Comparative Analysis of Line-start Synchronous Motor and Asynchronous Motor

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Abstract

Energy efficient motors are the key components of each industrial process. In the energy demanding society, requiring the energy efficient consumers, the line-start synchronous motor has gained more and more popularity due to the high efficiency and power factor combined with good operational characteristics. The disadvantages of the synchronous motors such as inability of starting without the inverter has been largely overcame with this type of the motor. However, the proper design of line-start motor regarding permanent magnets and the squirrel cage winding is crucial for motor starting and synchronization capability. In this paper, the line-start synchronous motor is derived from the asynchronous motor by redesigning the rotor. The obtained performance characteristics of the synchronous motor is compared with the data of the asynchronous motor (the analytical, measurements and from the motor producer) and they show reasonable agreement. The derived model of the synchronous motor is numerically modelled for obtaining the magnetic flux density distribution in the motor cross-section. The analysis and comparison is completed by obtaining the transient characteristics of both types of the motors. The designed synchronous motor has proven to have good starting and synchronization capabilities combined with the high efficiency. The dynamic response at sudden load changes is within expected limits.

Keywords: line-start synchronous permanent magnet motor, steady-state characteristics, transient characteristics, FEM models

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1. Introduction

Climate changes and the necessity of the reduction of CO_2 emission has stipulated introduction of various standards, which limit the air pollution and enforces the electricity savings. The European regulations for energy efficient motors are covered by IEC 60034-30-1, which defines the efficiency levels of the motors as IE1 standard efficiency, IE2 high efficiency, IE3 premium efficiency and IE4 super premium efficiency. Directive 2005/32/EC establishes that motors must meet following minimum energy performance standards: IE2 efficiency levels by June 16, 2011, IE3 efficiency levels by January 1, 2015 (for motors within the range of 7.5 to 375 kW) or IE2 in combination with an adjustable speed drives. IE3 efficiency levels have to be reached for motors from 0.75 to 375 kW, by January 1, 2017 or IE2 in combination with an adjustable speed drive.

From July 2021 the current regulation will be repealed and replaced by Regulation on electric motors and variable speed drives (EU) 2019/2018.The level of requirement will moreover increase, as three-phase motors with a rated output between 0.75 kW and equal or below 1000 kW must reach IE3 efficiency level by July 2021. Motors between 75 kW and 2000 kW must meet IE4 level as of July 2024. Motors that are more efficient will bring 57 TWh annual energy savings in the EU by 2020.

Taking into account the overall effect of the revised regulation, the annual savings will increase to 110 TWh by 2030. This means that 40 million tonnes of CO_2 will be avoided each year. The motor manufactures and industry are facing the challenge to design and use motors that are more efficient. The prime moving force in most of the industries that utilize motors with constant speed is the three-phase squirrel cage motor (AM). It is well-known as robust and reliable motor, which requires little maintenance. However, this type of the motor can reach premium efficiency levels (IE3) and encounters number of design issues when super premium efficiency levels (IE4) should be reached.

Permanent magnet synchronous motors are known as viable alternative to asynchronous squirrel cage motors as they have higher efficiency and power factor compared to asynchronous motors. Besides being more expensive than three-phase squirrel cage motors, synchronous motors require inverter for motor starting i.e., putting into operation. This makes the synchronous motor even more expensive alternative to asynchronous motors. The line-start synchronous permanent magnet motors (LSSPMM), designed as a hybrid of asynchronous squirrel cage motor and synchronous motor, can achieve super premium efficiency levels (IE4). As the name indicates, they are capable for line starting when they are plugged into the network voltage. This is due to the existence of squirrel cage winding on the rotor (like at asynchronous motors) which enables asynchronous starting of the motor. In addition, flux barriers with magnets are placed in the rotor. The permanent magnets and flux barriers contribute to torque component in the steady-state synchronous operation. The torque from the magnets is known as the breaking torque as it opposes the cage torque. Unlike asynchronous motor, LSSPMM operates with constant synchronous speed within the complete range of the loads. As it operates with constant synchronous speed, no current is induced in the rotor winding, once the motor reaches the synchronous speed. Consequently, the copper losses in rotor winding are nullified. The design of the LSSPMM, influence of the various motor parameters like number of the stator winding turns, rotor configuration or voltage unbalance, on the operating characteristics of the motor have been subject of investigation during recent years [1]-[10]. The other authors focus on the cogging torque reduction and improvement of the motor performance during start up and at steady-state operation [11]-[14].

The single-phase line-start synchronous motors have also attracted the attention of the researchers and motor designers as they can be widely used in various household appliances [15]-[16]. The research on the field of the line-start motors is not limited to the synchronous motors with permanent magnets. The capabilities of hysteresis and reluctance motors for direct line starting are investigated as well [17], [18]. Faults that can occur during operation of line-start synchronous permanent magnet motors are subject to the mathematical modelling, simulation and analysis [19]-[21]. Optimization algorithms have gained the popularity during the last decade and they are widely applied at the design of the motors as they allow obtaining the most favourable motor design regarding predefined motor parameters such as efficiency or torque [22], [23].

However, very few papers address the comparison of steady state and dynamic characteristics of the line-start synchronous motors and the asynchronous motors.

In this paper, the line-start synchronous motor is derived from the asynchronous motor by reconfiguring the rotor. Both motors are modelled in Ansys Maxwell software and the parameters and the steady-state characteristics of both motors are obtained. The design of the newly derived synchronous motor is further analysed by Finite Elements Method for magnetic flux density distribution. Software Simplorer is used for obtaining transient characteristics of both motors when they a fed by the symmetrical voltage supply from the network. The dynamics of the motors is analysed at no load and when step load is coupled to the motor shaft.

From the obtained results, the overall operation of the line-start synchronous motor is superior over the operation of asynchronous motor. However, its limitations are related to the limited starting capability due to the breaking torque from the permanent magnets. Therefore, LSSPMM are intended for driving low-inertia loads and they are not suitable for all applications. Thus, further research on finding the optimal rotor design with respect to the motor steady-state and dynamic operation should improve the overall operation of this type of the motor.

2. Motor Models

2.1 Analytical models of the motors for computer modelling

The key step in each motor analysis is to define accurately the motor model that is used for computer modelling. The starting point in the analysis is three-phase asynchronous motor, type 2AZ 155-4, product of company Rade Končar (AM). The asynchronous motor model is modelled in Ansys Maxwell, or more precisely, in the software module that allows obtaining the motor parameters and steady-state characteristics. We will refer to this model as analytical model of the asynchronous motor (AMAM).

A more detailed presentation of this model can be found in [24]. The accuracy of this model is verified by comparing the output parameters and characteristics of AMAM with data from the motor producer and measurements in the faculty's laboratory.

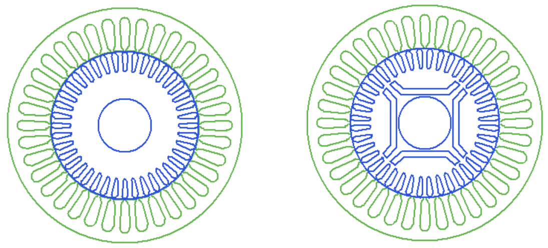
This comparison is presented in Table 1.

Table 1. Comparison of AMAM, producer and measurements

Analyt. model	Experi-ment	Producer	Parameter
5.24	4.88	5	phase current (A)
2.89	2.36	2.4	no-load phase current (A)
135	196	170	no-load input power (W)
22.1	22	21	locked-rotor phase current (A)
2.4	/	2.2	locked rotor torque ratio
2.19	1.94	2.2	nominal output power (kW)
0.8	0.78	0.81	***nominal power factor (/)***
1356	1410	1410	***rated speed (rpm)***
15.5	13.1	14.9	***rated torque (Nm)***

In order to obtained valid computer model for analytical calculation of motor parameters and steady state characteristics, all motor dimensions and properties of the materials must be input into the computer model. Once that was determined that the computer model of the asynchronous motor for analytical calculation of motor parameters and characteristics is sufficiently accurate, the motor was redesigned into line-start synchronous permanent magnet motor by redesigning the rotor and adding the flux barriers and magnets inside the barriers. All other remaining dimensions of the motor were not changed i.e. the same mounting frame was retained in both cases. This model will be referred as analytical model of the synchronous motor or AMSM.

The cross-section of both motor models is presented in Figure 1.



a) AMAM b) AMSM

Figure 1. Cross-section of motors

Both motor models, after they are solved in Maxwell's module for analytical calculation of motors, as an output give the motor parameters and steady-state operating characteristics. They will be presented in the next section.

2.2. Numerical models

The numerical techniques, i.e., Finite Elements Method (FEM) have become a regular part of motor design procedure as they allow accurate solving of Maxwell's differential equations i.e., obtaining the magnetic flux density **B** in each part of the machine cross-section [25]-[27]. The flux density in motor cross section determines the motor core losses. They are constant losses for each operating regime of the motor, i.e., they are not load dependant. The motors are modelled by dividing their cross-section into numerous elements i.e., creating the mesh of finite elements. The magnetic vector potential **A**, i.e., magnetic flux density **B** are calculated in each point of the motor cross-section, after models are solved in software Maxwell, i.e., its module for numerical modelling. The obtained results from these models will be presented in the next section.

2.3. Models for obtaining dynamic characteristics

The main obstacle in replacing the asynchronous motors with the synchronous is the ability of the latter for line starting and their dynamic behaviour at sudden changes of the load. Therefore, it is understandable that modelling of the dynamic characteristics of the motors is the integral part of their analysis. Both motors are modelled in Simplorer, the module of the Ansys Maxwell software that allows obtaining the transient characteristics of the motors at various operating regimes. Both motors are fed with network voltage i.e. symmetrical three-phase voltage. After transient models are solved, the dynamic characteristics of torque, speed and stator current at step load are obtained. They allow motor starting and dynamic behaviour to be analysed. The dynamic characteristics are also presented in the next section.

3. Results

3.1 Analytical models

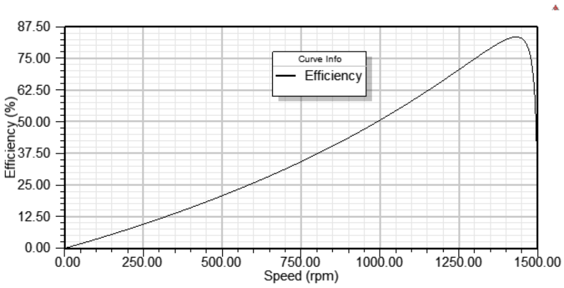
Analytical models of the motor that are solved in Maxwell software allow obtaining the parameters and operating characteristics of the motors. The comparison of characteristics of both motors is presented in Table 2.

Table 2. Comparison of performance characteristics

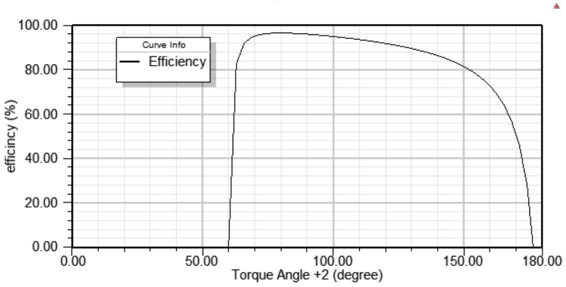
Rated load operation		
AMAM	**AMSM**	**Parameter**
5.24	3.74	stator phase current I_1(A)
11.4	12.39	motor total weight (kg)
3.55	1.95	phase stat. wind. resist. at 75 °C (Ω)
0.72	0.91	wire diameter of stator winding (mm)
27.7	6.91	iron core losses P_{FE} (W)
293.16	82.8	stator winding copper losses P_{cus} (W)
236	0	rotor winding copper losses P_{cur} (W)
568.08	101.1	total losses P_{loss} (W)
2.768	2.3	*input power P_1 (kW)*
2.199	2.2	*output power P_2 (kW)*
15.5	14.09	*rated torque T_{mech} (Nm)*
79.4	95.6	*efficiency η (%)*
0.802	0.933	*power factor cosφ (/)*
/	91.238	*torque angle (°)*
1355	1500	*rated speed n_n (rpm)*
0.0066	0.0066	*rotor inertial moment (kg·m^2)*
No-load operation		
2.88	1.29	*no-load current I_0 (W)*
134.68	28.8	*no-load input power P_0 (/)*
Locked rotor operation		
35.26	59.43	*locked rotor torque T_{start} (Nm)*

In addition, two operating regimes of both motors are compared: no-load, rated load and locked rotor.

Figure 2 presents the efficiency of both motors and supports the data in Table 2. For the asynchronous motor, efficiency is plotted versus speed (taking into consideration that 1355 rpm is the rated load speed), while for the synchronous, efficiency is plotted versus torque angle (taking into consideration that at rated load, torque angle is 91.2 °).



a) AMAM



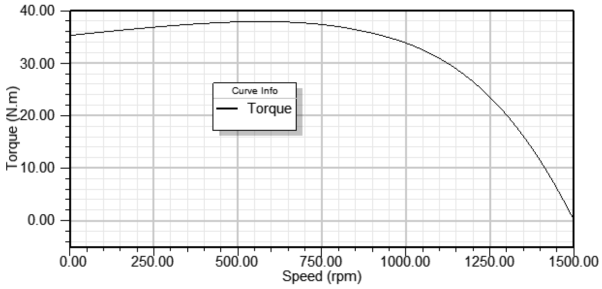
b) AMSM

Figure 2. Efficiency factor steady-state characteristics

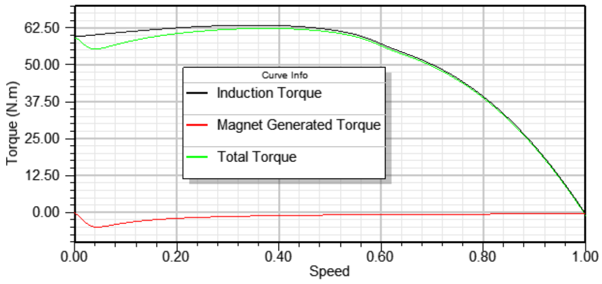
From the presented results in Figure 2, it can be observed that the efficiency of the synchronous motor is considerably higher than the efficiency of the asynchronous motor. This is mainly due to reduced winding losses, i.e., the stator winding losses are reduced while the rotor losses do not exist due the synchronous speed of operation and there is no induced current in the rotor winding at steady state operation. As the power factor of the LSSPMM is considerably higher than the power factor of the AM the input electrical power of the LSSPMM is lower than at AM which make this type of the motor highly energy efficient. i.e., the consumption of the electrical power at LSSPMM is lower than at AM.

The mechanical torque is another important operating characteristic of both types of the motors.

Figure 3 presents the torque for both motors. For the synchronous motor, all three types of torques that are present in the motor operation are presented in Figure 3.



a) AMAM



b) AMSM

Figure 3. Mechanical torque steady-state characteristics

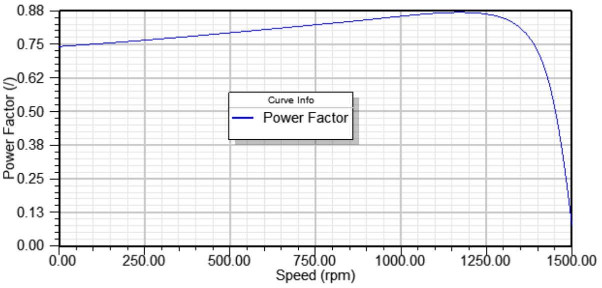
Asynchronous torque that is produced by squirrel cage aluminium rotor winding, also known as damper winding, the breaking torque that is produced by permanent magnets and the resulting torque, which is the sum of the previous two, are presented in Figure 3. They are plotted versus fraction of the synchronous speed.

The squirrel cage winding as well as permanent magnets are important for the proper operation of the synchronous motor. The squirrel cage winding contributes to the motor starting while the increase of permanent magnets material worsens the synchronization of the motor.

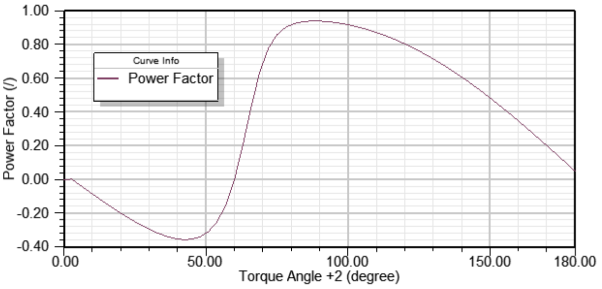
A proper rotor design is required to obtain the good starting torque, synchronization of the motor and stable operation with the synchronous speed at various operating conditions, i.e., loads. At the same time, it is necessary to maintain the high efficiency and power factor at steady-state operation for which the proper design of the flux barriers, the magnets and the air gap length is needed.

The third key parameter in operation of the motors is the power factor. Low value of power factor causes a reduction in the electrical system distribution capacity by increasing the current amplitude and voltage drop. The LSSPMM operate with a higher power factor than the asynchronous motors. This is due to a reduction of a stator current because of the decreased magnetizing current. This is also the case with our analysed synchronous motor, which at rated load operation, has a considerably higher power factor than the asynchronous motor (Table 2, *supra*).

The power factor is plotted and presented in Figure 4. For the asynchronous motor versus speed, and for the synchronous versus torque angle.



a) AMAM



b) AMSM

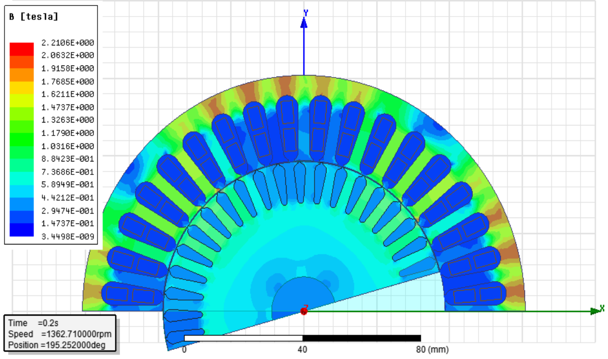
Figure 4. Power factor steady-state characteristic

The power factor is highly dependent on quantity of the permanent magnet material and the air gap length. As in the most design procedures one parameter cannot be evaluated standalone.

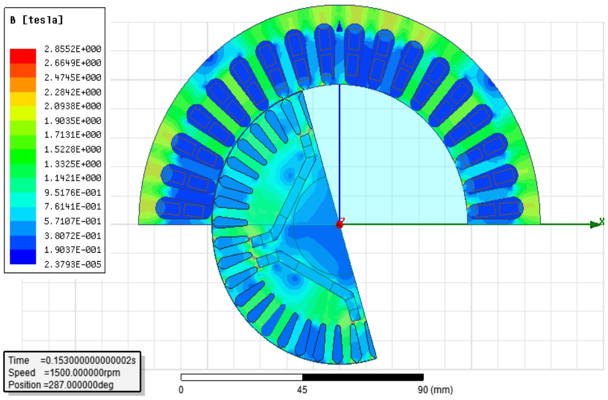
The increase of the air gap length maximizes the overloading capability of LSSPMM but increases the weight of the permanent magnet material. The increase of the permanent magnet material improves the power factor but worsens the synchronization capability of the motor. Furthermore, the increase of the permanent magnet material is associated with the increased motor weight and manufacturing costs. Therefore, a complex analysis of all aspects of the motor operation is need for a proper design of line-start synchronous motor.

3.2. Numerical models

Numerical models are useful in obtaining the magnetic flux density in motor cross-section. The parts of the motor core where the high saturation exists can be easily detected and consequently the motor design can be modified in order to avoid forming of “weak” parts in the motor construction. Both analysed motors are solved for the magnetic flux density by the aid of FEM and the obtained results are presented in Figure 5.



a) AM



b) LSSPMM

Figure 5. Magnetic flux density distribution

From the presented results in Figure 5, points of high flux density can be observed in both motor models. In the AM the most critical part is the stator yoke. Here should be noted that in both models the original motor dimensions from the motor manufacturer are preserved. Therefore, stator outer diameter is not enlarged which can be one of the measures to decrease the flux density in stator yoke. In LSSPMM, besides stator, the most critical part regarding magnetic saturation is the sharp edges near to the flux barriers. In the further research, the optimization of this motor model should be performed for obtaining the optimal dimensions of the flux barriers and permanent magnets regarding operating characteristics and flux density distribution in the machine cross-section.

3.3 Dynamic characteristics

The analysis and comparison of both motors is completed with obtaining the dynamic characteristics of speed, torque and current when motors are fed by three phase symmetrical voltage and are loaded with step load 250 ms after the acceleration of the motor has finished.

The obtained results of motor speed, torque and current are presented in Figures 6, 7 and 8.

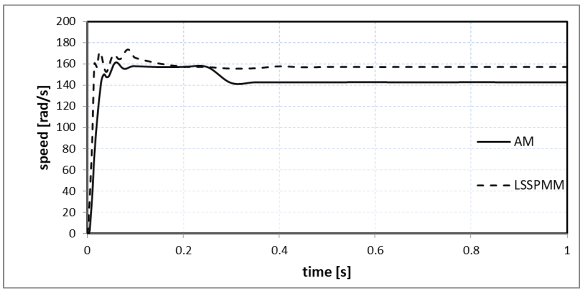


Figure 6. Transient characteristics of speed

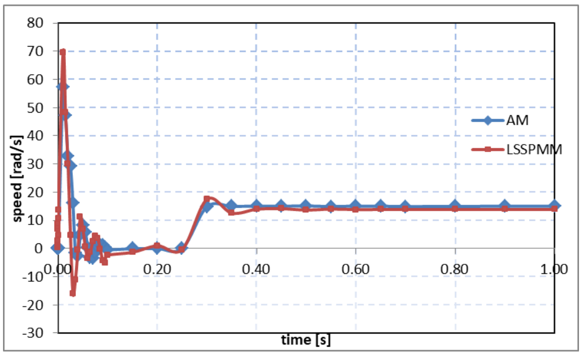
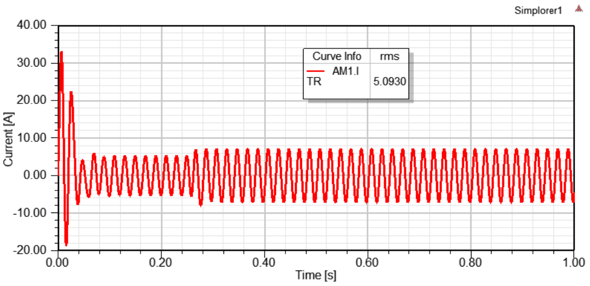
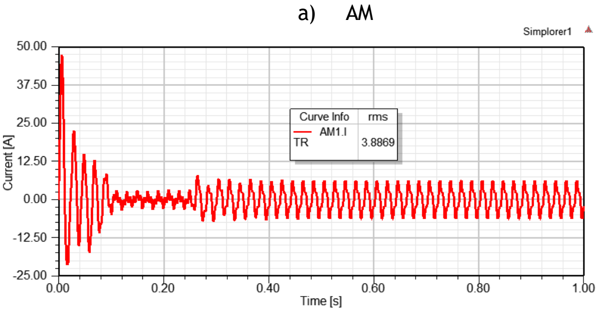


Figure 7. Transient characteristics of torque



a) AM



b) LSSPMM

Figure 8. Transient characteristics of current

Transient characteristics are of key importance in analysis of operation of LSSPMM. Motor starting as well as motor synchronization should be checked at various operating conditions.

From presented results in Figure 6, it can be observed that AM is accelerated at no load and reaches the no-load speed. Two hundred and fifty milliseconds from the motor starting, the step load is coupled to the motor shaft and it decreases the motor speed up to the rated speed.

For the synchronous motor, the situation is different. The motor accelerates successfully and synchronizes, i.e., after the acceleration has finished it continues to operate with synchronous speed regardless of the step load applied to its shaft, i.e., the motor successfully maintains the synchronous speed. The dynamic response of the motor can be considered satisfactory.

The moment when the step load is applied at the motor shaft can be clearly observed at transient characteristic of torque of both motors (Figure 7). After the transients of the torque during the acceleration are suppressed the torque drops down to the no-load torque (small value) and increases again at both motors up to the rated torque, as the rated load constant torque, is applied to the motor shaft of both motors. The phase currents follow the similar pattern. After motor acceleration, the current decreases up to the no-load current and increases again up to the rated current that corresponds to the rated load operating regime. The dynamic model of the motor from which the motor transient characteristics are obtained is an inevitable part of the motor analyses as it provides the useful data for the dynamic behaviour of the motors during start up, step load and steady state operation. Furthermore, it verifies the design of the LSSPMM as the proper one.

4. Discussion

The raising importance of the electricity savings has emphasized the need of more efficient electric motors.

According to some studies, electric motors are responsible for about 45 % of the total consumption of electric energy. A viable alternative to three-phase squirrel cage motors, which are the most often used motors in all industrial application, has become a main focus of many researchers and motor manufacturers, as the asynchronous motor is well known for its relatively low efficiency factor of around 80 %.

Two main modifications were derived in this paper in order to modify the three-phase squirrel cage motor into line- start three-phase permanent synchronous motor.

Firstly, the rotor was redesigned by adding flux barriers and permanent magnets inside the barriers.

Secondly, the diameter of the copper wire in three-phase stator winding was modified, i.e., the cross-section was increased, and consequently the resistance was lowered (Table 2). The reduced stator current and the stator winding resistance contributed to the lower copper losses. Lower copper losses in the line-start synchronous motor at steady-state operation are also attributed to the nullified copper losses in the squirrel cage winding. Almost 20 % of losses in the asynchronous motors associate with rotor cage losses. In steady-state operation of the synchronous motor, meaning motor is operating with the synchronous speed, no current is induced in the rotor winding and consequently there are no copper losses in it.

From the Table 2, it can be seen that the no-load current at LSSPMM is considerably lower than the no-load current of AM. The reason for this is that the magnets provide the magnetization in LSSPMM whereas the magnetization of the AM implies a magnetizing current in the stator winding. Consequently, the power factor of the LSSPMM was increased, which increased the electrical system distribution capacity, i.e., the motor input power P_1 was reduced, or consumption of electrical energy was reduced. The motor modification was performed with one constrain, the motor output power P_2 should remain unchanged (Table 2). Therefore, in both motors the output mechanical power remains almost unchanged (Table 2). The total losses were lowered as well, which consequently increased the efficiency factor from 79.7 % at asynchronous motor to 95.6 % at synchronous. In most cases, standard motors operate efficiently, with typical efficiency ranging between 80 and 93 %. Super premium efficiency motors perform significantly better. An efficiency gain of only 2 %, from 92 % to 94 %, results in a 25 % reduction of losses. Most of the motor losses result in heat emitted into the atmosphere. Reduced losses can significantly reduce cooling load in the industrial facility’s cooling systems. As the second motor operates with synchronous speed, which is bigger than the rated speed of the asynchronous motor, consequently the mechanical torque for the same output power is slightly reduced.

Figure 2 presents the efficiency factor for both motors, where can be read the efficiency at the rated speed, i.e., torque angle respectively for both motors. The presented results in Figure.2 support the data in Table 1.

The same conclusion is valid for the Figure 4, where the power factor of both motors is presented. Again, for the rated load operating point, the power factor for both motors can be read. The motor torque of the line-start synchronous motor is the sum of the breaking torque (produced by permanent magnets), and the asynchronous torque (produced by the squirrel cage winding). This is presented in Figure 3b. Generally, the line-start synchronous motors have good starting torque. However, for this type of the motors, the high load inertia, for example fans, can limit the synchronization capability of the motor. LSSPMM can start up but it will not be able to run into synchronism and can stall before the synchronous speed. The proper dimensioning of rotor bars and the dimensions and quantity of permanent magnet material is of key importance for this type of the motors. It can be stated that increase of permanent magnet flux in the machine worsen the synchronization capabilities.

On the other hand, the increase of permanent magnet material increases the efficiency and power factor in steady-state operation. The induction torque can be maximized near the synchronous speed in order to maximize the synchronization capability of the motor by lowering the cage resistance. On the other hand, the reduction of cage resistance reduces the starting torque of the motor. The modelled line-start synchronous motor is based on the same squirrel cage winding as it is in asynchronous motor. Motor is well designed regarding squirrel cage winding and permanent magnet material as it has sufficiently large starting torque and relatively low breaking torque (Table 2).

Better overview of the dynamic of the motors, i.e., behaviour of the motors during starting and in steady-state operation (after the motor accelerates up to the rated, i.e., synchronous speed) is illustrated in Figures 6 and 7.

In Figure 6, both motors were accelerated at no load up to the steady-state operation with rated load, meaning for the asynchronous motor the rated speed of 142.66 rad/s or 1362 rpm and for the synchronous motor up to the synchronous speed of 157.08 rad/s or 1500 rpm. Here should be noted that obtained results from the dynamic models are in very good agreement with the obtained results from the analytical models (Table 2), i.e., rated speed of 1355 rpm in the analytical model and 1362 rpm in the dynamic model of the asynchronous motor. Synchronous motor in both models (analytical and dynamic) operates with constant synchronous speed of 1500 rpm.

The overall comparison of the results obtained from the analytical and the dynamic models is presented in Table 3. The rated load operating condition is obtained by loading both motors with step load; two hundred and fifty milliseconds after the motors were accelerated.

The moment when the motors were loaded can be clearly observed in the dynamic characteristic of torque, presented in Figure 7. After the motor had accelerated, the torque dropped up to the no-load torque, which is a very low value, up to the moment when the step load is applied the shaft, equal to the rated torque, and consequently the torque of the motors increases up to the rated torque.

Again, the comparison between obtained results of the torque from the analytical and the dynamic models is presented in Table 3.

Similar behaviour is observed in transient characteristics of current (Figure 8), where the current in both motor models, reaches the steady state value, at rated load, of 5.09 A for the asynchronous and 3.89 A for synchronous motor. The obtained results of the current from the dynamic models are in very good agreement with the obtained currents from the analytical models, i.e., 5.24 A and 3.74 A (Table 3).

Table 3. Comparison of results from analytical and dynamic models

Analytical model		Dynamic model		Parameter
AMAM	AMSM	AM	LSSPMM	
5.24	3.74	5.09	3.89	rated phase current (A)
1355	1500	1362	1500	***rated speed (rpm)***
15.5	14.09	14.99	13.96	***rated torque (Nm)***

From the presented dynamic characteristics of line-start synchronous motor it can be concluded that motor accelerates and reaches the synchronous speed, i.e., for the presented example of the step load, it operates with synchronous speed without losing the synchronism. In transient regimes (start up and near to the steady state operating point), the operation of the asynchronous motor is more stable with very small oscillations in the transient characteristic during acceleration and when motor reaches the steady-state operating point.

The acceleration time of both motors is almost the same. Line-start synchronous motors should work, and they have advantages in applications involving frequent start and stops because permanent magnet motors have low inertia.

In this paper, the line- start synchronous motor is derived from the asynchronous motor with minimum modifications. Therefore, both motors have the same estimated rotor inertial moment. Super premium efficiency LSSPMM (which covers the motors with efficiency above 90 %) should be considered for the applications where motor is in use for more than 2000 hours per year. The magnetic flux density distribution in the cross-sections of the motors verifies the proper design of the motors. In case of the synchronous motor, the points of high flux density are discovered near the sharp edges of the flux barriers.

The motor uses Samarium Cobalt magnets, which are known as strong rare earth magnets, generally ranked similarly in strength, to neodymium magnets. In the future research redesigning and improvement of the rotor configuration should be considered, in order to lower the flux density in critical parts. This could be a challenging task considering that motor operating characteristics should remain the same or even improved.

One of the advantages of line-start synchronous motors is that they come in the same frame size as conventional asynchronous motors for the same motor power rating. This makes them an attractive replacement of the conventional standard efficiency asynchronous motors. The line-start, without the need of controller or feedback device, makes their operation easy and cost efficient.

5. Conclusions

Electric motors are large electricity consumers. Large portion of them are three-phase asynchronous motors, known for the relatively low efficiency factor.

Current regulations impose strict standards for the efficiency class, especially for large motors. Asynchronous motors are limited with respect to the efficiency improvement. This is due to motor construction, which requires relatively high magnetizing current, consequently the power factor is low, and the electrical consumption is increased due to the low power factor and high stator current. There are relatively high copper losses in the rotor winding due to the induced rotor current because of the motor slip. However, one of the major obstacles is the fact that there is a limit on how small the air gap can be, at asynchronous motors. The smaller the air gap in the asynchronous motor is, the higher the efficiency and power factor are. On the other hand, the tolerances on the die stamping of the laminations are low. In addition, too small air gap increases the motor vibrations and noise. Some modification and improvements can be done such as the use of larger wire gauge to reduce stator copper losses, incorporation of longer stator and rotor to lower the core losses by decreasing the magnetic flux density. Other measures for efficiency improvement incorporate the use of the low resistance rotor bars, optimization of the air gap, and the use of premium-grade steel and thinner laminations to decrease the eddy current losses. However, even with the incorporation of all of these losses-reduction techniques, efficiency factor of three-phase asynchronous motors cannot reach the premium efficiency levels. Synchronous motors have been studied as viable alternative to asynchronous motors due to high efficiency factor and high-power factors. Permanent magnet synchronous motors can have larger air gaps without affecting the efficiency. With larger air gap, the required amount of magnet material increases, so the associated cost. In addition, line-start synchronous motors have overcome the difficulties of the synchronous motors, regard starting and the need of voltage inverters for their starting. They can be directly started when fed with the network voltage.

Paper presents the modification of the three-phase asynchronous motor in the line-start synchronous motor with minimum interventions in the motor design. The motor outer dimensions remain unchanged, the rotor is redesigned, and the gauge of the stator wired is changed. The applied modifications resulted in efficiency increase from 79.7 % to 95.6 %. Power factor is also considerably improved from 0.8 to 0.93. Motor line current is decreased as well as no-load current.

Beside analytical calculations, which were done in module of the software Maxwell for analytical calculation of motor parameters and steady-state characteristics, numerical models of the motors were derived as well. They allow magnetic flux density in the cross-section of the motors to be calculated. These models detected the points of high saturation of the magnetic core near to the edges of flux barriers in the rotor of the synchronous motor. The further research should be focused on improving the rotor design in order this saturation of the rotor core to be avoided. Dynamic models for obtaining the transient characteristics of the motors at starting and acceleration up to the rated speed were also derived. Both motors were accelerated at no load and step load was applied to the rotor shaft two hundred fifty seconds after the acceleration had finished. The line-start synchronous motor accelerated and reached synchronous speed when fed by the network voltage. In addition, it operated with the rated load applied on the motor shaft, after the acceleration had finished, without losing the synchronism. The up to now research on the design of the line-start synchronous motor shows promising results. However, the line-start synchronous motor is not the ideal replacement of the asynchronous motor.

There are number of manufacturing difficulties that should be overcome. The design of the rotor is more complicated, compared to the squirrel cage motor, manufacturing costs are higher; the price of the magnets increases the cost of the synchronous motor. Therefore, the focus of the further research will be again on combining the good features of the asynchronous and synchronous motors in the line-start synchronous reluctance motor, which is magnet free.

The design of the flux barriers, without magnets, combined with the adequate design of the squirrel cage winding for achieving good starting and steady-state operating characteristics will be a challenging task.

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