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Co-Simulation of permanent magnet synchronous motor with demagnetized fault fed by PWM inverter

***Abstract**. Advanced modelling and simulation techniques, are often employed to study and analyse the dynamic behaviour of electrical machines under different operating conditions. One of the main issues with permanent magnet synchronous machines (PMSM), especially inset-PMSM and surface-mounted PMSM, is demagnetization. In this article the dynamic of healthy and faulty inset-PMSM fed by a pulse width modulation (PWM) inverter is simulated. The Flux2D model is developed using finite element method (FEM) modelling tool and a partial and a complete demagnetized magnets are introduced in the model. The electric drive system of the motor is modelled using Simulink.*

***Streszczenie.** Do badania i analizy dynamicznego zachowania maszyn elektrycznych w różnych warunkach pracy często wykorzystuje się zaawansowane techniki modelowania i symulacji. Jednym z głównych problemów związanych z maszynami synchronicznymi z magnesami trwałymi (PMSM), zwłaszcza PMSM wstawianymi i PMSM do montażu powierzchniowego, jest rozmagnesowanie. W tym artykule symulowana jest dynamika sprawnego i uszkodzonego modułu PMSM zasilanego przez falownik z modulacją szerokości impulsu (PWM). Model Flux2D opracowano przy użyciu narzędzia do modelowania metodą elementów skończonych (FEM) i do modelu wprowadzono częściowo i całkowicie rozmagnesowane magnesy. Elektryczny układ napędowy silnika zamodelowano przy użyciu Simulink. (**Współsymulacja silnika synchronicznego z magnesami trwałymi z błędem rozmagnesowanym zasilanym przez falownik PWM**)*

Keywords: inset-PMSM, demagnetization, Finite element method, Pulse width modulation.
Słowa kluczowe: inset-PMSM, rozmagnesowanie, metoda elementów skończonych, modulacja szerokości impulsu

Introduction

Permanent Magnet Synchronous Motors (PMSMs) are widely regarded as state-of-the-art motor technology due to their numerous advantages over other motor types. PMSMs are known for their high torque , high power density, outstanding dynamic response, efficiency, and precise control capabilities, making them ideal for a wide range of applications, such as general-purpose industrial drives, high-performance servo drives, and numerous particular ones where size and weight are constrained, such as in automotive , renewable energy systems, and aerospace applications.

The demagnetization occurs when the strength of the permanent magnet inside the PMSM decrease. This demagnetization can occur as a combination of thermal, electromagnetical, mechanical, low-quality magnets and environmental stress [1]. Wide operating temperatures cause changes in the metallurgical structure of the material, which loses its magnetic properties and its ability to be re-magnetized [2]. The effect of temperature on the magnetic properties of magnets is most often represented by a family of demagnetization characteristics. Fig.1 show that NdFeB magnets can suffer irreversible demagnetization at temperatures higher than 80◦C. [3,4].

Chemicals and humid environment favour the corrosion and oxidation of rare-earth magnet materials, which also cause changes in the metallurgical structure. The structurally altered parts exhibit lower remanence and coercivity levels and hence are more prone to demagnetization. On the other hand the electrical current of the stator produce an inverse magnetic field that oppose the induction of the permanent magnet and can cause demagnetization [5]. Demagnetization may be total, affecting the entire pole, or partial, affecting only a portion of the pole. [6, 7].

It is difficult to model demagnetized magnet in specific regions of the PMSM using parameters because parametric models assume symmetry in mechanical and electromagnetic fields, which is not present in this case. To address this limitation, finite-element analysis (FEA) simulations can be performed. FEA is the best solution for solving partial differential equations across complicated domains.

For motor simulation, (FEA) method have shown to be an important tools used for diagnosing electrical machine faults because of its accuracy, reliability and its ability to provide more definite information of the machine [8,9]. The benefit of FEA makes it more comparable to real machine analysis by taking into account the nonlinearity of materials, magnetic saturation, slot effects, and winding effects. [10].Hence transient FEA has been a popular tool for demagnetization investigations during the past fifteen years [9,11].For example in [12] a samarium cobalt magnet, was demagnetized in an experimental fixture that was also modelled in the FEA program COMSOL, and a good agreement was found between FEA results and measurements.

The Flux 2D is a finite element method (FEM) software. This software allows the extraction of machine electromagnetic properties and analysis of machine performance. The machine parameters from Flux 2D can be imported into power electronics simulation platforms such Simulink, where the appropriate motor drive and control scheme can be more readily developed.

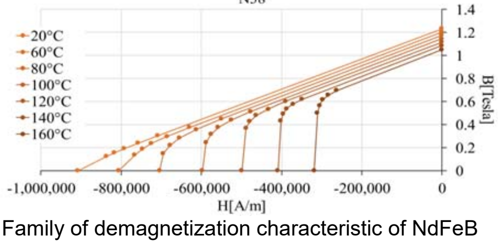


Fig.1. Family of demagnetization characteristic of NdFeB

Dynamic model of the inset PMSM

1) Mathematical model of healthy PMSM in the *dq* reference frame

The stator voltage equations, the stator flux linkage, the electromagnetic torque and the speed of healthy PMSM in the *dq* axis reference frame can be expressed as follow [13, 14, 15].

$$v_d = R_s i_d + \frac{d\psi_d}{dt} - \omega_e \psi_q \quad (1)$$

(2) $$v_q = R_s i_q + \frac{d\psi_q}{dt} + \omega_e \psi_d$$

With

(3) $$\psi_d = L_d i_d + \psi_f$$

(4) $$\psi_q = L_q i_q$$

(5) $$T_e = \frac{3}{2} Z_p \left(\psi_d i_q - \psi_q i_d\right) = \frac{3}{2} Z_p \left(\psi_f i_q + \left(L_d - L_q\right) i_d i_q\right)$$

Where v_d ,v_q ,i_d ,i_q ,L_d , L_q ,ψ_d and ψ_q represent the *dq* axis stator voltage (V) , current (A), inductance (H) and flux linkage (Wb), respectively , R_s is the stator phase résistance (Ω) ,ψ_f is the amplitude of the flux linkage established by the permanent magnet (Wb), T_e is the electromagnetic torque (N.m), Z_p is the number of pole pairs and ω_e is the rotor electrical angular velocity (rad/s). The rotation of motor could be described by the following dynamic equation.

(6) $$J \frac{d\omega_m}{dt} = T_e - B_v \omega_m - T_L$$

With J denoting the total inertia, B_v viscous friction coefficient, T_L load torque and ω_m the mechanical speed. The equations of the PMSM in rotor reference frames are assembled in a form that facilitates the computer solution as follow.

(7) $$\begin{cases} \frac{di_d}{dt} = \frac{1}{L_d}\left(v_d - R_s i_d + \omega_e L_q i_q\right) \\ \frac{di_q}{dt} = \frac{1}{L_q}\left(v_q - R_s i_q - \omega_e L_d i_d - \omega_e \psi_f\right) \\ \frac{d\omega_e}{dt} = \frac{Z_p}{J}\left(\frac{3}{2} Z_p \psi_f i_q - \frac{B_v}{Z_p}\omega_e - T_L\right) \end{cases}$$

Therefore, the only way the solution of the system (7) can be obtained is by a numerical solution. The solution is then obtained by integrating the differential equations. The Runge–Kutta method can be used for numerical integration

2) Mathematical model of PMSM with demagnetized magnet

When the permanent magnet demagnetization occurs, the permanent magnet flux linkage amplitude and direction will change. The flux linkage amplitude varies from initial ψ_f to ψ_{fr} , and there is a deviation angle γ between the direction of the rotor flux and the *d* axis of the reference frame. Fig.2. illustrates this case [14, 16].

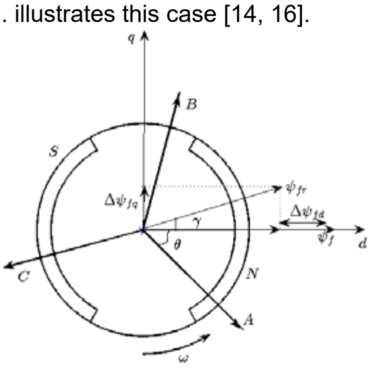


Fig.2. Variation of PMSM flux-linkage.

The equation (3) and (4) no longer hold and became.

(8) $$\psi_d = L_d i_d + \psi_f + \Delta\psi_{fd}$$

(9) $$\psi_q = L_q i_q + \Delta\psi_{fq}$$

(10) $$v_d = R_s i_d + L_d \frac{di_d}{dt} - \omega_e L_q i_q + \frac{d(\psi_f + \Delta\psi_{fd})}{dt} - \omega_e \Delta\psi_{fq}$$

(11) $$v_q = R_s i_q + L_q \frac{di_q}{dt} + \omega_e L_d i_d + \frac{d\Delta\psi_{fq}}{dt} + \omega_e\left(\psi_f + \Delta\psi_{fd}\right)$$

After irreversible demagnetization $\frac{d(\psi_f + \Delta\psi_{fd})}{dt} = 0$ and $\frac{d\Delta\psi_{fq}}{dt} = 0$ .Then the set (7) can be rearranged as (12)

$$\begin{cases} \frac{di_d}{dt} = \frac{1}{L_d}\left(v_d - R_s i_d + \omega_e\left(L_q i_q + \Delta\psi_{fq}\right)\right) \\ \frac{di_q}{dt} = \frac{1}{L_q}\left(v_q - R_s i_q - \omega_e L_d i_d - \omega_e\left(\psi_f + \Delta\psi_{fd}\right)\right) \\ \frac{d\omega_e}{dt} = \frac{3Z_p^2}{2J}\left(\left(\psi_f + \left(L_d - L_q\right)i_d\right)i_q + \left(\Delta\psi_{fd} i_q - \Delta\psi_{fq} i_d\right)\right) \\ \quad - \frac{Z_p}{J}(T_L + B_v \omega_m) \end{cases}$$

With the presence of the unknown parameters $\Delta\psi_{fd}$ and $\Delta\psi_{fq}$ in (12) , it is not possible to obtain a numerical solution for this system .To overcome this drawback, simulations by means of finite element analysis can be carried out.

Modeling of inset-PMSM motor using co-simulation

1) Simulation model of PMSM

The inset PMSM is simulated by the software Flux2D on the data mentioned in Table 1, and the model is shown in Fig.3..The PMSM was given the partial demagnetization fault by choosing one of the six permanent magnet, and set the 33%, 66% and 100% material of the permanent magnet to vacuum to simulate the corresponding partial demagnetization .The specific setting are shown in Fig.4.

Table 1. Specification of the studied PMSM

Stator Outer Radius/ Inner Radius	77.5 mm/38 mm
Rotor Outer Radius/ Inner Radius	36 mm/24.5 mm
Air-gap Length	1 mm
Stack length	117 mm
Stator slots	18
Poles pairs	3
Phase End-turn Inductance	1.6 mH
Phase End-turn resistance	0.8 Ω
Magnet type	NdFeB
Core Material	M19
Inertia	1.8 kg.cm²
Motor voltage constant	33 V/1000 rpm
Maximum current	33 A
Rated torque	3 Nm

Fig.5. shows the changes in the form of the no-load air gap magnetic flux density waveform in each faulty sate against to healthy state operation. This change is more highlighted for a complete demagnetization in comparison of health operation.

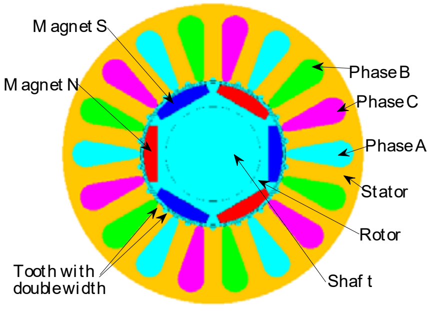


Fig.3. Cross section of the studied machine.

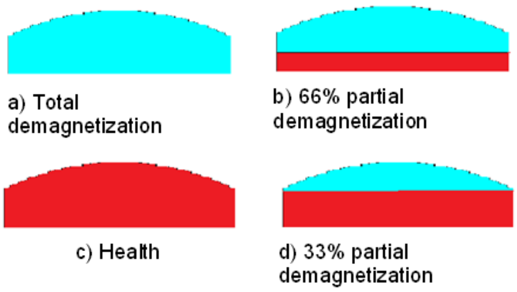


Fig.4. Single PM demagnetization model

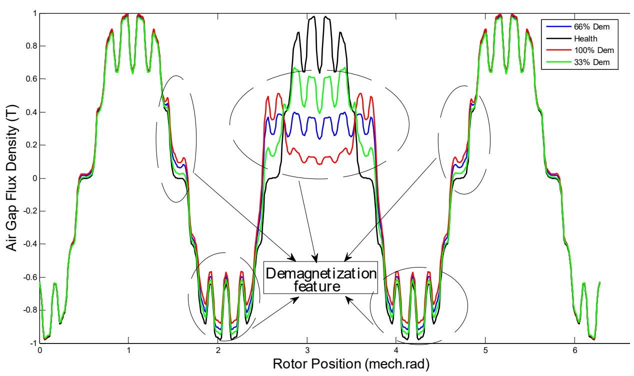


Fig.5. The no-load air-gap magnetic flux density in PMSM

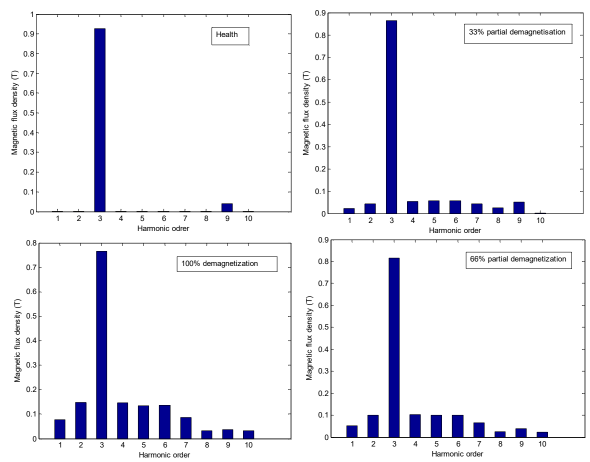


Fig.6. The no-load air-gap magnetic flux density spectrum

The changes of harmonic component of amplitude of FFT analysis of the flux density as shown in Fig.6. is a feature that can be used for demagnetization fault detection. The amplitudes of the main harmonic order of the magnet flux without and with faults are given respectively by: 0.9268T, 0.8645T, 0.8160T and 0.7644T. For the healthy case, the spectrum contains only the 3rd and 9th harmonics. Conversely, new fractional and whole harmonics appear and increase significantly in the spectrum in the case of the 33%,66% and 100% faulty state.

2) Co-simulation model

To solve the system of differential equations (12), a numerical model of a PMSM motor operating under demagnetized magnet circumstances is created using the Flux2D, and the electric drive system for the motor's operation is produced using Simulink .The input voltages for AC drives and power converter are realized by the PWM generation and inverter. The complete simulation model operated in open loop, as shown in Fig.7. consists of a Flux2D machine's model of PMSM, PWM and IGBT inverters.

The stator voltages and load torque are the motor's input parameters while the stator currents, angular speed, electromagnetic torque and the electrical angle are the motor's output parameters.

The comprehensive modelling of the machine drive, while requiring a significant amount of computational time, results in more reliable solutions since the machine physical geometry, material qualities, boundary conditions and demagnetized permanent magnet are all taken into account during PMSM motor drive operations.

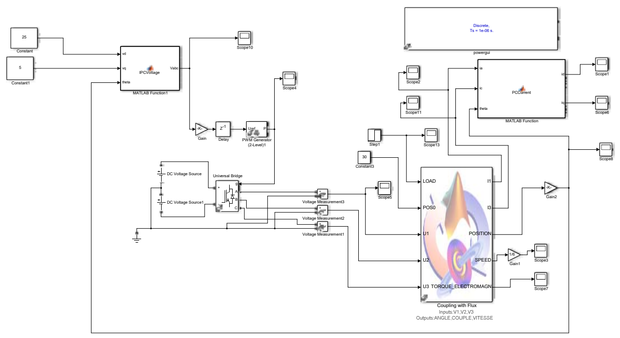


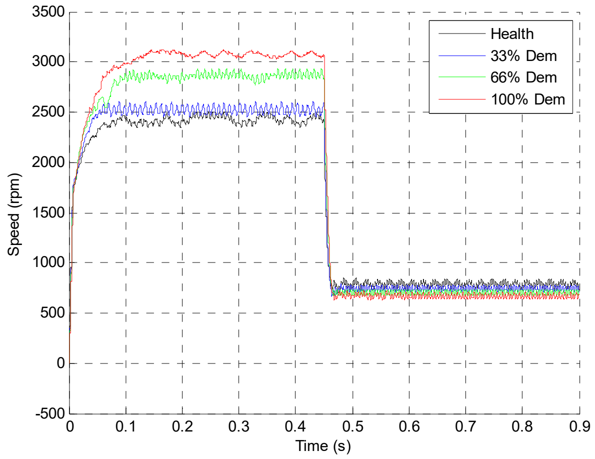
Fig.7. Implementation of the proposed Co-simulation

Results and discussion

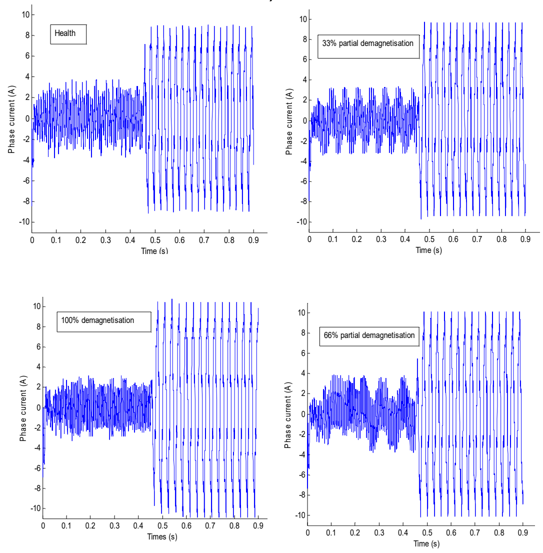
The co-simulation is performed using the following parameters:the *DC* bus voltage $V_{DC} = 80V$, $v_d = 25V$, $v_q = 5V$, PWM carrier frequency $f_{ca} = 1.05\,kHz$, power electronic computational interval $T_{cs} = 1\times10^{-6}$, sampling interval $T_{in} = 20\times10^{-6}$, switching frequency of the IGBT $f_c = 20\times10^{3}$, the simulation time $t = 0.9s$. The motor start with no-load and after $t = 0.45s$ a load $T_L = 3N.m$ is applied.

The analysis of results obtained from co-simulation of healthy and faulty machine indicate that the motor's dynamics and performance are significantly affected by introduction of permanent fault.

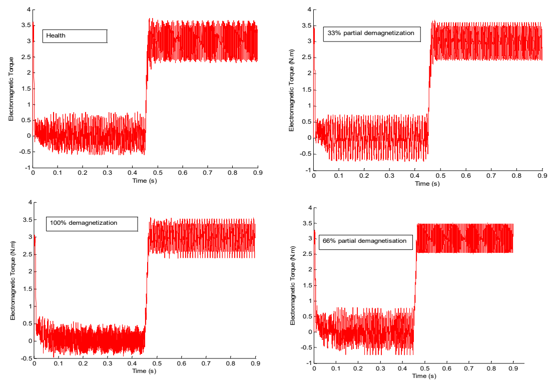
1. Demagnetization of the permanent magnet weakens its magnetic field, leading to an increase speed at very light loads Fig.8.a.
2. The reduction in magnetic field strength will lead to a decrease in the torque produced by the motor . Since the torque is responsible for driving the motor's rotation, a decrease in torque will result in a decrease in the motor's speed, especially under load conditions Fig.8.a
3. Fig.8.b show the increases of the current demand of the motor to achieve the same level of torque output Fig.8.c. The maximum current is 9.06A for healthy machine which increases to 9.75A for 33% demagnetization and 10.14A for 66% demagnetization and 10.74A for 100% demagnetization.



a)



b)



c)

Fig.8.Comparison between the healthy and faulty cases:
(a) speed (b) current and (c) torque

Conclusion

In this article, the effect of demagnetized magnet on the dynamic of an inset-PMSM is analysed by co-simulation Flux2D-Simulink. Three cases of fault severities such as one pole demagnetized by 33%, 66% and 100% are considered for analysis. The results show that, in order to generate the same torque as in healthy operation the value of the stator current increase which leads to more machine losses. As a result, the magnet's demagnetization point drops as machine temperature rises (Fig.1.), and the magnet can be further demagnetized. The speed-torque curve of the motor is altered, requiring adjustments in the control strategies to achieve the desired performance.

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