Heidari, Hamidreza; Rassõlkin, Anton; Kallaste, Ants; Vaimann, Toomas; Belahcen, Anouar

Harmonics distortion in inverter-fed motor-drive systems

Published in:
Electric Power Quality and Supply Reliability Conference and Symposium on Electrical Engineering and Mechatronics, PQ and SEEM 2019

DOI:
10.1109/PQ.2019.8818230

Published: 01/06/2019

Document Version
Peer reviewed version

Please cite the original version:
Heidari, H., Rassõlkin, A., Kallaste, A., Vaimann, T., & Belahcen, A. (2019). Harmonics distortion in inverter-fed motor-drive systems: Case study. In *Electric Power Quality and Supply Reliability Conference and Symposium on Electrical Engineering and Mechatronics, PQ and SEEM 2019* [8818230] IEEE. https://doi.org/10.1109/PQ.2019.8818230

Harmonics Distortion in Inverter-Fed Motor-Drive Systems: Case Study

Hamidreza Heidari, Anton Rassõlkin,
Ants Kallaste, Toomas Vaimann,
Department of Electrical Power Engineering and Mechatronics
Tallinn University of Technology
Tallinn, Estonia
haheid@taltech.ee

Anouar Belahcen
Department of Electrical Engineering and Automation
Aalto University
Espoo, Finland
anouar.belahcen@aalto.fi

***Abstract*— Current and voltage harmonics lead to iron losses in motors. As the iron losses have the largest portion of total losses in many motors, harmonic analysis of motors is of paramount importance. In this study, we compared the new designed permanent magnet assisted synchronous reluctance motor (PMSynRM) and synchronous reluctance motor (SynRM) with an industrial induction motor (IM) in terms of harmonic currents and harmonic voltages. To investigate the performance of the motors in terms of harmonic distortion, an industrial frequency converter based on direct torque control (DTC) strategy is adopted. The study shows the high harmonic injection of frequency converter to the system.**

Keywords—permanent magnet synchronous reluctance motor, synchronous reluctance motor, induction motor, power quality

I. INTRODUCTION

Nowadays, Variable Speed Drives (VSDs) have become so popular in the industry, even for some fixed-speed applications. To save energy, extend motors' operation life and performance optimization, VSDs are the best choice in the industry. On the other hand, in the power quality point of view, VSDs as any power electronic devices integrated into grid produce distortions since they have non-linear loads into electric power systems that has become a serious issue in recent years [1], [2]. Power quality requirements of loads that have over 100% current total harmonic distortions (THD) may not be precisely regul ated [3].Moreover, harmonics affect power factor as shown in [4]. Considering this critical issue, it is needed to study VSD-fed drives in terms of harmonics and their effects on the power quality of systems. As an extensive solution for AC drives' harmonics distortion, some harmonics were eliminated by using passive [5], [6] or active [7] filters. Using passive filters on the grid-side before the frequency converter decreases the currents harmonics notably. Moreover, the structure for this method is quite simple and affordable to implement. However, it causes further disadvantages, which in some cases will cause irreparable damages to the system. Since the passive filters are configured based on the system design and limitations, the changes and modifications in the system can cause even higher distortions [8]. Besides, the size and cost of passive filters are also high which makes the active filter application more reasonable. Lack of inductors makes active filters size quite small and decreases the cost. The disadvantage of these filters can be a more power supply requirement [9].

VSD-fed IMs are widely used nowadays. However, SynRMs are gaining popularity in some applications such as pumps, fans, compressors, extruders, conveyors, and mixers [10]. Rotor anisotropy in SynRM results in high flux density fluctuations in the iron. As a result, the harmonic currents in SynRM are striking. As the rotor anisotropy is the same with PMSynRM, the harmonic currents in PMSynRM are high. Due to the fairly high iron losses in these motors, the study in this area seems necessary. Determination of iron losses requires a precise study for design purposes. In terms of computation time of total loss calculation, it is crucial to choose an economical method. A nonlinear analytical model of SynRM has been proposed in [11] to calculate iron losses considering the magnetic iron saturation and slotting effect. Using coupled finite element method and response surface methodology the characteristic analyses of SynRM is done in [12].

DTC is a well-established and interesting control technique for different electric motor drive systems. in industrial frequency converters. The switching table-based DTC strategy benefits from fast dynamics response and simple control method, compared to the PWM-based techniques such as field oriented control (FOC) strategy. Because of the nonlinear characteristics of DTC, its DC-side harmonics spectrum is much different from that of PWM, as it does not have a deterministic model for its harmonics patterns [13]. A probabilistic AC-side voltage harmonics model was proposed in [2]. Also, DTC suffers from high harmonic currents which degrades its performance and affects the power quality of the system [14].

This paper focuses on the analysis of the grid-side and motor-side harmonics produced by industrial frequency converter running IM, SynRM and PMSynRM. For this purpose, a comparative study is obtained in terms of the current and voltage harmonics, when the aforementioned motors are driven using DTC strategy.

II. TEST SETUP

The test bench was designed in Electrical Machine Group Lab of Tallinn Technology University. Fig. 1 shows the implemented setup which the three motors were changed in three separate tests.

In this setup, we have coupled an industrial IM as a load to all three motors to test them under the same load condition. All the motors were driven by an industrial frequency converter, which is based on DTC strategy.

For control objectives, DTC method was chosen for all tests that is defined in the industrial frequency converter's setup. For measuring the currents, the Fluke 1400s AC current clamps with bandwidth of 5 kHz were used. The harmonic currents up to 100 times of the fundamental frequency were measured. NCTE 4000 Series 50Nm non-contact rotary torque sensor with 360 CPR angle sensor was implemented to measure the motors torque and speed. The NCTE 4000 series

The present research has been supported by the Estonian Research Council under grant PUT1260.

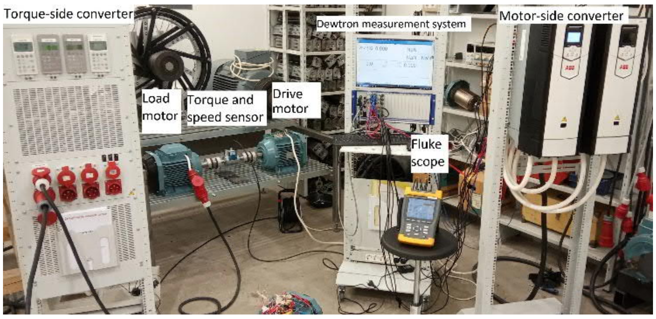

Fig. 1. Experimental setup.

is coupled to the load and motor mechanically. To measure voltages of lines, the DEWETRON data acquisition system was implemented. Displaying and registering all the measured data from torque and speed transducer and current clamps were done by the DEWETRON system, providing a universal measurement system for the tests. Using the Oxygen platform in the DEWETRON system, the harmonics were measured online and all power analysis and data acquisitions were done, simultaneously.

III. Harmonic Current Analysis

The harmonic currents and voltages due to the frequency converter-fed electric motors highly affect the performance indices of the systemsuch as power quality. The voltage and current harmonic contents also lead to the torque variations. Windings, slotting, magnetic saturation and other geometrical configuration such as air gap length inequalities lead to flux spatial harmonics. Induced voltage of these harmonics results in harmonic currents in rotor windings in the IM. Moreover, VSDs distort the voltage and current shape and cause harmonics in grid and the motors, as well. DTC has attracted increasing attention in recent decades as it has quicker dynamic response comparing to the other control methods such as field oriented control (FOC) due to the usage of look-up table instead of modulators. Lack of direct current controller has also led to more simplicity of this method. However, direct control of the torque and flux contributes to low frequency current harmonics, especially the fifth and seventh harmonics. The $6n \pm 1; n =$ odd order harmonics These harmonics causes harmonics loss and will affect electromagnetic interference. In addition, DTC has variable switching frequency as well as nonlinear elements in the control loop which complicate the analytical studies, including harmonic analysis, in this method. To cover this complexity, probabilistic analysis has been performed in [13].

In DTC method for IM, the flux vector is calculated from the voltage and current vectors as follows:

$$V_i = V_{dc} e^{\frac{j(i-1)\pi}{3}} \quad \text{for } i = 1 \text{ to } 3 \tag{1}$$

$$\Phi_s = \int (U_s - R_s I_s) dt \tag{2}$$

where, j is the square root of –1, Φ_s is stator flux, U_s, I_s are the stator voltage and current, respectively, and R_s is the stator resistance.

The harmonic currents in the rotor interact with harmonic fluxes in the stator and cause harmonic torques, vibrations and noises in the motor. Stator windings carry sinusoidal currents with some harmonics. This is also true for the SnyRM and the PMSynRM, considering less effect on the rotor side due to cold rotor of these motors. Since the flux wave shape is half-way symmetry and it is odd, the even harmonics are absent in Fourier series. Consequently, the currents have only the odd harmonics. Among these harmonics, third harmonics of each phases decrease each other's magnitude and this harmonic always has a negligible value. As a result, third harmonic of air gap flux is so small as the phase currents. On the other hand, fifth harmonic and seventh harmonics have striking magnitudes. In case of the torque, the fifth harmonic is called braking torque since its rotation direction is just apposite of the fundamental frequency. Besides, the seventh harmonic flux has the same rotational direction with fundamental flux. This results in the same torque production of the fundamental torque frequency and the seventh frequency. On the motor side, the current's harmonics are negligible leading to low losses. Motors, as a low pass filter avoid the high frequency harmonics. The low order of harmonics are measured by the order of 20 times higher than fundamental frequency.

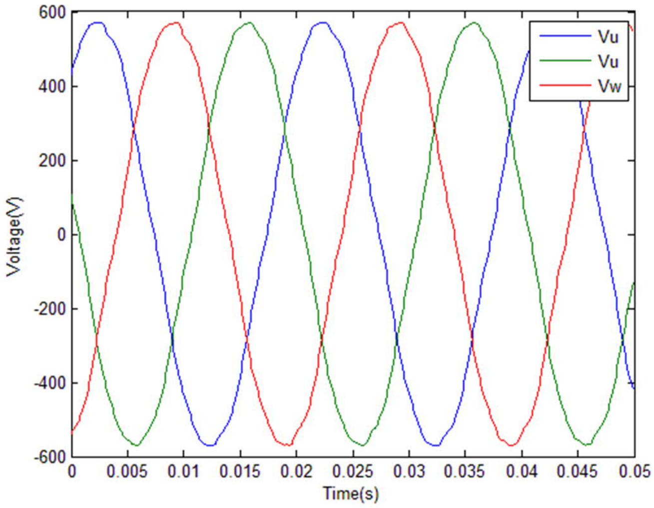

Fig. 2. Grid Input voltages of grid connected IM drive.

IV. Test Results

To compare the harmonics of voltage and currents, all the dive systems were tested under 59 Nm load condition. In these tests, the result values are exported from oxygen platform and analyzed by MATLAB 2018b. This analysis enabled us to compare the harmonics of the drive systems in terms of voltages and currents Fig. 2 shows the input voltages of the three phases of IM, which was connected to the grid without frequency converter. Basically, the voltages were supposed to be constant during all the tests as the grid is considered as an infinite bus bar. As a result, comparing Fig. 2 and Fig. 3, the same results are measured from the inverter-fed IM and grid connected IM. The figures show the low effect of the dirve systems on the grid. In this test, the IM has been connected in delta connction and the measured voltages were the line voltages, which could be different with the phase voltages in terms of harmonic voltages.SynRM and PMSynRM were connected in star connection as well. It should be mentioned that the neutral point for the motors and the grid were not connected and the results for third harmonics were not preciesely confidable.

To analyze the voltage harmonics of the both grid connected and inverter-fed IM, the Fast Fourier Transform of the voltages were calculated. Fig. 4 gives information about the low order harmonics of line 1st grid input voltage. The harmonics were supposed to be the same for all three phases

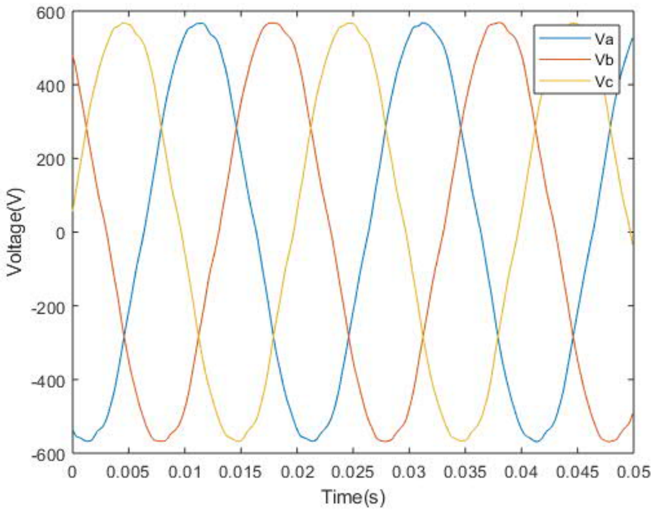

Fig. 3. Grid input voltages of inverter-fed IM drive.

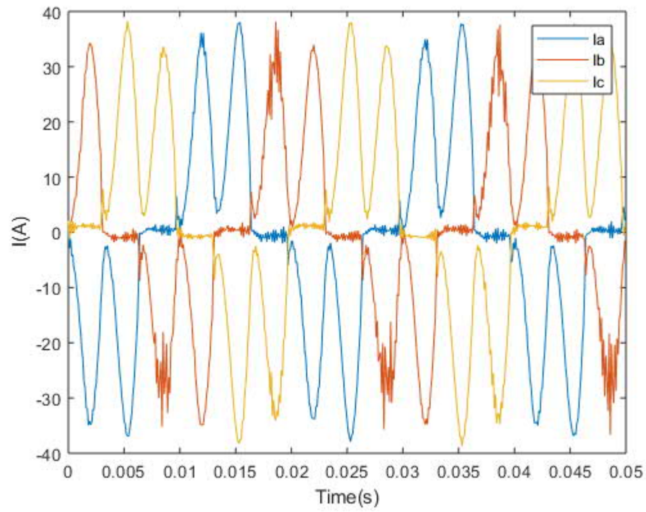

Fig. 5. Grid input currents of inverter-fed IM drive.

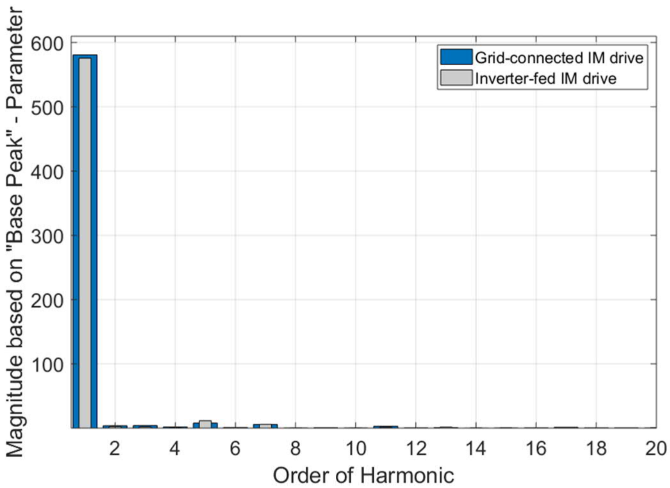

Fig. 4. Grid input voltage harmonics of IM drives.

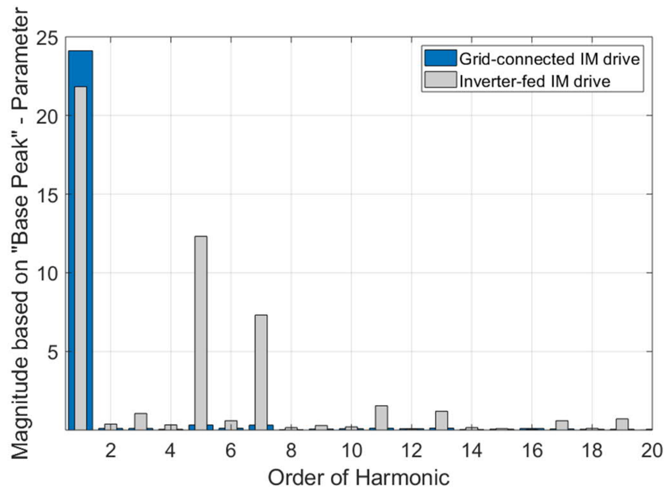

Fig. 6. Grid current harmonics of IM drive systems.

and only one phase was investigated. It was found out that the frequency converter has almost no effect on the grid voltage and injects no extra harmonics to the grid due to infinite bus.

On the other hand, the frequency converter made the input currents to the grid completely distorted. The three phase currents are shown in Fig. 5. The shape of currents were quite distorted and they were almost in the same shapes. To investigate the harmonics distortion injected by frequency converter, the harmonics of the IM were studied in both grid connected and inverter-fed drive. Fig.6 shows that the results the fifth and seventh harmonics of the grid current was a big deal in inverter-fed drive, comparing to the grid connected drive. This result conforms the low amount of third harmonic produced by the frequency converter. The harmonics higher than 20th were not considerable and were neglected in this study.

To compare the effect of the three motor drive systems on the grid current, the harmonics were calculated for all the test and showed in Fig. 7. Taking the fundamental frequency magnitude into account, the PMSynRM produces higher fifth and seventh harmonics which are generally the most striking differences between the motor drive systems. Comparing SynRM and IM, almost the same fifth harmonic were calculated. The seventh harmonics of the two drive systems have the same magnitude which considering the fundamental frequency, it was found out that the IM has higher seventh

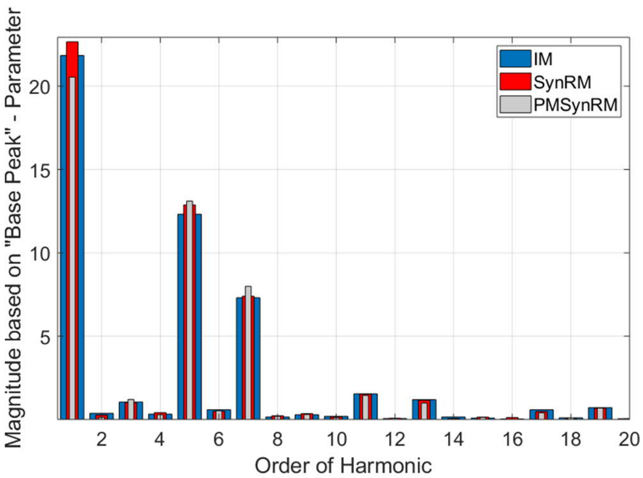

Fig. 7. Grid current harmonics of inverter-fed drives.

harmonics than SynRM. The higher order harmonics had negligible magnitudes.

On the motor side, the motors have different harmonic voltages which is shown in Fig. 8. Generally, the motors' voltages have no significant harmonics and driving the motors by the same industrial frequency converter, almost the same results has been achieved. Besides, the industrial frequency

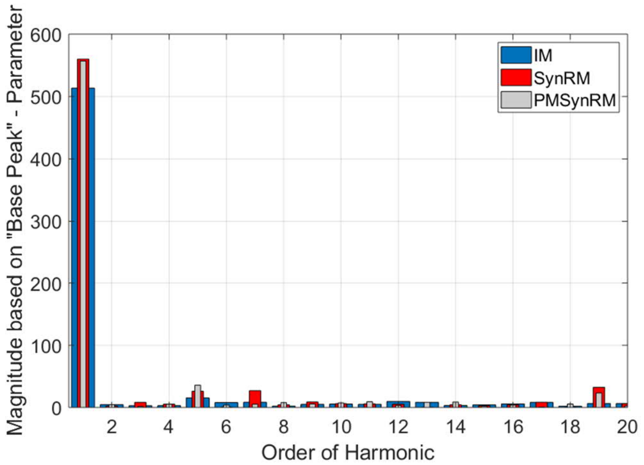

Fig. 8. Motor voltage harmonics of inverter-fed drives

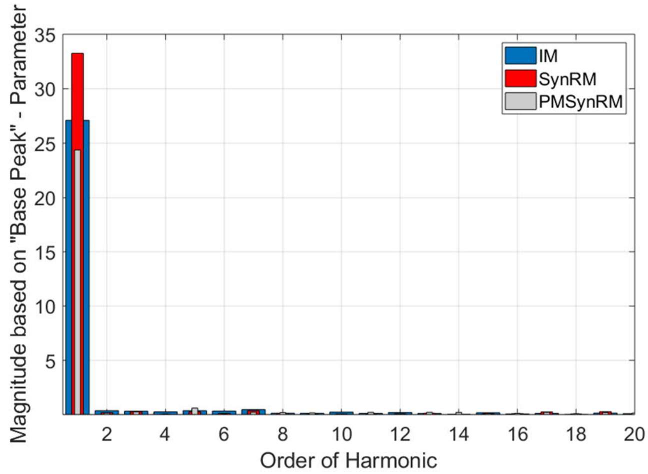

Fig.9. Motor current harmonics of inverter-fed drives

converter has a filter which avoids some harmonics to be injected to the motor. In case of fifth harmonics, PMSynRM has the biggest harmonic. Having look on the seventh harmonics, SynRM produced the biggest seventh harmonics.

As the motors are low pass filter, the harmonic currents have very small magnitudes which is negligible. Fig. 9 demonstrates the motors' current harmonics. It can be clearly seen that no harmonic has been produced in motors' current. The motors' current shaped are supposed to be almost pure sinusoidal.

V. CONCLUSIONS AND DISCUSSION.

To investigate the motor drive systems in terms of power quality, it is inevitable to study voltage and current harmonics. In this study three different motors are driven in the same loading and driving status. The IM is driven in both grid connected and inverter-fed mode to analyse the effect of frequency converter to the system behaviour. In terms of harmonic voltages, the two systems have the same harmonics. In inverter-fed drive system, currents are distorted and the shape of input currents are not sinusoidal. The most significant harmonics are the fifth and seventh harmonics, which are injected to the grid. The even harmonics have negligible magnitude. Comparing motor voltage harmonics in inverter-fed drives, all the three motors have almost the same behaviour which is mostly because of the same stator structure. SynRM and PMSynRM have higher motor current harmonics, which are caused by rotor anisotropy in these motors.

REFERENCES

[1] M. Farbis, A. H. Hoevenaars, and J. L. Greenwald, "Oil field retrofit of ESPs to meet harmonic compliance," IEEE Trans. Ind. Appl., vol. 52, no. 1, pp. 718–728, Jan. 2016.

[2] H. Liu, J. Liang, and L. Qi, "Harmonics mitigation and stability analysis of DTC motor drives in MVDC systems," in 2015 IEEE Energy Conversion Congress and Exposition (ECCE), 2015, pp. 3172–3178.

[3] J. Niitsoo, I. Palu, J. Kilter, P. Taklaja, and T. Vaimann, "Residential load harmonics in distribution grid," in 2013 3rd International Conference on Electric Power and Energy Conversion Systems, 2013, pp. 1–6.

[4] W. Mack Grady and R. J. Gilleskie, "Harmonics and how they relate to power factor," Proc. EPRI Power Qual. Issues Oppor. Conf. (PQA'93), San Diego, CA, Nov. 1993., no. November, pp. 1–8, 1993.

[5] T. Hruby and S. Kocman, "Using broadband passive harmonic filters for harmonic mitigation in AC drives," Proc. Int. Conf. Harmon. Qual. Power, ICHQP, vol. 1, no. 3, pp. 172–176, 2014.

[6] N. A. Azeez, S. Pramanick, K. Gopakumar, and C. Cecati, "A 5th and 7th order harmonic suppression scheme using capacitive filtering for 2-level VSI fed IM drive," in 2014 International Symposium on Power Electronics, Electrical Drives, Automation and Motion, 2014, pp. 780–783.

[7] W.-H. Ko and J.-C. Gu, "Impact of shunt active harmonic filter on harmonic current distortion of voltage source inverter-fed drives," IEEE Trans. Ind. Appl., vol. 52, no. 4, pp. 2816–2825, Jul. 2016.

[8] J. C. Das, "Passive filters – potentialities and limitations," IEEE Trans. Ind. Appl., vol. 40, no. 1, pp. 232–241, 2004.

[9] "Basic Introduction to Filters – Active, Passive, and Switched-Cap (Rev. A) Analog and Mixed-Signal SNOA224A - TI.com.".

[10] A. Rassõlkin, H. Heidari, A. Kallaste, J. P. Acedo, and E. Romero-Cadaval, "Efficiency map comparison of induction and synchronous reluctance motors," in 26th International Workshop on Electric Drives: Improvement in Efficiency of Electric Drives (IWED), 2019, pp. 4–7.

[11] H. Mahmoud et al., "Synchronous reluctance motor iron losses : considering machine nonlinearity at MTPA, FW, and MTPV operating conditions," IEEE Trans. Energy Convers., vol. 33, no. 3, pp. 1402–1410, 2018.

[12] Jung Ho Lee, Il Kyo Lee, Yong Hyun Cho, and Tae Won Yun, "Characteristics analysis and optimum design of anisotropy rotor synchronous reluctance motor using coupled finite element method and response surface methodology," IEEE Trans. Magn., vol. 45, no. 10, pp. 4696–4699, 2009.

[13] S. Kaboli, E. Vahdati-Khajeh, and M. R. Zolghadri, "Probabilistic voltage harmonic analysis of direct torque controlled induction motor drives," IEEE Trans. Power Electron., vol. 21, no. 4, pp. 1041–1052, 2006.

[14] H. Heidari et al., "A novel vector control strategy for a six-phase induction motor with low torque ripples and harmonic currents," Energies, vol. 12, no. 6, p. 1102, 2019.