Demagnetization fault is the most widespread fault in permanent magnet synchronous motors (PMSMs). Diagnosing this fault and extracting appropriate indexes for the PMSM are proposed and discussed in this paper. The index-extracting techniques and their advantages, disadvantages, and significant ambiguities are proposed, and it is emphasized how these ambiguities can be eliminated. This can help the newcomers to this field as well as designers and manufacturers of protection and fault diagnosis industry. In light of this information, the readers will have a full view on different aspects of each index. An optimum index can be chosen based on the sensitivity of application and the cost of index implementation.

**Index Terms**—Demagnetization fault, indexes, permanent magnet synchronous motor (PMSM).

## I. INTRODUCTION

Permanent magnet (PM) motors are widely used in different applications, such as electrical vehicles, wind energy, home, and industrial appliances. The reasons include simple and compact structure, easy manufacturing, and high power density, more precise control compared with other electrical motors, and high power factor over constant torque region. PM machines can also be used as electrical generators, by direct coupling to wind turbines, and employing industrial drives [1]–[3]. They are very appropriate candidates for applications in which low volume and weight are dominant factors [4]. Torque on the shaft of the motor is developed by the interaction between the stator winding magnetic field and the PM magnetic field that develops. Therefore, any fault in these two elements of the motor can disturb the operation of the motor due to the deviation of the stator and rotor fields from the desirable design values.

In this paper, demagnetization in the PM machine, as a magnetic fault, is proposed, and available indexes for its diagnosis are introduced. This fault occurs due to the electrical, thermal, mechanical stresses, and/or environmental conditions [5]–[8]. There are uniform and partial demagnetization faults.

The impact of the demagnetization fault on the machine is very intensive. The fault can severely reduce the electromotive force (EMF) of the PM machine. In addition, this fault leads to the variations of the air-gap flux density, stator currents and voltages, and developed torque. It also increases the acoustic noise and vibrations in the machine. A significant reduction of the output developed torque, higher input current for developing a definite torque, temperature rise of the windings, and more drops of flux are some results of the demagnetization fault in the motor. One major reason for diagnosis of this fault at the initial stage of its occurrence is the ever-increasing cost of the rare-earth PMs.

There are some terminologies in the field of fault diagnosis that are considered here. Non-invasive means that there is no need to dismantle the motor, or change the structure, or insert any device and sensor inside of the motor. The purpose of the online index is that the fault is diagnosed in the rotating motor under load, and there is no need to stop or disconnect the load or lock the rotor. In this case, the fault diagnosis is possible by the index during the operation of the motor. This can be considered as an advantage of the index.

The indexes are categorized into several types depending on the proposed signal for extracting the fault index. This categorizing generates general groups of the indexes related to current, voltage, torque, and magnetic flux.

Overall, for irreversible demagnetization fault detection due to the four above-mentioned groups, 17 indexes are introduced. The merits and drawbacks of each index and the applied techniques in extracting these indexes are presented. Finally, these indexes are compared and the best and worst indexes for each operational mode are determined.

It is noted that this paper is the outcome of careful and comprehensive investigation of the available literature on demagnetization fault diagnosis of the PM machine, in which the merits, drawbacks, and ambiguities of each index have been extracted based on the given information. Except for the 8th and 9th indexes as part of our work, other indexes have been directly taken from the literature.

## II. CURRENT-BASED DEMAGNETIZATION FAULT INDEXES

The first group of the indexes, which are investigated in this paper, is the current-based indexes. These indexes are very popular and common due to the easy availability of the current signal, their simple mathematical and analytical logic, and more understandability. However, these indexes also have many limitations. To remove these limitations, different current-based indexes have been so far introduced; each concentrating on one of its disadvantages. This could help evolve the indexes and open some research areas in the future.
the generated magnetomotive force of PM is decreased, and any operating point on the magnetization characteristic moves to the knee of the magnetization characteristic and the flux linkage in the coil with $i_d$ for further increase of $i_d$ current is required to saturate the core and for further increase of $i_d$, the core saturates. The saturated core reduces both the differential inductance $L_d$ and $L_d'$ in the eccentricity fault case and zero injected $i_d$ current is lower than that of the healthy machine. While in the demagnetization fault, $L_d'$ for $i_d = 0$ is equal to its corresponding value in the healthy machine. Therefore, this index can easily distinguish the eccentricity fault from the demagnetization fault by the initial value of $L_d'$. This can be observed in Fig. 2. Considering that the harmonic effects of the demagnetization fault and eccentricity are very similar and sometimes identical, distinguishing these two faults is a challenge for any index and can be accounted as a major advantage.

As shown in Fig. 2, in the case of demagnetization fault, $i_d$ corresponding to $|\Delta L_d'|_{\text{max}}$ increases, and the level of this current indicates the fault degree.

This index can be used only in the standstill conditions. Physical concept of this index is clear, and the index can be easily estimated. This is a flux-based index and provides the identical results under reversible and irreversible demagnetization fault. However, using this index needs an additional inverter for injecting dc and ac magnetic fields for the fault diagnosis. The sensitivity of the index to the fault varies in different types of motor. This index is able to diagnose the uniform and partial demagnetization fault. Using the value of $i_d$ in which $L_d'$ variations are maximized, the fault degree can be detected. This index only needs accessing machine terminals for current injection. This index is extracted in the standstill conditions, and consequently, there are no problems of motor load and speed change. This index is usable in the inverter-fed

\begin{equation}
L_d = \frac{\lambda_d - \lambda_m}{i_d} \tag{1}
\end{equation}

\begin{equation}
L_d' = \frac{d\lambda_d}{di_d} \tag{2}
\end{equation}

where $L_d$ is the $d$-axis inductance, and $L_d'$ is the $d$-axis differential inductance. $\lambda_d$ is the $d$-axis flux linkage, and $\lambda_m$ is the flux linkage in the coil with $i_d = 0$. The motor under standstill conditions open circuit ($i_d = 0$) operates in the linear region of the $\lambda - i$ characteristic [Point a in Fig. 1(a)]. In this situation, $L_d = L_d'$; however, by increasing $i_d$, the operating point moves to the knee of the magnetization characteristic and for further increase of $i_d$, the core saturates. The saturated core reduces both $L_d$ and $L_d'$ leading to $L_d \neq L_d'$. By completing the saturation trend, $L_d$ and $L_d'$ approach their steady-state levels. To determine $L_d'$ in this condition, ac field can be injected to the motor in the $d$-axis direction [9]. If this ac field was not so high, the reactive component of the impedance in any operating point on the $\lambda - I$ curve is $L_d'$. In a healthy saturated machine under the standstill condition, a defined dc current in the $d$-axis is injected to the motor, and $L_d'$ is replaced by $\Delta L_d'$. However, in the demagnetization condition, the generated magnetomotive force of PM is decreased, and the $\lambda_d$-axis shifts to the left-hand side, as shown in Fig. 1(b).

A. Injected Saturated $d$-Axis Current in Standstill (First Index)

Two $L_d$ and $L_d'$ inductances of PM motor are defined as follows:

Fig. 2. Variation in the $d$-axis differential inductance $L_d$ and change in $L_d$ and $|\Delta L_d'|$ versus $I_d$ curves with PM demagnetization and eccentricity fault [9].
When stator magnet field angle with respect to the horizontal axis.

\( R_s \) PM temperature using stator winding resistance \((R_s)\) estimation methods \([10]\).

This index is able to diagnose and distinguish the uniform and partial demagnetization and determine the fault degree. This non-invasive and offline index also needs low computational effort.

B. Steady-State Waveform of Positive Peak Plus Negative Peaks of Phase Current Under Pulsating Field Excitation (Second Index)

Suppose \( \theta_m \) is the rotor magnetic field angle and \( \theta \) is the stator magnet field angle with respect to the horizontal axis. When \( \theta_m = \theta \), the generated magnetic flux is maximized, core saturates, and inductance minimized. If \( \theta_m + \pi = \theta \), the generated magnetic flux is minimized. When the standstill machine is excited by a pulsating magnetic field, the magnetic field pulsates at \( \theta \) and \( \theta + \pi \). In this condition, the current waveform is shown in Fig. 3 \([11]\).

In the healthy machine, \( I_{pn} \) waveform is sinusoidal, as shown in Fig. 4, and differs for machine with local and uniform demagnetization. It is noted that the local magnetization causes variations of the generated rotor resultant magnetic field angle. On the other hand, the volume of PM material has been reduced, so the amplitude of the waveform has also been decreased and led to a phase shift. However, in the uniform demagnetization, only the PM volume is reduced, and consequently, magnetic intensity is decreased. This leads to the reduction of the amplitude of the mentioned waveform. By reduction of the volume of the PM material, the generated magnetic field intensity decreases and core moves to the linear part of the magnetization characteristic; therefore, difference between the maximum and minimum inductances is smaller. Therefore, the difference of \( I_p \) and \( I_n \) is lower, and the amplitude of \( I_{pn} \) waveform reduces. Thus, the amplitude and phase shift of \( I_{pn} \) can be used as an appropriate index for the diagnosis of the demagnetization and determination of geometrical position of the fault \([11]\). This index is extracted in the standstill conditions and to inject a pulsation field, an additional inverter is required. Monitoring PMs temperature using stator phase winding resistance methods \([10]\) may lead to irrecoverable demagnetization fault detection, while recoverable demagnetization fault occurs. An irrecoverable demagnetization due to temporary temperature rise in PMs causes the decrease of the PMs magnetic field. This reduction has irrecoverable demagnetization effect. However, by reduction of the temperature, PMs return to their healthy case. Therefore, the only procedure for distinguishing the type of the two demagnetization faults is using PMs temperature beside the investigation of \( L_d' \). In the case of inverter programming, this index can be automatically obtained. Therefore, this can be applied to the remote monitoring of the motor. For extracting this index, there is no need to dismantle the motor or rotate the motor externally. In addition, the index is independent of the parameters of the motor and robust against noise, static and dynamic eccentricity, unbalanced load, misalignment, and variations. This index is able to diagnose and distinguish the uniform and partial demagnetization and determine the fault degree. This non-invasive and offline index also needs low computational effort.

C. Stator Phase Currents Frequency Distribution (Third Index)

Partial demagnetization fault causes an asymmetry in the PM machine (in asymmetrical stator windings) which leads to harmonic components with the following frequency pattern in the stator current:

\[
\begin{align*}
    f_{demag} &= f_e \left( 1 \pm \frac{k}{p} \right) \quad k = 1, 2, 3, \ldots
\end{align*}
\]

where \( f_{demag} \) and \( f_e \) are the demagnetization and fundamental frequency components, respectively, \( k \) is an integer, and \( p \) is the number of pole pairs. These harmonic components in the stator currents are generated by the induced harmonic components within the EMF. Obviously, there are no such harmonics in the stator current spectrum of a healthy machine. Demagnetization fault causes these components and a higher degree fault enhances its amplitude. Therefore, the amplitude of harmonic components is an appropriate criterion for fault diagnosis \([12]\), \([13]\). Fast Fourier transform (FFT) can be applied to this signal for demagnetization fault detection.
FFT averages the stator phases current in time domain [14]; and in frequency domain, it resolves into the complex exponential sinusoidal terms [15]. This transformation means missing the occurrence time of a series of events, such as speed variation and load variation.

This analysis is very convenient in stationary conditions but not applicable to light load, variable speed, and load. In addition, those components that appear over a short period and then disappear might be ignored by this transform. Dynamic eccentricity and partial demagnetization faults generate the identical frequency components in the stator phase current signal frequency spectrum and these faults are not distinguishable. In addition, in the case of symmetrical stator windings, no fault frequency components appear in the stator current frequency spectrum. The mentioned index is independent of the temperature and parameters of the motor. In addition, this index is under intensive influence of the current controller, and perhaps, there is no new component in the current frequency spectrum under the fault due to the controller operation. This index enables to determine the fault degree based on the harmonics level. This non-invasive and online is independent of the motor parameters and requires short computation time, there is no fault generated harmonics in the stator current due to the symmetry of the machine in the case of uniform demagnetization; therefore, this index is unable to detect the type of the fault.

D. Frequency–Time Distribution of Stator Currents (Forth Index)

This index is the completed and modified version of the index introduced in Section II-C. This index is the amplitude of the fault harmonic with frequency pattern predicted by (4), and they appear as coefficients in the stator phase currents frequency–time distribution. Each coefficient is the weighted factor of the frequency component with particular frequency in the overall waveform of the signal representative of the harmonic component amplitude. So far, wavelet transform [16], [17], Hilbert-Huang transform [18], [19], and Cohen’s class distribution [20] are the transformations used for extracting the stator current signals frequency–time distribution for demagnetization fault diagnosis. This index is successfully applied in non-stationary conditions, but more computational effort needs compared with the above-mentioned index.

This index, such as the third index, is online, independent of the machine parameters, needless to the neutral of the machine and usable in axial and radial flux machines. On the other hand, it has all the drawbacks of the third index except the motor speed and load level. The impact of power electronics converter on the third and forth indexes must be considered. The drive of PM synchronous motor (PMSM) has normally an external speed loop which determines the torque reference (q-axis reference current); in addition, this drive has two current loops for controlling $i_d$ and $i_q$. PMSMs are normally controlled in the $dq$-axis rotor rotating frame, as shown in Fig. 5. The fault causes the increase of variations of the speed ($\Delta \omega_r$), and the speed variations are transferred to the speed controller by feedback. In [21], the bandwidth due to the current controllers (current follow exactly the command currents) is taken to be infinite, and the impact of the speed controller bandwidth is studied. When a bandwidth of the speed controller is very narrow, controller cannot compensate the speed variations and torque command generated in its output which leads to a dc and sinusoidal current in the machine in the $dq$ and abc reference frame, respectively. When the speed controller bandwidth is very wide, it is fed through to the torque command and harmonics generated by the variations are observable in abc and dq currents. Therefore, in narrow bandwidth speed controller, the third and forth indexes are not efficient, and voltage signals are recommended for fault diagnosis. However, for wide bandwidth, the third and forth indexes are efficient.

E. Harmonic Components in Phase Winding Branches Due to Fault (Fifth Index)

In the machines with series branches in the stator phase winding, no new harmonic in the induced EMF, stator currents, or electromagnetic torque are generated under demagnetization fault and only their amplitudes vary. For machines with parallel branches in the stator phase winding, demagnetization fault generates the induced EMF in the parallel branches, and harmonic components having frequency pattern of $nf_s/p$ (n is the odd number) [22]. These components cause harmonic currents in the parallel branches. These harmonic components circulate in the branches and do not interface with the phase current. An index for demagnetization fault diagnosis has been introduced merely for a 4-pole machine

![Fig. 5. Flow diagram of PMSM drive system [27].](image)
with two parallel branches. The fault degree $\mu$ has a value between 0 and 1 and is estimated as follows:

$$\hat{\mu} = \frac{I_{1/2} + I_{3/2}}{I_N} \times 100\%$$  \hspace{1cm} (5)

where $I_N$ is the peak phase current and independent of the load level. $I_{1/2}$ and $I_{3/2}$ are the amplitude of the current components in the branches with the frequency of 0.5 and 1.5 $f_1$, respectively. It is noted that this index is only related to the above-mentioned topology, and it may be extended to other topologies. Since it is not easy to access the currents in the branches of every machine, the extension of this non-invasive index to other topologies of winding is impossible.

III. VOLTAGE-BASED DEMAGNETIZATION FAULT INDEXES

This section introduces voltage-based indexes, and the merits and drawbacks of each index are proposed. These indexes are very useful when fault harmonics do not appear in the stator current spectrum due to the winding configuration. Of course, the indexes in this case have some drawbacks and limitations which are discussed in the following parts.

A. Instantaneous Back EMF (Sixth Index)

Partial demagnetization fault, back EMF (bemf) of slot conductors always leads to the predicted fault frequencies shown by (4). Depending on the winding topology, a different number of harmonics may appear in the bemf of whole slots conductors and phase currents. However, the common feature of all topologies of stator windings is that the phase bemf in the healthy and faulty machines, respectively. It is noted that this index is only related to the above-mentioned topology, and it may be extended to other topologies. Since it is not easy to access the currents in the branches of every machine, the extension of this non-invasive index to other topologies of winding is impossible.

$$I_{\text{effective}} \times \sin(\omega t + \phi)$$

where $e_{\text{healthy}}$ and $e_{\text{faulty}}$ are the phase bemf in the healthy and faulty machines, respectively. $K$ is the demagnetization degree [23], [27], [28] which is obtained from the monitoring and comparing bemf of the phase of machine with its corresponding value in the healthy machine. It is noted that the impact of the speed and load variations has not been considered in this case. This index is usable only for generator, because the bemf of the phase in the motor is not available. However, it seems that this index can be extended to motor mode. This simple index requires low computation effort. In addition, stator winding topology change has no impact on the applicability of the index. This online and non-invasive index is able to diagnose the fault and act independent of the machine parameters.

B. Fundamental Component of ZSVC (Seventh Index)

Zero-sequence voltage component (ZSVC) is a very popular signal and applicable in various applications. This signal can be successfully applied to the detection of rotor position [24] and stator winding fault of poly-phase machines [25], [26]. The decoupled drive and current controllers have no impact on the ZSVC. In addition, in the demagnetization fault, there is no new harmonic in the symmetrical windings; therefore, the analysis of ZSVC is the best choice for the fault diagnosis. PMSMs are supplied by pulse width modulation inverter, which injects ZSVC to the motor. In addition, the terminals of the phases are not accessible. In order to eliminate the component related to the modulation, a three-phase balanced resistor network is inserted between the motor and the inverter; as a result, the injected ZSVC by the inverter has no interface with the ZSCV due to the demagnetization fault, so it cannot disturb the fault diagnosis process. It is noted that $V_0$ can be determined as follows:

$$V_0 = V_{0,c} + V_{0,m}.$$  \hspace{1cm} (7)

The terminal voltages in (7) can be observed in Fig. 6.

In [23], [27], and [28], the following $V_{0,m}$ has been taken as the proposed signal:

$$V_{0,m} = -k \frac{d\lambda_{pm0}}{dt}.$$  \hspace{1cm} (8)

where $k$ [already used in (6)] presents the demagnetization degree. The amplitude of the fundamental component (corresponding to the third harmonic of the supply frequency) of $V_{0,m}$ is used to extract the index. For the healthy machine, $k$ is equal to 1, and it has been introduced as the fault index. Load variation has no impact on the ZSVC, but variations of the speed can change the index. The fundamental harmonic component of ZSVC ($V_{0,m}$) is decreased by increasing the fault degree. However, this index can be applied if the neutral point of the machine is accessible. This point is accessible in the fault tolerant machines due to the link of the fourth leg of the inverter to the neutral of the machine. Online monitoring and measuring of $V_{0,m}$ makes it possible to scale the voltage sensor based on the ZSVC value, hence the sensitivity of the measurement system can be enhanced.

IV. TORQUE-BASED DEMAGNETIZATION FAULT INDEXES

The torque-based indexes are introduced in this section. The torque signal is generally extracted using torque sensors,
which are more expensive than other sensors. In addition, inherent vibrations of the machine cause higher noise in the raw extracted signal. This is the reason that this family of indexes is less common.

A. ASBC of Developed Torque of Motor (Eighth Index)

The developed torque of the motor can be calculated as follows:

\[
T_e = T_c + \sum_{i=1}^{\infty} T_i \sin(\lambda w_s(t) - \alpha) + \sum_{\lambda=1}^{\infty} \sum_{\zeta=1}^{\infty} T_{\lambda,\zeta} \left( \left( \frac{\lambda \pm \zeta}{p} \right) w_s(t) - \beta \right) \tag{9}
\]

where \( \lambda \) and \( \zeta \) are the integer numbers, \( \alpha \) and \( \beta \) are the space variables, and \( T_e, T_c, \) and \( T_i \) are the torque components. Demagnetization fault causes disturbance in the air-gap flux density distribution and intensifies the torque ripples. The increase of the torque ripples causes the increase of amplitude of the sideband components (ASBCs) within \((\lambda \pm \zeta/p)f_s\) frequencies. It is noted that the mentioned frequency pattern is under influence of the supply frequency, saturation, and harmonic components of the supply voltage. Therefore, this index is not recommended for fault diagnosis in inverter-fed motors. In addition, ASBCs in the mentioned pattern are under influence of the saturation, stator slots, and supply voltage condition. The normalized harmonic components of torque in \((\lambda \pm \zeta/p)f_s\) pattern has been introduced as an index for demagnetization fault detection [30]. The ASBCs increase by increasing the fault degree and are independent of the load level due to the normalization process. Speed variations impact upon the index has not been considered and can be further investigated. Since accelerometer and torque meter are expensive, the torque-based methods must be used only in large machines. This index is unable to distinguish eccentricity fault from the normal and uniform demagnetization fault. Since this index uses the mechanical signal, it is sensitive to the noise and vibration. The fault degree can also be detected using this index.

B. Rotating Radius of Torque First Difference Time Series (Ninth Index)

Disturbance in the developed torque of the motor is an obvious sign of the demagnetization fault, which increases by increasing the fault degree. The time delay embedding (TDE) method is an appropriate one for extracting and detecting the hidden patterns in the time series information [31], which has been used in [30] to obtain an index from motor torque in the case of the demagnetization fault. By implementation of TDE on time series of the torque profile, a 2-D presentation of the torque series in the phase space is obtained. Its rotation radius \( R_g \) is an appropriate index for fault diagnosis. By increasing the fault degree, the radius of the rotation reduces. It is noted that this index varies by load level variations. Therefore, for correct diagnosis of the healthy and faulty motor, the fault at the same load must be compared. However, this index may be made robust against the load level; the impact of the speed variation on the index could also be investigated. This index is more suitable for large machines. The merits and drawbacks of this index are similar with that of the eighth index except that it has not been normalized and is sensitive to the load level.

C. Estimated Torque Constant (Tenth Index)

In PM motors, the inverter dc link \((i_{dc})\) is distributed between two phases of the motor over every 60 electrical degrees. Each 60° sector is called a number 1–6.

For each sector, the torque is as follows:

\[
T_e = \frac{(e_{as} - e_{bm})i_{dc}}{w_m} = \frac{(p\lambda_{as(pm)} - p\lambda_{bs(pm)})i_{dc}}{w_m} = 2 \frac{d\lambda_{pm}}{d\theta_x} i_{dc} \tag{10}
\]

where \( \lambda_{pm} \) is the magnetic flux linkage of the phase, and \( \theta_x \) is the rotor mechanical angle with respect to the horizontal axis. In every 60° sector, \( d\lambda_{pm}/d\theta_x \) is assumed constant, and the torque is as follows:

\[
T_e = k_i i_{dc} \tag{11}
\]

which is similar to the torque of a separate-exited dc motor, and \( k_i \) represents the PM power [12]. This condition is satisfied in every sector. In the \( i \)th sector, the bemf of the two conducting phases is added and called \( E_i \). Finally, the total \( E \) is determined as follows:

\[
E = E_1 + E_2 + E_3 + E_4 + E_5 + E_6. \tag{12}
\]

In addition, \( k_i \) is calculated as follows:

\[
\hat{k_i} = \frac{E}{w_r}. \tag{13}
\]

There are different procedures for the estimation of bemf of each sector. \( k_i \) is a proper index [12] which is independent of the rotor faults, such as static or dynamic eccentricity. In the case of temperature variations of the motor, modification factors must be applied in order to consider the temperature variation impact on the magnetic power and resistance of PM; this has not been considered in [12]. It is noted that this index has inherent error in \( k_i \) estimation. For low degree of demagnetization, this error can hide the small changes in the bemf. In this case, direct reading of \( k_i \) can be a good solution. This index is able to distinguish eccentricity fault from uniform demagnetization fault for different topologies of winding. However, it is sensitive to the parameters of the motor, load and speed variations can derange the operation of the motor or reduce the accuracy of the index.

D. Measured Torque Constant \( k_t \) (11th Index)

The difference between this index and index 10 is its higher precision and inherent errorless nature. To obtain this index, the motor is supplied by a direct current and rotated by an external device [29]. This is an offline method and there is no need to dismantle the motor. However, it is not a desirable method due to disconnecting the load, de-energizing the motor, necessity of an external device for rotating, low speed of the test, requiring additional sensors, and low sensitivity against local demagnetization. This index is very sensitive to the PM temperature and \( k_t \) decreases by temperature rise.
determines the estimated value of EMF. The attempt has been made to minimize the following objective function:

$$\min_x \sum_j \left( e_k^j(x, \theta) - \hat{e}_k^j(\theta) \right)^2$$  \hspace{1cm} (14)$$

where $e_k^j(\theta)$ is the induced EMF by the model versus angle, and $\hat{e}_k^j(\theta)$ is the real EMF of the machine. The minimization of this cost function is done using a gradient algorithm. If the generated EMF of the model was equal to the estimated EMF of the model, we can be sure that the estimated $B_{i,j}$ by the model is also correct. However, if $B$ in each element was lower than a definite value for a healthy PM, a demagnetization fault has been occurred. Therefore, $B_{i,j}$ can be used as an appropriate index to diagnose the degree and location of the PMs demagnetization [22], [33]. These indexes have been introduced only for radial flux machines and it may be extended to the axial-flux machines. In addition, this index can only be applied to the uniform axial demagnetization due to dividing each PM into 2-D form and it may be extended to 3-D sectored PM. In this index, infinite permeability for the stator and rotor back iron has been applied. This index strongly depends on the system parameters and it is not valid when parameters vary. This online and non-invasive index is able to distinguish eccentricity fault from demagnetization, detect the fault degree, and diagnose the uniform demagnetization fault. In addition, this index can be used in different topologies of the winding.

B. $d$-Axis Flux of PM in Synchronous Reference Frame (14th Index)

Demagnetization decreases the magnetic field strength of the rotor, and consequently, the $d$-axis flux which links the stator to the rotor. As a result, this flux is considered as an appropriate index for local and uniform demagnetization fault diagnosis. The following equation can be used to estimate this flux in the rotor reference frame [13]:

$$\lambda_d^{(pm)} = \frac{V_{qs}^e - r_s i_{qs}^r}{w_r} - L_{ds}^e i_{ds}^e$$  \hspace{1cm} (15)$$

where all quantities are instantaneous values, and $\lambda_d^{(pm)}$ is the total $d$-axis flux linking the stator windings, $i_{qs}^r$ and $i_{qs}^e$ are the $d$-axis and $q$-axis stator currents, respectively. $L_{ds}^e$ is the $d$-axis stator inductance, $V_{qs}^e$ is the $q$-axis stator voltage, $r_s$ is the stator resistance, $\lambda_d^{(pm)}$ is the $d$-axis PM flux linking the stator windings, and $w_r$ is the rotor speed. The average value over time of $\lambda_d^{(pm)}$ is a direct measure of the magnet flux. Then, it is transferred to the synchronous reference frame by

$$T_e = T(\theta_e) = \frac{2}{3} \begin{bmatrix} \cos(\theta_e) & \cos(\theta_e + \frac{2\pi}{3}) & \cos(\theta_e - \frac{2\pi}{3}) \\ \sin(\theta_e) & \sin(\theta_e + \frac{2\pi}{3}) & \sin(\theta_e - \frac{2\pi}{3}) \end{bmatrix}$$

$$\lambda_d^{e^{(pm)}} = \frac{V_{qs}^e - r_s i_{qs}^e}{w_e} - L_{ds}^e i_{ds}^e$$  \hspace{1cm} (16)$$

$$\lambda_d^{e^{(pm)}} = \frac{V_{qs}^e - r_s i_{qs}^e}{w_e} - L_{ds}^e i_{ds}^e$$  \hspace{1cm} (17)$$
where \( w_e \) is the synchronous speed, \( \hat{L}_{ds}^{\text{pm}} \) are the transformed values of \( L_{ds} \), \( V_{qs}^e, V_{ds}^e, i_{qs}^e, i_{ds}^e \), and \( L_{ds}^{r} \) are the transformed values of \( L_{ds} \), \( V_{qs}^r, V_{ds}^r, i_{qs}^r, i_{ds}^r \). This algorithm determines the BLDC motor system matrix using the line voltage equations in inverter freewheeling and non-freewheeling cases. This algorithm predicts irreversible demagnetization fault and its degree by studying the PM’s operating point, considering the saturation and even considering short-circuit turn fault. If the operating point passes the knee point of \( B-H \) curve, demagnetization fault is diagnosed and the new \( B_r \) is estimated. It is emphasized that both the uniform and partial demagnetization fault change the operating point of the PMs; therefore, both of faults can be detected by the index. This online and non-invasive index is able to distinguish the eccentricity fault from the demagnetization fault, and there is no need to access the neutral point of the machine. In addition, load and speed have no impact upon the operation of the motor. This index depends on the parameters of the motor and is sensitive to the PM’s temperature.

### C. PMs Flux Pattern (15th Index)

In order to obtain this index, it is necessary to dismantle the motor and use a Gauss meter for the measurement of the flux pattern in the magnetization and circumferential axis of the PM [34]. This PM flux pattern can be used to diagnose the demagnetization fault. This needs flux pattern of the PM surface using precise measurement equipment. In addition, the signs of damage (crack and broken PM) may be found by eyes and magnet viewer. To obtain this index, the motor must be dismantled and accessible through offline tests [34]. This invasive index can directly investigate the impact of the fault, namely, PMs magnetic field reduction; therefore, it has high accuracy and reliability. This index does not need any signal processing after extracting the raw signal for detecting the fault and its degree.

It is noted that this index cannot quickly detect the fault because in order to do the required measurements, the motor must be dismantled and this is a time-consuming process. Therefore, it is not practical to apply this index in in-field application and only usable in laboratory.

### D. PMs Operating Point on \( B-H \) Curves (16th Index)

Irreversible demagnetization fault moves the PMs operating point below the knee point of \( B-H \) curve. In such case, the residual flux density \( B_r \) is lower than that of the operating case above the knee of \( B-H \) curve and its value can be estimated. In the normal operation of the motor, the PMs back half is under an intensive magnetic field opposite to the PM magnetization. As a result, the irreversible demagnetization begins in the back half of PMs and spreads forward. In [35] and [36], an algorithm has been presented to determine the PMs operating point and magnetic flux density within every PM element.

### E. Magnetization Coefficients of PMs (17th Index)

If a factor \( k \) is used for each piece of PM in the PM machine, \( k = 1 \) shows the healthy machine, and \( k = 0 \) indicates fully demagnetized PM. Factor \( k \) is called the magnetization coefficient of PM which can be used as an index for demagnetization fault detection. In [36], an inverse algorithm has been introduced which receives input three-phase currents, geometrical parameters of the machine, rotor speed and terminal voltages of three phases and estimates \( k \) factor relevant to each piece of PM using an analytical model. This model considers the stator slotting effect and the end winding inductances. The advantages of this index include its capability to determine the healthy and faulty PMs. The disadvantages of this index are lower precision in determining factor \( k \) in the faulty PMs, if the faulty PMs are placed beside each other and also its sensitivity to the measured noise and variations of circuit parameters of the machine, such as armature resistance (\( R_a \)) and leakage inductance (\( L_s \)). In [37], the inverse algorithm has been modified in order to reduce the operation sensitivity to the parameters \( R_a \) and \( L_s \). However, further work for improving this online and non-invasive index (particularly sensitivity on the precision of \( R_a \) value) and reduction of its sensitivity to the measured noises can be recommended. It is noted that this index needs a large number of sensors and this increases the sensitivity to the noise. This index is sensitive to the temperature.

### VI. Merits, Drawbacks, and Comparison of Indexes

In Section V, 17 indexes were introduced for the demagnetization fault diagnosis in the PM machines, and details of each index were investigated. In this section, the performance of these indexes under different operating conditions and structures is proposed, and the characteristics of each index are studied. To do this, the 19 following statements are proposed.

**A1:** Introduced index can distinguish the demagnetization fault from dynamic eccentricity fault.

**A2:** If uniform demagnetization occurs, this index also announces PM demagnetization fault.
### TABLE I
**Comparison of 17 Indexes**

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A3: There is no need to use additional sensors to obtain the index.
A4: Index is able to detect the fault degree.
A5: Changing load level does not cause disturbance and unreliable index.
A6: Changing speed does not cause disturbance and unreliable index.
A7: Index is independent of motor parameters.
A8: Index is usable for demagnetization fault detection in inverter-fed motors.
A9: Index computation is short.
A10: Index is able to diagnose the fault in radial and axial field machines.
A11: Index is online.
A12: Index is non-invasive.
A13: Saturation has no impact on the index.
A14: Index is robust against noise.
A15: Index has no sensitivity to PM temperature.
A16: There is no need to disassemble motor for extracting this index.
A17: Index is reliable for different topologies of stator winding.
A18: Index has been experimentally validated.
A19: Index has been validated by the 3-D simulation.

Before evaluating the indexes, it is necessary to present explanations on some statements. In A6, the purpose of unreliable index under non-stationary and variable speeds is that the announced results for the fault or non-fault case by an index and/or degree of detected fault has no reasonable accuracy. This can be due to inability of some indexes in tracking the fault harmonic components (third index) and/or change of the index value due to the speed variation (seventh index), and/or so on. This restricts to apply the index for fixed speed operation. It is noted that the offline indexes and the indexes extracted in the standstill conditions are unable to diagnose the fault in non-stationary speed and load variation cases. The reasons are that the machine is out of service or stationary and under no-load conditions, so they do not satisfy A5 and A6 conditions and are non-stationary against A5 and A6 conditions.

It is noted that A16 has large overlap with A12 index; the latter index examines the non-invasive feature of indexes. Because it can be realized that dismantling the motor for the index extraction shows the non-invasive feature of the index and its sub-division. This feature prevents the use of this index in-field applications. Therefore, separating A16 from A12 is very useful and informing. For A19, the 2-D simulation with sufficient time is quicker than the 3-D simulation; however, in the 2-D simulation, flux distribution in the third dimension is not considered and this means that the accuracy of the 3-D simulation is higher than that of the 2-D simulation and is a more reliable method for the verification of the theoretical fault diagnosis index.

If any statement for index is satisfied the sign (+) and if non-satisfied the sign (−) is inserted. If the statement is undefined (not considered in the literature), the sign (∗) is inserted. It is noted that the sign (∗) can be considered as a new research topic and also a probable weakness point. The situation of these 17 indexes compared with the 19 statements has been summarized in Table I. If the sign (∗) is not seen as a weakness point, Fig. 8 shows the bar diagram of the number of faults of any index.

In this case, index 15 is the weakest index, and indexes 7 and 16 are the best index. However, Fig. 9 shows the rod diagram of the probable weakness point of any index. In this case, index 16 is the best, and indexes 9, 13, and 15 are the worst indexes.

Perhaps, investigating all these indexes in general may not be reasonable. Sometimes, there is need to have an index which can detect partial and uniform demagnetization fault. In such conditions, if the index has no such capability, it is not employed even if it has some good features.

In addition, sometimes only online techniques are acceptable, and the offline indexes are not applicable. Such conditions are also proposed for non-invasive indexes.
Finally, as non-invasive indexes, again, index 16 is the best, and 13 is the worst index. There are different aspects for comparison and evaluation of these indexes and the attempt was made to introduce the most reasonable criteria in order to provide an appropriate viewpoint to the readers.

VII. CONCLUSION

In this paper, the demagnetization of PMs as the most important fault in the rotor of PMSM was proposed. Seventeen indexes in four general groups for this fault diagnosis were described in detail. All indexes were criticized based on the defined statements. Then, the strongest and weakest indexes based on the different applications were determined.

In addition, available techniques were discussed and their merits, drawbacks, and possible improvement procedures were presented.

This review can help designers of protective devices for confident choose of the best index for fault diagnosis and protective equipment of PMSMs considering the full information about limitations of each index.

REFERENCES


TABLE II

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