

Energy savings in concrete production

By O Dobzhanskyi and R Gouws, North-West University

The cement and concrete industry in South Africa has been growing rapidly for the last couple of years.

The rapid growth of the cement and concrete industry has created the need for concrete products such as concrete pipes, culverts, manholes, slabs, piles, etc. Since the role of electric machines in the concrete industry is vital, this article focuses on presenting the design of an energy efficient concrete mixer drive. The novelty of the proposed synchronous permanent magnet (PM) motor is in its ability to develop helical movement of the rotor. This allows the mixer blades to mix concrete compound effectively with minimal energy consumption. The machine was analysed in 3D FEM and Matlab/Simulink software. Efficiency and rated power were also determined. The energy consumption of the proposed synchronous motor drive is compared to that of a conventional induction motor. Conclusions about the effectiveness of using the proposed machine in concrete mixers were made. The advantages of the proposed motor over conventional induction drives used in industrial mixers are also discussed.

Concrete production technology is a complicated process and electric power is used almost in every stage of the concrete preparation. One of the most energy consuming stages is when the concrete is mixed in concrete mixers. There are many techniques proposed in the literature on how to make concrete mixers more efficient through control applications [1, 2]. Williamson [3] and Zhao et al [4] discuss various energy-saving technologies for concrete mixing process. Most articles are not concerned about electric motors which drive the mixers. Mechanical power of the mixer blades is developed by the electrical drive connected through a gear or directly to the shaft where the blades are attached. Hence, the electric drive efficiency is important for the energy consumption of the concrete plant.

The issue of PM machines versus induction motors for concrete mixers exists. Some concrete mixer producers [5] suggest applying PM machines which usually have higher power density, higher efficiency, but also higher cost. Induction machines, however, still dominate in the concrete production process.

This article introduces a novel design of a PM drive for concrete mixers. The high efficiency and simple structure of the proposed motor promises energy savings and lower cost advantages. The motor discussed is not a conventional synchronous PM motor. The machine is designed in such a way that 'To Degrees of Mechanical Freedom' (TDMF) of the rotor is achieved by the magnet's skew on its surface. In other words, the rotor of the machine moves helically (rotary and linear movements are combined). There are various designs of electric machines with TDMF that have been proposed in the literature. Most of the designs are induction- or reluctance-type motors [6 - 9]. Chen L et al [10] designed a PM motor with TDMF. However, there are two

windings (rotary and linear) placed in one stator, which can cause mutual inductance between them. Shuang Ye et al [11] introduce a synchronous PM drive for chaotic mixing. But in this case chaotic movement of the compound is achieved by geometrical asymmetric design of the mixing tank.

Design

Figure 1 shows the stator core and the rotor of the proposed machine. The rotor, placed inside of the stator, is a movable part able to move axially and rotary. The rotor consists of the rotor core made of solid iron, and permanent magnets mounted on its surface. The PMs on the rotor are skewed by six tooth pitches (12 slots). The design of the proposed motor is similar to the design of a conventional PM synchronous machine. The difference in the design and principle of operation is in magnet skew on the rotor.

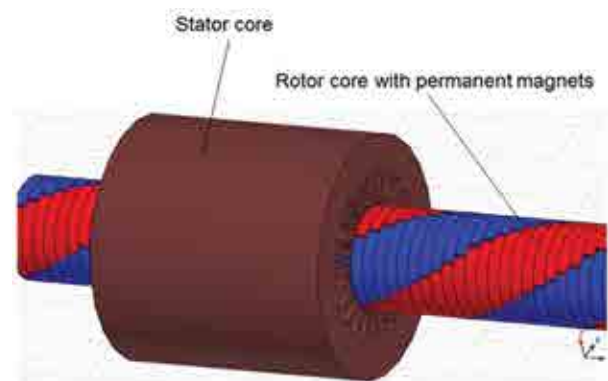


Figure 1: The motor with TDMF.

The dimensions of the motor were calculated to meet the required power at rated speed. After the dimensions were determined, the motor was analysed in 3D FEM software. During the analyses the dimensions were optimised to satisfy admissible values of magnetic flux density distribution in the stator and rotor cores. The basic dimensions of the motor are shown in Figure 2.

The novelty of the proposed synchronous Permanent Magnet (PM) motor is in its ability to develop helical movement of the rotor.

PM – Permanent Magnet
TDMF – To Degrees of Mechanical Freedom

Abbreviations

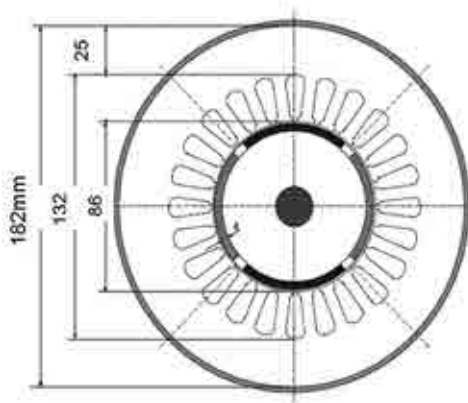


Figure 2: Stator and rotor dimensions of the machine.

The dimensions of the single slot are determined by the area needed to pack 72 conductors of AWG 16 wire. These dimensions are presented in Figure 3.

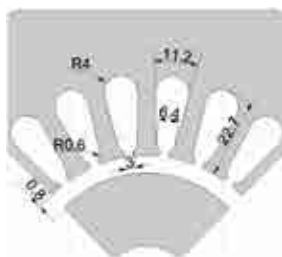


Figure 3: Detailed stator slots dimensions.

The rotary winding of the machine is a three-phase overlap winding distributed in the slots according to the scheme shown in Figures 4 and 5.

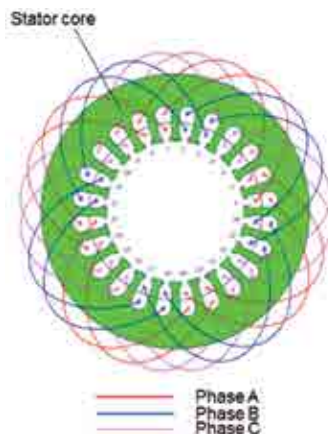


Figure 4: Three-phase overlap winding distribution in the slots.

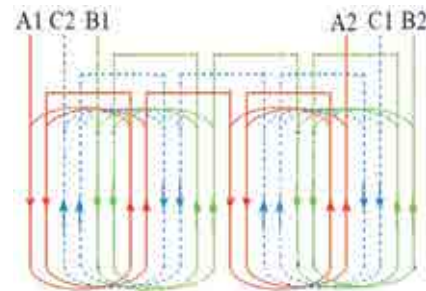


Figure 5: Rotary winding diagram.

The motor magnet, winding, and basic dimensions data are enclosed in Table 1.

Table 1: Design data of the machine.

Winding	
Number of phases	3
Number of poles	4
Number of slots per pole per phase	6
Number of wires per slot, Nw	72
Filling factor, Kw	0,5
Wire	AWG16
Permanent magnets	
Type	NdFe40
Relative permeability	1.09967
Bulk conductivity, S/m	625000
Basic dimensions	
Stator diameter, mm	182
Rotor diameter, mm	86
Length of the armature, mm	100

Principle of operation

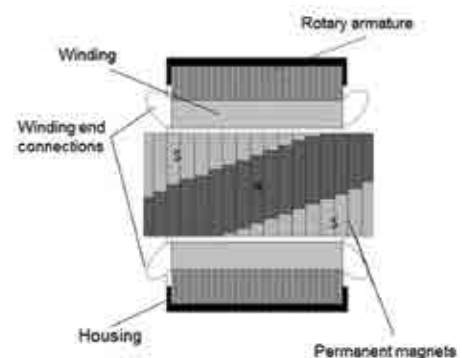


Figure 6: Motor cross-section.

The rotary three-phase winding placed in the stator slots produces rotating magnetic field in the air-gap. The rotating magnetic field moves with speed (ω_s). Interacting with magnetic flux of the permanent magnets, the force (F) acting on the rotor is developed. This force is perpendicular to the magnet *lineas* shown in *Figure 7*.

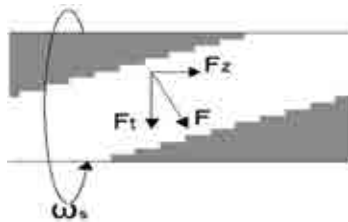


Figure 7: Forces acting on the rotor.

The force (F) can be split into two components – rotary (F_t) and linear (F_z). If the rotary magnetic field starts to rotate in the opposite way, the linear force (F_z) will also change its direction to the opposite. Hence, the machine can produce helical movement on both axial directions – to the right, and to the left. The trajectory of the rotor movement is shown in *Figure 8*.

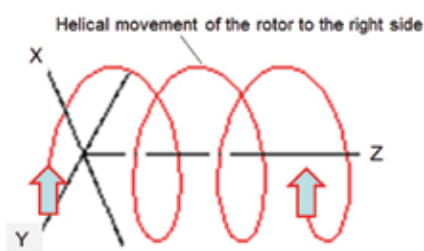


Figure 8: Trajectory of the rotor movement.

Application of the TDMF motor in the industrial concrete mixer

The design of the motor allows attaching blades to its shaft directly, without a gear. Thus, the blades' moving trajectory will also be helical.

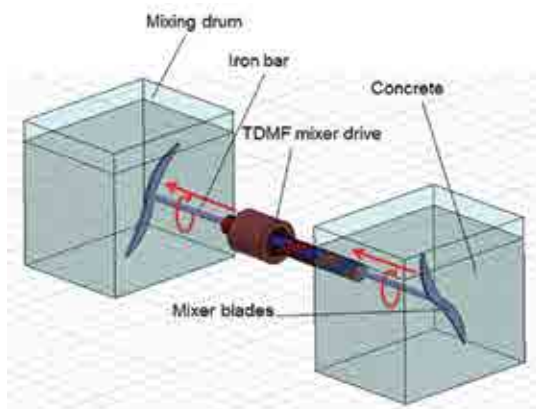


Figure 9: Schematic image of the concrete mixer with the TDMF drive.

The motor is placed between two mixing drums containing concrete compound. Two iron bars holding the mixer blades are attached firmly to the rotor yoke on both sides. The blades travel helically through the compound.

When the rotor with PMs approaches the mixing drum, the supply voltage direction gets switched to the opposite. This causes the rotor to go backwards. The concrete compound in both mixing drums gets mixed simultaneously.

Since the mixer produces rotary and linear moves at the same time, the blades' design can be much simpler. Very often in conventional concrete mixers with only rotary movement of the rotor, blades have a complicated shape. Moreover, two shafts with blades are used. Each of the shafts is driven by a separate motor.

Such a complicated design is done in order to embrace a maximum amount of concrete compound during mixing. *Figure 10* shows the design of the conventional two-shaft concrete mixer used in the industry [12].

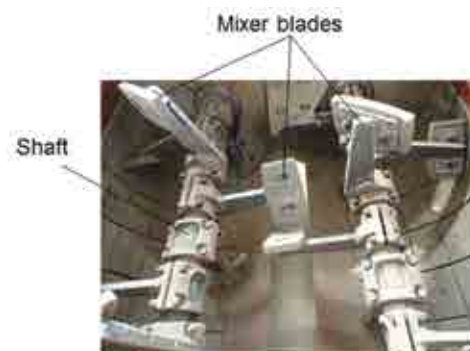


Figure 10: Design of the industrial concrete mixer.

Another advantage of the proposed mixer is that it is direct-driven. This means no mechanical power is lost in gears and chain/belt mechanisms. This increases the efficiency of the process and decreases cost. Most of the conventional industrial mixers have gear mechanisms to transmit mechanical power from the rotor to the mixing blades. Mechanical power in gears is lost mainly due to the friction between gear teeth. Chains and belts dissipate power through stretch and wear, and friction as well. The total mechanical losses of gear mechanisms can reach more than 5 %. Gear and chain mechanisms also increase maintenance of the industrial concrete mixers.



Figure 11: Industrial concrete mixer with a gear and chain mechanism [5].

Efficiency analysis of the motor

The introduced motor with TDMF was designed to meet the following criteria:

- o Rated power – 5 kW
- o Rated speed – 2 500 rpm
- o Electromagnetic torque – 28 Nm
- o Linear force – 800 N

In order to compare the motor with a conventional drive which is used in industrial mixers, the induction motor, with similar output power, rated speed and torque, was chosen. The parameters of the induction motor are as follows:

Rated power – 5 kW

Rated speed – 2 500 rpm

Electromagnetic torque – 32 Nm

Both machines are able to provide the same power at rated speed for a concrete mixer. Two motors are compared in terms of efficiency at different load conditions. The comparison is done to verify the energy use by both machines. Energy consumed by an electric motor depends on three factors: Operating hours, load, and efficiency. The relationship between them is calculated as follows [13]:

$$\text{Energy consumption} = \frac{\text{Operating hours} \cdot \text{Load}}{\text{Efficiency}}$$

The equation demonstrates if the higher level of efficiency, the lower energy consumption by a motor. The efficiencies of both machines are shown in Figure 12.

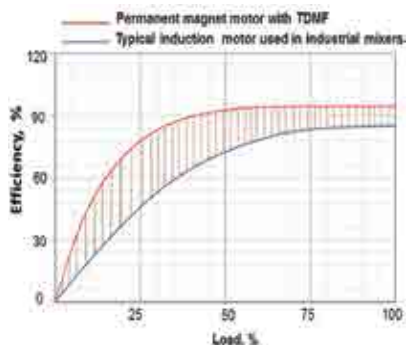


Figure 12: Efficiency curves of the PM motor with TDMF, and the typical induction motor, at different load conditions.

The efficiency of the TDMF motor at full load is 94 %; the efficiency of the induction motor is close to 87 %. The dashed area between the two curves represents how much more energy is consumed by the induction motor.

Conclusion

A three-phase permanent magnet motor with two degrees of mechanical freedom was designed in order to be used in industrial concrete mixers. Electromechanical parameters such as: Output power, rated torque, and linear force were calculated using 3D FEM. The advantages of the proposed motors are: Simple design, helical movement of the rotor, ability to connect blades directly to the rotor. The

machine was compared with a conventional induction type of drive for industrial concrete mixers. The efficiencies of both motors were calculated and compared. The results show that induction motor was less efficient than the PM machine. The induction motor, therefore, will consume more energy from the power system of the concrete plant.

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Principal author: Oleksandr Dobzhanskyi holds a Ph.D degree in Electrical Engineering. He graduated from Louisiana State University (USA) in 2012. Currently he is taking his post-doctoral research at the North-West University in South Africa.



Co-author: Rupert Gouws holds a Ph.D. degree in Electrical and Electronic Engineering from the North-West University (Potchefstroom campus). He consulted to a variety of industry and public sectors in South Africa and other countries in the fields of energy engineering and engineering management. Currently he is appointed as a senior lecturer specialising in energy engineering, electrical machines and control at the North-West University. The Engineering Council of South Africa (ECSA) registered him as a Professional Engineer and the Association of Energy Engineers (AEE) certified him as a Certified Measurement and Verification Professional (CMVP). Enquiries: Tel. 018 299 1902 or email Rupert.Gouws@nwu.ac.za