Powdered iron material based switched reluctance motor-drive performance comparison with conventional construction

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In the article, the research results of switched reluctance motor drive performance comparison were presented. The idea of improving the energy performance of the SRM drive through the introduction of modern construction materials of magnetic circuit made from powdered iron in relation to the classic design of isolated, rolled metal sheets was defined. Purposes and motivation of research based on general descriptions of comparable properties of magnetic materials were introduced. The structure of a novel motor drive with developments in the implementation of control algorithms imply the possibility of a fair comparison, which is the subject of the publication. The actual state of research, its methodology and the results of studies were described with an emphasis on aspects of energy consumption in static and dynamic states of drive work. In conclusion, an attempt to determine the validity of the main idea was made and area of further research was outlined.

KEYWORDS: SRM, electric drive, iron-powder material

1. Introduction

1.1. Goals and the motivation

Most of the today's publications in the field of electric drives are treated as a combination of an electric motor (EM) and the power inverter (PI) focus primarily on the power inverter with it controller. These analysis covers: the structure and control of converters to improve the dynamics (high performance), reliability (fault tolerant) and sensorless control. The article to withstand this trend presents preliminary results of a comparison of the switched reluctance motor drive (SRMd) – based on iron-powdered magnetic materials with conventional counterpart made of rolled metal sheets.

Analysis of the complete electric drive in terms of the material structure of the electric motor alone – although it seems an unnecessary complication – there are justified. One could ask the question: why not explore the same engine in a simplified supply system thereby reducing the long chain of energy conversion? The answer is simple. SRM motor is a DC synchronous machine, so it is not possible to its direct power from electric 3-phase grid. The moreover, in practical applications [1] – because of the strong non-linearity of switched reluctance motor – a simple voltage control in an open system (without any position feedback) could not be applied [2]. Therefore, the comparison of the engine structural materials should be carried out for the drive forming a functional unit processing path into mechanical energy. To highlight the merits of the work done for further research and expectations with respect to analysis of the results, there will be characterized magnetic materials used in the comparison in the next section.

1.2. Power magnetic materials

Soft magnetic materials are mainly used in electrical machines to transform electrical energy (transformers, static converters), its generation (generators, alternators) and conversion into mechanical energy (electric motors). Most are alloys of iron and silicon (a relatively cheap metal) /nickel (high initial permeability value) /cobalt (high value of the maximum magnetic permeability). The desirable features of a good soft magnetic material are [3]: high permeability, respectively, low coercive field value, a minimum core loss, high saturation flux density value – means you can make as many mechanical force engines (proportional to the square of induction), high resistivity, resistance mechanical stability of the parameters of the variable temperature, resistance to external conditions, the ease of making finished products, low price.

Due to the rapid loss of primary energy resources and the high cost of electricity, it is important to continuous improvement of the properties of magnetic materials, especially reducing their losses. Over the past few years, research on electrical steel focused on improving devices with higher power, which poses a potentially greater economic benefits. Ones of the loss components are quasi-static magnetic core losses caused by hysteresis and dynamic core losses emanating from eddy currents. Such a strict separation of the loss is not practicable and is only a certain idealization [3]. Aside from these issues the article focuses on the analysis of the energy efficiency drive. The largest size of the domain, and thus the most inert, can be found in the metal sheets (conventional material). Although the properties depend on the specific chemical composition, thickness of the plate and the direction of the roll, it could be defined general characteristics of these materials: low operating frequency, high saturation flux density (of the order of 1.5 [T]), relatively high power losses caused by induced eddy currents, low price.

The second type of magnetic material used in the comparison is a powdered iron. Ground into small particles, mixed in some cases with "improver" is treated with an organic filler, compacted under high pressure in an appropriate form. Form gives the material shape of the magnetic core. After the compression of such material between the iron particles are forming a so-called air gap occurring dispersed throughout the volume of the core. A core made of such a material has a non-linear magnetization as a function of the external magnetizing force, therefore its specific properties are used for storing large amounts of energy. Conventional cores made of pure iron powder (material -26) are the cheapest and most common materials. The saturation flux density is 1.2 [T], and the maximum operating frequency is about 80 [kHz]. A disadvantage of powder cores is susceptible to ageing which is an irreversible process and occurs at high temperatures. It is recommended so the work of all iron powder cores at up to 363 [K] (90° C). The latest alternative to standard powder material cores are a SMSS, recognized today as the most valuable magnetic material [4]. Special doping possible to achieve such as: higher efficiency at high temperatures, high current carrying capacity, high energy storage capacity, low loss (10 times smaller in relation to the iron powder cores). These cores have been designed with the aim of replacing the powdered iron cores in systems operating in the frequency range 25-500 [kHz], while maintaining high performance stability during operation. All this makes them a high potential for use as building material of SRM magnetic circuit .

2. Research

2.1. Drive structure

As has been mentioned, the object of the study is Switched Reluctance Motor. It is the oldest type of electric motor used in practice, and the historical significance of the SRM due to the simplicity of its construction. The most important feature of SR motor is a monolithic construction of the rotor resulting in high reliability operation. On the other hand, the non-linearity in many aspects necessitates the use of complex control algorithms and the mechanisms of position /speed control. The parameters of the engine used in the study are as follows: rated power $P_N = 250$ [W], maximum speed $\omega_{MAX} = 10\ 000$ [rpm], voltage $U_N = 220$ [V]. Topology engine is 12/8 (three phase two pairs of stator poles and eight rotor teeth). Standard model comes with Maytag Neptune washer which is marketed in the United States.

Figure 1 shows a conventional, factory engine design (separately the stator and the rotor with bearings) of rolled metal sheets. In Figure 2, the structure based on powder materials.

Fig. 1. Stator and rotor of conventional SRM model

Fig. 2. Stator and rotor of SRM made from powdered material

Custom design of the converter was publications on the subject of: systemic solutions of asymmetric bridge inverter topology [5], the nature of the feedback signal and the concept of phase synchronization [6], controlling the SR motor [7] and the general characteristics of the drive [8]. These articles provide a detailed picture of the work on the construction of the drive control algorithms embedded in low-cost system based on microcontroller STM32F1. One of the major difficulties in controlling the motor turned out to be asymmetric nature of the feedback signal, as presented in Figure 3.

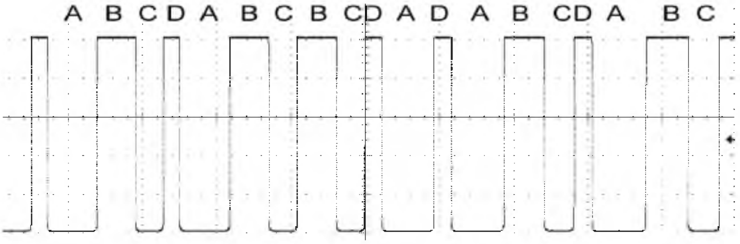

Fig. 3. Position feedback signal at constant speed

Common - N-phase coupling feedback position interface has been replaced by information encoded on a single line. The signals are encoded by signal level and by their width. Finally, digitized 4 letters code with twelve-element sequences are repeatable. The system theoretically allows clear identification active phase corresponding to the motor shaft position, which in the final implementation has been achieved thus stabilizing the motor start-up process.

Figure 4 shows the structure of the SRM motor control system. It lists the four essential elements: SRM motor with shaft position sensor, asymmetrical bridge, electrical isolation system and microprocessor system. The control signals of the upper transistors (A+, B+, C+) operate in the speed loop control system, the lower transistors (A-, B-, C-) are responsible for switching the motor phases (control of commutation process). The microprocessor system consists of the following blocks: KPZ - triggered external interrupt controller feedback signal slopes inflicting PLL synchronization signal, PPLL - software PLL algorithm, the PPLL counter (CNT) as an input signal for commutation (KOM) and the signal of the excitation offset angle (O) and advance of it angle (F) for drive the transistors A-, B-, C-.

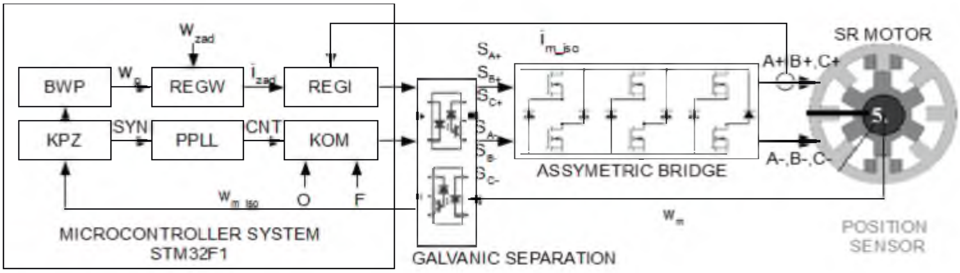

Fig. 4. SRM control system structure schema

Speed control loop of microprocessor system comprises: block determining the speed of the drive that base on the pulse signal duration (BWP), a series of proportional-integral speed (REGW) and phase current (REGI) controllers. Maximum value of the phase current was limited to 6 [A] and was unchanged during the study. The rotational speed was inflicted by potentiometer at control panel built into the inverter system. The second potentiometer serve for setting: the PLL phase shift relative to the reference signal (O) and the angle of advance (F).

2.2. Laboratory stand

Figure 5 shows a picture of the laboratory stand. It consists of: a PC allowing to monitor and change drive control system parameters and downloading the program to the microcontroller, two oscilloscopes: Tektronix DPO3014 and MSO3014 for trending signals specific to the motor (phase currents, speed, load torque, encoder position feedback) and network grid supply parameters (current, voltage, power).

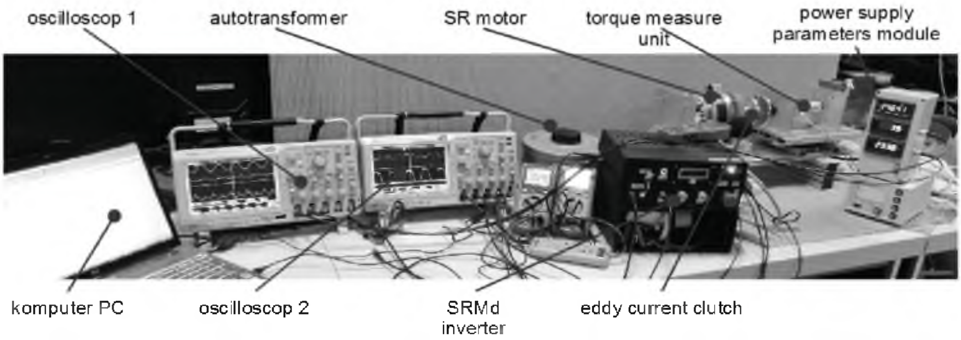

Fig. 5. Laboratory stand picture

Next, there was applied auto-transformer to change the input voltage, the power section and the control section of the inverter, power supply parameter measurement module (RMS current, voltage, power) and the MW2006-3S interface device for shaft toque measurement system 3Nm MT-15. SRM motor is coupled to the measuring shaft through a eddy current clutch.

2.3. Static characteristics

Implementation of the software PLL (Phase-Locked Loop) and motor synchronization in the SRM drive allowed comparison of conventional construction and powder based one by compensating for inaccuracies orientation sensor target position relative to the distribution of rotor teeth. Improper adjustment resulted in an incorrect motor phase commutation process leading to slower growth and energy characteristics of the drive. The development of control algorithms based on the PLL resulted in the ability to change the angle of advance and a significant enlargement of the drive performance for the achievable speeds/ load torque.

Before the appropriate test for a given engine design, commutation angles were determined in such a way that at idle and at supply voltage of about 50 [V] achieved the highest possible speed that provides the optimal setting for selected conditions. Further comparison of the two construction took place in the same type of work (control algorithm, power supply voltage).

Figure 6 shows the waveforms of drive power for different speeds at idle. It could be seen from them that conventional drive over a wide speed range has a much lower power consumption. It was the result of noticeably higher rolling resistance of the rotor bearings.

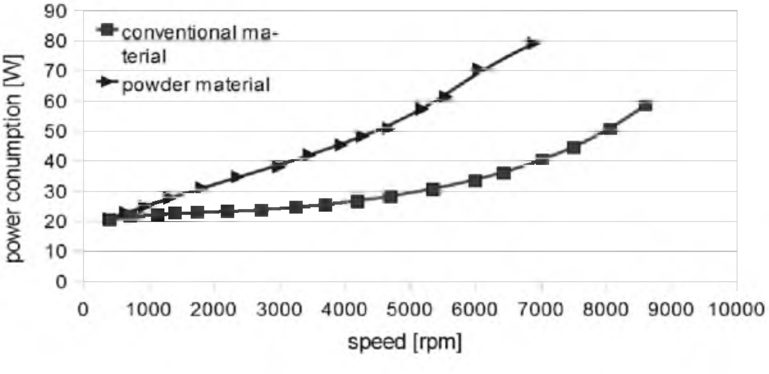

Fig. 6. Waveforms of drive power for different speeds at idle state (P = f(ω))

Conclusion from the graphs in Figure 6 was that the analysis of the power consumption of the drive, depending on the load torque could be comparable at low speeds (1000 [rpm]), for which the rolling resistance torque differences are relatively small. As can be seen from the waveforms in Figure 7, the initial differences resulting primarily from losses for idle until 0.25 [Nm] going to that point, over which the drive with powder material (1) has advantage over conventional one. It seems that the source of this advantage can be found in lower material losses in the iron-powder based motor. Using the linear regression coefficients can be calculated slope characteristics, respectively: 253 [W/Nm] for classical structures and 218 [W/Nm] for the structure based on powdered iron. There is presented another waveform (powder material – 2) related to the motor with bearings witch less rolling resistance toque.

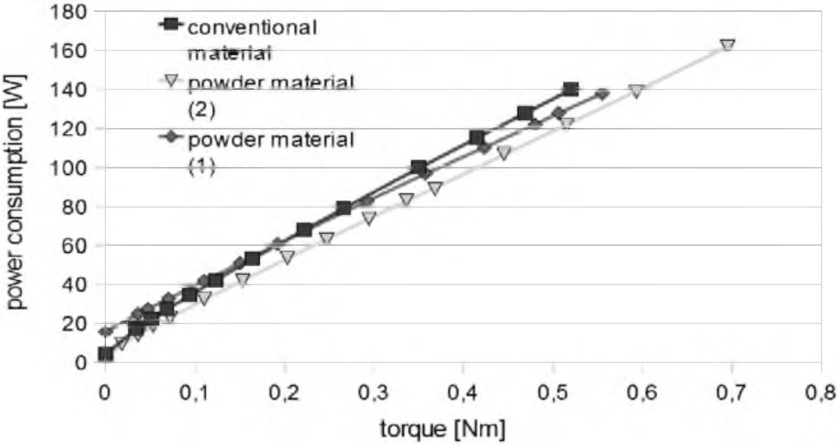

Fig. 7. Waveforms of drive power consumption to the resistive torque (P = f(T_O))

2.4. Dynamic performance

Figure 8 shows the relative comparison of the structure for the selected dynamic processes. These processes are abrupt changes in speed reference value in the conditions defined as shown in Table 1. Relative changes in the angle of advance are relative to the width of the demagnetization phase angle, i.e. at 100% it would be off until the next switching point.

Table 1. Description of trials of the drive speed step responses

trial	description
1	ref. speed step from 1000 to 2000 [rpm]; advance angle +00[%]; torque 0,00[Nm]
2	ref. speed step from 1000 to 2000 [rpm]; advance angle +80[%]; torque 0,00[Nm]
3	ref. speed step from 4000 to 5000 [rpm]; advance angle +80[%]; torque 0,00[Nm]
4	ref. speed step from 1000 to 2000 [rpm]; advance angle +80[%]; torque 0,15[Nm]
5	ref. speed step from 1000 to 2000 [rpm]; advance angle -80[%]; torque 0,00[Nm]
6	ref. speed step from 1000 to 2000 [rpm]; advance angle -80[%]; torque 0,15[Nm]

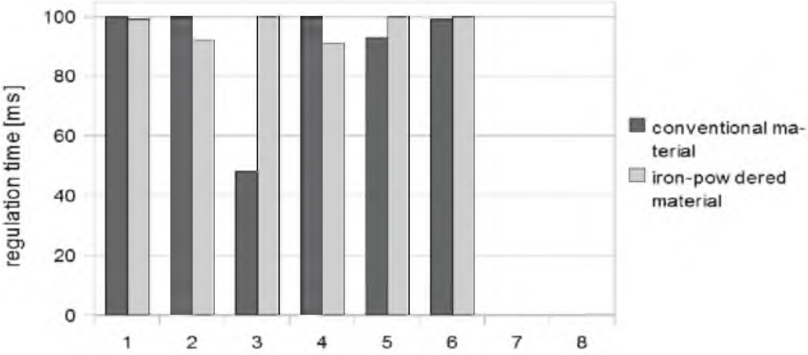

Fig. 8. Relative regulation time comparison (% of maximum value measured on each trial) at different drive step responses

Comparisons on Figure 8 shows that in the trials of low-impact rolling resistance (at low speeds) motor from powder material has better dynamic properties. In general there are no significant differences in drives dynamic performance between two types of construction materials. More detailed researches in the field of dynamic performance need to be done.

3. Summary

This paper presents the preliminary results of extensive research over powder magnetic circuit of switched reluctance motor and comparison with a classic design with isolated, rolled metal sheets. There was defined thesis on improving the energy performance of the SRM drive through the introduction of modern construction materials doped with iron powder magnetic circuit. Achievements in other fields of this technology use led to the initial justification and motivate the implementation the hardware system to validity of the presented thesis. The achievements in the implementation of control algorithms – particularly in the field of software phase-locked loop (SPLL) implies the further development of the control system and allows the possibility of objective comparison of the SR motor material construction by compensating mechanical imperfections of shaft position sensor.

In the paper the design of bench – including the main measurement tools and methodology of the study was presented. Research with an emphasis on the static and dynamic properties of the drive was shown. Despite the considerable differences of the mechanical rolling resistance caused by different rotor bearings used in compared constructions, the improvement of the energy performance of iron powdered magnetic circuit was clearly shown.

A careful analysis of the obtained data confirms the established view. It seems reasonable to check the drives performance comparison at different supply voltage level and with the approximate characteristics of the bearings used in both designs in the future.

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