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A Review on Poles Demagnetization in Permanent Magnet Motors

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Abstract: - Permanent magnet motors like BLDC and PMSM are widely used in industry and electric vehicles. Demagnetization of permanent poles in motors is the biggest problem. To design a machine that has good efficiency and no demagnetization problems, real-time fault diagnosis is necessary. Various causes of demagnetization, detection, and measuring methods are discussed by researchers analyzed in this paper. Apart from the comparison of different methods of fault detection, a general comparison among the different methods of various strategies has been made based on the torque ripple, analysis of harmonics, current waveform, back e.m.f. waveform and losses of the PM motor. Finite Element Analysis (FEA) and analytical method adopted by some researchers to get the results. Moreover, considering the importance of BLDC in the electric vehicles (EVs) industry, the selection of the best method to detect demagnetization has been discussed.

Keywords: Demagnetization, Permanent magnet, Cross magnetization, Inter-turn fault, BLDC motor, FEM, Irreversible Demagnetization

I. INTRODUCTION

Permanent magnet synchronous machines and brushless DC machines are extensively used in industry because of their good qualities like high-efficiency, high power density, better speed control, heavy starting torque and robustness. Despite all the good qualities cost of machines limits applications of a machine in the industry. The use of high-quality rare earth magnets in PM machines makes a cost-saving challenging task [1]. The demagnetization curve of a permanent magnet limits the magnetic overload capacity of the machine [2]. The general causes of demagnetization of magnets are heavy inrush current at the time of sudden overloading or winding fault, temperature rise due to heat losses in a winding, heat in magnets because of eddy currents from it, armature reactions, mechanical damage, rusting in case of in-wheel PM motors and aging [1], [3]–[6]. Demagnetization faults in PM machines may significantly reduce output torque and spoil motor characteristics.[7] Demagnetization is classified into two types: reversible and irreversible demagnetization. The first one occurred because of frequent overloading of a machine or say frequent field weakening phenomena and the second one is permanent demagnetization of the magnet due to operation of it beyond magnetic loading capacity and exposure to high temperature [3]. To maintain the output torque at the same speed motor takes a high current with weak magnetic poles and again rises temperature. Operation motor at high temperature may produce severe demagnetization. Demagnetization faults may also generate harmonics in current and mechanical vibration in machine [1].

To design machines that have fewer demagnetization faults, many researchers had suggested different slots/pole selection, various winding patterns, selection of the number of phases and control strategy. In this paper method to detect demagnetization of poles and design parameters suggested by some researchers are analyzed.

II. DEMAGNETIZATION OF PERMANENT MAGNET

When using a permanent magnet as a pole in an electrical machine, an operating point of the magnet must be considered as a very important point. Operation of the machine at an extremely high load, operation point of a magnet may slip below-knee point demagnetization characteristics of PM. After partial demagnetization of the magnet operates on a minor loop different than its original B-H loop [8]. Causes of demagnetization are mainly divided into two parts: Thermal demagnetization and cross magnetization.

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Every magnetic material has a characteristic temperature known as the Curie Temperature. At this temperature, the thermal agitations apply more force than the resistance of the magnetic domains to movement and the domains of the magnet randomize. After the material reaches the Curie temperature throughout its bulk, it will show virtually no net magnetization and can be treated as virgin material. In the case of ceramic permanent magnets, there is an additional factor to consider. The Curie temperature of most ceramic magnets is on the order of 250-450°C. At these temperatures, the material itself will tend to break down magnetically. After this process, the material's performance will be significantly degraded. Therefore, it is generally considered impractical to ceramic magnets in high power machines.

A magnet can be partially demagnetized based on the magnetic load placed upon it. This effect is normally studied by a study of the second quadrant of the hysteresis curve of the magnetic material. Typically, this is the only section of the hysteresis curve that is reported for the hard magnetic material. This curve in fig.1[9] shows the response of the magnets delivered flux into the space around it (B) to the demagnetizing force (H) imposed on the magnet. To assess the performance of the magnet material in each situation, the user should calculate the ratio of B/H.

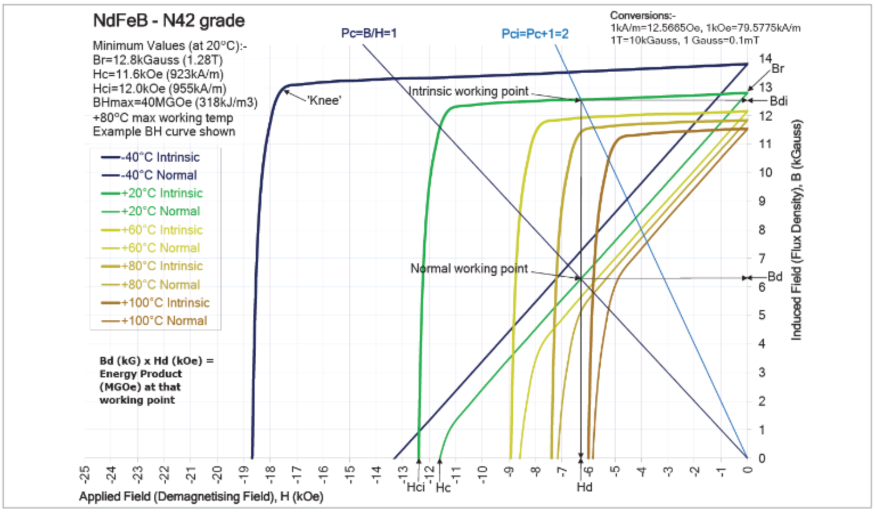

Fig.1 NdFeB- N42 Demagnetization characteristics

A. Stator winding configuration influence on permanent magnet pole

Stator winding in the PM the machines classified as star and delta, fractional slot and integral slot, double layer and single layer, full pitch, short pitch and variable pitch, series and parallel winding. In PM motors delta connected winding is used only in low power motor only. Because of the circulating current around the delta connection and torque repulsion is more compared to star connection. Owing to the high number of slots and poles in lower speed PM motors slot/pole ratio is a fractional number. Usually less than 1. Due to the lower winding factor, fractional slot windings develop harmonics in air gap m.m.f. Since both the torque production capability and back e.m.f. increase proportionally with winding factor, in PM Motors with fractional winding utilization of winding is poor leads high current to meet the torque demand [1].

To detect the demagnetization in motor most researchers prefer variation in phase current spectrum analysis. Due to the fractional winding pattern and harmonics in air gap m.m.f., analysis through phase current spectrum is not enough. So, phase current analysis with zero-sequence voltage component (ZSVC) monitoring was adopted [1]. Monitoring of ZSVC required extra neutral point lead from star point of winding and neutral point at inverter side. The proposed arrangement is shown in fig.2[1]

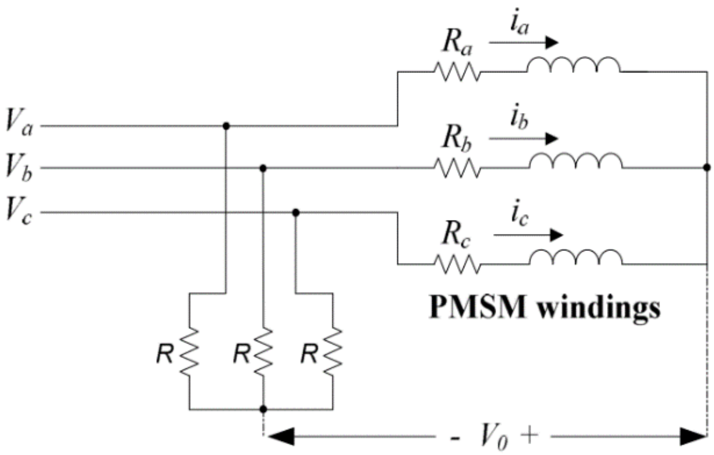

Fig. 2. Diagram for measuring the ZSVC in a PMSM.

The V_0 displayed in fig. 2 is decoupled from drive effects, may be expressed as

$$V_0 = -k_{dem} \frac{d\lambda_{PM,0}}{dt}$$

where, $\lambda_{PM,0}$ being zero sequence flux component due to permanent magnet, p the number of pole pairs and k_{dem} the demagnetization degree.

For different six winding topology effects of demagnetization monitored using the stator phase current incorporation with ZSVC. Results from simulations for series-connected winding with slots/pole/phase is 1 or less shown in fig. 3(a) and 3(b)[1]. Which clearly show the third and ninth harmonic component in ZSVC method which are absent in the stator current spectrum.

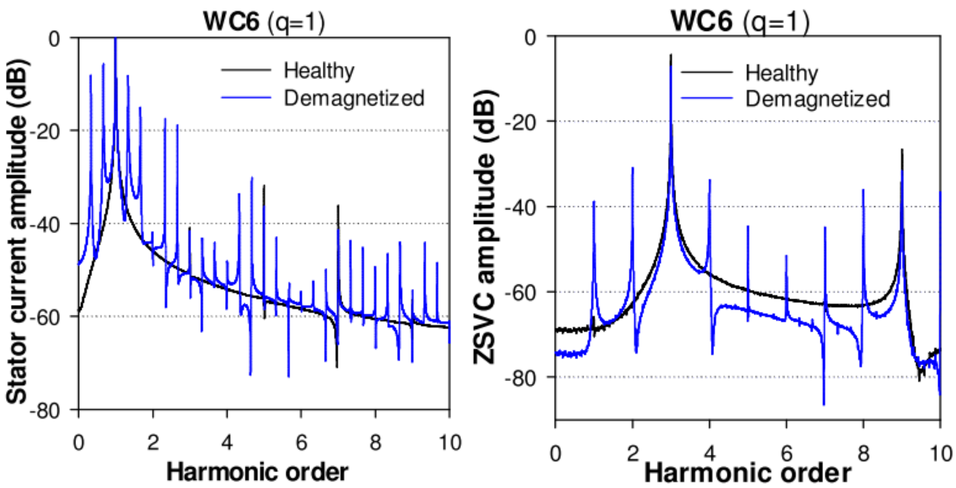

Fig. (3a) stator current spectrum   Fig. (3b) ZSVC spectrum

In-vehicle application to achieve different drive modes, a changeable winding pattern is in an application. When the motor is running with the full load condition, a change in winding connection creates a very high current fluctuation. Momentarily operation of switching of winding and current fluctuation leads to demagnetization of PM [3]. For analysis of switching effect on PM, the position of rotor fixed at 15˚electrical concerning stator. To reduce the fluctuation in current optimized switching suggested. Two steps switching and five steps switching of winding simulated and verified by the researchers in the laboratory. Torque speed characteristic for two-step and four-step switching is as shown in fig. 4(a) and 4(b).

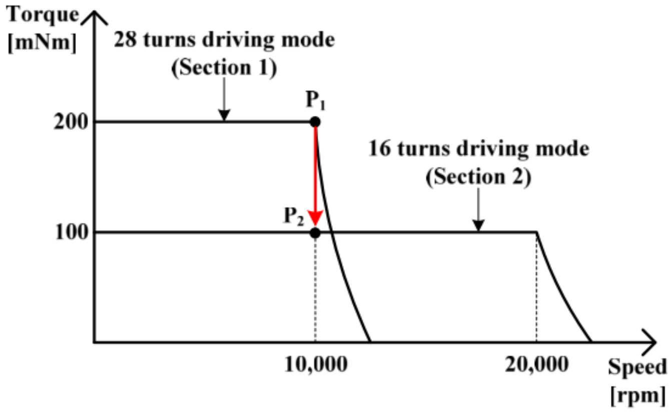

Fig. 4(a). Two steps switching of winding.

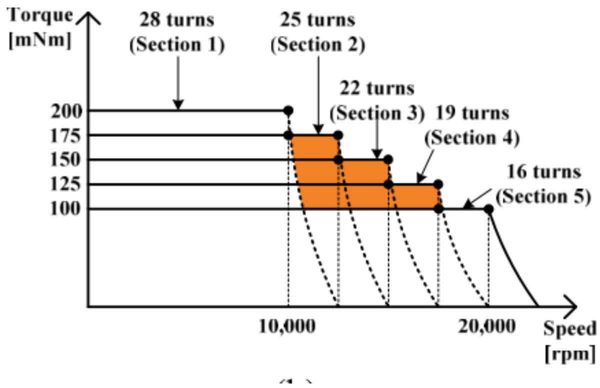

Fig. 4(b). Five steps switching of winding

Transient current spectrum and pole magnet demagnetization from simulation and experiment of the five-step switching method is as shown in fig. 5(a) and 5(b)[3]. From the current spectrum and FEM of pole demagnetization, the author proved that increasing in steps of switching demagnetizing effects of transient current on a pole can be reduced. [3]

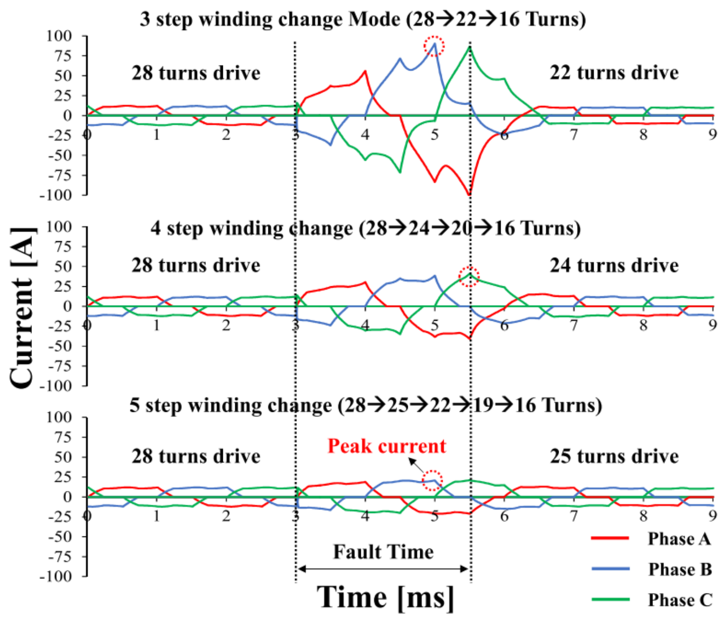

Fig. 5(a). Transient current spectrum at switching of winding.

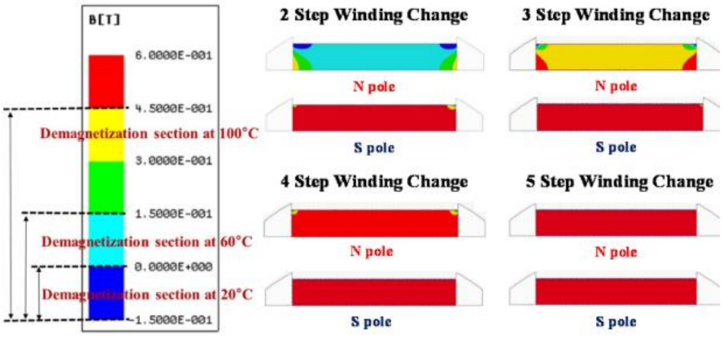

Fig. 5(b). Demagnetizing effects switching of winding.

In both, the paper demagnetization effect of armature reaction due to transient currents in stator windings on PM is discussed deeply. Still, analysis of the effect of temperature, eddy current and mechanical damage on the magnet is missing.

B. Demagnetization due to armature reaction

Among all faults, inter-turn faults in stator winding should be diagnosed in an early stage to avoid degradation in performance and major damage to the motor. Inter-turn fault reduces the resistance of winding and allows heavy current to flow from it, which may lead to the burning of whole winding and severe irreversible demagnetization of PM. In case of opening of a strand in multi-strand conductor, other strands of conductors carry a high current than the rated current in order to maintain torque demand may increase temperature, copper loss and deteriorate magnetic property of PM.

In inter-turn fault and demagnetization of PM, phase current from stator winding increase to maintain torque demand. So, the analysis of stator current can be a common way to detect faults. The electromagnetic torque of the PM motor is proportional to the linkage flux of poles and current vector. For analysis of phase current d-q model is preferred. Voltage and current vector is as shown in fig.6[5]. Resistance losses in windings are ignored.

$$Te = \frac{3P}{4}(\psi PMiq + (Ld - Lq)idiq) \quad (1)$$

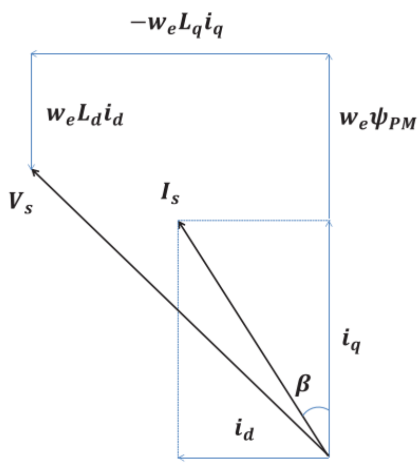

Fig. 6. Voltage and current vector in PMSM machine ignoring resistance loss component.

In a surface-mount magnet machine *Ld = Lq*, so there is no reluctance torque. But in variable reluctance machines like IPMSM reluctance torque value is considerable. From the equation of electromagnetic torque, motors without reluctance torque need more current to maintain the same torque compared to the reluctance torque motor. For IPMSM electromagnetic torque is affected by β.

$$Te = \frac{3P}{4}(\psi PMIsCOS\beta + \frac{1}{2}(Ld - Lq)Is^2SIn(2\beta)) \quad (2)$$

$Where,\ Is = \sqrt{(id^2 + iq^2)}\ \ and\ \ \beta = tan^{-1}(\frac{id}{iq})$

As PM gets demagnetized. The flux per pole decreases and the magnitude of β increases compared to normal conditions. In PMSM inductances increases with smaller decay in flux per pole. Usually, Ld changes more than Lq because the PM is placed in a direct axis. To do a proper analysis separates the effects of demagnetization and inter-turn short fault (ISF) discussed. The demagnetization and ISF are different faults, but they increase current from winding by similar characteristics. However, β was increased by demagnetization and increased by ISF [5]. Demagnetization of pole is not only due to d-ais current, but also due to cross saturation by the q- axis component of current [2]

Inter-turn fault also known as stator turn fault (STF) occurs because of incorrect switch of inverter, at the time of starting and rotor locked conditions. All these three conditions are common for electric vehicles. To study demagnetization fault under dynamic and transient state algorithm was proposed by author. FEM 2-D model was developed to analyze algorithm functionality. Using algorithm currents in normal running condition and faulty condition analyzed. For star connection winding and six switch inverter current flowing path in normal and faulty condition is as shown in fig. 7[6]

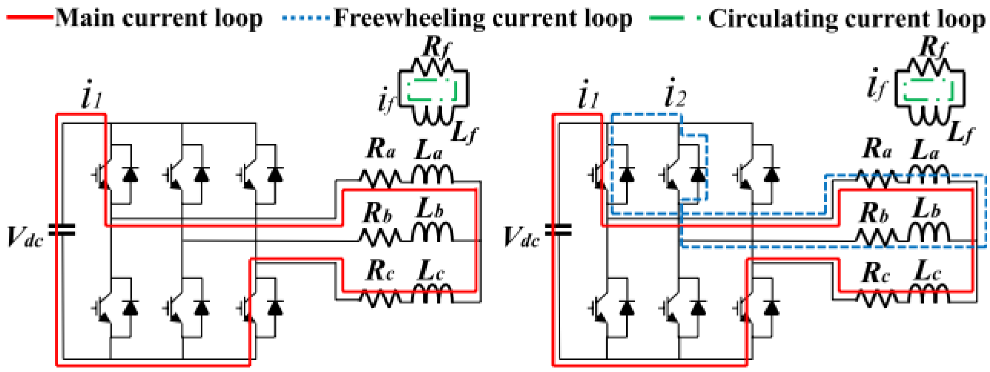

Fig. 7. Current loop in normal condition and stator turn fault condition

For analysis input current calculated by the algorithm. Current increased by creating a fault in four turn intervals. The calculated current value is applied in the 2-D FEM model to check the demagnetization of PM. However, the magnitude of the input current gradually increases under eight turn fault state because of the irreversible demagnetization, which decreases the EMF in a machine. By laboratory experiment, the effectiveness of the algorithm verified with temperature variation by conducting tests on a motor in Owen set up[10].

In maximum case analysis of demagnetization done from the spectrum of inrush current at starting and locking position of the rotor. To get the maximum current position for design purpose analysis of current for other fault conditions is also required. Irreversible demagnetization characteristics are different for the same temperature in static and dynamic conditions. In dynamic state irreversible demagnetization occurs at a low current value as compared to in the static state [11], [12].

The proposed algorithm is helpful to investigate the demagnetization of PM under the inter-turn fault condition. By experiment temperature effect on PM and motor performance analyzed.

C. Demagnetization due to eddy current

To achieve high power output from machines the use of high flux density magnets is necessary. Rare earth, NdFeB and Sm-CO magnets are used in PMSM. These magnets are good conductors of electricity too. Eddy current losses occur in magnet and higher in case of high frequency driven motor. Eddy currents flowing from magnets produce heat in the magnet which becomes a cause of partial demagnetization. Partial demagnetization of magnets results in heavy current flow in winding to fulfill the torque demand. In some motors segmented poles are preferred in place of single magnet per pole to reduce the eddy current loss. Eddy currents accelerate the demagnetization phenomena in motor.

Eddy current is proportional to the speed and magnitude of the linkage magnetic field. So, analysis of demagnetization due to eddy current was done with different speed of rotor. Simulation on motor of 3000 rated rpm carried out and compared eddy current loss in non-segmented magnet pole machine with 3, 5 and 7 segmented poles machines. Result of simulation tabulated as in table 1.[13]

Eddy current loss in watt	**Motoring**	**Generating**	
	3000 rpm	**4000 rpm**	**12000 rpm**
Non segmented pole	32.18	14.25	63.88
3-segment	2.50	1.47	10.75
5-segment	1.56	1.02	7.43
7-segment	0.98	0.71	5.13

Table 1: Eddy current loss in magnet pole at different rpm

Due to eddy current in poles operating point falls below knee point and irreversible demagnetization occur. Irreversible demagnetization characteristic analyzed at 100˚C. Rated current of motor is 350A, but supplied current is three, five and seven times to occur demagnetization. Results of study tabulated as in table 2.[13]

Demagnetization ratio [%]	**Rated current**	**3 times current**	**5 times current**	**7 times current**
Non- segmented	-0.83	-2.00	-16.72	-36.06
3-segmented	0.4	0.29	-11.11	-28.13
5-segmented	0.25	0.11	-11.17	-27.62
7-segmented	0.27	0.28	-10.94	-27.33

Table 2: Demagnetization ratio comparison [%]

In proposed technique of application of segmented magnetic poles eddy current loss reduced and demagnetization of poles reduced. At the same time the strength of magnetic path reduced because of air gap between magnets. By segmentation of pole magnets risk of eddy current loss in magnet can be removed but demagnetization due to high fault current and transient current is still there. Demagnetization of magnets reduced by the cost of total power out-put in this case.

D. Demagnetization due to temperature

Use of rare earth magnets in PM machines increase cost this create interest in research in ferrite magnets as ferrite magnets are cheaply available. The main challenge in the use of ferrite magnet is the requirement of high flux density. Ferrite magnets behave differently from rare earth magnets when exposed to temperature and armature reactions. The coercivity of ferrite magnets increase with increase in temperature and coercivity of rare earth magnets decrease with increase in temperature[8], [14]. Ferrite magnets are positive temperature coefficient and rare earth magnets are negative temperature coefficient for coercivity. The remanence of both the magnets decreases with increase in temperature. Knee point appears at low temperature in ferrite magnets and at high temperature in RE magnets. In hub motor application the possibility of demagnetization of rare earth magnets is less because of continuous heat dissipation in rotor rim. In the same application use of ferrite magnets at low temperature invite risk of demagnetization due to inrush current.

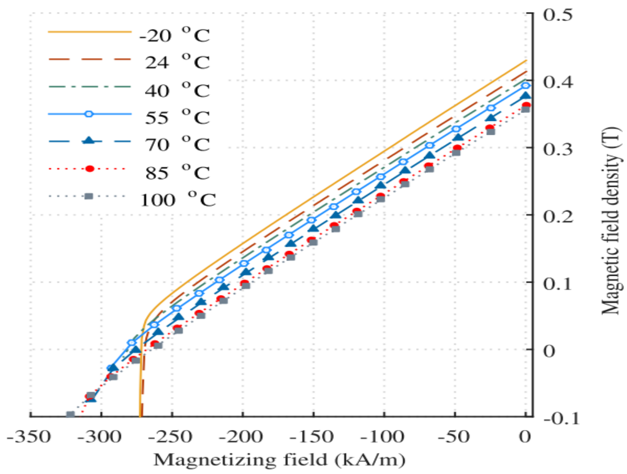

Fig.8. Demagnetization characteristics of ferrite magnet for different temperature

The remanence of ferrite magnets varies with temperature. The Br diminishes by more than 10% when temperature rises from -20˚C to a steady state magnet temperature under load condition (assumed 55 to 70 ˚C) and this variation crates impact on the performance of motor. demagnetization characteristic of ferrite magnet is as shown in fig.8[14]

E. Demagnetization due to push pull process

Considering rotor and stator surface interfacing as a considerable component in the performance of the PM machine. When a machine is running push and pull, force is created between rotor and stator magnets. Surface-mounted magnets are more susceptible to demagnetization. Due to the push process, the operating point of magnets drops the B-H curve due to the demagnetizing field arising from stator m.m.f. To avoid demagnetization of magnets in particularly two-phase machines discussed. Winding pattern adopted which create on pull force on rotor magnets. The proposed technique reduces the risk of demagnetization on the cost of torque output. Comparison of torque, flux linkage and e.m.f winding in a new winding pattern is as shown in fig.9 [4].

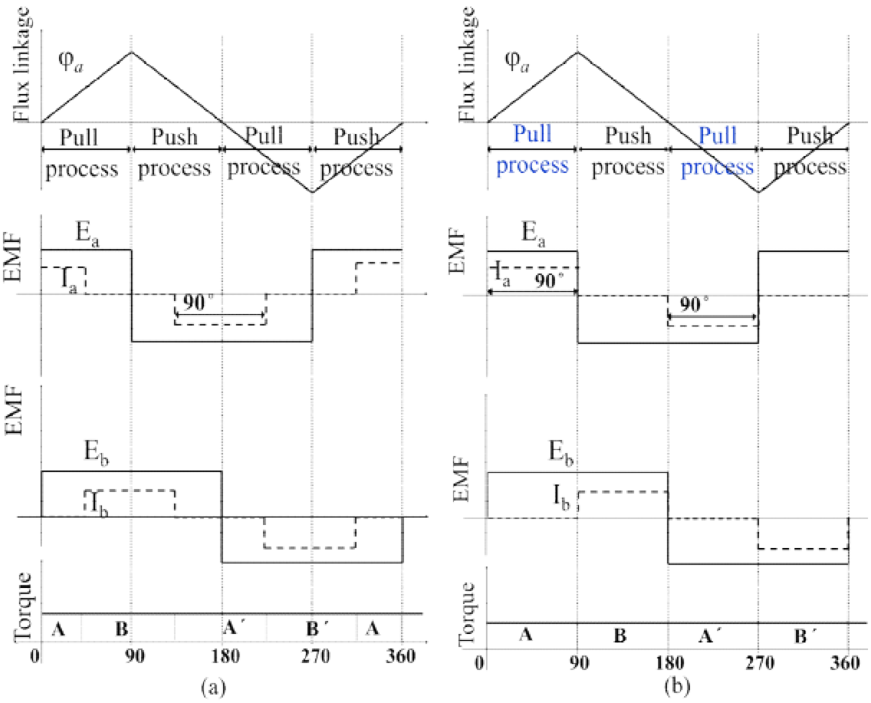

Fig.8. (a)conventional push pull process, (b) only pull process

Various positions of magnets, eccentricities, mechanical damage to rotor and misalignment affect the motor performance. Faulty magnets in the motor effect on current from winding, reduce average torque developed and increase torque repulsion. From the current harmonics' spectrum, the magnitude of existing harmonics is increase with partial demagnetization. In the case of uniform demagnetization of one magnet and two magnet at 90˚ and 180˚ relative position, second-order harmonics found in the current spectrum. Comparison of current. average torque and torque repulsion is as shown in table 3. [15]

Model		**Irms (A)**	**Te,avg (Nm)**	**Te,ripple (%)**
Healthy Magnet		23.52	3.25	15.3
One Faulty Magnet	25%	26.48	3.47	21.7
	50%	30.19	3.85	25
	100%	39.83	4.38	32
	Partial	24.48	3.41	32
Two Faulty Magnet	Adjacent	36.28	4.3	11.62
	90˚	37.14	4	27.4
	180˚	36.31	4.1	28

Table 3: rms current, average torque, torque repulsion comparison in different pole demagnetization condition

III. CONCLUSION

Demagnetization of pole magnet can be analyzed from the back emf, phase current and air gap flux spectrum. It is difficult to generalize a diagnostic method for demagnetization faults. Since fault signatures depend on various parameters. Winding configuration and inter-turn faults in windings cause inrush current in winding and demagnetization due to increase in temperature occur. This paper has reviewed various causes of demagnetization of the permanent magnet, methods to analyze demagnetization and effects of pole demagnetization on the performance of PM Motors. This paper helps in the selection of various design parameters of PM Motors and further fault analysis.

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