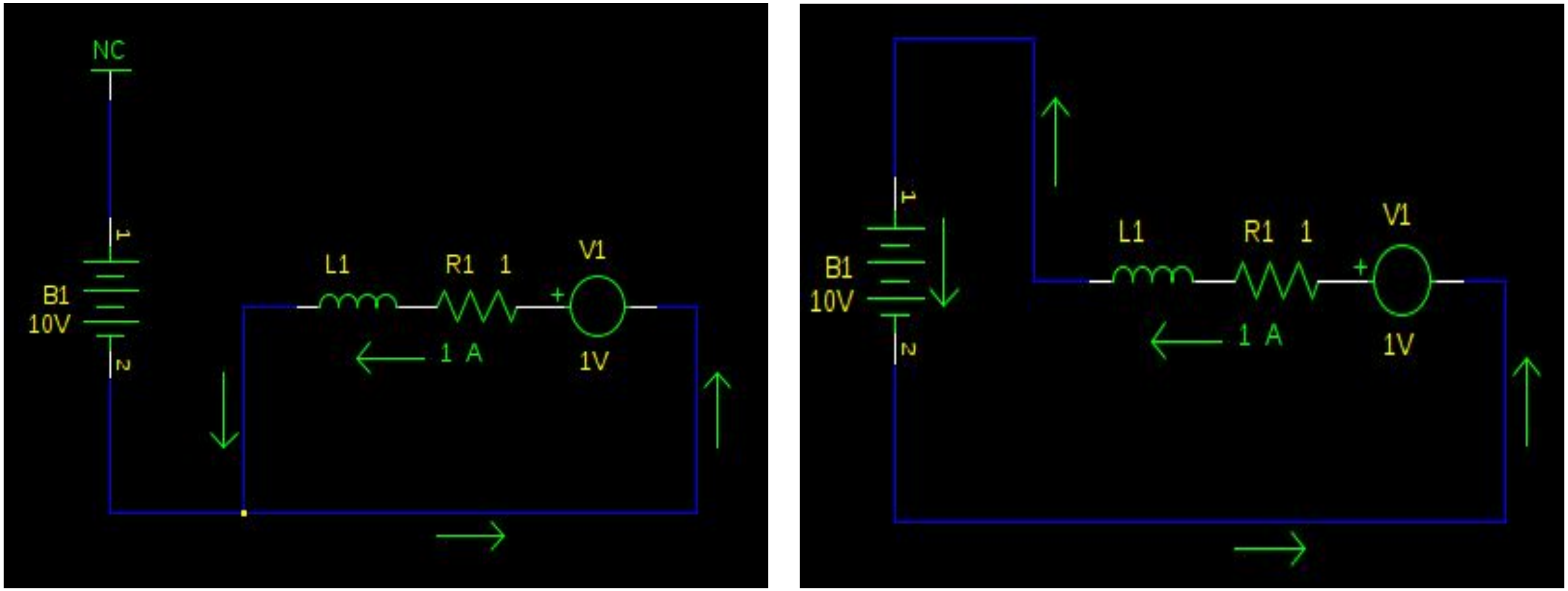


Fig.11[4]

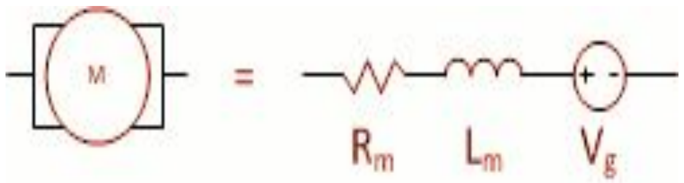
STRATEGY-1

- There are different cases like
  - Maximum regeneration power
  - Constant current regeneration
  - Maximum braking current control
  - Maximum regeneration efficiency

- To get the maximum regeneration power, the duty cycle was set to be a ratio equal to half of back-emf to the battery voltage $D = 1 - E/2U$

- The back-emf was estimated from Faraday's law $E_{back} = \omega\Phi$

STRATEGY - 2



$$V_g = V_{mot} - I_{mot}R_m$$

$$V_{mot} = V_{bat}(t_{on} - t_{off})/t_{cycle}$$

$$I_{bat} = (I_{mot})(t_{on} - t_{off})/t_{cycle}$$

$$I_{bat} = (V_{mot} - V_g)(t_{on} - t_{off})/t_{cycle}R_m$$

$$I_{bat} = (V_{bat}(t_{on} - t_{off})/t_{cycle} - V_g)(t_{on} - t_{off})/t_{cycle}R_m$$

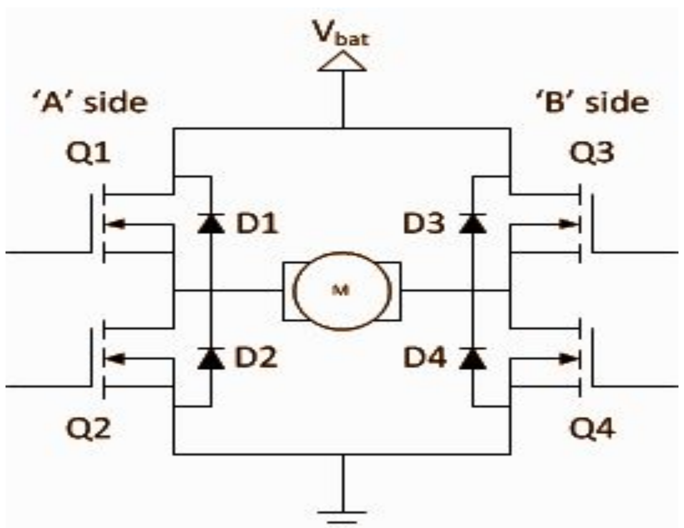


Fig.12[5]

- If we want to slow down the motor, back emf will have to be greater than average motor voltage
- From first equation it is clear that I will be negative, a reverse torque being applied
- For highest negative battery current necessary condition is $V_{mot} = V_g/2$

STRATEGY - 2

- The back emf was assumed calculated in a similar way to the earlier part
- The domain of regenerative braking is between 50% duty cycle to where V bat equals back emf
- The q-axis current was set equal to $I_q = -V_g/2R$
- This ensures the motor average voltage is half of back emf

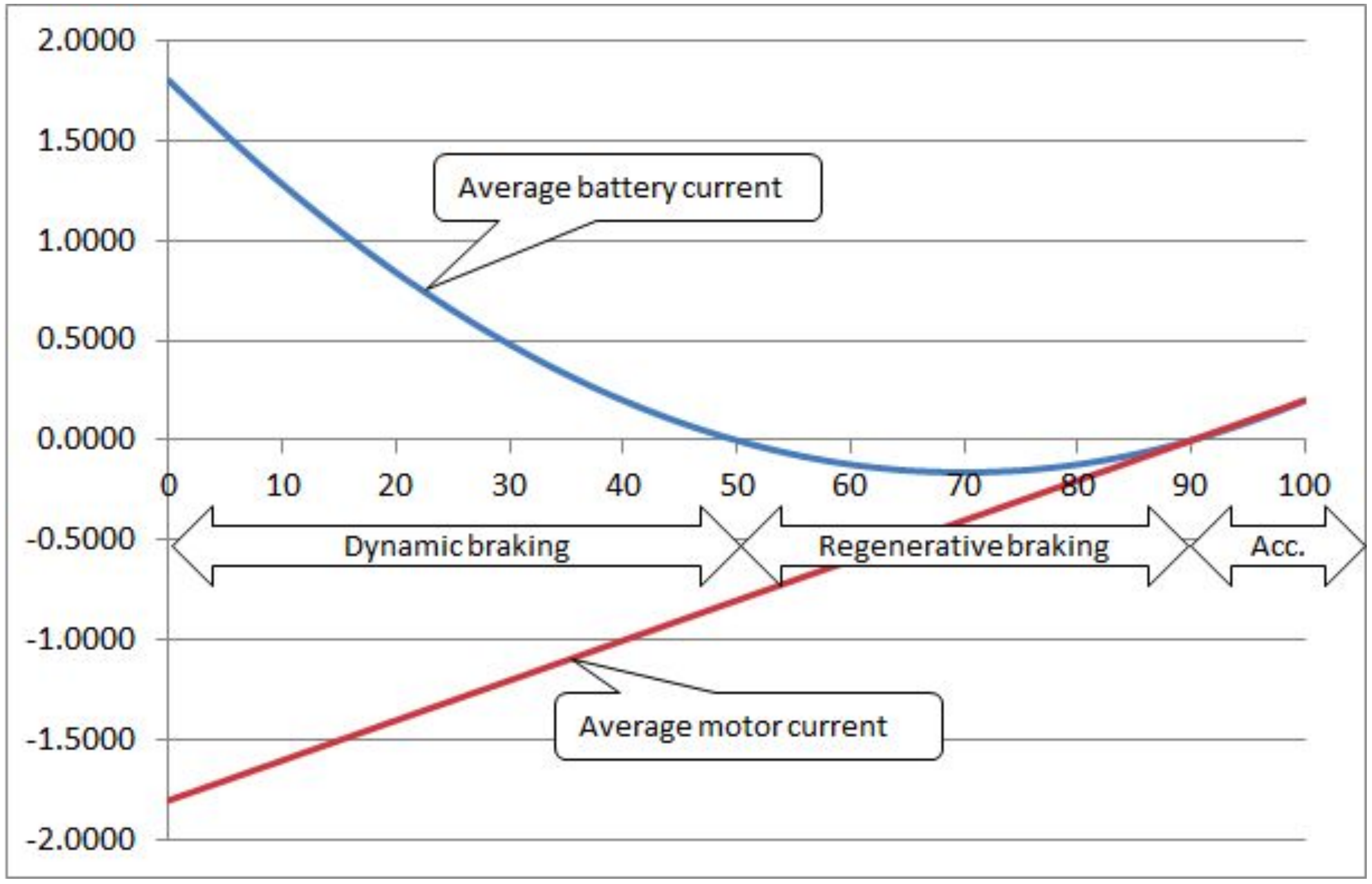


Fig.13[5]

STRATEGY - 2

- In order to emulate the road conditions we had to attach the other motor
- The torque provided by second motor emulates what friction does on road
- This torque supports the motion of the first motor as the friction on road changes direction during braking
- Most of the kinetic energy was found to be lost in the form of internal friction work
- The work done by applied frictional force determines how much energy is being pumped back into the battery
- Quite naturally it is proportional to the inertia of the system and the dissipative force doesn't really depend on the mass

$$W_{external friction} = K(Mass) = C(Regen)$$

$$W_{dissipated} = K(Dragconstant)$$

- The torque from second motor was set equal to the torque that would have been generated by the q axis current supporting the motion of the first motor

STRATEGY - 2

- Few interesting facts were verified by experimentation
- The ratio of energy regenerated to total kinetic energy increased as speed was increased

Fig.14

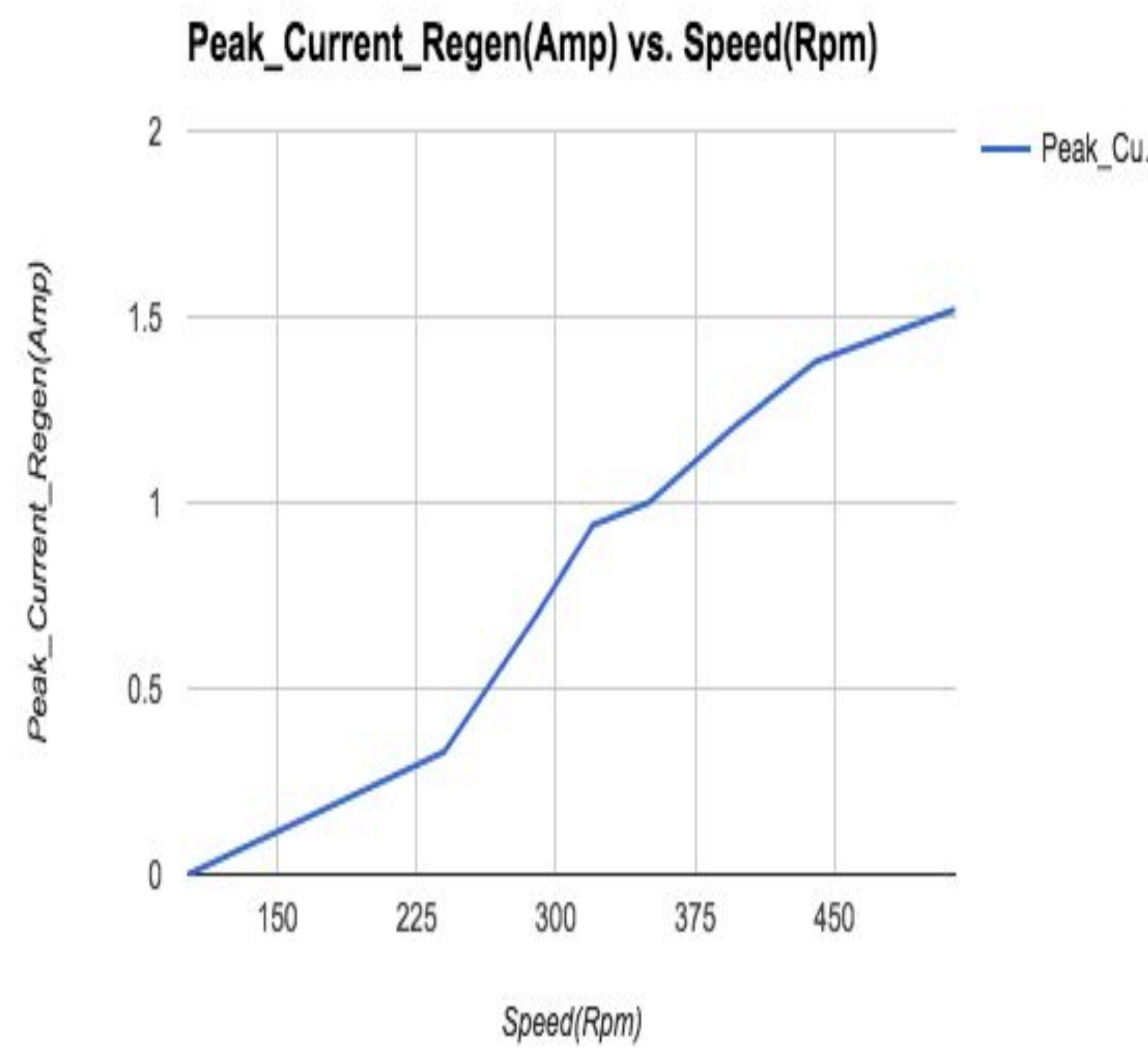


Fig.15

STRATEGY - 2

- The torque input from second motor was varied in the form of ratio of q axis currents provided to both the motors

- Second plot shows how external torque influences the regen energy

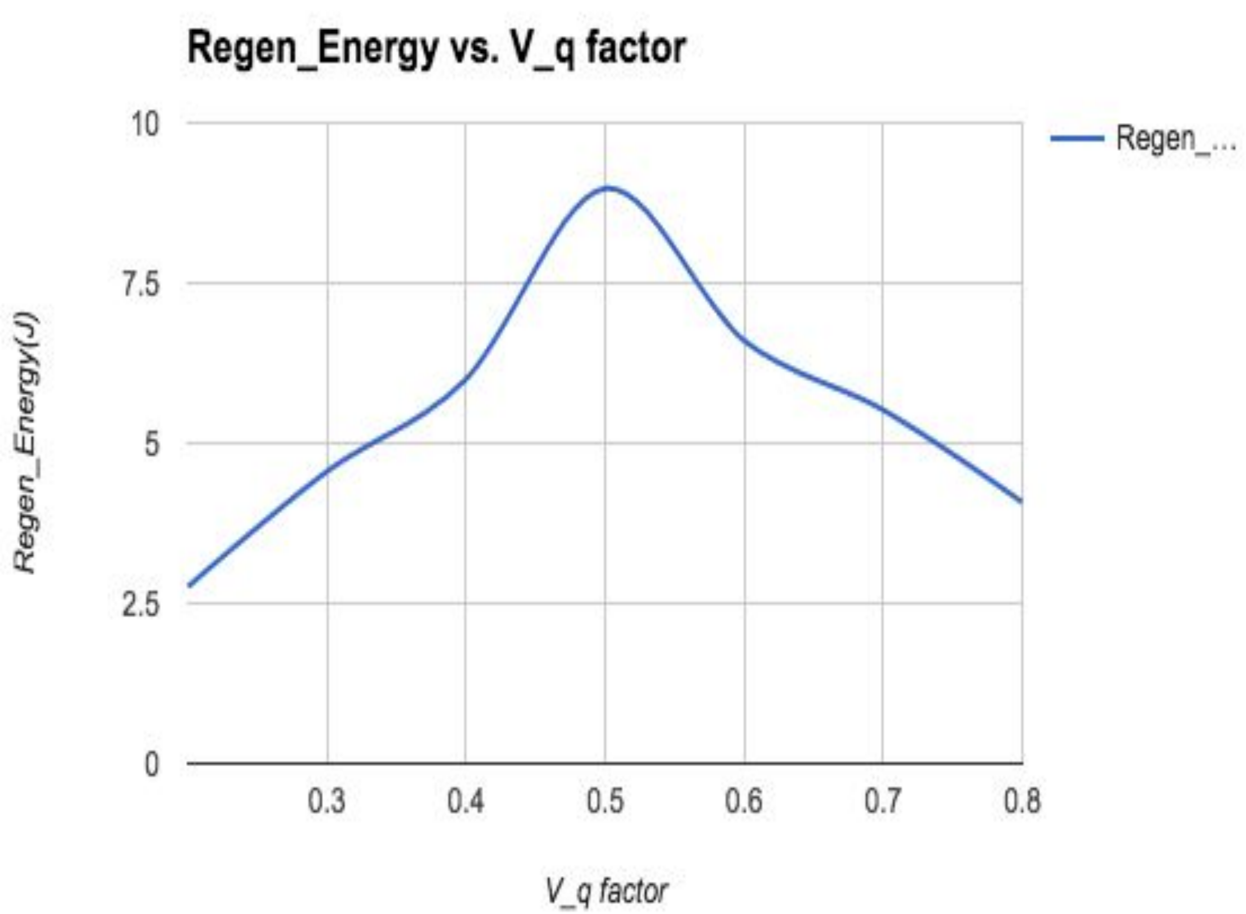


Fig.16

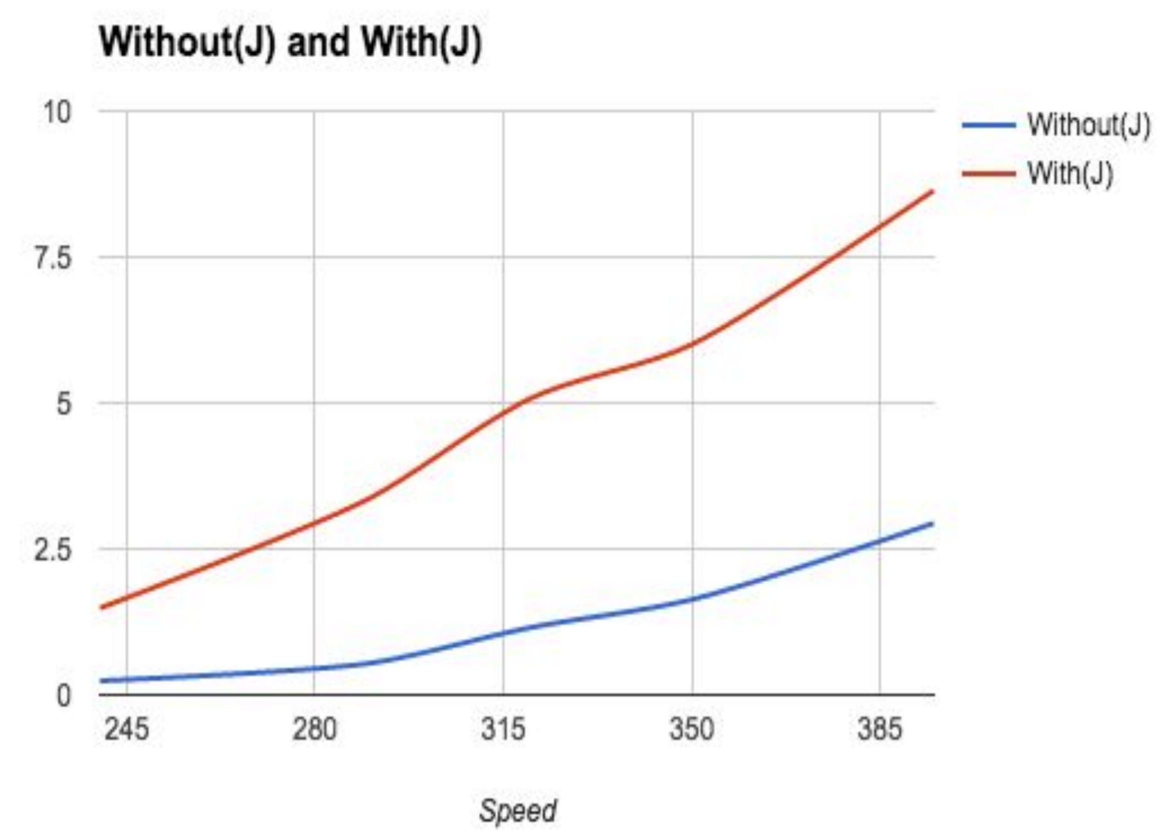


Fig.17

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