ARCHIVES OF ELECTRICAL ENGINEERING **VOL. 66(1), pp. 199-206 (2017)**

DOI 10.1515/aee-2017-0015

Asynchronous slip-ring motor synchronized with permanent magnets

TADEUSZ GLINKA, JAKUB BERNATT

Institute of Electrical Drives & Machines KOMEL
188 Rodzieńskiego Ave., 40-203 Katowice, Poland
e-mail: glinka.tadeusz@gmail.com, dyrekcja@komel.katowice.pl

(Received: 16.09.2016, revised: 16.01.2017)

Abstract: The electric LSPMSM motor presented in the paper differs from standard induction motor by rotor design. The insulated start-up winding is located in slots along the rotor circumference. The winding ends are connected to the slip-rings. The rotor core contains permanent magnets. The electromechanical characteristics for synchronous operation were calculated, as were the start-up characteristics for operation with a short-circuited rotor winding. Two model motors were used for the calculations, the V-shaped Permanent Magnet (VPM) – Fig. 3, and the Linear Permanent Magnet (IPM) – Fig. 4, both rated at 14.5 kW. The advantages of the investigated motor are demonstrated in the conclusions.

Key words: motor with permanent magnets, slip-ring rotor winding, asynchronous start

1. Introduction

Synchronized asynchronous motors (SAS) are slip-ring induction motors characterized by the fact that after asynchronous starting they are excited with direct current and can self-synchronize with the power network. The SAS motors are most often used in high power electrical drives. Starting of the motor is achieved by means of a rheostat connected to the rotor circuit via slip-rings and brushes. The start-up current does not usually exceed the double value of the rated current, and the perturbation (transient) current, at the first time instant after connecting the motor to the network does not exceed $4I_N$. The start-up torque can be significantly higher than the rated torque. After start-up the rotor winding is supplied with the direct current and the motor self-synchronizes. After synchronization it operates as a synchronous motor. The SAS motors exhibit the advantages of both induction slip-ring motors and synchronous motors.

When the induction slip-ring motors are compared to squirrel-cage induction motors, it is observed that they are characterized by smooth start-up, the current and torque surges are not as high as in the squirrel-cage motors. The rheostat greatly decreases the start-up current and is also helpful in shaping the torque versus speed curve. During steady-state operation, the

SAS motor exhibits higher efficiency than the induction motor, its power factor is capacitative and cosφ ≤ 1. The negative feature of the SAS motor is the excitation circuit. Power losses in the excitation circuit result in decreased overall drive efficiency; the rings require periodical inspection and maintenance (cleaning), the brushes wear out and must be replaced from time to time.

The designs of motors with a cage rotor winding and permanent magnets built into a rotor core are known [2, 5, 6]. The cage winding is made up of copper bars placed in slots along the outer rotor circumference; at the coil outhangs the bars are short-circuited with the rings. The permanent magnets are placed in grooves in the interior of the rotor core. The cage winding is used for asynchronous start-up. When near-synchronous speed is attained during starting, the magnetic flux of the permanent magnets tends to self-synchronize the motor, which means that the motor speed increases and arrives at synchronous speed. During synchronous operation this type of motor, in comparison to a standard induction motor working in an identical system, has higher efficiency and its power factor cosφ ≈ 1. This is a very great advantage, since this is an energy-saving design as opposed to the induction motor.

The disadvantages of cage induction motors synchronized with the magnetic field of permanent magnets may be listed as [3]:

- high start-up current; the steady-state component is *c*. 7 times higher than rated current, and the surge component is *c*. 1.8 times higher than the steady-state component,
- during the start-up heat is generated in the rotor cage; its amount is approximately equal to the kinetic energy of all rotating masses coupled with the motor shaft. This heat causes an increase in the cage rotor temperature and gives rise to possible hazard of thermal demagnetization of permanent magnets (this is particularly dangerous in case of repeated/frequent/start-ups),
- electromagnetic resultant torque, generated by the cage winding and permanent magnets, in the range of speeds from 0 to about half the rated speed ($0 \leq n \approx 0.5n_N$) may be less than motor's rated torque.

The motors with the cage winding and permanent magnets play their role in the drives of mechanical devices and machines with small start-up loads and short start-up times [2, 5]. These conditions are fulfilled by pumps and fans, where the load torque is proportional to the quadratic function of the speed. However, lots of driven machines are characterized by high start-up torque or long start-up time. High load torques, frequently greater than the rated torque, are present in: belt conveyors with belts fully loaded, filled coal pulverizers in power plants, thermal power plants and copper ore preparation plants, traction vehicles. Examples of mechanical devices and machines with high moments of inertia and started under load, characterized by long start-up times, are coal mine shaft fans, forced draft and induced draft fans in power plants and thermal power plants, loaded belt conveyors. The use of the cage induction motors with permanent magnets in rotors in the drives mentioned above is not recommended, since starting may be impeded, in particular in grids with high short-circuit reactance, and the permanent magnets may be exposed to the hazard of thermal de-magnetization, e.g. in the case of frequent start-ups.

2. Rotor design

The stator of the discussed electric motor, i.e. a core and winding, is identical as in an induction motor. The rotor is equipped with the winding wounded into slots and permanent magnets located in the steel yoke [1]. The rotor's winding is three-phase, made of insulated copper wire and connected into star or delta arrangement. Ends of phases are connected to three-slip rings located at the rotor shaft.

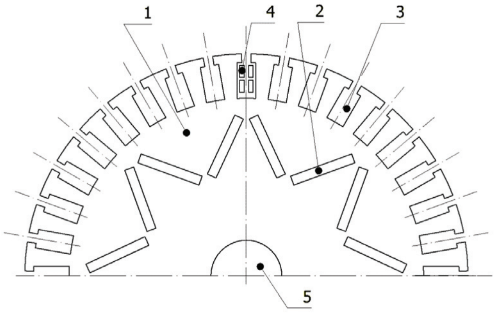

Fig. 1. Cross-section of the VPM motor rotor core with V-shape permanent magnets [1]

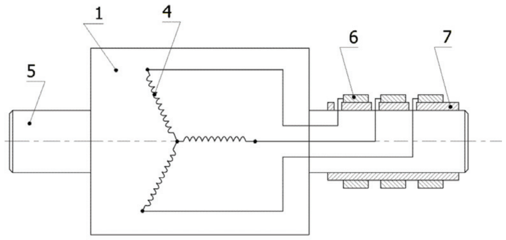

Fig. 2. Star arrangement of the rotor winding, winding ends are connected to slip-rings [1]

The brush holder together with the brush lifting device is attached to the bearing plate of the motor. The design of a slip-ring rotor with the winding and permanent magnets is shown in Figs. 1 and 2. The motor's rotor is laminated, and lamination stack placed at the motor shaft 5 constitutes core 1. Core 1 is grooved (the slits are usually rectangular in shape) and permanent magnets 2 are placed there. In the rotor lamination sheet shown in Fig. 1 the permanent magnets are positioned in the shape of letter "V". The permanent magnets' grooves may also be cut differently. Winding 4 is placed in slots cut into outer circumference of core 1. The winding 4 is three-phase, made of insulated copper wire and connected into delta or star arrangement. The ends of winding 4 are connected to three slip-rings 6, located at insulation sleeve 7, which is positioned at the rotor shaft 5. The wires connecting winding ends 4 with slip-rings 6 may be laid on the surface of shaft 5 or inside the hollowed-out shaft 5. When the motor is assembled, the brushes touch the slip-rings 6. Brushes are copper-graphite type and placed in the brush holder. The brush holder together with the brush lifting device is attached to the bearing plate of the motor.

3. Synchronous characteristics of model motor

The model motor has been designed using laminations of a slip-ring induction motor rated at 14.5 kW, 400 V, 28.6 A, 50 Hz, 1430 rpm, 96.83 N · m, $\cos\varphi = 0.84$. Electromechanical characteristics of two variants of placement of permanent magnets inside the rotor were calculated. The outer/inner diameters of laminations are: stator 246/162 mm and rotor 161/66 mm, core length 194 mm. The slots are trapezoidal in the straight part, and upper and lower parts are shaped as circle arcs. The number of stator slots is 36 and the number of rotor slots is 24. Two variants of magnetic circuit design have been calculated: with V-shape permanent magnets (VPM rotor) and linear magnets "I" (IPM rotor). NdFeB magnets were used: material N42UH, at working temperature 120°C, $B_r = 1.16$ T; $H_{cB} = 848$ kA/m; $\mu = 1.085$. The magnets dimensions are: "V" magnets – 22.85×6 mm and "I" magnets – 51.6×6 mm. The calculations of magnetic flux density distributio in the magnetic circuit of the machine excited by permanent magnets were conducted by a field method, for rotational speed $n = 0$, and current $I = 0$. The results of the calculations are shown in Figs. 3 and 4.

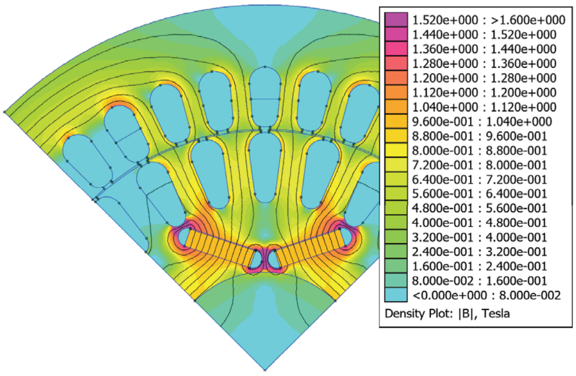

Fig. 3. Distribution of magnetic field in the magnetic circuit of motor excited with V-shape permanent magnets

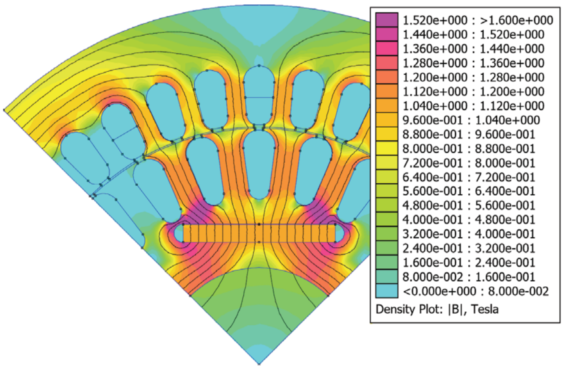

Fig. 4. Distribution of magnetic field in the magnetic circuit of motor excited with linear permanent magnets "I"

Using the magnetic field distributions, the calculations of characteristics for synchronous operation of the motor were performed. The calculations were performed using the circuital method with assumptions:

- slots in the stator of the model motor are straight; in the rotor a skewed slot is equal to one slot pitch,
- data for a stator winding were set the same as for the slip-ring induction motor with the rated data given above,
- supply voltage: 3 × 400 V,
- steady-state operation.

The synchronous electromechanical characteristics: torque (T_{el}), current (I_{pf}), power factor (cosφ) and efficiency versus angle between magnetomotive force (MMF) of permanent magnets and MMF of the stator winding are shown in Figs. 5 and 6.

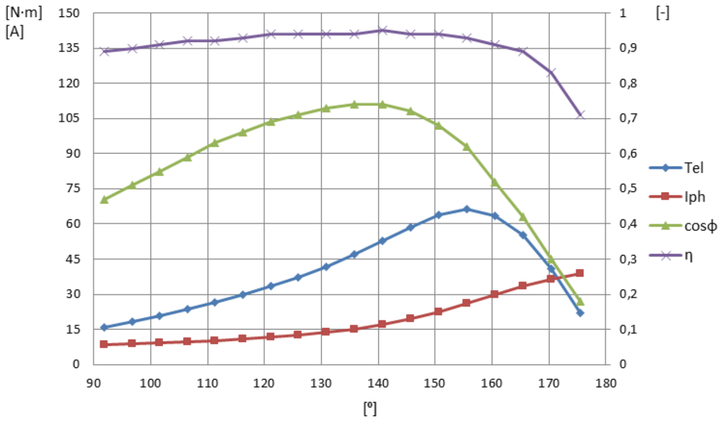

Fig. 5. The electromechanical characteristics of "V" motor: torque (T_{el}), current (I_{ph}), power factor (cosφ) and efficiency (η) versus angle between MMF of permanent magnets and MMF of stator winding

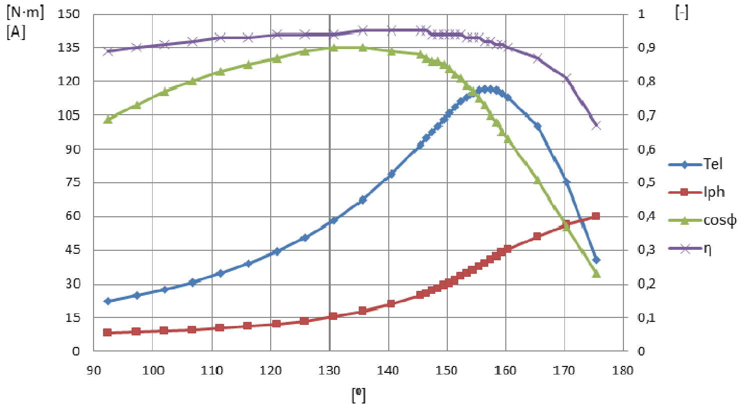

Fig. 6. The electromechanical characteristics of "I" motor: torque (T_{el}), current (I_{ph}), power factor (cosφ) and efficiency (η) versus angle between MMF of permanent magnets and MMF of stator winding

The maximum synchronous torque determines practical use of the motor. The maximal torque of the motor with the VPM rotor is 66 N · m, and in the case of the IPM rotor, the maximal torque is 117 N · m. This means the torque is 56% higher for the IPM motor and 18% higher than the nominal torque of the induction motor. The efficiency of the motor at the maximum torque, in both designs is equal to approximately 93%; power factor cosφ for the VPM motor is 0.64, and for the IPM motor is 0.7.

4. Asynchronous torque of the model motor

The start-up of the motor determines its practical use as a synchronous motor.

During the start-up the magnetic flux generated by permanent magnets during the start-up induces voltage in a stator winding; frequency of the voltage is equal to electrical frequency of rotation $f_2 = n/60p_b$. The current flowing through an armature winding is composed of two components: network component I_1 of f_1 frequency and component I_2 of f_2 frequency. The current component I_1 generates asynchronous torque which determines the motor's start-up, while current component I_2 generates synchronous torque, which varies in accordance with speed during the start-up and impedes the start-up process.

The averaged characteristics of asynchronous torque generated by a short-circuited rotor winding and braking torque caused by permanent magnets were calculated for the model motor. The resultant (averaged) asynchronous starting torque of the model motor was calculated as superposition of the torque mentioned above. The calculations were conducted using the Maxwell software. The results of the calculations are shown in Figs. 7 and 8.

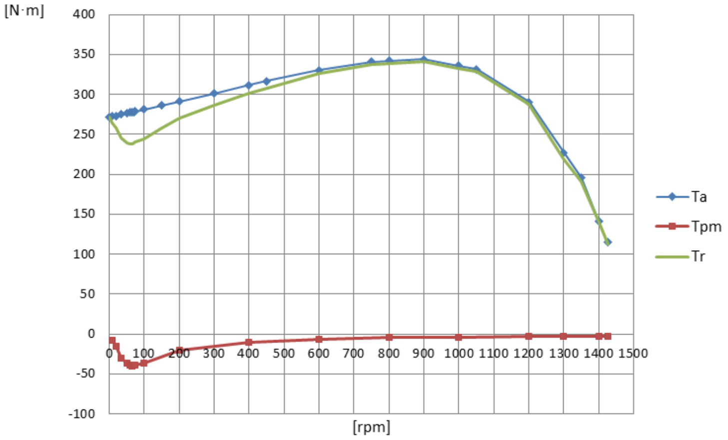

Fig. 7. Torque versus speed curves for "V" motor: asynchronous torque (T_a), braking torque (T_{pm}), resultant (total) torque (T_r)

The start-up of the induction slip-ring motor is carried out using starting resistors that adapt the asynchronous torque-speed curve of the motor to the start-up demands of the load machine. The success of the start-up thus is determined by the maximum torque.

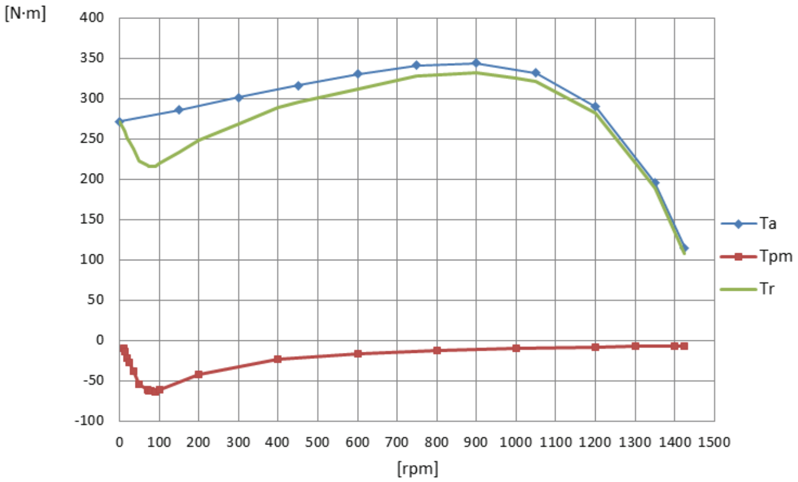

Fig. 8. Torque versus speed curves for “I” motor: asynchronous torque (T_a), braking torque (T_{pm}), resultant (total) torque (T_r)

Figures 7 and 8 show that in the both embodiments of the rotors (VPM and IPM) the maximum torque is about 340 N m, and it is 2.9 times higher, then the maximum torque of synchronous motor type “I”. Therefore, there is no danger that the motor will not start.

5. Conclusions

The electric motor excited with permanent magnets and with a slip-ring start-up winding shows improved start-up features in comparison to squirrel-cage induction motors synchronized with permanent magnets, such as:

- the motor start-up is smooth, since a rheostat is used and the start-up current and start-up torque may be set by controlling the value of connected resistance in accordance with the rotational speed; there is no danger of motor stopping in the middle of the start-up,
- the start-up torque in the whole rotational speed range may be significantly greater than the rated torque, since it is appropriately adjusted with the resistance of the rheostat,
- the start-up current usually does not exceed the doubled value of the rated current; the perturbation (transient) current, at the first instant after connecting the motor to the network, does not exceed $4I_N$,
- the torque surge occurring after switching the motor on is proportional to the square of the perturbation (transient) current and is several times less than in the induction cage motor,
- the heat generated during the start-up of the motor driving load machine is generated and dissipated for the most part in the rheostat rather than in the rotor winding, so that there is no danger of overheating the permanent magnets, even in the case of repeated (frequent) start-ups,

- motor may be used for driving machines started under load and with long start-up times,
- the motor with a starting ring winding is more expensive than the motor with a squirrel-cage rotor.

After the start-up, the motor self-synchronizes and operates as a synchronous motor excited with the magnetic field of permanent magnets. After synchronization the brushes contacting the slip-rings may be short-circuited or lifted. It is better to lift the brushes, since brushes and slip-rings do not then wear down; friction is absent and no additional power losses are generated. This type of motor may be used for any type of electrical drive.

If we compare the asynchronous and synchronous characteristics of motor designs "V" and "I", it may be observed that their shapes depend on the rotor construction and the placement of permanent magnets in the rotor core. For each investigated motor design a proper design of a rotor winding and the placement of permanent magnets in a rotor core must be selected, taking into account the criteria of maximum synchronous torque and maximum asynchronous torque. In the case of the discussed model motor, the motor with "I" rotor is characterized by the maximum synchronous torque higher by *c*. 56% with respect to the motor with "V" rotor.

References

[1] Bernatt J., Gawron S., Glinka T. et al., *Rotor of electric motor with permanent magnets,* (in Polish), Polish patent application, P.415273 (2015).

[2] Rossa R., *Reluctance motor with additional permanent magnets excitation,* (in Polish), PhD Thesis, Department of Electrical Machines and Devices, Silesian University of Technology, Gliwice (2006).

[3] Zawilak T., *Utilizing the deep bar effect in direct on start of permanent magnet machines*, Przegląd Elektrotechniczny, vol. 2013, no. 2b, pp. 177-179 (2013).

[4] Zawilak T., Zawilak J., *Line start permanent magnet synchronous motor in ball mill application,* (in Polish), Maszyny Elektryczne – Zeszyty Problemowe, vol. 2016, no. 3, pp. 169-173 (2016).

[5] Ogbuka C., Nwosu C., Agu M., *Dynamic and steady state performance comparison of line-start permanent magnet synchronous motors with interior and surface rotor magnets*, Archives of Electrical Engineering, volume 65, issue 1, pp. 105-116, ISSN (online) 2300-2506, March 2016, DOI: 10.1515/aee-2016-0008

[6] Khazdozian H.A., Jiles D.C., Hadimani R.L., *Magnetic flux focusing for generator designs*, Magnetic Technology International, pp. 24-28, ISSN (print) 2047-0509 (2017).