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REVIEW

Recent challenges and reviews on sensorless, PWM techniques and controller possibilities of permanent magnet motors for electric vehicle applications

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ABSTRACT

Permanent Magnet Motor (PMM) demand is burgeoning with the trend of electro mobility opportunities flushed to reach sustainability in the world electric drive market. This paper presents a comprehensive review of the recent challenges in PMM and post-COVID-19 emerging options of PMM, freedom of choice of sensor/sensorless PMM, the list of PWM techniques, control opportunities, fault tolerant and future scopes of PMM. The PMM is widely used in electric vehicle (EV), beverage, food industries, aerospace, oil, paper industries and robotics. With the advancement of power converter circuits, efficient batteries, ultra-capacitors, control techniques and energy management schemes, the researchers have targeted their scope on PMMs. Recently, the conventional transportation has been initiated with the prioritized accessible power rating that ranges from 25 kW to above 300 kW realization of PMM. In addition, the annulment of the torque ripples due to the process of commutation. Hence, the prelim goal is to introduce a preferential commutation process which reverses the dc-link current by using a space vector modulation strategy in the field-oriented control (FOC)-adopted BLDC drive system. The validation of the developed SVPWM-based FOC control of BLDCM is accredited by MATLAB/Simulink and SPARTAN III Field Programmable Gate Array (FPGA) controller that includes real-time prototype. Experimentation validation confirms that the proposed SVPWM-FOC-BLDC system is efficient for the wide speed range without the reversal of dc-link current and torque ripple.

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KEYWORDS
Permanent magnet motors; pulse width modulation; control techniques; electric vehicle; smart city

1. Introduction

As per the government of India's directives towards the initiative of a smart city, smart nation, it is mandatory to provide a sustainable environment, with environmentally friendlier transportation towards the public. The government has announced many subsidies towards the promotion of smart cities. After this, many researchers and industries R & D cell turned their focus on assured environmentally friendlier digitalised transportation. More recently, giant transportation manufacturers (i.e. TATA motors, Hyundai motors) launched their electric vehicles, with various parts imported globally. Hence, initially, it costs more. In 2020, due to the sudden spread of the COVID-9 pandemic in India, the government initiated a lockdown to reduce the spread since March 23 and continued it till May 31 ['As on April 29, 2020. The Diplomat listed in the website; As on April 10, 2020, The Economic times listed in the website; As on May 24, 2020, Financial Express listed in the website']. During this lockdown, even highly polluted Delhi people had an opportunity to breathe clean air and be able to view blue skies, since no industries were allowed to function. The government also recognised the hazardous-free environment leading to improve the diversified life span of animals and birds and even remembering the olden era of human life ['As of May 2, 2020, India Today listed in the website']. To overcome the bad economic situation over the lockdown period, the government announced various schemes covering about 20 lakh crores. Accordingly, over 3 lakh crores was released towards the emergency credit funding to improve the national-level businesses through MSME. The objective of releasing a huge amount towards MSME is to promote self-reliance which is becoming the most needed measure to motivate the MSME-based industries. These benefits may help the economic activities of the entire country and encourage to make our products using our label 'Made in India' which intends to enrich our Indian enterprises compete in the global market ['As of May 18, 2020, The Times of India listed in the website'].

Based on these measures, definitely, in near future post-COVID, any industry should set probable primary objectives, namely

- It will not pollute the environment,
- Ensure the entire product should be made from our own resources; should not import any product.
- To spread awareness about green energy utilisation for the consumption of energy.

The researchers view the intelligent control techniques called data learning and artificial intelligence to dominate the entire globe for another decade. India stands third in the globe for

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the production and consumption of electricity. As per internet sources, India's national power grid has a 370.10GW of installed capacity as of March 2020, infrastructure of power generation. Such a huge generation of power may directly or indirectly affect the environment, hence to address this issue the ministry of power has started promoting renewable energy resources. However, the equality in production and consumption of electricity clearly depicted the severity to search the opportunities to find/motivate the energy consumption technologies ['As of March 28, 2020, Economic Times: Energy World listed in the website']. Therefore, the challenges and research guidance in energy consumption technologies are becoming significant issues in today's scenario and need to be addressed. Before addressing the energy-saving techniques, it is essential to identify the devices consuming the maximum power per day. During this COVID-19 pandemic lockdown, it was realised that be around a 19% to 25% decline in the consumption of electricity (source: India today, POSOCO). The decline was due to the shutdown of industrial operations and agricultural activities contributed to the huge energy consumption ['As of April 23, 2020, Mongabay listed in the website']. This scenario seems most of the industrial and house hold equipment facilitates electric motors as more than 60–70% of energy is contributed to their automotive utilities.

Hence, environment-friendly transportation and energy consumption scenarios, both issues to be concluded with the single thread that recently permanent magnet motors are considered to be an effective option to play an efficient role in addressing issues like

- The opportunity to provide many start-ups to make environment-friendly transportation using PMM with our resources.
- PMM is the only option where the less energy consumption is possible.

The permanent magnet motor is categorised under a special type of motor since the rotor is made of a permanent magnet. In 1882, John Urquhart an electrician advised the inventors of motors about the future replacement of electro magnets with permanent magnets in his critique on electrical motors ['As of 2015, OHIO electric motor listed in the website']. In 1950 the first evidence of permanent magnet material, named ferrite magnet, was fortuitously noticed by Philips industries. Similarly in the same year, William Shockley proposed silicon-controlled rectifier called a thyristor [well-realised solid state devices were fairly obsolete in bringing the thoughts of John Urquhart's inspiration in permanent magnet replacement in motors]. Later in 1962, Duke University professor T.G. Wilson and Wright Machinery Company Engineer P.H. Trickey unveiled the conceptual evidence about 'solid state commutation based DC motor' or the so-called brushless DC motor. [In 1980, because of the refined development in magnetic material becemes an invaluable part of the machine manufacturing industry.] Hence, POWERTEC industrial corporation engineer Robert Lordo realised that the industrial actual need for new efficient structures should provide an option in the right circumstances and unveiled the permanent magnet brushless DC motor ['As of January 2022, Shodhganga: A reservoir of Indian theses is listed in the website']. The generalised functional block diagram with basic closed-loop control blocks of PMM is shown in Figure 1.

The general prerequisite of a PMM drive consists of a PWM control strategy, an inverter, a current reference generator, a basic controller for speed and a PM motor. These entire modules are usually modelled and combined to execute the real-time operations of PM motors. In this paper, the detailed literature survey has been investigated to improve the torque quality in BLDCM drive is a stimulus topic of many researchers. This paper analysed the recent challenges and reviews on controller possibilities, in section 2 discusses the development of investigational evidence of the sensorless approach. Section 3 deals with the predilection of precise torque ripple mitigation schemes accessible for PMM for EV applications and focuses on abrogation of the commutation torque ripple present in the BLDCM, section 4 briefs commendable evidence of importation about the PWM realisation on PMM, section 5 discusses a variety of controllers in PMM, section 6 discusses the fault diagnosis options of PMMs, sections 7 and 8 brief recent research on predictive control algorithms of PMMs and recent trends and innovation status of PMM. (Latest Innovations), section 9 deals with the problem identification in PMBLDC motor, section 10 discusses a

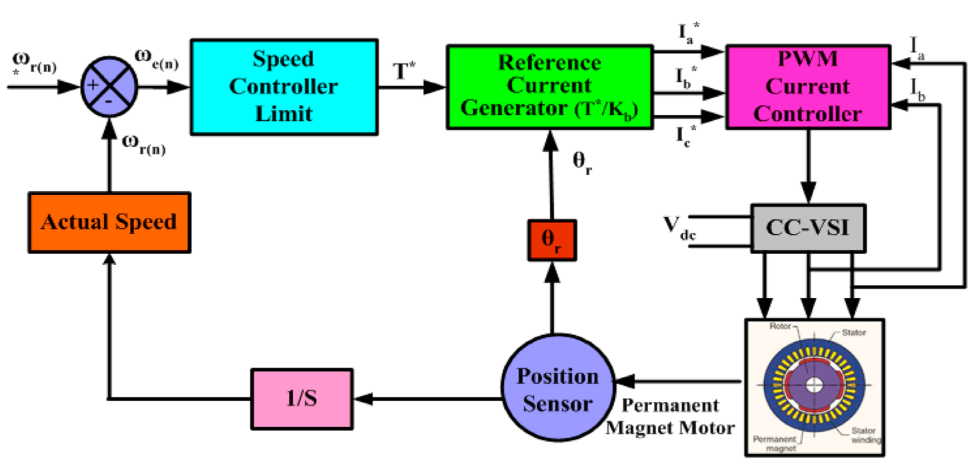

Figure 1. General block diagram of permanent magnet motors.

newDC-Link Current Control Strategy in FOC BLDC Motor Drive and experimental validation has been incorporated, simulation results under one Switch Turned OFF condition during Commutation and SVPWM with Fully Controlled Commutation are given in section 12 and 13 and ended up the conclusion in section 13.

2. Codevelopment of investigational evidence in sensorless approach applicable for PMM

Position Sensorless drive option is the most prevalent area owing to many research contributions from the past two decades to the present day. In 1985, the first evidence of sensorless technique was proposed by Kenichi Iizuka and Hideo Uzuhashi (Iizuka et al. 1985). Initially, the main target of the proposed sensorless technique deals with the investigation of control techniques applicable to locate the exact position of the rotor. In the literature, numerous sensorless methods have been reported and listed as follows:

- Back EMF estimation method
- Detection of the third harmonic voltage component of the stator
- Estimation of zero crossing point of back EMF
- Indirect back emf detection without neutral potential
- Prepositioning of switching instants by advancing the switching pattern by 60°.

PM motor requires six digitalised position information for its electronic commutation operation. The hall sensors are mounted on the surface of the stator of the motor to avail the digitalised position sequence. However, hall sensor utility has certain uncertainties such as maloperation of the sensor due to a raucous environment, sensitivti to temperature, sensor cost, machine design sizing, inaccurate startup point and extra external wiring connection that may cause the motor to dislodge its reliability performance (Acarnley and Watson 2006). Hence, to avoid the above-said uncertainties the sensorless drive system may provide a reliable control and ensure that the motor is under stable operation.

The practical and very basic approach to sensorless BLDC motor drive was proposed by (Iizuka et al. 1985). The aim of the suggested sensorless approach to detect the back EMF based on the terminal voltage sensing. During standstill condition there is no back EMF; understarting the motor is allowed to start with separate synchronous motor control and in running condition the microcomputer changes the signal to enable self-controlled sensorless BLDC motor mode.

The motor terminal voltage sensing approach has been the root cause method for the sensorless motor drive purely based on the mathematical analysis (Jahns, Becerra, and Ehsani 1991; Johnson, Ehsani, and Guzelgunler 1999; Ogasawara and Akagi 1991).

The terminal voltage of the BLDC motor has been estimated with a mechanical sensor at each switching transient. The terminal voltage and neutral point voltage relationship has been mathematically arrived at ($V_X = V_N$, $Vy = V_N$ and $Vz = V_N$). Based on the relation, it has been identified that the difference in angle between terminal voltage and neutral voltage point needs to be delayed by 90° to ensure the stable modulation for switching. Hence, the low-pass filter has been provided to achieve the delay, the resultant shape of terminal voltage is the triangular signal. The comparator has been provided to compare the filtered terminal voltage with neutral voltage, to match the required pulse signal and synthesised to the six-step inverter (Damodharan and Vasudevan 2010).

2.1. Back-EMF integration technique

The position prediction has been recognised by the non-switching phase back EMF integration approach. The start of integration begins the silent phase back EMF that crosses zero and stops the integration when it reaches the threshold limit set during commutation instant (Ertugrul and Acarnley 1994; Kim and Ehsani 2004; Moreira 1996).

2.2. Flux linkage-based technique

From the evaluated voltages and currents of the stator, the flux linkage can be determined. The estimation of flux relation has been suggested based on the basic strategy of integration of machine voltage and current. Based on the variables of the machine with respect to the initial position and the acquired relationship between flux linkages to the position of the rotor, the rotor can be located.

2.3. Freewheeling diode conduction

Diode freewheeling-based position detection: In this method for every power electronic switch there is provision of a freewheeling diode connected in antiparallel. The current in a freewheeling diode (Conduction) due to non-active phase-based sensorless detection has been possible, because of the initiative of back EMF zero crossing in the non-active phase for a short duration (Wu and Slemon 1991).

The virtual third harmonic back EMF-based sensorless strategy has been proposed for high-speed BLDC motor drives. The proposed sensorless scheme offers two significant parts, namely a signal processor circuit and a point detector of commutation (Song, Han, and Wang 2019). A signal processor circuit has been utilised to process the magnitude of the virtual third harmonic back EMF signal. Commutation point detectors are aimed to catch exactly at 30° lagged back EMF zero-crossing. The back EMF power factor synchronic frequency extractor (BEPF-SFE) compensation has been adopted to adjust the total commutation error by normalising the angle of BEPF to zero. The proposed compensation provides an efficientl extract of the commutator error.

A rail-guided moving system has been proposed for BLDC motor availed for a security system (Bae and Lee 2018). The developed model aims to provide a micro-stepping method that allows an estimated torque angle based on the variable current magnitude. The slip coefficient that has been evaluated between the roller and rail surface is utilised to control the position of the motor. A variable gain controller has been presented to attain smooth deceleration without suffering any position error of the BLDC motor.

A highly efficient non-salient sensorless technique from starting to high speed has been presented for BLDC motors (Zhou et al. 2018). To guarantee a smooth start process the proposed sensorless drive analyses the correlation between transient speed, energising time and pre-position current. The correlation provides a forced alignment stage to the

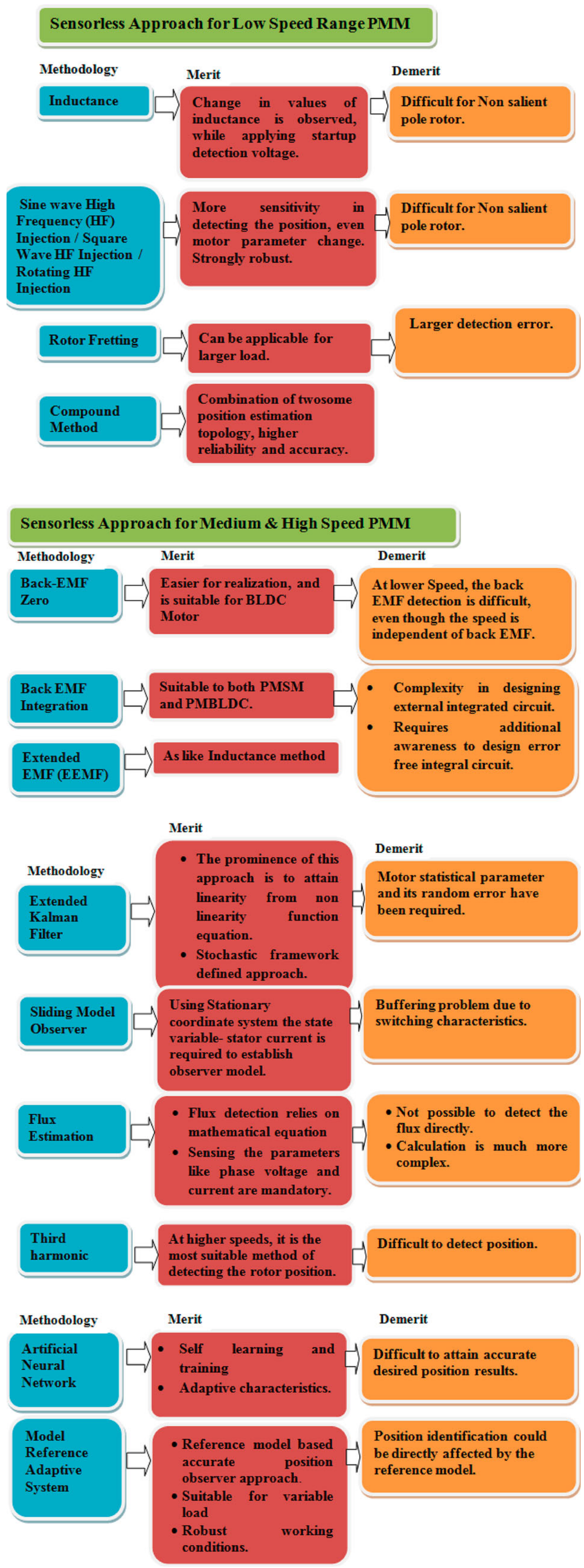

Figure 2. Investigational evidence in sensor-less approach for PMM.

self-synchronisation stage possible, without an external-synchronisation stage.

A novel correction method for sensorless commutation error compensation has been proposed for BLDC motors in relation to the difference in the integral of phase current (Li et al. 2020). The proposed approach initially deployed the analysis of commutation error, normally the commutations are categorised as ideal, advanced and delayed. The distortion of phase current is due to the deviation of ideal commutation. The analytical estimation has been carried out to compensate for the commutation error. With the adoption of hysteresis controller deployment, the correction process has been carried out stepwisely manner, and the optimal correction has been made and mitigated the error due to commutation.

The commutation point detection approach in addition to the phase deviation correction approach has been proposed for the sensorless BLDC motor (Zhou et al. 2019). The proposed method of detection is based on the measure of voltage between the phase terminal of the inactive phase and the midpoint of the DC link. It neglects the usual detection techniques of virtual neutral voltages zero-crossing BEMF. Then the commutation point variation has been corrected using the fuzzy neural network controller approach. The proposed commutation error correction controller effectively exhibits its speed control both in steady and dynamic state conditions. Investigational evidence in the sensorless approach applicable for PMM with its merits and demerits is listed in Figure 2.

3. Predilection of precise torque ripple mitigation schemes accessible for PMM

The mitigation of torque ripple and cogging torque issues are the real challenges emphasised in the PM motor. In lifting into modern electrified technology, it is mandatory to have energy-efficient PMMs types, which provide feasible characteristics and have an opportunity to satisfy the challenges the designer addressed (Hanselman 1994). Owing to the evolution of Finite Element Method (FEM) software can assist appreciable adjustment in geometries of complex design. However, in PMMs, the torque deviation investigation becomes perpetual; still the researchers recommend a variety of modifications in the geometries of machines to find out the optimal quality of torque. The torque instigated in PMMs is categorised into (i) due to undulations and (ii) cogging (Studer et al. 1997). The major source of torque undulation issues arises due to the lack of phase current commutation and the variance caused between the wave shapes of rectangular stator current and non-actual sine back EMF. Over the past two decades, numerous publications have been ardent in support of the curbing of the torque ripple ploy of BLDC motor drives. The reason for cogging (parasitic effect) is due to the interrelation of co-energy extracted in the slots of the stator to rotor MMF (Permanent magnet). A variety of modulation and control techniques has been recommended to curtail the torque undulations. However, the investigations on torque due to cogging are continuous until reaching out the proper design. Researchers have realised the concurrence of opportunities (variation in geometry) to achieve the finest design since the design adjustments of software tools become user-friendly. Numerous geometry variation techniques have been listed both in the stator and the rotor sides of the machines to abridge the cogging torque. The renowned techniques are i) slot skewing (Hwang, John, and Wu 1998), ii) optimisation of pole arc (Aydin et al. 2007), iii) retainment of ratio of slot/pole (Aslan et al. 2011), iv) shifting of the slot (Wang, Wang, and Jung 2013), v) slot opening (Wanjiku et al. 2015), vi) auxiliary slot (Lan et al. 2017), vii) teeth notching (Hwang et al. 2000), viii) teeth pairing (Ma et al. 2017) and ix) magnet shaping.

Stator side slot skewing, along with slot displacement adjustment, is ardent to curtail the cogging torque of about 75%, while the stator slot displacement alone is 60% (Ozturk and Toliyat 2011). In optimised pole arc approach, it has been realised about a 51% dip in peak torque (Aydin, Qu, and Lipo 2003). The ratio of a combination of no. of slots/pole has been opted with multiple of least common value to demotion the torque due to cogging (Libert and Soulard 2004). A 2 mm slot opening at the stator has a significant dip of about 25% for the torque of 0.9N-m and 70% mitigation was appreciable in the provision of adding ann auxiliary slot. In teeth notching at the rotor, which has a significant dip of about 60% and in the shaping of the magnet around 66% mitigation in cogging torque. In pairing the rotor teeth a significant mitigation of about 85% torque due to cogging has been noticed ('As of January 2022, Shodhganga: A reservoir of Indian theses is listed in the website'). All these approaches have been performing better to reach the preliminary objective to mitigate the torque due to cogging and the secondary objective to reduce the vibration and acoustic noise in PMMs (Kuptsov et al. 2019).

Direct power control to minimise the torque ripple of BLDC motor has been proposed with the utility of an improved finite control set model. The developed scheme employs a two-voltage vector-based direct power control strategy (Lee et al. 2018). Finite control set model-based direct power control (FCS-DPC) comprises three basic control blocks: 1. Lookup table of predicted back EMF wave shape with flux estimation of the rotor, 2. Prediction block of active and reactive power and 3. Minimisation of the cost function. The optimal vector selection has been identified to provide zero power error, from the tracked reference of active and reactive power in the two-vector (FCS-DPC) control technique. The developed power control scheme ensures a smooth torque profile by choosing the controlled power transmission.

The performance upgradation of torque quality in open winding PMSM has been proposed, which has been achieved by effectively adjusting the switching frequency and zero sequence current (ZSC) (De Castro et al. 2018). A novel injection of current in the q-axis-based shift angle voltage distribution approach has been developed to open winding PMSM. With this approach, the torque undulation due to ZSC has been cancelled out and a noteworthy factor of 33% reduction of switching frequency is feasible by discarding the zero vectors.

4. Commendable evidence of importation about the PWM realisation on PMM

The performance of the BLDC motor entirely depends on the drive circuit, known as the voltage source inverter's outer and inner control method capability. Outer control of a voltage source inverter (VSI) encompasses the adjustment of voltage in its output and input side with the adoption of external control circuits (Bertoluzzo et al. 2015). The external control circuit is a tedious one, indeed to address stability issues. Hence, the inner control called PWM switching frequency adjustment technique has been prioritised as a familiar one, and it satisfies the needs of today's industry.

From the survey of the literature, assortments of PWM schemes have been examined for PMMs. Those schemes have the pulse generations pattern based on the combination of deterministic and non-deterministic nature (Krishnakumar, Kamaraj, and Adrien 2016; Krishnakumar, Kamaraj, and Jeevananthan 2014; Lynn Kirlin, Michael, and Andrzej 2002; Rathnakumar, LakshmanaPerumal, and Srinivasan 2005). The basic PWM schemes opted for PMMs have been listed in Figure 3.

The main objective of these modulation schemes is to ensure the efficient generation of pulse patterns to retain efficient switching and curb the harmonics and switching losses.

Recently in the applications of robotics automotive, electric vehiclesand medical instruments, the inclusion of highly efficient electric motor drives has become mandatory. Moreover, any electric motor type requires a drivé power electronic converter circuit, so-called VSI. This VSI drive always utilises inviolable SPWM strategy. A list of PWM strategies has been suggested from the literature; all these strategies aim to satisfy the possibilities of better drive performance (Trzynadlowski et al. 1994). The primary intention of the PWM strategy includes attaining the utmost voltage at the output, THD with the scope of limit, the linear interrelation between modulation deepness and voltage at output and diminution of the lower magnitude harmonics; the secondary intention includes calculation of harmonic power spread factor, focus on EMI minimisation, performance indices factors such as copper loss of rotor, switching loss, etc. are moreover equally responsible (Jadeja, Chauhan, and Ved 2015).

The PWM strategies examined so far outflank in their particular targets without a doubt, whereas the output voltage spectrum of harmonics is equation-based and predictable. The SPWM, SVPWM, THIPWM (third harmonic injection), Hysteresis-controlled PWM techniques belong to the categories of deterministic PWM since the scope of harmonics spectra is based on the formulaic computation nature of PWM techniques. Usually, they have large clustered/huddled harmonics around their carrier multiples with an unbearable magnitude of frequency ranges. Hence, the above PWM technique suffers from the existence of voltage harmonics tending to arrive at current harmonics at relevant frequencies. Thus, current harmonics that may expose sudden heat rise in winding may create winding losses and affect the efficiency. Furthermore, these harmonics can worsen the developed torque quality and create intolerable vibration and acoustic noise.

A higher frequency of switching has been utilised to lessen the acoustic noise. But it could be the reason for unreasonable switching losses and stress on power electronic switches. Thus the research insights focus on finding an appropriate PWM technique to curb the acoustic noise by distributing the prevailing harmonics in the inverter output. The harmonic suppression has been appreciable in the scheme of Random PWM (RPWM) so-called non-deterministic technique, popular for the accumulation of harmonics multiples in induction motor drives. Recently, the fruitful features of the scheme of RPWM have been expanded to PMMs (Kirlin, Bech, and Trzynadlowski 2002).

More recently, an inverted PWM driving approach has been developed to control the BLDC motor. The proposed approach compares the efficiency and power loss of the conventional PWM and has developed an inverted PWM-driven BLDC motor (Lee and Kim 2019). The inverted PWM scheme with reduced sync MOSFET diodes has an appreciable improvement in efficiency and power losses than the conventional PWM strategy.

5. Variety of controller research practice greatness beyond barriers in PMM

Owing to categories of permanent magnet motors, the controller selection is impelled based on the drive utility. Once the design and development process of the permanent magnet motor is concluded, the immediate investigation is on the suitable selection of controller (Li, Yu, and Chen 2013). The characteristics of the motor include transient and steady state, the performance of the drive and the application requirement of the motor which are key parameters that directly influence the efficient selection of various strategies of control. Recent days have seen the controller being crowned as the 'central trapped part' and the thrust research area utilised to fine-tune the issues related to instability of the system, an unfair performance due to feedback error, exterior disturbances and non-linearity in coupling with the load. Favourably, the permanent magnet motors are adopted for electric vehicle applications since they have faster dynamic response, compactness, higher remanence and power factor. Figure 4 shows the list of controllers applicable for PMMs.

Numerous controllers that are suggested for permanent magnet motor types in the literature, are segregated into two: i) Universally adopted basic controller includes the DTC (direct torque control) and decoupled control called dq-abc or vector control ii) Advanced intelligent control includes fuzzy, neural, sliding mode and adaptive controllers. Permanent magnet motors have two variants i) Trapezoidal EMF and rectangular stator current known as PMBLDC and ii) Sinusoidal EMF and stator current known as PMSM (Estima and Cardoso 2011; Li and Gerling 2010). Sensor-less control has been developed for a dual permanent magnet motor (Geng et al. 2022) which injects the high-frequency square wave voltage in zero vectors half period with a modified duty cycle strategy. It promises the viewpoint of not using any additional circuits. Eddy current loss estimation at permanent magnets in permanent magnet machines has been designed (Tong et al. 2022) which arrives with the analytical model Permanent Magnet Eddy Current Loss (PM ECL) for PMSM and provides the division of non-concentric magnetic poles (NCMP) for radial and circumferential direction. This has the advantage of higher frequency conditions, the NCMP division structure effectively suppresses the PM ECL.

PID Controller: Across the globe, the Proportional Integral and Derivative (PID) controller is the most appreciable control practice, because of its trouble-free tuning process, making it easier to evaluate the control variables by utilising uncomplicated mathematical computations. This controller is persuasive and effectively derogates the howler between the set reference and actual value attained through feedback. The scope of the

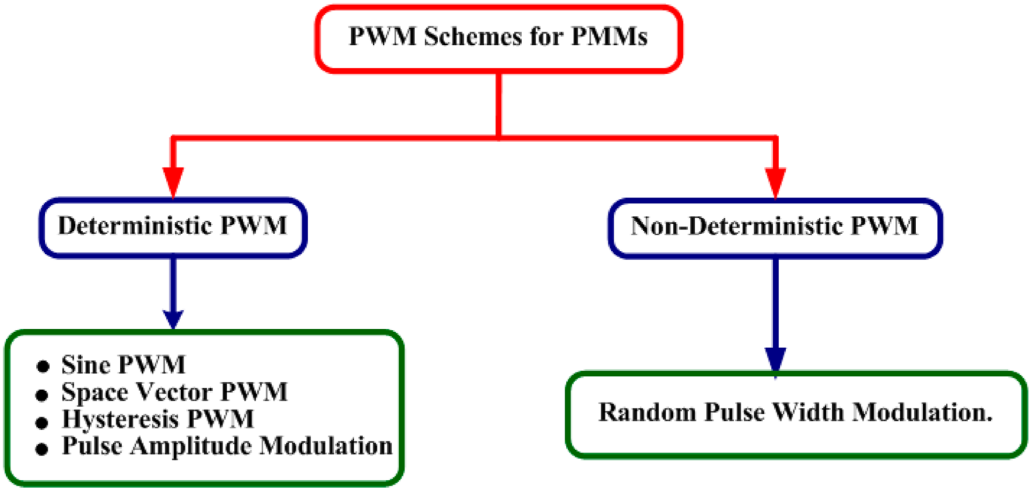

Figure 3. PWM schemes opted for PMMs.

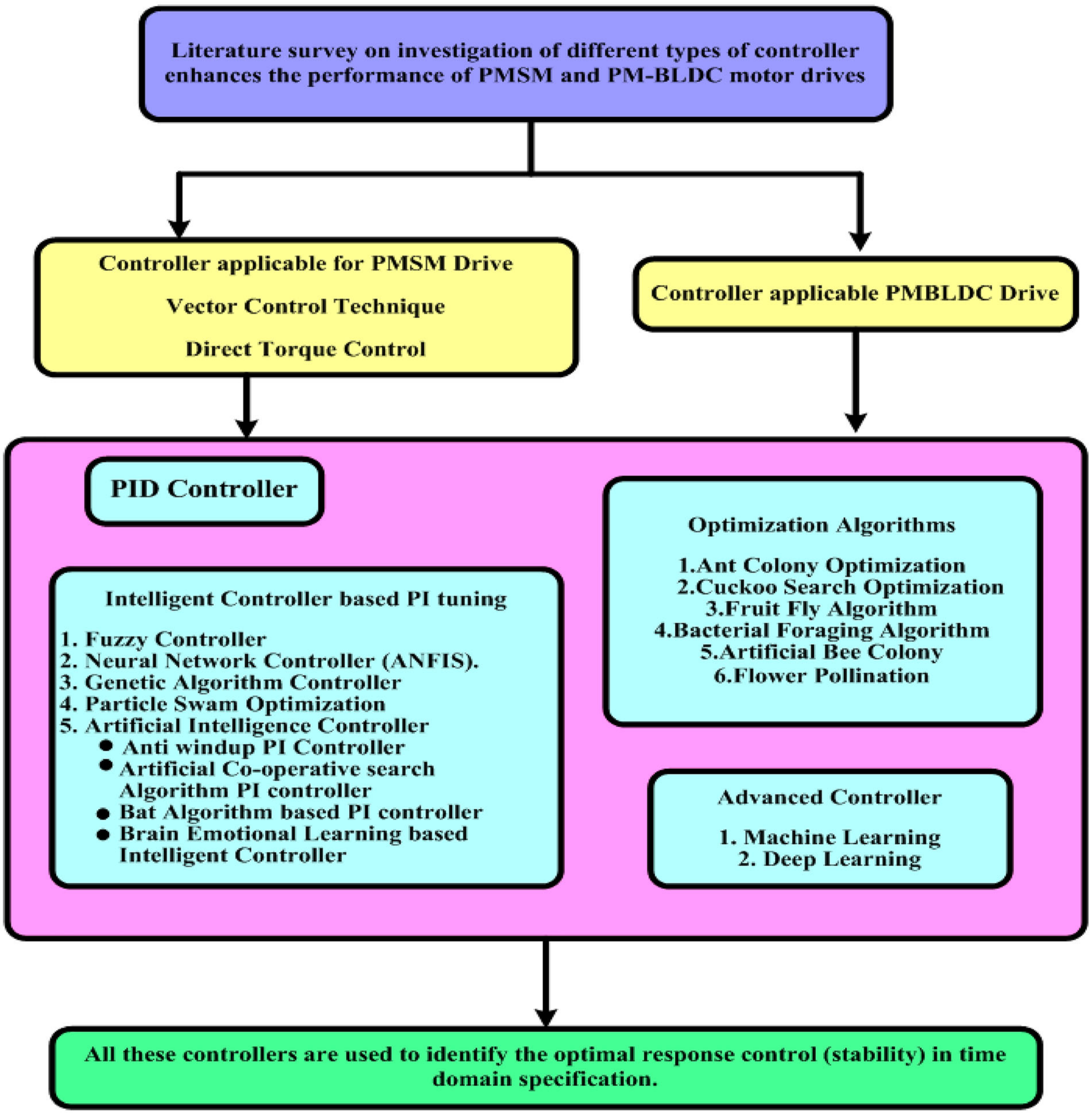

Figure 4. Various types of controller applicable for permanent magnet motors.

Table 1. Types of learning process.

Linear Regression	Decision Tree	Support Vector Machine	Ensemble of Tree
Very common and fundamental learning. Future foretells easy updates, linear prediction of variation of input-output relations. (Montgomery, Peck, and Vining 2015; Quinlan 1986).	A widely approved learning process is used to diagnose the fault of the motor. Various categories of data have been pre-determined similar to the structure of a tree. Data are inseparable. (Drucker et al. 1997)	Can able to execute data of multiple scopes with a supervisory approach. Belongs to the optimal category. During un healthier environment, able to provide perceptible solution for the problems.(Drucker et al. 1997)	Depends on single-dimension learning. Depends on the forecaster, for accurate decisions. Not accurate and effective learning since it has the possibility of the feeble forecast. (Basak, Pal, and Patranabis 2007)

Table 2. Various controller performances listed for PM BLDC motor.

Parameters		PI & PID	FUZZY	ANN	ANFIS	PSO	GA
	0–500 RPM	0.006	0.005	0.004	0.003	0.002	5E-04
Rise time	500–700 RPM	0.004	0.003	0.003	0.002	0.001	0
	0–500 RPM	0.025	0.023	0.02	0.016	0.011	0.002
Settling time	500–700 RPM	0.0075	0.005	0.003	0.002	0.001	0
	0–500 RPM	0%	0.70%	0.90%	0.93%	0.96%	0.99%
Steady-state error	500–700 RPM	0%	0.70%	0.90%	0.93%	0.96%	0.99%
	0–500 RPM	7.9 N.M	5.2 N.M	3.2 N.M	2.2 N.M	1.2 N.M	0.2 N.M
Starting torque	500–700 RPM	2.2 N.M	2.3 N.M	1.3 N.M	0.8 N.M	0.5 N.M	0.1 N.M
	0–500 RPM	5A	5A	3A	3A	1A	0.2A
Starting current	500–700 RPM	3A	3A	1A	0.5A	0.3A	0.1A
Speed variation	0.80%		0.70%	0.6	0.40%	0.20%	0.10%
Power Factor	0.2		0.7	0.8	0.9	1	1

controller design aims to adjust and derogate the error provoked in the linear system due to external ruction and thereby process its appropriate error-free responses.

Vector control: Owing to the impelled performance of separated control of field flux and torque in the DC separate excited motor, similar control inference has been made possible in AC motors since 1971. Blaschke. Fa engineer belonging to Siemens suggested decoupled coordinated transformation control called vector control (Rahman and Hoque 1998; Sharma et al. 2008). The stator current of the motor has been unyoked to field component current i_d and torque component current i_q with the utility of transformation technique so-called Clark, park along with the rotor flux direction. With the advent of this type of control the PMSM achieved a new hike in its market growth and efficient performance has been paved in bringing its expansion to automotive and recently demanded electric vehicle applications.

Direct Torque Control (DTC): This approach has been familiar since 1996 since this approach has been feasible forPMSM and PMBLDC motors. This approach has been profound by Takahashi and developed by Zhong. The uncertainty posed by observing the fluctuation in stator flux and the torque in coordination with the stator axis of reference by vector control has been reshaped with this control approach (Buja and Kazmierkowski 2004; Pacas and Weber 2005; Vyncke, Boel, and Melkebeek 2006). The estimation of stator flux from stator voltage integration and estimation of torque from motor current and predicted stator flux cross product. The computed torque has been compared reference and effective switching has been made (Jan, Tseng, and Liu 2008; Rong Chen 2009).

Artificial intelligence: The technology advancements impelled the researchers and enforced their focus on intelligence techniques to address the prolonged issues. Artificial intelligence, machine learning and deep learning have bridged their transformation by feeding external data intelligence to machines that may resemble the same level of human intelligence (Hoo and Haris 2011). Recently, these intelligent techniques have become unavoidable, performing smarter than the creator, now the creator has great trust in its empowered growth and its being a strong alternative for control application in electrical equipment. These fruitful features of intelligent control techniques have been expanded to PMSM and PMBLDC (Gupta, Kumar, and Bansal 2010; Negnevitsky 2005; Perl 2004).

Fuzzy logic control (FLC): Yager in 1987 attempted to recognise the range for systems operation. This control has been exhibited by incorporating the concepts of decision-making-based rule of if and then (Elmas, Ustun, and Sayan 2008). Fuzzy control has created a remarkable impact since it embeds a linguistic, heuristic rule-based approach, the solution of stability search becomes easily addressable for any system based on the acquired data (expert human knowledge). The FLC does relinquish the Mathematical computation models. For example, if a person rides a bike at 70 km/hr may experience over speed. Then suppose a person may ride at 69.7 km/hour may not experience 'over speed'? Definitely, the answer is yes, and there exists a limit of scope 'ranges' where a person is probable to experience over speed (Ustun and Demirtas 2008). Hence, the fuzzy set logic predicts more precise ranges, rather than the choices of either/or decision. Hence fuzzy systems optimised over the limit between 0.0 and 1.0 with infinite fuzzy set values.

Neural network (NN): This technique is prominent because of its ability to learn a network of neurons, predictions of time series, pattern recognition, soft sensors and anomaly detection. A purely trained algorithm-based model its nature resembles conceptualisation of the search for similarities trained from the human brain and does not require a specific programme or instruction for finishing a task. The human cerebrum can be portrayed as an organic neural system, an interconnected snare of neurons transmitting structures becomes an example of an electrical signal (Lin and Wai 2008). Basic neural systems comprise four elements: dendrites, axon, soma and synapses. Neuron accepts inputs from dendrites and process united through soma, implement resultant non-linear task through axon and final outputs through synapses. The most widely recognised utilisation of NN is to foresee what will undoubtedly occur (Zhang et al. 2008). The key attributes of NN have been extended to figure out how to solve the control issues of electrical machines, especially if it has been applied to permanent magnet motors. NN-based DTC has been investigated for PMM and performs well for low-speed applicationa. However, later with the radial function basis approach NN has accomplished a good choice to attain smooth speed and torque performance.

Genetic algorithm (GA): This approach has been developed based on the motivation of Charles Darwin's evolution of natural living beings. The search for the selection of the fittest solution for attaining optimal value has been experienced by this algorithm. GA depends on a relationship to the hereditary code from our structured DNA, where the chromosome coding has been made of digital sequence representation of genes (Sudhoff et al. 2005). This approach belongs to a heuristic experience-based learning algorithm which disposes of the qualities when they don't encourage optimal findings. If the disposed characteristics can be reintroduced if the need arises in a later situation to address the optimum solution for the system. Thus, the GA offers the optimal solution search comprised all feasible ways to handle any sort of problem. The basic optimisation process includes three easy steps 1. Reproduction 2. Crossover 3. Mutation utilised to find the optimal solution.

Deep Learning: Whenever the advancements in technologies commence, then the need to observe its features initially, and after acquiring deep knowledge need to adopt it for our utilities. Likewise, deep learning is a booming algorithm, which is a very newer field of research which has been perceived s the offspring of machine learning (Jin, Wang, and Yang 2017). Deep learning becomes unique, utilises many hidden layered network and neurons can resolve complex functions based on their learning intelligence. During the initial introduction, the learning has been effectively adopted for recognising the sequence of pattern applications, for example recognition of speech, human action and handwritten digits. Later, the researchers extended their focus on application possibilities in the field of automotive control.

Machine Learning: Recent days, the rapid growth of automotive applications demands excessive manufacturing of machines in industries prevailed to provide guaranteed fault tolerant accurate predictive control. The control schemes in the literature are not experts in fault tolerance, diagnosis predictive analysis and hence the search to shift advancements algorithms, such as machine learning and data learning (Ali, Ing, and Wahler 2016). Usually, the PID control strategy has been universally adopted for motor control. Since it's easier to design. However, during dynamic behaviour the system turns down to its performance deviation. Hence, the researchers started switching to intelligent control strategies which have been widely accepted because of their improved accuracy and performance.

Table 3. Comparison of types of faults in PMM.

Description	Electrical faults	Mechanical Faults	Magnetic Faults
Details of Fault	Winding of motor due to erroneous connection, poor grounding, short and open circuits of windings	Slot bolt loosening, rotor permanent magnet smash up, ageing of bearing, shaft bend and unconventional behaviour of airgap	Due to demagnetisation, Magnet ageing issues, sudden rise in current in the stator winding, due to thermal effect
Percentage of fault	35–40	40–50	5–10
Reason for fault	Stator winding insulation breaks up due to the continuous function of the motor, which leads to short winding and tends to excess flow of current. A winding collapse in the stator may lead to an open circuit of any one phase.	Manufacturer sloppy assembly of the motor. Installation inappropriateness. Corrosion Shaft alignment issues. Bearing fatigue may tend to fissure the metals. Airgap displacement	Reversal of Magnetic field. Armature reaction. Demagnetisation consequence.
Final Cause	Torque undulations, Fluctuations in torque, anomalous vibrations and acoustic noise.		

For the analysis of the PMSM torque control scheme the machine learning algorithm requires German OEM's trial product, required to attain the dataset to train the model of PMSM. Dataset encompasses all the parameters involved in the motor model ('voltage, current in coordinate system, temperature at yoke, rotor magnet, motor torque and speed') are recorded to train the system (Abraham and Shrivastava 2018; Dou et al. 2018; Li et al. 2009). Based on the deviation of torque, the prior learning knowledge of various parameters dataset has been utilised to retain the stability and ensure the control over torque during the operation. The types of machine learning processes have been compared in Table 1. A variety of control algorithms has been simulated with the basic model of the BLDC motor as listed in Table 7. The comparison of various time domain specifications for various control techniques is listed in Table 2 ('As of January 2022, Shodhganga: A reservoir of Indian theses is listed in the website').

6. Fault diagnosis options of PMMs

Most industries and household applications applicable to PMMs have been erected in unhealthy environments, where it creates direct stress on its operations under various loading conditions. During continuous long-run work, the commencement of inevitable fault has been noticed under certain circumstances which may lead to an ebb the reliability and endanger the operation of the motor (Nandi, Toliyat, and Li 2005). The comparison of different types of fault with detailed analysis has been discussed in Table 3. (Cira et al. 2016; Moosavi et al. 2017).

The methods of fault diagnosis with its merits and demerits have been discussed in Table 4 (Chen et al. 2019; Ishikawa, Seki, and Kurita 2013; Rosero et al. 2006; Zhongming and Bin 2000).

Table 4. Different FD approaches and their comparisons.

Model-based FD method (mathematical Modeling)	Method of Signal Processing (Before Signal Experience)	Data-Driven Intelligence Method (Data Estimation)
Based on the mathematical model analysis of the motor, the fault investigation has been made on mathematical references in two ways 1. Magnetic and 2. Electrical equivalent circuit. The deviation of the model calculation has been resolved. FEM has been a commonly utilised stimulating tool to accurately diagnose faults.	Universally identified method of FD. The electrical and mechanical integration forms the motor' physical and working structure. The signal of electrical components comprises frequency, voltage and current. The other signals are vibration, heat, noise and radiation. Based on the signal characteristics the extraction of fault has been successfully attempted based on its deviation of characteristics from its uniqueness.	Based on the estimated prior expertise knowledge, the fault can be identified and resolved. Artificial intelligence techniques, including fuzzy, neural network and machine learning algorithms, have been paved as the best alternatives for the fault diagnosis approach.

Table 5. Various controller timer domain-specification performance comparison of IPMSM (Source: ShakilaBanu Research Thesis).

Various Intelligent Controllers	Peak Overshoot (%)	Settling time (s)	Speed drop during load change (%)	Restoration time (s)
PI Controlled	6.8	0.095	1.6	0.09
Anti-Windup PI controller	4.4	0.09	0.98	0.067
Artificial Cooperative Search Algorithm with PI Controller	0.8	0.03	4	0.139
Fuzzy PI Controller	4.2	0.09	1.46	0.123
Bat Algorithm(BA)-based PI controller	0.4	0.006	2.39	0.105
Brain Emotional Learning-Based Intelligent	1.75	0.023	1.38	0.05
Bat Algorithm-based Brain Emotional Learning intelligent controller	1.2	0.027	1.12	0.011

Based on the intelligent control techniques tested with interior PMSM at a speed of 1500 rpm, the peak overshoot, time at which it settles, during load change (%) the speed characteristics and restoration time have been computed and shown in Figure 5 and Table 5. (Source: ShakilaBanu research thesis) (Shakila Banu and Wahida Banu 2013; 2014).

7. Recent research on predictive control algorithms of PMMs

Estimating predictive control of the current strategy has been proposed for PM BLDC motor-based on a stationary frame. The appreciable reduction of current harmonics and torque undulations has become possible when adopting the predictive current control schemes compared to usual PI-speed and PWM control schemes (Trivedi and Keshri 2020). Three schemes of predictive control called finite control set, deadbeat and hysteresis have been estimated and applied to the BLDC motor and it's observed to track the supreme shape of hexagonal trajectory in the plane of stationary. Every predictive controller performance has been compared with the usual PI-based PWM strategy. It has been observed that with the average torque of 67% of actual speed, the PI-PWM loses its control while the deadbeat control retains up to 87%.

A predictive control approach has been proposed for BLDC motors to minimise torque undulations. The proposed approach evaluates the reason for torque undulations analytically (Xia et al. 2020). During the sequence of commutation, the phase current rising rate has been hopped down by altering the duty ratio of a particular switch. The duty cycle change and phase current during non-commutation have been predicted and accessible control through the PWM-based model predictive control approach.

The stability controversy of PMSM synchronised with the wind energy conversion system (WECS) has been addressed with the adoption of new control based on an adaptive fractional fuzzy integral sliding mode strategy (Mani et al. 2019). The utmost aim of boosting the convergence rate by executing fractional control for PMSM nonlinearity instead of an integer control strategy. Lyapunov's theory of stability has been espoused to ensure the closed-loop system of PMSM coupled WECS global stability.

A fault-tolerant approach for the hall sensor has been proposed for the BLDC motor based on a binary diagnosis. The proposed approach utilises 3-bit memory to perceive the hall sensor fault (Mousmi, Abbou, and El Houm 2020). In addition to fault identification, the hall signal effective reconstruction approach has been analysed.

Recently, deadbeat predictive control has become a noticeable technique in predictive control extending its prudence to control the voltage vector in the space vector PWM applicable to the PMSM drive system (Yuan, Zhang, and Zhang 2019).

8. Recent trends and innovation status of PMM

The error of current phase delay in the BLDC motor has been compensated with the introduction of d-axis current as the function utilised to detect the commutation error. The error in phase delay has been determined indirectly by utilising the space vector-coordinate transformation. The error in phase delay has been denoted by ϵ_{lag}. Post-transformation ϵ_{lag} has been transformed in the variation between the back EMF vector and current vector in the d-q synchronous reference frame. The magnitude of the d-axis current deviated from zero so the harmonics in the d-axis current have been extricated with the proposed LMS adaline filter, in addition to the adoption of phase advance angle control the d-axis current has been compensated (Wang et al. 2021). Maximum torque per ampere (MTPA) approach has been proposed to directly control the torque of the BLDC motor. Most of the researchers in the field of BLDC motors have relegated the iron loss effect in BLDC motor control. The iron loss in the BLDC motor creates an impact on torque, 1. Torque error 2 could not track the minimum current required to generate the desired torque. Therefore, the proposed MTPA, IOFL scheme of control has been necessitating to compensate for the iron loss. In addition, the proposed compensation utilises the Lagrange's theorem to design the criterion of MTPA, realised to achieve direct control of torque by preventing the current and feed-forward loops (Khazaee et al. 2021). Three-phase non-ideal asymmetric back-EMFs-based sensorless BLDC motor has been proposed (Jin et al. 2021). Angular acceleration tracking with the adoption of active damping along with an invariant surface approach has been proposed for BLDC motors. The proposed speed control does not demand true information on motor parameters, thus removing the current feedback. The effective utilisation of proper disturbance observer design in combination with Luenberger observer recovers the aspiration to detect the dynamics through the cancellation of pole-zero. Practicability advantages have been demonstrated with the 50-W prototype set-up of the BLDC motor (Park et al. 2021). Peak Current tracking-based current starting sensorless strategy to control BLDC motor has been proposed for PV-based irrigation water pump. To ensure the proposed sensorless control the average current and over-current peak has been calculated and based on this calculation the phase current exceeds the over-current peak then immediately the phase commutation is done. If the phase current is lower than over current peak, then the timing instant of commutation and reset internal time of the digital signal processor has been compared once the internal time crosses the commutation time, then immediately the switching of commutation is done. The robustness and stability of the drive system have been verified with a prototype in addition to the incremental conductance method for solar MPPT has also been presented to improve the performance (Sen and Singh 2021). A carrier-synchronised PWM topology has been developed to mitigate the commutation error in BLDC motors driven at high speed. The proposed topology focuses on two contributions: first protect the unstable sensor operation and current oscillation due to low frequency by ensuring low F_{ratio}. The F_{ratio} is the ratio between switching frequency to fundamental frequency. Second to truncate the delay in commutation interval generated due to digital PWM can be compensated by proposed carrier synchronised PWM topology. The proposed topology has been validated experimentally and the performance of the control parameter of current in the BLDC drive has been significantly enhanced with the avoidance of the instability phenomenon (Yang et al. 2021). The quickest compensation method to mitigate the error due to commutation has been proposed for sensorless control applicable for BLDC motors deployed for magnetically suspended gyro-moment control. The proposed circuit is composed of a buck converter in the preliminary stage and a commutation point determination circuit at the next stage. The foremost contribution in the proposed work utilises an extended state observer (ESO) based on the novel computation of voltage expression of derived DC-link to detect the one-cycle commutation error. Hence, the proposed compensation technique observes the deviation in conducting back EMF detected through ESO and compared with standard motor EMF the disturbance estimation has been obtained. The effectiveness and reliability of the proposed commutation error compensation have been validated for the gyro system (Zhang and Li 2021). The optimal method of correcting deviation in commutation has been proposed for the BLDC motor. The proposed method properly detects the internal power factor angle utilised to correct the deviation in commutation. Then issues such as the asymmetry nature of back EMF, the integration of rectangular phase current and a second-order dual improved generalised integrator along with a positive sequence component extractor have been proposed. Hence, the proposed method performance has been experimentally verified and tested for its high precision in sensorless operation and correction value of commutation deviation (Zhang et al. 2021). For ensuring the sensorless operation of the BLDC motor, the ideal rectangular current and symmetrical back EMF characteristics are the prerequisite requirements. However, in real-time implementation because of the environmental condition and external loading, the motor parameter deteriorates the commutation signal which brings out the error in commutation. From the literature, many compensation strategies have been proposed from which the recent notable contribution has been virtual neutral voltage start stop counting detection through the counter. The real-time calculation of commutation time has been calculated through the counter. Thus, the effectiveness of the implemented method has been verified

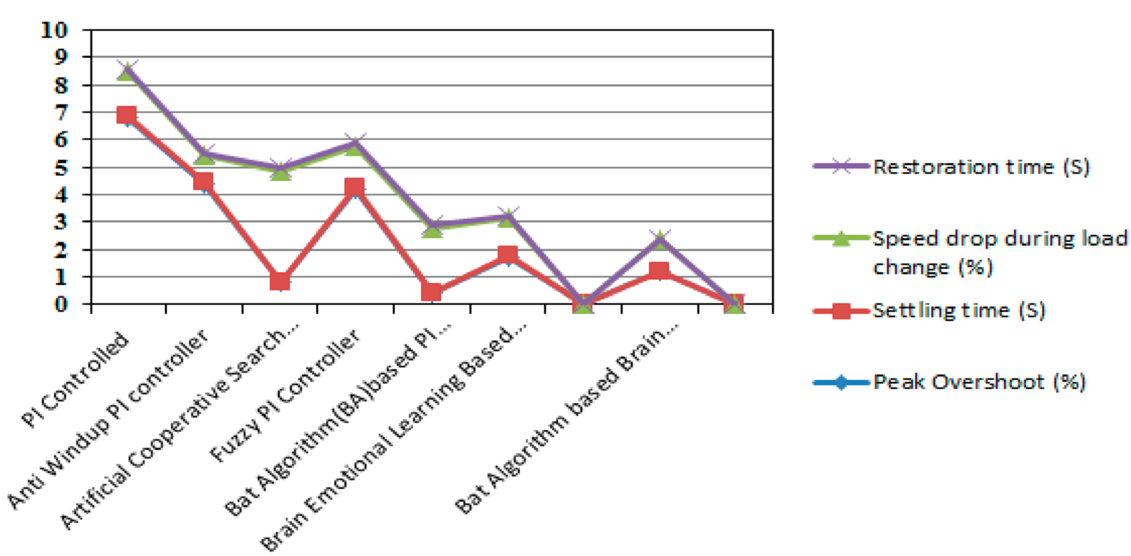

Figure 5. Various controller time domain specification performance comparison of IPMSM. (Source: ShakilaBanu Research Thesis).

(Zhao et al. 2021a). A novel phase delay exemption method of commutation has been proposed for BLDC motors. The interference of the commutation pulse always influences the impact on the zero crossing point of back EMF in the BLDC motor leading to the collapse of the motor performance. Hence to bring out the solution the adoption of a low-pass filter with a higher phase angle delay has been recommended in the literature. However to handle the above issue the removal of interference commutation pulse interference through freewheeling signals detection preliminarily. Then finally the unresolved part of the signal has been eliminated through the proposed fixed delay digital signal (Zhao et al. 2021b). Winding structure investigation has been performed for asymmetric and unbalanced 3-phase winding of PM machines (Demir, EL-Refaie, and Aydin 2021). The dynamic modelling and various performance parameters have been analysed for electric vehicles. The prerequisites to develop an electric vehicle have been proposed. The analyses help to distinguish the best suitability of EV vehicles against conventional vehicles (Sharmila et al. 2021). The filtering tactics have been proposed to mitigate the intrusion of electromagnetic interference in BLDC drives deployed in EVs. The proposed work elaborates on various EMI issues due to the utility of EV components along with their solution (i.e.) shielding and LC filtering (Karthik et al. 2020). A new slotted stator tooth (stator tooth16/ stator pole 6) approach has been proposed for SRM, and it has been effectively utilised for EV. The proposed design has been synthesised with the FEA tool and attained about 36% improvement in peak torque and 4.7% stator core material saving (Patel et al. 2021). Test station for EV bicycles has been developed by utilising an Arduino emulator. The proposed work provides brake test vetting for different dynamic loading. Consistent audit, spare estimation and information about resource have been accurately estimated in the developed test station (Ashokkumar et al. 2020). A 48 V, 3KW PMSM has been designed through Magnet (software) utilised for EV (Sheela et al. 2020). A new intelligent transport system in addition to a charging schedule for EVs has been proposed. The proposed technique finds solutions for traffic issuesand the availability of parking and diminishes the traffic difficulties. The grey sail fish optimisation algorithm has been developed to schedule the charging of EVs. The various performance parameters have been validated and improvement has been observed (Rajasekaran et al. 2022). Brain emotion-based intelligent controller has been proposed to control PMBLDC motors utilised for EV applications (Balan et al. 2022). A hybrid approach has been proposed to manage the energy in EVs. The Lichtenberg optimisation and heap optimiser has been integrated to achieve the enhanced power factor in addition to the minimised cost of energy (Vijayaragavan, Krishnakumar, and Vasan Prabhu 2022).

9. Problem identification in the PMBLDC motor

The detailed literature survey shows that improving the torque quality in BLDCM drive is a stimulus topic of many researchers. This paper analysed the recent challenges and reviews on controller possibilities, co-development of investigational evidence of sensorless approach, Predilection of precise torque ripple mitigation schemes accessible for PMM for EV applications and focuses on the abrogation of the commutation torque ripple present in the BLDCM. Most of the recommendations from the publication evidence have suggested solutions for torque undulations in PM motors. But still, it becemes an indispensable predicament and sought appropriate design processes for challenging applications such as EV design and biomedical instruments. With the basic analysis of PMM, the performance indices of PMM have been strengthened to focus on proper optimisation of torque undulations. Primarily because of inverter-fed electronic commutation, there subsist the harmonics due to the transformation of phase current, hence the supremacy of torque undulations. Furthermore, the lag in the transformation of software design geometry to the machine manufacturer subsists the variation in physical geometry, hence the supremacy of cogging torque in PMM. The above are the two paramount reasons; still many researchers have prioritised their research on innovations in optimisation with new design software.

From the above analysis, the commutation pattern and the phase current quality largely affect the nature of torque which results indispensable in almost all practical applications. During the commutation approach, the filtrate DC link capacitor reversion of the DC link capacitor current, which bestows on extreme voltage ascend in the DC-link and henceforth a grim ripple on the torque. The ripple reduction approach has been proposed to admonish a preferential commutation process to circumvent the reversion of DC-link current by using a space vector modulation strategy in the field-oriented control (FOC) adopted BLDC drive system. The validation of the developed SVPWM-based FOC control of BLDCM is accredited by MATLAB/Simulink and SPARTAN III Field Programmable Gate Array (FPGA) controller that included real-time prototype validation.

The transient analysis of the BLDCM drive for the duration of a step change in speed, start-up behaviour and distinct load changes are the major focus during design arrangements. The basic circuits of VSI-fed BLDCM are shown in Figure 6, which are valuable in realising the reversion of DC-link current flow for the period of commutation of traditional methods. Figure 7(a) shows the consistent conduction duration during the mode 1. During the period of commutation, there is a possibility of phase commutation between two upper arms switches S_1 and S_3. The commutation of exposed two transit states slide possibility of any one transit is shown in Figure 7(b) or 7(c). The open phase (c-) and inward phases (b+) are independently connected to the negative and positive poles of DC-link, respectively. Next to that, the leaving phase (a+) is linked to the positive pole of the DC-link through a freewheeling diode (D_3) in the upper arm leg and to the negative DC-link pole through D_4. Based on the outcome diode from the inner loop tends to circulate the current, the polarity inversion of the DC-link current is observed from these consequences. Similarly, Figure 7(c) communicates the happening of similar reversion of the DC-link current during the commutation instant followed by two lower arms of leg-phase commutation. The commutation time interval is the only reason for the reversion of i_{dc} existence, which confers the increase in torque ripple, as highlighted in Figure 8. These sorts of perturbations can reflect extreme harm on the DC-link capacitor due to the reversion of the DC-link current. Subsequently to fortify the DC-link capacitor and the three-phase VSI, a dc-link current limiter is mandatory. Right now, the researchers attempt to curb the DC-link current. To identify this DC-link current, two methodologies are in practice; (i) measurement of phase currents and ii) DC-link current measurement. The first method is expensive as it requires more sensors and numerical calculations are entailed, hence the priority belongs to the second method which is cheaper.

10. Proposed DC-link current control strategy in FOC BLDC motor drive

The basic switching of SVPWM operates at 180° conduction, with concerning BLDCM operation, to get EMF trapezoidal, power output constant and torque output constant. Thus, the current is obtained through the winding of the motor becoming a smoother part of the back-EMF wave shape. In BLDCM, just two switches are pulsed on at a time, one in the upper arm and the other in the lower arm, as pointed out in Figure 6. To operate BLDCM, two phases are in conduction and the third phase is silent in star-connected winding motor, thus the two phases are linked in series with the DC-bus. Henceforth, the SVPWM needs an alteration to exertion in 120° operation mode. For every switching cycle, the focal switch in each arm is incited for 120°. To get this condition, the SVPWM pulses are embraced with BLDC 120 mode and the final pulse is generated. Superficially, for every 60°, there exists a commutation instant among phases. Successfully, it implies that there is a transition of current at every 60°. The rotor position knowledge is mandatory for appropriate commutation, hence position sensors are connected to directly detect or observe the back-EMF on silent phase estimation of the rotor in a sensor-less manner. However, from the above critique, the reversion of the DC-link current takes place whenever there is a rise in motor phase current than the rated DC-link steady current value of the specific loading.

Right now, the announced SVM strategies are not satisfactory to retain the rigid performance of the DC-link current during commutation instant. Hence to ensure protection between the inverter switches and DC-link capacitor current, a simple option can be suggested to turn off all VSI switches. However, besides this blocking/protection state, the VSI could function like a three-phase diode rectifier and link the freewheeling current by means of a DC-link capacitor. As an inference of the inversion of polarity, the DC-link current direction is reversed. Figure 9(a) depicts the freewheeling diodes (D_3 and D_5) associated with phases b and c are linked with a positive DC rail, whereas the freewheeling diode (D_4) associated with phase, a is linked with a negative DC rail. Correspondingly in Figure 9(b), the positive DC rail is linked with phase c and the negative DC rail is linked with phases b and c. Therefore, there is a possible reversal of DC link's current direction. The DC link capacitor discharges during the reversion of the DC-link current, which may climb the DC-link voltage. Hence the recommended full commutation does not fulfill the control objective of reversion of the DC-link current. From the above critique, all switches' commutations (pulsed OFFs) ought to be responsible for I_{dc} inversion. This may be the source of torque undulation as per the earlier discussion. The regulation of I_{dc} (phase currents) as per suitable current reference can be the constrained control activity to control the motor torque. The significance at this stage is that I_{dc} is not equal to phase currents.

The primary choice of circulating the freewheeling current surrounded by windings of the motor is for the positive DC-rail and the next choice is to circulate the freewheel current as for the negative dc-rail. In these two cases, the current in the motor winding is not circulating reversal to the DC-link capacitor. Consequently, climbing up DC-link voltage can be evaded in the DC-link capacitor. For clear understanding, in mode-1, in Figures 7 and 9 (mode diagram) the recommended DC-link current reversal has been neatly explained. The conduction mode and period of commutation (mode-1) are explicated through VSIs when switches S_1 and S_2 are engaged. During regular operation, the S_1 and S_2 switches are Turned ON from 0 to 60 degrees, whereas from 60° to 120° during mode-2 conduction happens by utilising S_2 and S_3.

During regular periods of conduction, the phase current entry only through the DC-link, when the duration of commutation the rush in DC-link current sources the reversal circulation of current in DC-link, bringing about a sudden rise in DC-link capacitor voltage. This situation cannot be reduced even by all switches turned OFF (separated) scheme. However, the accepted preferential turned OFF method is utilised (discussed as the primary alternative in mode 1), during the commutation of S_2, the circulating current of the motor is directed via VSI switch S_1 and D_3 and D_4 diodes. S_1 is triggered ON continuously and S_2 is turned OFF if the detected DC-link current is greater than its threshold value (Proposed Mandatory One Switch Turn OFF (MOST)). Similarly in the second choice, the S_2 is triggered ON and S_1 turned OFF and the circulation of phase current is directed via the VSI lower leg by the switch S_2, D_4 and D_6 diodes.

Hence a new idea using a sampling strategy has been proposed to compute the precise time for the switching turned OFF happening depending on the rise and fall magnitude of the DC-link current. Figure 10 clarifies the basic idea of the measurement of switching turned OFF period. The comparison of the measured DC-link current with the assigned DC-threshold value during the clock of each sampling period, and finally the generation of a control signal (switching logic) has to be made. When $I_{dc} < I_{dc-thrs}$, the signal selector logic enables the gate driver signal to switch S_2 beside S_1 till the next cycle of sampling. When $I_{dc} > I_{dc-thrs}$, the signal selector logic enables the stop signal to gate driver of S_2 (turned OFF instruct) to circumscribe the current of DC-link shown in Figure 11. During the above-discussed cases, the continuity of the gate signal is ensured to re-enable the action of switching from the block of enable logic, after ensuring I_{dc} within $I_{dc-thrs}$.

The current limit controller uses a comparator which is used to compare the DC-link current increase and decrease information, required to identify the switching sequence. In each clock sampling period, the actual DC-link current is compared with the threshold value, and finally, the control signal (switching logic) is produced. Space vector switching for the two-phase conduction mode is shown in Figure 12. The mode 1 (zero to 60-degree interval) is taken for discussion in generating pulses to exploit the new commutation scheme, as shown in Table 6.

10.1. Case-1 (Normal sector conduction mode): $I_{dc} < I_{dc-Thrs}$

The Sector selector selects the active voltage vector that corresponds to the hall signal. The inverter operates in a normal

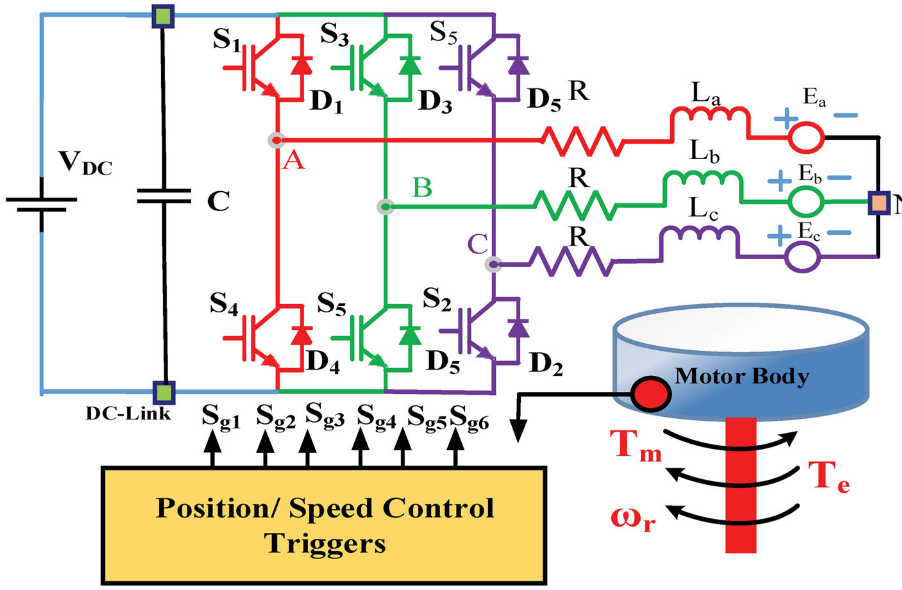

Figure 6. Basic control view of PMBLDCM drive.

Table 6. Vector selection table of proposed partially turned OFF/ON method.

Sector	$I_{dc} < I_{dc-Th}$ V_{active} (S_1, S_2, S_3, S_4, S_5, S_6)	$I_{dc} > I_{dc-Th}$ Case-1 V_0 (S_1,S_2,S_3,S_4,S_5,S_6)	$I_{dc} > I_{dc-Th}$ Case-2 V_0 (S_1,S_2,S_3,S_4,S_5,S_6)
Sector 1	V_1(110000)	V_0(100000)	V_0(010000)
Sector 2	V_2(011000)	V_0(010000)	V_0(001000)
Sector 3	V_3(001100)	V_0(001000)	V_0(000100)
Sector 4	V_4(000110)	V_0(000100)	V_0(000010)
Sector 5	V_5(000011)	V_0(000010)	V_0(000001)
Sector 6	V_6(100001)	V_0(000001)	V_0(000001)

conduction period during these modes from Mode-(1–6) with the corresponding time intervals from (t_1–t_6).

10.2. Case-2 (Sector-to-sector commutation period):$I_{dc} > I_{dc-Thrs}$

The sector selector selects the proposed mandatory one switch turned ON (V_0- Zero Vector) instead of the zero vector (000) insertion during commutation interval (i.e.) at the time of switching transition. The signal block stops the signal to the gate driver of the S_2 (turn OFF command) for limiting the DC-link current, as shown in Figure 8. During this period, the enabling logical block mandatory one switch turned ON (instead all switch turned OFF) by the proposed zero vector V_0 (either case 1 or case 2) gives a signal to the sampling block to re-enable the switching action to ensure I_{dc} within the I_{dc-Th}.

11. Simulation results under one switch turned OFF condition during commutation

The parameters used for simulation are listed in Table 7. The typical experimental and simulation performance confirms the possible achievability of the current limit approach feasible for BLDCM drive using the FOC technique. In the proposed and conventional schemes of SVPWM, the motor with an input voltage of 100v, a speed of 1200 RPM constant and a load torque of 8 Nm, forever operated in steady-state condition. Preferential single switch Turned OFF strategy schemes are simulated and compared with their performance merit in both cases.

12. SVPWM with fully controlled commutation

Besides, the recreation is done using simulation with SVPWM-based completely controlled commutation (PDTSVPWM). The switching cycle of the motor is transformed from regular switching to proposed switching logic. At this moment, during the interval of commutation between inverter switches and motor winding, the DC-link current is sustained in a unique direction between initial zero to peak DC voltage of 100 V as displayed in Figure 13. This maintains the phase current of the motor and DC-link current as shown in Figure 14(a) and 14(b), which give the enhanced performance of torque with less torque undulations. In Figure 14(b), the current portion wave shape at the top is flat, which is multiple times smaller than the full switch turned OFF strategy. The established truth, in turn, OFF of all switch logic may have a current decrease much higher than the proposed preferential turn-OFF logic.

In Figure 15, the reversal of the DC-link current is completely mitigated by circumventing the looping between the back EMF energy of motor winding and DC-link capacitor through the developed commutation, which conceded the lower undulations on the torque and retained the capacitor life durability.

Table 7. Motor specifications.

Parameters	Values
Stator phase resistance, R_s	2.875 mΩ
Stator phase inductance, L_s	850 µH
Pole pairs	4
DC supply voltage	100VDC
Current limit threshold	20A
DC Bus Capacitance C_1 and C_2	200 µF
Inertia, viscous damping, static friction constants	0.8e-3J(kg.m^2), 1e-3 F(N.m.s)

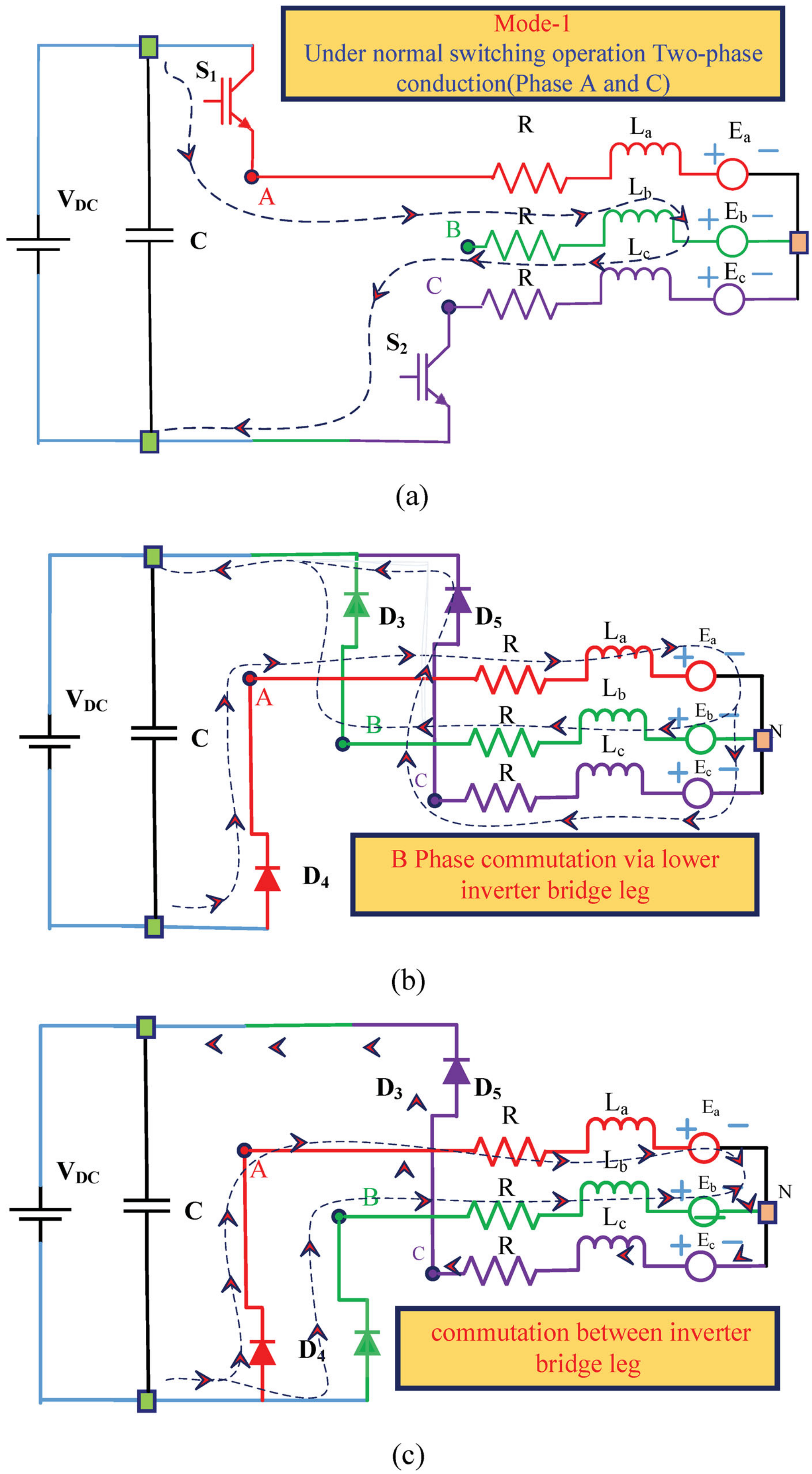

Figure 7. Current paths during mode-1 during (a) Conduction period; (b) Commutation period – existence of inner looping between upper bridge arms and (c) Commutation period – existence of inner looping between lower bridge arms.

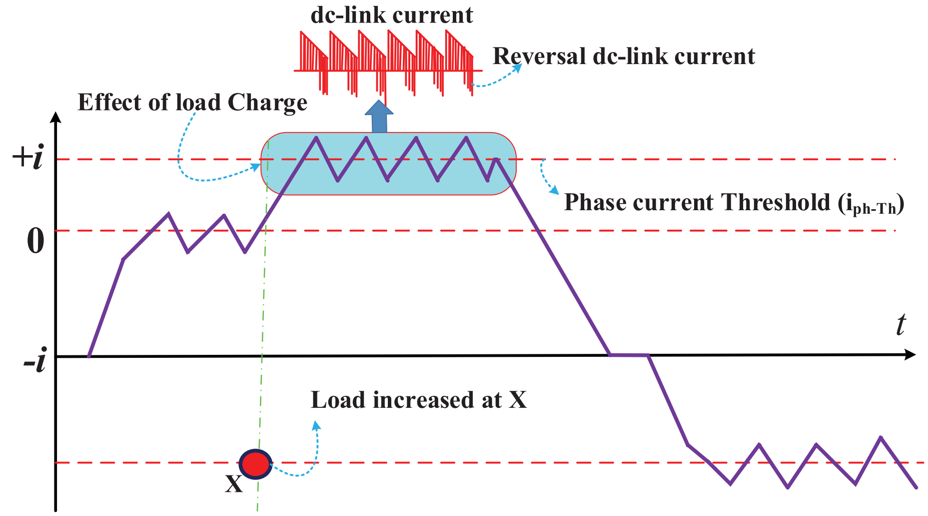

Figure 8. Phase current when a motor is loaded- Rise and reversal of DC-link current indicated.

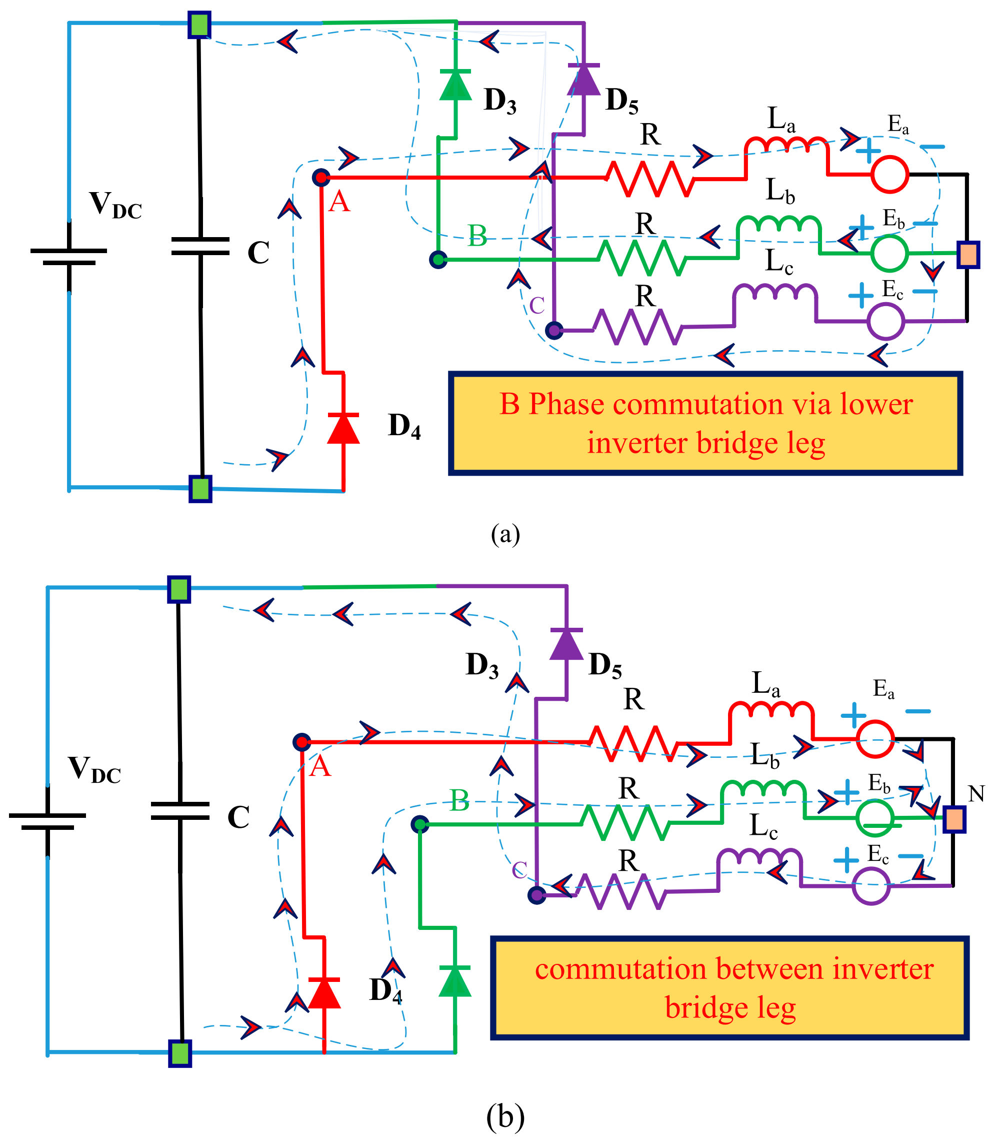

Figure 9. Mode circuit for fully turned OFF state(a) Commutation between upper legs (b) Commutation between lower legs.

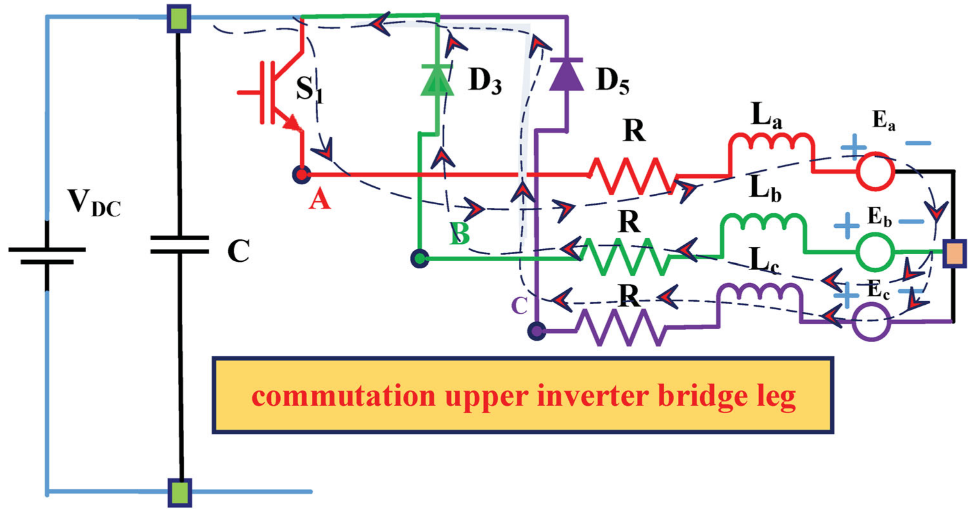

Figure 10. Working diagram MOSFET using upper arm switch during commutation.

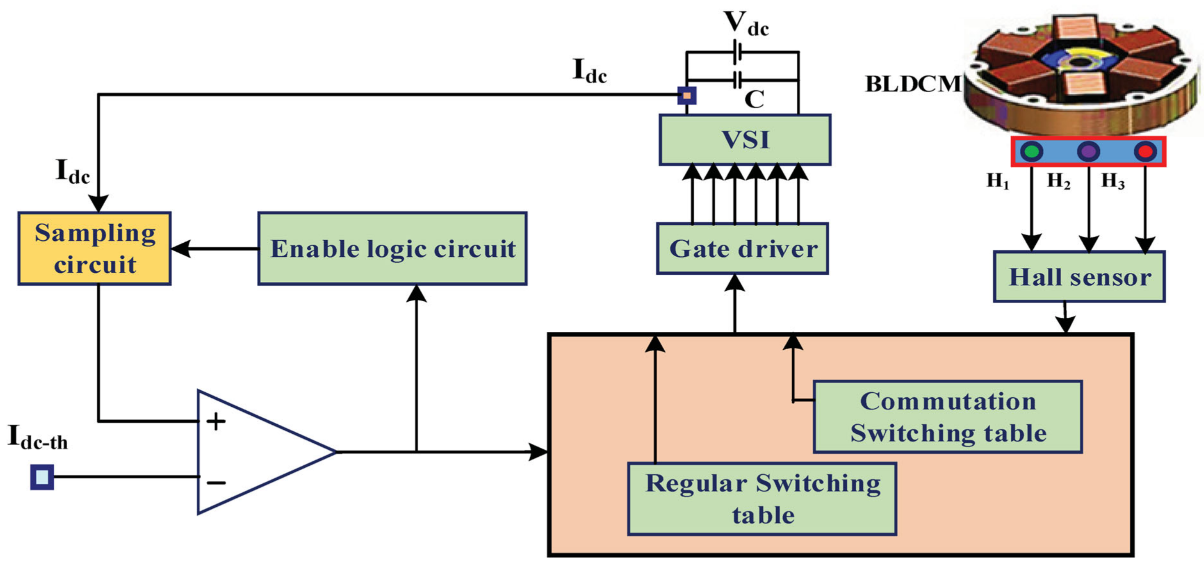

Figure 11. Experimental set-up for BLDC motor drive- system layout.

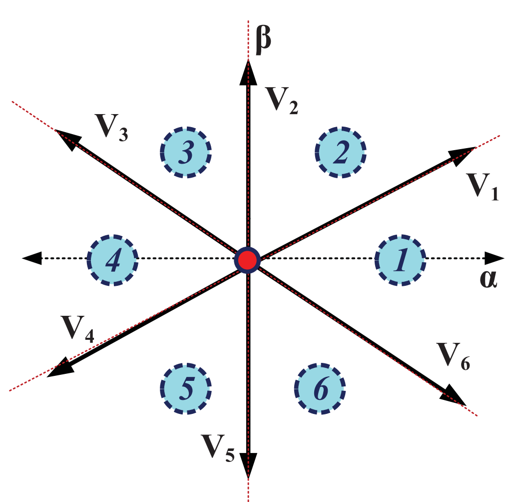

Figure 12. Space vector switching for two-phase conduction mode.

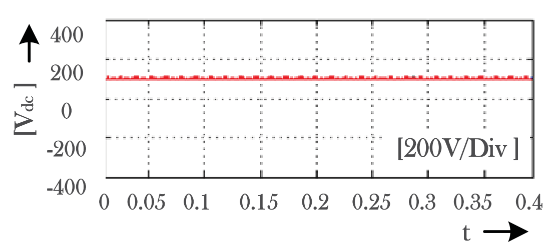

Figure 13. DC-link voltage when motor operated with MOST.

The validation of torque undulation for the proposed preferential turn OFF (MOST) method is utilised to limit the torque undulation at 8.82% which is 36.36% during the fully turned OFF method.

The torque undulation for fully turned OFF duration

$$\text{Torque ripple} = \frac{T_{max} - T_{min}}{T_{average}} = \frac{9.2 - 6.4}{7.7} = 36.36\%$$

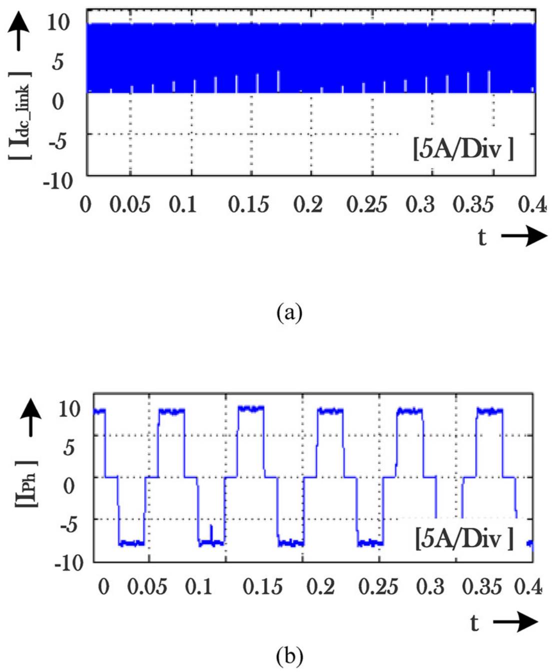

Figure 14. When motor operated with MOST (a) dc-link current (b) Motor phase current waveform (a) DC-link current, when motor operated with MOST (b) Phase current waveform when motor operated with MOST.

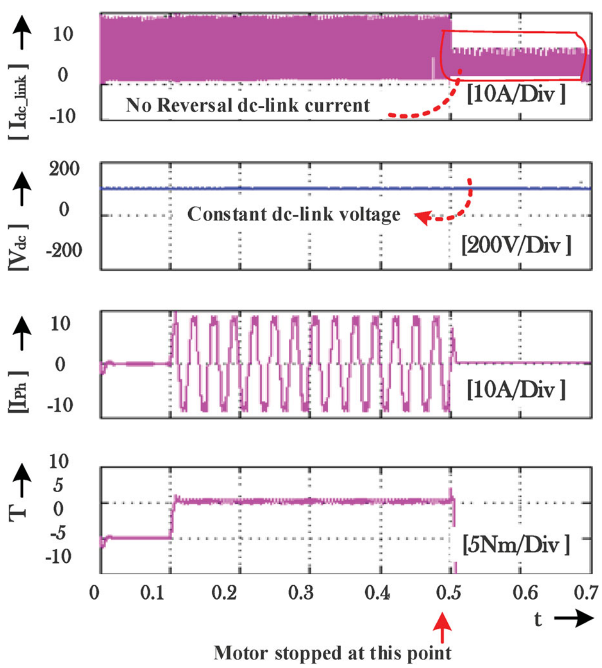

Figure 15. Steady-state and transient response at proposed tuned OFF conditions.

Torque ripple for the proposed partial turn OFF

$$\text{Torque ripple} = \frac{10.9 - 10}{10.2} = 8.82\%.$$

13. Conclusion

The recent challenges, reviews on sensor-less drives, torque undulations with torque due to cogging, PWM strategy and various controllers are appreciable along with recent predictive control methods applicable for PMMs have been discussed. Post-COVID, based on the review the sustainable transportation need and energy revamp satisfaction have been fulfilled by opting for the PMMs. From the review, it is inferred that the demand in search of efficient sensor-less strategy, torque undulation, cogging mitigation based on geometrical modification, PWM technique and controller for PMMs is a never ending process and in can expect more user-friendlier FEM software and the recent control techniques such as machine learning and deep learning could also be replaceable one. The reasons for the torque ripples are highlighted with simulated evidence. This paper evaluated a novel SVPWM-MOST strategy for torque ripple minimisation by controlling the DC-link current. The main idea of the proposed ripple minimisation is exhorting a completely controlled commutation process (during the commutation interval) to avoid the reverse DC-link current by using an innovative space vector modulation technique in the field-oriented control (FOC)-based BLDCM drive.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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