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Research Article

Reducing Speed Ripples and Vibrations in Permanent Magnet Synchronous Motors with Unbalanced Loads

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ABSTRACT

Permanent Magnet Synchronous Motors (PMSM) have important features such as high torque, high power density, high acceleration, small volume, low noise and high efficiency. With these features, is widely used in the industry. One of the negativities that occur during the operation of electric motors is speed fluctuations and vibrations due to the unbalanced loads. Unbalanced loading can be caused by the character of the load, as well as the poor mounting of the motor to the load, the misalignment on the shaft and the load itself being an eccentric load. Especially at high speeds, this causes permanent damage to the motors. Specification and elimination of these fluctuations, which occur for different reasons, are very important for a reliable operation. In this study, unbalanced load situations are investigated in an unbalanced PMSM and the speed ripples in the unbalanced load of the motor are attempted to be decreased by the proposed Adaptive Harmonic Injection approach. The simulation is carried out under various operating conditions by abruptly and linearly changing the motor speed under unbalanced load. It is observed that speed fluctuations in the motor can be effectively suppressed under different operating condition.

Introduction

High torque, high power density, quick acceleration, small volume, low noise, and high efficiency are some of the key characteristics of Permanent Magnet Synchronous Motors (PMSM). With these features, PMSMs are widely used in the industry [1, 2]. Axial misalignment, speed ripples, and vibrations brought on by unbalanced loads are some of the drawbacks of using electric motors. Unbalanced loading can be caused by the character of the load, as well as the poor mounting of the motor to the load, the misalignment on the shaft and the load itself being an eccentric load. Especially at high speeds, this causes permanent damage to the motors. Specification and elimination of these fluctuations, which occur for different reasons, are very crucial for a reliable operation. The speed ripples in unbalanced loaded motors are attempted to be decreased by the proposed Adaptive Harmonic Injection (AHI) approach in this study that investigates the unbalanced load conditions in an unbalanced PMSM.

Imbalances in the rotor in electrical machines are mostly caused by eccentricity, shaft misalignment, bearing failures and unbalanced loads [3, 4]. During the rotation, this imbalance causes a variation in centrifugal force on the rotor or the movement of the center of mass in the rotor away from the center of rotation. This causes vibration in the motor. One of the most important fault in rotating machines is axial misalignment in electric motors. The air gap between the stator and rotor is not equally distributed when the motor is out of alignment. Misalignment in the motor causes problems such as the increase in the amplitudes of the harmonic components of the flux density in the air gap, fluctuation in speed and torque, decrease in the average value of the torque, decrease in efficiency due to the increase in losses, heating of the motor and increase in noise.

In the literature, there are different studies conducted by researchers on the unbalanced load caused by axial misalignment in motors. [5] have presented a method to simulate the air gap eccentricity in induction machines. The geometry and winding configuration of the machine have been used to compute the motor parameters. Thus, the calculated machine inductances have involved the effect of eccentricity in this study. In [6], a real-time PMSM drive system platform is used to test the control algorithm in order to reduce motor vibration. They have concluded that the vibrations in the different motor speed have decreased by the proposed controlled strategy. A PMSM drive systems, the evaluation of a compact imbalance technique is suggested in [7]. In this study, a filter is merged with an open-loop torque observer and an imbalance estimator to predict the unbalance. [8] estimated static eccentricity, dynamic eccentricity and mechanical eccentricity in three-phase PMSMs using Artificial Neural Networks (ANN). The simulated current is given a white Gaussian noise addition, and it is concluded that the sideband frequency is created in the current and voltage spectra by the eccentricity defect in the PMSM. In [9], stator current has been used to estimate the amount of eccentricity occurring in the Brushless DC Motor. The Morlet main function has been used to detect whether there is any misalignment. The experiment has been validated by FFT. In [10], it has been suggested that model predictive control and iterative learning control be combined to speed up the system's response time and significantly lessen speed ripples. The obtained results confirm the effectiveness of the model predictive control and iterative learning control scheme. In [11], it has been recommended to use the virtual cogging torque control method to suppress the direct-drive PMSM servo system's speed ripple at low speeds. This study has shown that the control mechanism utilized to smooth the speed during low-speed operations is facile and efficient. Unbalanced loads encountered in motors are mostly caused by misalignment, curvature of the shaft or loading the motor with an unbalanced load. In misalignment, the air gap is not evenly distributed [12]. Axial misalignment is examined in three categories as static misalignment, dynamic misalignment and mixed misalignment. The unbalanced load caused by the load imbalance occurs when the center of gravity in the motor is different from the center of rotation. Vibrations occur as a result of oscillation at the moment of equilibrium. The rotor or mechanical load imbalance generates vibration at high speeds due to a bearing or shaft defect, which can cause mechanical failure. The degree of rotating unbalance must be determined in real-time in order to prevent malfunction and reduce mechanical vibration. One of the methods used in PMSM to reduce speed fluctuations caused by eccentricity and load imbalance is harmonic current injection. Speed fluctuations encountered in motors are generally periodic. Therefore, speed fluctuations can be reduced by injecting current harmonics with suitable amplitude and frequency into the motor [1]. In this study, speed fluctuations brought on by unbalanced loads are reduced using the Adaptive Harmonic Injection (AHI) method. The decision values of the various sub-data are linearly combined to form the basis of the AHI algorithm. In an active coupling approach based on vertical projections on the convex set defining these values, the decision values are linearly combined with online-updated weights. The algorithm and the results are presented in sections 2 and 3, respectively.

Dynamic Model of PMSM under Unbalanced Load

One of the conditions that cause the unbalanced operation of the motor in PMSMs is axial eccentricity. Eccentricity faults can occur in three different situations: Static Eccentricity (SE), Dynamic Eccentricity (DE), and Mixed Eccentricity (ME). SE is a steady amount of shift of the rotor on the vertical or horizontal axis. The minimum air gap that occurs in axial misalignment does not change with time. It creates a constant thrust in the direction of the small air gap. In DE, unlike SE, the position of the rotor and the air gap are not fixed due to the rotation of the rotor around the rotation axis of the stator. These two situations concurrence in ME [13]. Pulsating radial electromagnetic forces are caused by eccentricity's induction of an imbalanced magnetic attraction. As a consequence of that, additional frequency components are occurred into the current spectrum. The following is an expression for these induction motor frequency components:

$$f_{eh} = \left[(kR \mp n_d)\left(\frac{1-s}{p}\right) \mp \nu\right] f_e \quad (1)$$

Here n_d and k are integer and in case of SE n_d taken as zero. R is total slot number and s is slip in the formula. Both of them is taken as zero in PMSM. ν is the odd numbered supply harmonics in the supply frequency p indicates the number of pole pairs. Thus, in case of ME, harmonic components can be represented as follows [14]:

$$f_{eh} = f_e \mp k(1/p) f_e \quad (2)$$

The mechanical system can be simulated as illustrated in Fig. 1 in order to analyze the mechanical and electrical phenomena of the PMSM drive with a mechanical unbalance [7]. A mass of total unbalance (m_u) can be used to express both the rotor unbalance of a PMSM and the load unbalance of a mechanical system, such as a dynamic eccentricity. The unbalanced mass m_u and the gravitational acceleration g produce a gravitational force. When it acts at a distance e from the center of the rotating parts, gravitational force generates a torque that is in the opposite direction of rotation. The torque depends on mechanical rotor position θ_{rm} and mechanical rotor speed ω_{rm}.

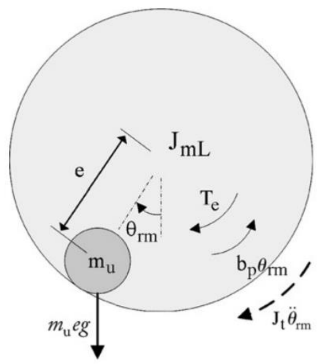

Figure 1. Rotational unbalanced model of the motor [7]

The free body diagram for the rotational model, demonstrated in Fig. 1, is used to calculate the equation of motion (Eq. 3) for rotational dynamics under the assumption that the mechanical system with unbalance is mounted horizontally along its rotating axis..

$$J\dot{\omega}_{rm} + B\omega_{rm} = T_e - m_u e g \sin\theta_{rm} \quad (3)$$

where J is the total moment of inertia, B is the coefficient of friction and T_e is the induced electromagnetic torque of motor. Harmonics in the motor phase currents are caused by the unbalance's electromagnetic torque.

The stator current's harmonic components have revealed a dynamic eccentricity, such as an unbalance. Current harmonics occurring in unbalanced loading are as defined for ME in Eq. 2. Electromagnetic torque can be defined as in Eq. 4 for PMSM:

$$T_e = \frac{3}{2} p \lambda_m i_q \quad (4)$$

The electromagnetic torque T_e (Eq. 4) is substituted into the load torque (Eq. 2) to produce the unbalanced q-axis current at an exact constant speed by ignoring friction and moments of inertia as follows:

$$i_q = \frac{2}{3p\lambda_m}(m_u eg \sin\theta_{rm}) \quad (5)$$

As can be seen from Eq. 5, oscillations occur due to unbalanced load depending on θ_{rm}.

The Adaptive Harmonic Injection Algorithm

In unbalanced loaded PMSMs, torque fluctuations vary periodically according to rotor position and appear as speed fluctuations. Thus, injecting the proper current harmonics into the motor is one of the most effective ways to reduce speed fluctuations. According to Eq. 2, fluctuations caused by unbalanced load in PMSM occur in mechanical rotor frequency. Therefore, ripples can be reduced by injecting harmonic currents at this frequency into the motor. The harmonic to be injected can be expressed as in Eq. 6 [1]:

$$x_h = x_m \sin(h\theta + \phi) \quad (6)$$

In the above equation, h is the harmonic order, x_m is the amplitude of the injected harmonic and ϕ is the phase angle.

$$x_m \sin(h\theta + \phi) = x_m[\sin(h\theta)\cos(\phi) + \sin(\phi)\cos(h\theta)] \quad (7)$$

Here, if w1 is written instead of $x_m \cos(\phi)$ and w2 is written instead of $x_m \sin(\phi)$, Eq. 8 is obtained as follows:

$$x_m \sin(h\theta + \phi) = w_1 \sin(h\theta) + w_2 \cos(h\theta) \quad (8)$$

Any harmonic order can produce a harmonic component with the required amplitude and phase if the sine and cosine terms are weighted with the proper values. Appropriate values are called as weights. The weight values are determined by the Adaptive Harmonic Injection (AHI) technique. The Normalized Least Mean Square (NLMS) technique is used to update the weights. The main drawback of the pure LMS algorithm is its sensitivity to the scale of its input $X(n)$. Because of this, choosing a learning rate μ that assures algorithm stability is very difficult [15]. By normalizing with the input's power, the NLMS, a variation of the LMS algorithm, resolves this issue.

In order to express this idea mathematically, let $\hat{w}(n)$ stand for the filter's old weight vector at adaptation cycle n and $\hat{w}(n+1)$ for its updated weight vector at adaptation cycle n + 1.

$$\hat{y}(n) = X^T(n)w(n) = \sum_i w_i(n)X_i(n) \quad (9)$$

Here $\hat{y}(n)$ is an estimate of the weighted component $y(n)$ of any harmonic in step n and the error vector can be written as follow:

$$e(n) = y(x,n) - \hat{y}(x,n) \quad (10)$$

The Mean Square Error is minimized in order to update the weights.

$$min_{wi} E[(y(n) - \hat{y}(n))]^2 \qquad i=1,\dots.N \quad (11)$$

Here E is the expectation operator. If the derivative of the weight is taken and set to zero:

$$\frac{\delta E}{\delta w} = -2E[(y(n) - \hat{y}(n))X_i(n)] = -2E(e(n)X_i(n)) \quad i = 1, \dots N \quad (12)$$

$$-2E\big(e(n)X_i(n)\big) = 0 \quad i = 1, \dots N \quad (13)$$

When the Wiener solution is applied to the N equation group and the necessary adjustments are made, an equation is obtained as in the NLMS algorithm. In this equation mu is the update rate.

$$w(n+1) = w(n) + \mu \frac{e(n)}{\|H(n)\|^2} H(n) \quad (14)$$

This algorithm's primary benefit over competing approaches is that it includes a controlled feedback mechanism that depends on the error term. Eq. 14 describes an online, controllable, and quick adaptive method for adjusting harmonic weights.

Simulation Results

The simulation of PMSM control using Field Oriented Control (FOC) is applied as the initial step of the study. Table 1 provides information on the motor's parameters in the simulation. The sampling time Ts is 2e-5 s and the DC link voltage of the inverter is 100 V in the simulation.

Table 1. Motor parameters

Rated power	4 kW
Rated speed	2000 rpm
Armature resistance	0.0485 Ω
Armature inductance	0.000395 H
Number of poles	4

First, the effectiveness of the AHE method is investigated by making up the unbalanced load model of PMSM with equations (4) and (5). In the calculation, unbalanced loads are approximately 5 $sin\theta_{rm}$ Nm. In Fig. 2, the simulation results are given for 300 rad/s speed, both 5 Nm constant and 5 Nm unbalanced loads. While speed is fluctuating between 255 and 305 rad/s, with the applying of the method in t = 2 s, the fluctuations caused by unbalanced load have been removed.

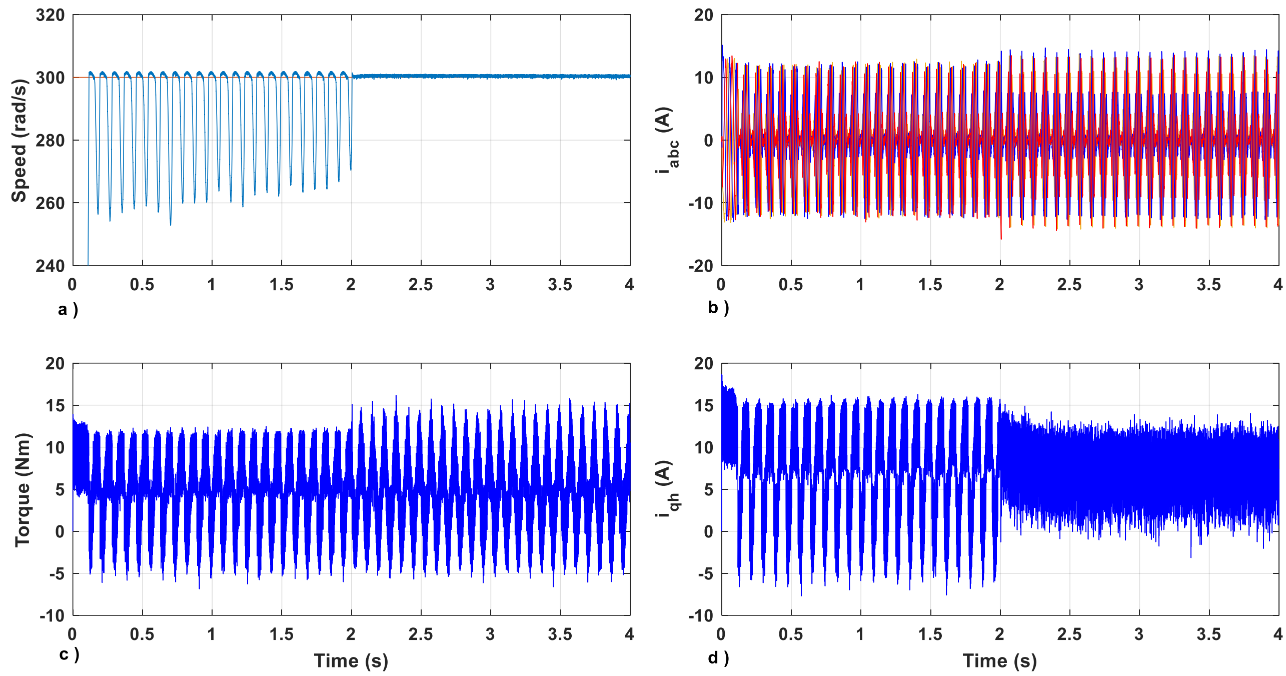

Figure 2. a) Motor speed b) Phase current c) Motor torque d) Harmonic injected iq current

In Fig. 3, FFT analysis are given in cases where the method is applied and not. Top side figures represent that the method is not active and bottom side figures represent that the method is active. In the FFT analysis of the motor speed, it is observed that harmonics in 12 Hz and multiples with motor mechanical frequency are removed when the method is activated. It is also observed that side-band harmonics are removed in the torque FFT analysis.

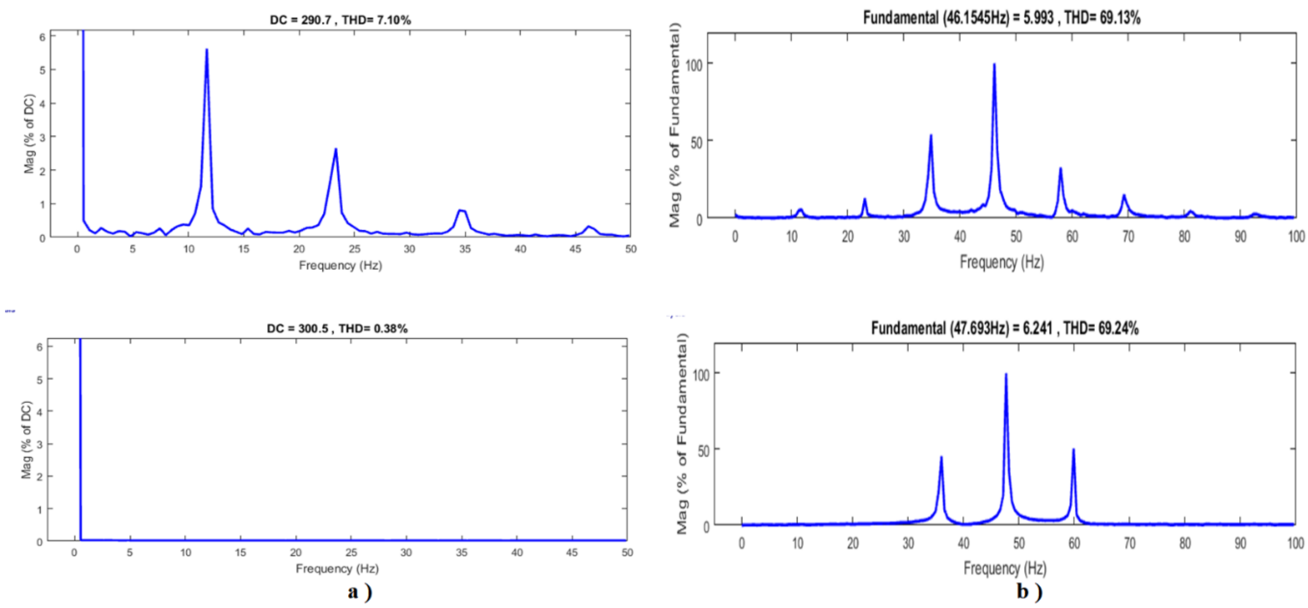

Figure 3. a) Motor speed FFT analysis and b) motor torque FFT analysis

In order to test that the proposed method is adaptable, the motor at a constant speed of 200 rad/s is loaded with unbalanced load between t=1 s and t=2s. As shown in Fig. 4, there is no impact on the speed when the unbalanced load enabled and disabled abruptly.

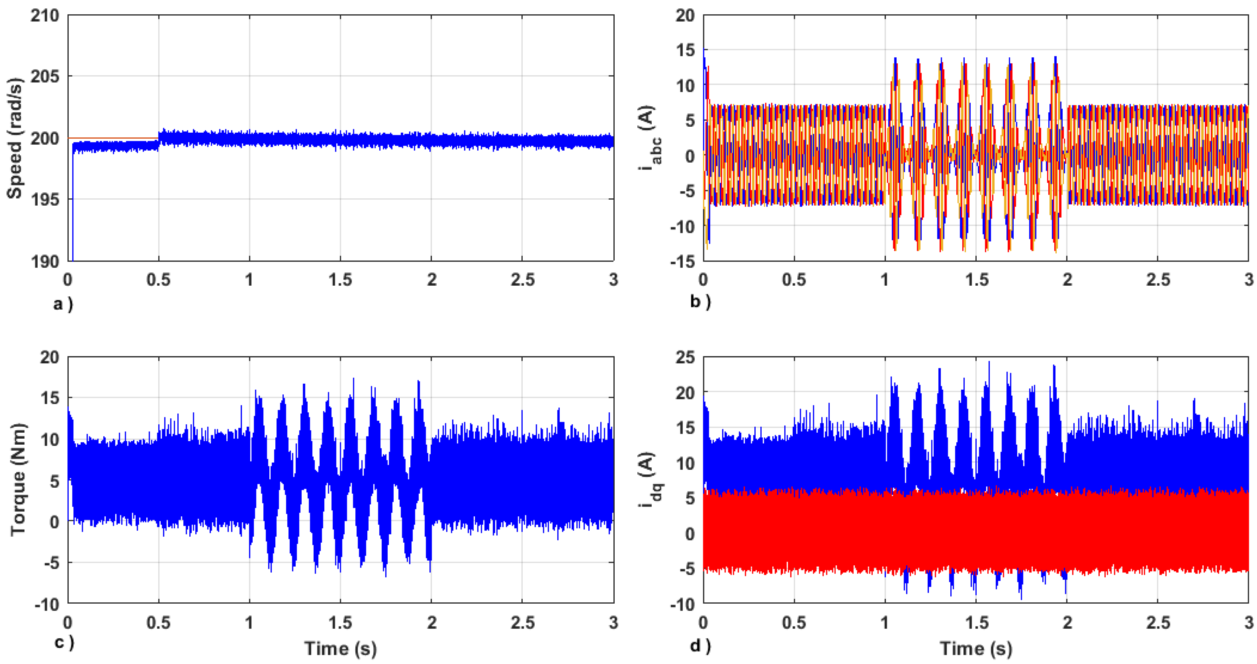

Figure 4. a) Motor speed b) Phase current c) Motor torque d) idq current

Fig. 5 shows the simulation results regarding the linear change of the speed between 100 rad/s and -200 rad/s at Ty=5 Nm constant and 5 Nm unbalanced load. In the study, the effectiveness of the method in reducing the speed fluctuations in case of changing the rotation direction of the motor under unbalanced load is investigated. With the commissioning of the method at t=1 s, it has also been observed that the method eliminates the fluctuations in case the rotation direction changes and the motor speed follows the reference speed.

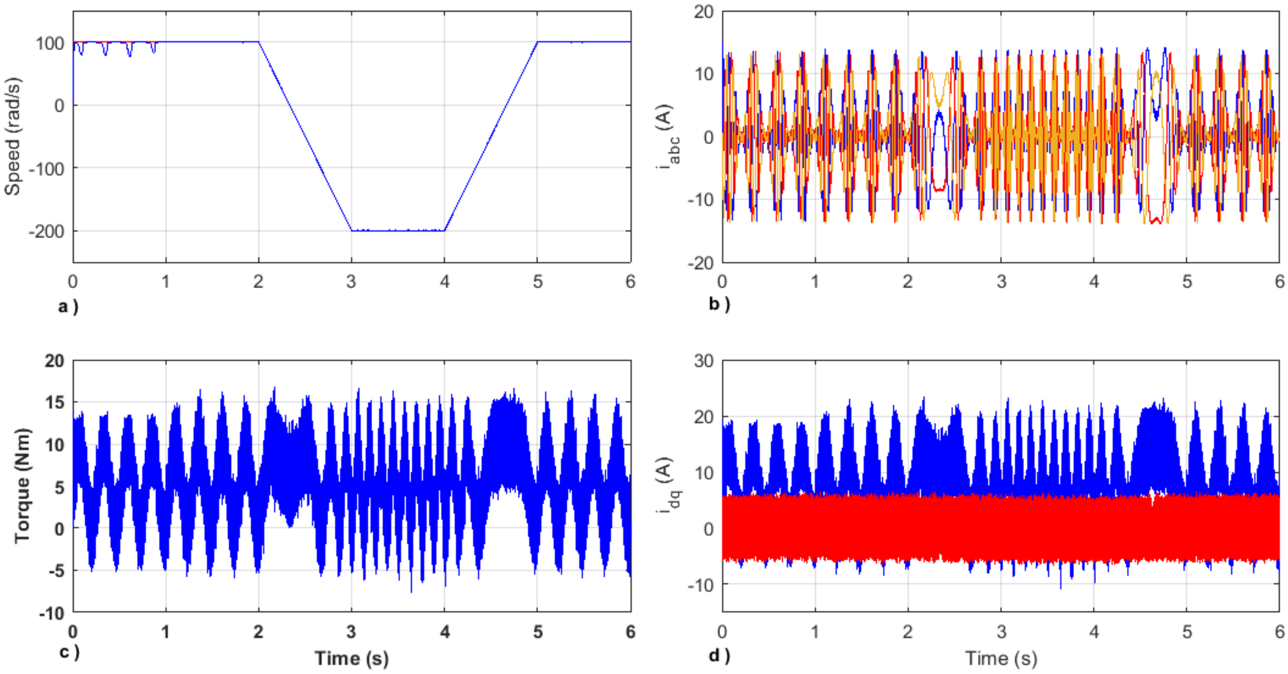

Figure 5. a) Motor speed b) Phase current c) Motor torque d) idq current

In another study, the results of the abrupt change of the speed at 100 rad/s, 200 rad/s and 300 rad/s in Ty=5 Nm constant and 5 Nm unbalanced load are given in Fig. 6. With the activation of the method at t=1 s, the speed ripples are eliminated, and no speed ripples occurred when the speed changed abruptly.

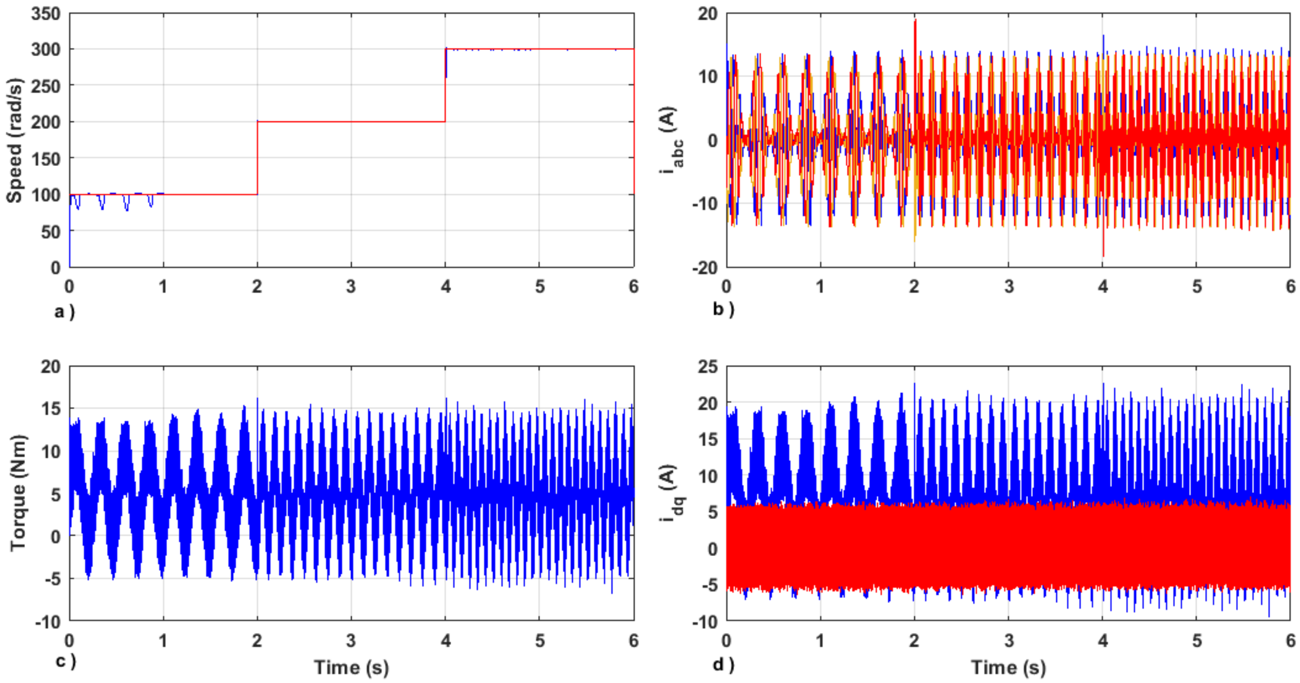

Figure 6. a) Motor speed b) Phase current c) Motor torque d) idq current

Finally, the simulation results regarding the activation of an unbalanced load of 2.5 Nm at t=1 s and 5 Nm at t=2 s at 200 rad/s speed and Ty= 5 Nm constant torque are given in Fig.7.

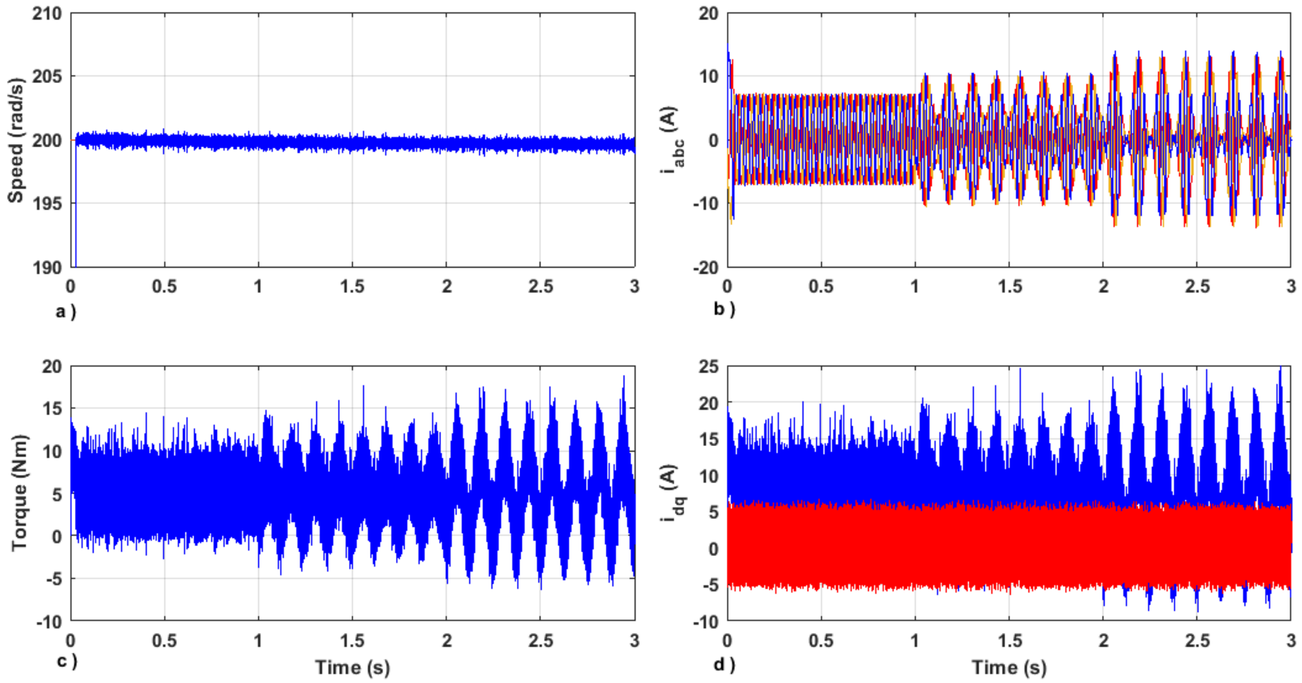

Figure 7. a) Motor speed b) Phase current c) Motor torque d) idq current

When the variation of the speed is examined, there is no fluctuation in the speed in case of unbalanced loads. It is observed that the current and torque changes are correlated with change in the load. The results show that the applied AHE method is effective in reducing speed fluctuations brought on by an unbalanced load and that the method is adaptive to variation in speed and load during motor operation.

Conclusions

In unbalanced loaded electric motors, speed and torque fluctuations occur, resulting in harmonics in motor currents.

This can cause permanent damage to the machine. The resulting fluctuation generally occurs at the frequency and multiples of the mechanical speed of the motor. In this study, unbalanced loads encountered in electrical machines are analyzed, speed fluctuations occurring in PMSM under unbalanced load are determined and a method is proposed to reduce these fluctuations. The proposed AHE method is based on the Normalized LMS algorithm. Simulation studies are carried out by creating an unbalanced load model of the motor and applying Field Oriented Control to the motor. In the study, the speed of the motor is changed abruptly and linearly, and the unbalanced load is activated and deactivated during the operation. Even in these cases, speed fluctuations in the motor are effectively suppressed. As a result, it has been observed that the proposed AHE method effectively reduces the speed fluctuations in case of unbalanced load, and the method is also adaptively effective in case of possible variation in the motor speed and load during the operation of the motor.

Authors' Contributions

We declare that all Authors equally contribute.

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