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Experimental-Base Analysis of the Effect of Adding PM Disc to the Hysteresis Motor Under Steady-State Conditions

Ali Behniafar

Department of Electrical Engineering, Faculty of Engineering, Gonbad Kavous University, Gonbad Kavous, Iran

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ABSTRACT

The hysteresis synchronous motors have attracted the attention of the nuclear industry due to their advantages such as low noise, high mechanical strength, and group feed capability. These motors have some disadvantages such as low power factor, low output torque, low efficiency, and the hunting phenomenon that created fundamental limitations in related industries. One of the most practical methods to decrease the shortcomings of the hysteresis motor is to combine it with a permanent magnet synchronous motor. This hybrid motor is called a permanent magnet hysteresis synchronous motor (PMHS). In this article, a permanent magnet disc will be added to the hysteresis motor to form the PMHS motor. Then, by performing several experiments on two hysteresis and PMHS motors, the performance of each will be analyzed and evaluated. Experimental results show that by combining a permanent magnet motor with a hysteresis motor, the defects of the hysteresis motor are significantly reduced and the new motor performs much better than the hysteresis motor.

***Index Terms*—**Axial flux structure, disc-type, hybrid machine, hysteresis motor, permanent magnet hysteresis synchronous motor (PMHS), permanent magnet motor

I. INTRODUCTION

One of the best motors in the use of nuclear centrifuges is the hysteresis motor. The reason for this choice is that the hysteresis motor has very low noise and also due to its simple and integrated rotor structure, it has high mechanical strength, which makes it very suitable for high-speed applications. In addition, the presence of starting torque in the hysteresis motor, as well as the lack of need for a rotor position sensor, has provided the possibility of group feeding of this motor which plays a significant role in reducing the cost of the nuclear industry. On the other hand, low power factor, low efficiency, and low output torque of the hysteresis motor are among its main disadvantages. This has led to major limitations on the nuclear industry. Also, since the rotor poles of the hysteresis motor do not have a specific location on the rotor surface, with a slight disturbance, the motor speed begins to oscillate at low frequencies, which is known as the hunting phenomenon. These speed changes will also have unfavorable effects on the output of the nuclear industry.

The basic idea of using the hysteresis phenomenon to produce torque in electrical motors was proposed by Steinmetz in 1917 [1]. He stated that the stator of the hysteresis motor is identical to a conventional induction machine, but its rotor is made of a material with noticeable hysteresis features. If the rotating field of the stator sweeps the surface of the rotor, according to the hysteresis characteristic, the induced field in the rotor falls slightly behind the stator field, which causes torque. He also found that the hysteresis motor has disadvantages such as low efficiency and low power factor. Many methods and researches have been presented to eliminate these disadvantages, the most important of which will be discussed below.

Until 1947, the only use of hysteresis motors was in watches with an output power range of 5–10 mW. The input power of these watches was about 2–3 W, which means that the motor efficiency was 0.5% in the best case and 0.16% in the worst case. Therefore, the construction of a hysteresis motor on a larger scale was not economical at all. Roters changed the stator structure of the hysteresis motor, which significantly increased the efficiency of the motor [2]. He found that the stator with slot opening caused fluctuations in the air gap flux distribution. These

Corresponding author:
Ali Behniafar

E-mail:
ali_behniafar@gonbad.ac.ir

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high frequency oscillations cause many hysteresis and eddy current losses, which are called parasitic losses. This reduces the efficiency of hysteresis motors. In older structures, air gap was increased to reduce parasitic losses, which increased the magnetization current as well as copper losses. By construction of a stator with closed slots, Roters was able to reduce parasitic losses and greatly improve the efficiency of hysteresis motors. Closing the stator slots increases the leakage flux of the stator windings and therefore reduces the power factor and has other adverse effects on the behavior of conventional synchronous and asynchronous machines, but in the case of a hysteresis motor, the advantages of slot closure are so valuable that its disadvantages can be overlooked.

Copeland and Slemon published their studies on the hysteresis motor in three papers [3-5] in 1963, 1964, and 1969. They found that if the stator input voltage were reduced after the motor reached steady state, the efficiency and power factor of the machine would be improved, while this would also reduce the motor torque. Therefore, there must be an optimal point at which compromises are made between power factor and efficiency with torque.

In 1982, Kataoka et al. investigated the effects of overexcitation on hysteresis motor performance [6]. The magnetic behavior of the rotor hysteresis material will change when the stator voltage increases and then returns to its nominal value. By presenting a method for analyzing these changes in the magnetic behavior of the rotor hysteresis material, they stated that the motor performance is greatly improved under these changes.

In 1987, Cannistra and Sylos investigated two cylindrical hysteresis motors of circumferential flux and radial flux [7]. By examining and analyzing the radial flux motor, they found that the permanent magnet characteristic of the rotor material has a significant effect on the motor efficiency. The use of Alnico-5 makes it possible to compare the efficiency of a hysteresis motor with the efficiency of a conventional induction motor.

Another idea to improve the performance of the hysteresis motor was to restructure it. Here are some of the most important methods in this field.

In 1958, Papst introduced a method of restructuring the hysteresis ring [8]. In this method, the hysteresis ring used in the cylindrical hysteresis motor is made by putting several separate curved pieces (split bow-shaped). The gaps created between the curved pieces of the rotor create magnetic saliences that increase the synchronous torque (reluctance torque).

In 1978, Wakui carefully examined the structure presented by Papst [9]. He found that the magnetic field intensity in the circumferential direction in a rotor with a gap is much greater than in a rotor without a gap. This leads to a better power factor, efficiency, and starting conditions in a hysteresis motor with a gap than in conventional hysteresis motors.

In [10], by using slotless disc-type structures, including double-sided, multi-layer structures and a combination of circumferential and axial flux structures, they have led to the improvement of hysteresis motor performance. This reference presents different structures for hysteresis motor in one frame. All of these structures have slotless stator core, and by adding hysteresis discs or changing the connections of the windings, they have created and evaluated various structures such as axial flux, circumferential flux, one-side, double-sided, etc.

In [11], a new structure for the hysteresis motor was presented. In this structure, by combining the disc-type structure with the cylindrical structure, an attempt was made to improve the efficiency of the hysteresis motor.

Other methods that have been proposed to improve the performance of the hysteresis motor include combining this motor with other motors.

The first permanent magnet hysteresis synchronous motor (PMHS) motor was proposed by Perov in 1959 [12]. He combined the permanent magnet with the hysteresis material to provide a new structure for the rotor. In this machine, the total torque at synchronous speed is obtained from the sum of the torques caused by the permanent magnet and the hysteresis material.

In 1984, Rahman et al. investigated the effect of adding a permanent samarium-cobalt magnet to a cylindrical hysteresis motor [13]. They showed that the use of this magnet compared to other magnets, such as Alnico 5, improves the performance of the machine due to the increase in the excitation voltage of the air gap.

In [14], a disc-type PMHS motor was presented. This reference has provided an analytical method for predicting the steady-state performance of the PMHS motor. Also a prototype PMHS motor has been built and tested. In this reference, it is shown that the disc-type structures are very suitable for combining a permanent magnet with a hysteresis motor.

In [15], a new numerical method for transient analysis of magnetic hysteresis motor was presented. In this reference, the hysteresis behavior of the rotor material is modeled using the Jiles–Atherton model and showed that the initial magnetization state of the rotor material can have a significant effect on motor performance.

Reference [16] also provides a new structure for combining the PM motor with a hysteresis motor. This structure, which is in the category of cylindrical structures, has improved the performance of the hysteresis motor to some extent. One of the biggest weaknesses of this structure is the incorrect choice of path for the flux of the magnets.

The purpose of this article is to add a permanent magnet disc to the disc-type hysteresis motor and to evaluate and compare the performance of both motors (hysteresis and PMHS). In this article, two double-sided disc-type motors are manufactured. One motor has two hysteresis discs (hysteresis motor) and the other has a hysteresis disc and a permanent magnet disc (PMHS motor). Then their performance is evaluated and compared based on practical experiments. In the next section, the structure and design information of the two motors are presented, and finally, in the third section, the results of the experiments are analyzed.

II. THE STRUCTURES OF THE PROPOSED HYSTERESIS AND PMHS MOTORS

In this section, the structures of the proposed hysteresis and PMHS motors are introduced. According to the analysis performed in [10, 14], the selected structure of this article is a double-sided slotless disc-type structure. In general, the reason for choosing this structure can be summarized as follows:

1. flexibility and fit of disc-type structures for use in hybrid structures;
2. slot removal to reduce air gap fluctuations and hence to reduce parasitic losses;
3. use of toroidal type winding to reduce the end winding length and thus to reduce the leakage flux;
4. use of holders made of Teflon to increase the power density of the machine.

The proposed structure for both hysteresis and PMHS motors is shown in Fig. 1. The stator of both motors is made by rolling the silicon steel sheet, and its winding is toroidal. The hysteresis discs are made of Fe-Cr-Ni-Mo-C alloy, known as VCN-150. The property of magnetic residue in this alloy appears after performing a special heat treatment. The material of the hysteresis disc holders is selected from a light nonmagnetic material (Teflon) to close the flux path inside the hysteresis disc circumferentially and also to increase the power density of the machine. The magnet holder is made of ferromagnetic material (steel-CK45) to pass the flux of magnets with minimal attenuation.

The PMHS motor was created by replacing one of the hysteresis discs with a PM disc. The nominal specifications of the two hysteresis and PMHS motors are given in Table I. The information in Table I is the nominal parameters of the machine in the steady-state and maximum loading condition and is sufficient to adjust the test conditions. It should be noted that the tests were performed at maximum load conditions because the analysis of the

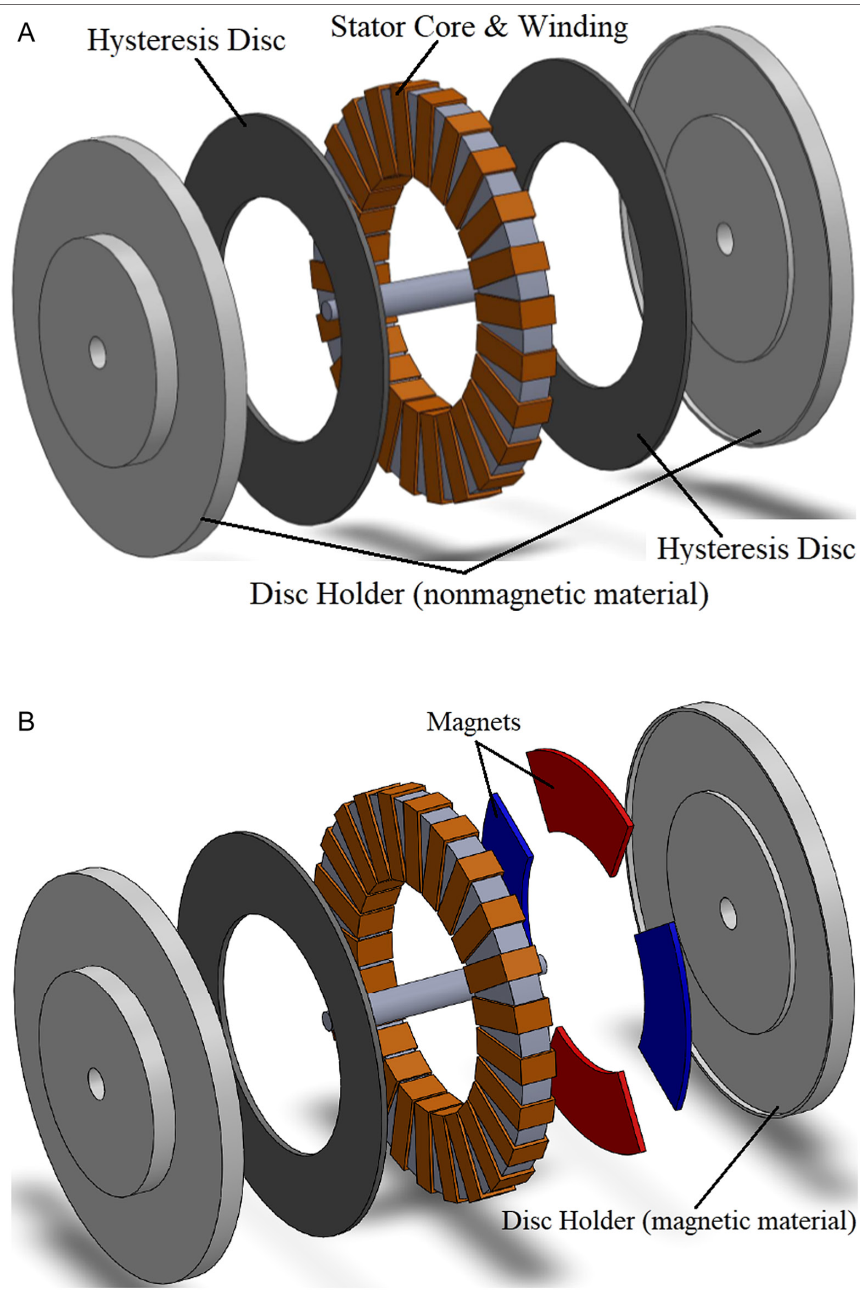

Fig. 1. Proposed structure. (a) Hysteresis motor, (b) PMHS motor.

TABLE I. NOMINAL SPECIFICATIONS OF HYSTERESIS MOTOR AND PMHS MOTOR

Quantity	Value
Motor output power	$P_{out} = 60$ W
Terminal voltage	$V_{t,L\text{-}L} = 130$ V
Number of phases	$m = 3$
Frequency	$f = 50$ Hz
Rotor speed (synchronous speed)	$n_m = 1500$ rpm

PMHS, permanent magnet hysteresis synchronous motor.

behavior of hysteresis motors at partial loads is very complex and requires hysteresis curve modeling methods. Of course, it is necessary to mention that since the suffering of load changes at synchronous speed is small for hysteresis motors, the machine nominal information is approximately equal to the maximum load condition information.

Using the relationships presented in [10, 14], a hysteresis motor and a PMHS motor are designed and built, the design information of which is presented in Table II. It should be noted that the design information of the hysteresis motor and the PMHS motor is the same and differs only in the PM disc. The dimensions of the PM disc have also been adopted in such a way that the nominal power of both motors is equal.

TABLE II. DESIGN INFORMATION OF TWO HYSTERESIS AND PMHS MOTORS

Quantity	Value
Number of winding turns per phase	$N_s = 192$
Number of winding layers per phase	$N_{layer} = 4$
Number of turn per winding layer	$N_c = 48$
Number of coils per phase	$N_{coil} = 2$
Connection type of armature windings	Star
Coil pitch	Complete
Wire diameter	$d_{wire} = 0.7$ mm
Inner diameter of hysteresis disc	$D_i = 150$ mm
Outer diameter of hysteresis disc	$D_o = 250$ mm
Thickness of hysteresis disc	$t_r = 4$ mm
Axial thickness of stator core	$L_s = 20$ mm
Remanence of PMs (for PMHS motor)	Ferrite, $B_{r,PM} = 0.4$ T
Axial length of PMs (for PMHS motor)	$l_{pm} = 5$ mm
Axial thickness of magnet holder disc (for PMHS motor)	$L_r = 10$ mm
Airgap length	$g = 1.5$ mm

PMHS, permanent magnet hysteresis synchronous motor; PM, permanent magnet.

III. EQUIVALENT CIRCUITS OF HYSTERESIS AND PMHS MOTORS

In this section, in order to gain a better understanding of the performance of hysteresis and PMHS motors, the equivalent circuit of each of them is analyzed and examined in a steady state at synchronous speed and with maximum load. According to the equations presented in [14], the equivalent circuit of the double-sided disc-type hysteresis motor in a constant state and maximum load conditions is shown in Fig. 2.

In the equivalent circuit of Fig. 2, V_t, R_s, R_C, X_g, and E_f represent the input voltage of each phase of the stator, the resistance of the stator windings, the equivalent resistance of the core losses, the reactance of the air gap, and the induced voltage of each disc, respectively. In this equivalent circuit, the R_h and X_h are equivalent impedance of the hysteresis disc. The larger the area of the operational hysteresis loop of the rotor, the larger the R_h value and the lower the X_h value [14]. This leads to an increase in power factor, output torque, and motor efficiency. There are two ways to achieve a large area hysteresis loop. One method is to increase the input terminal voltage. Increasing the terminal voltage will increase the current and heat, as well as disrupt insulation. The second method is to use a material with a higher hysteresis property, which also creates many limitations and costs.

Another way to improve the performance of a hysteresis motor is to add a permanent magnet to it (PMHS motor). The equivalent circuit of the PMHS motor is shown in Fig. 3 [14].

In the equivalent circuit of Fig. 3, E_{fPM} and X_s are induction voltage of the PM disc (back electromotive force (emf)) and synchronous reactance, respectively. It is clear that the presence of back emf of PM disc in the equivalent circuit reduces the current and increases the power factor. Also, the output torque at synchronous speed in this machine is obtained from the sum of hysteresis torque and PM torque. This leads to increased torque and ultimately increased machine efficiency.

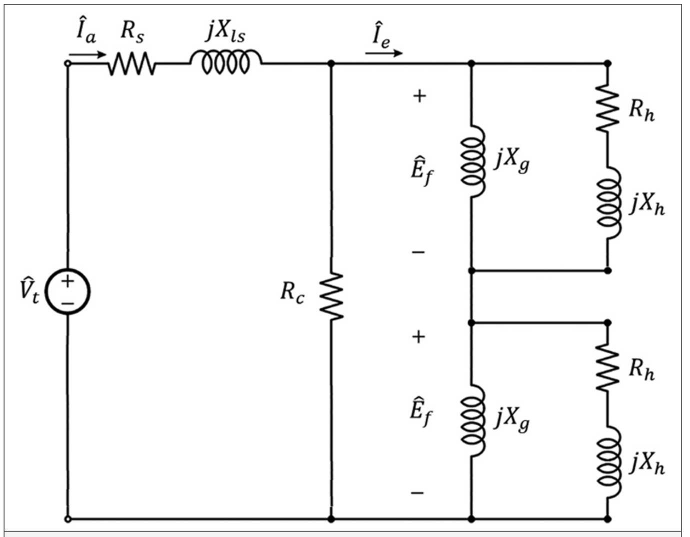

Fig. 2. Equivalent circuits of double-sided disc-type hysteresis motor.

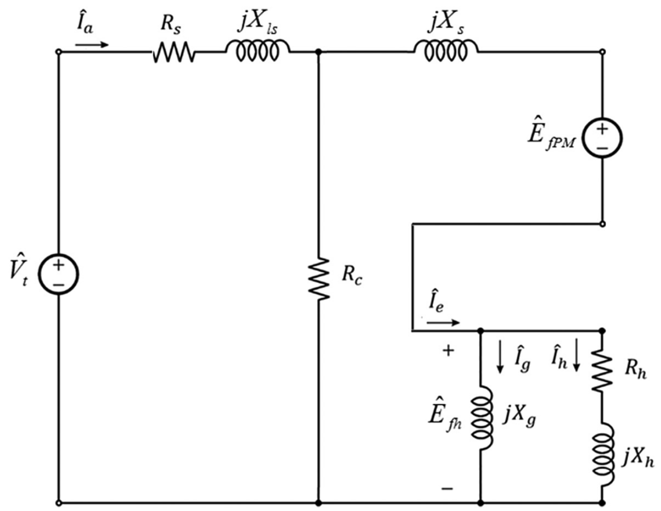

Fig. 3. Equivalent circuit of the disc-type double-sided PMHS motor.

IV. EXPERIMENTAL RESULTS

In this section, the experimental results of the two hysteresis and PMHS motors are analyzed.

Fig. 4 shows the built motors as well as the test stand. These motors are built based on the design information presented in Table I and Table II.

In the following, the most important performance parameters of the hysteresis and PMHS motors, which are obtained from experimental results, are compared with each other and analyzed. It should be noted that in these experiments, an attempt has been made to provide maximum load conditions at synchronous speed (1500 rpm). This condition is achieved by applying frictional torque. In this way, at each terminal voltage, the exit threshold of synchronism was measured by increasing the frictional torque to the shaft. It should be noted that the practical measurement of synchronous torque of hysteresis motors requires advanced equipment (due to their low range) that is less available. Of course, by excluding iron losses, the output power of the car can be obtained from the difference between input power and copper losses. Then, having

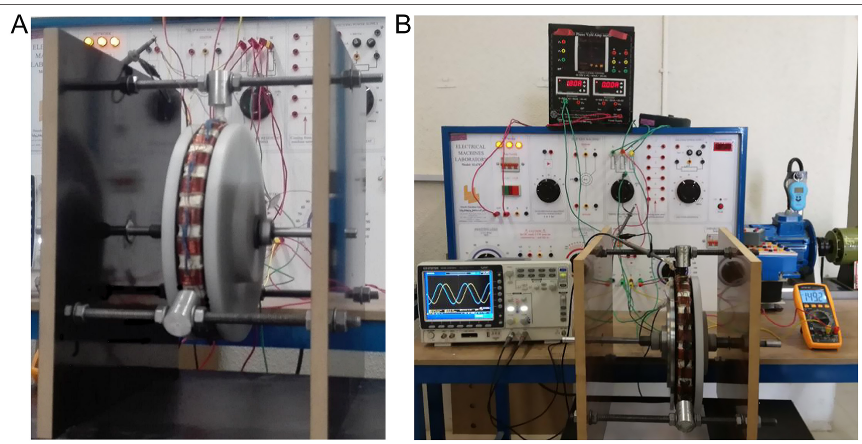

Fig. 4. (a) Built hysteresis motor. (b) Test stand for the PMHS motor.

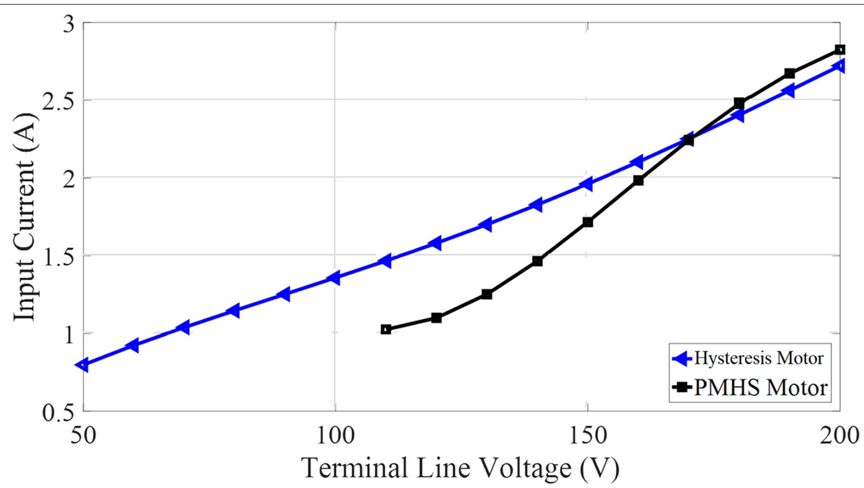

Fig. 5. Variations of input current versus input line voltage for hysteresis motor and PMHS motor.

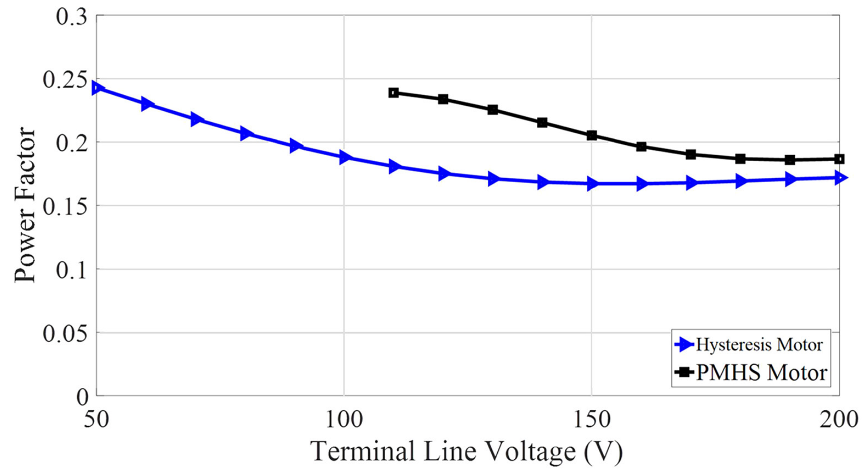

Fig. 6. Variations of power factor versus input line voltage for hysteresis motor and PMHS motor.

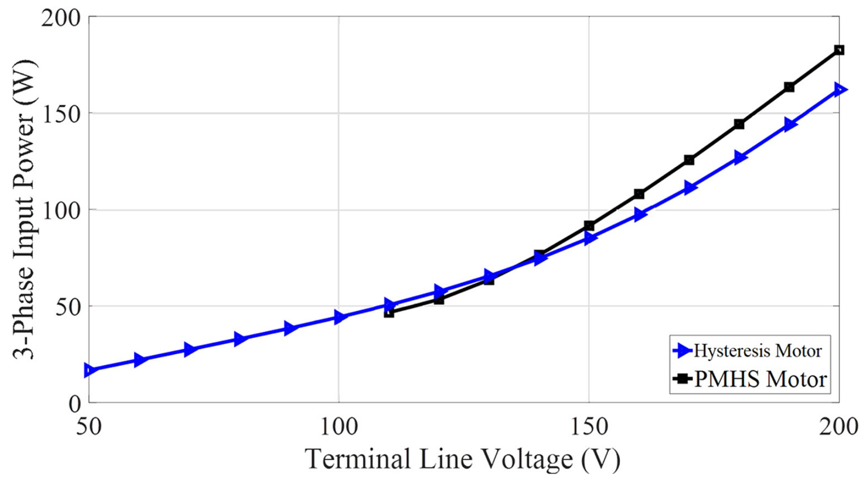

Fig. 7. Variations of input power versus input line voltage for hysteresis motor and PMHS motor.

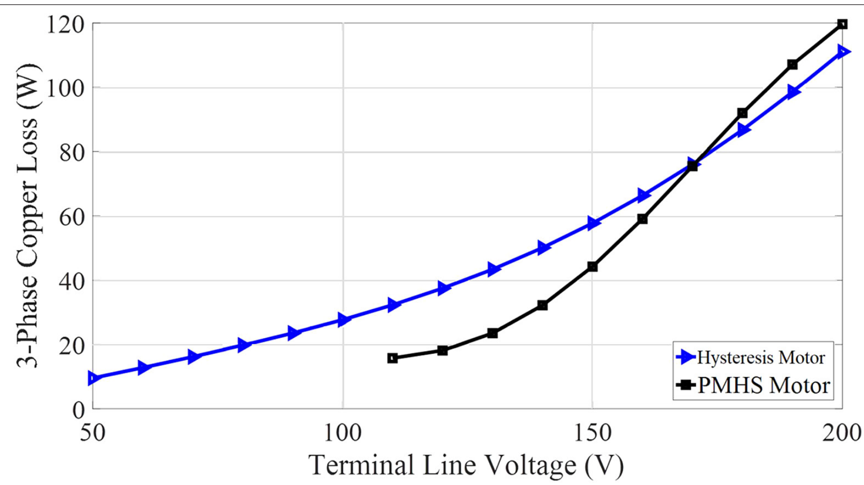

Fig. 8. Variations of copper loss versus input line voltage for hysteresis motor and PMHS motor.

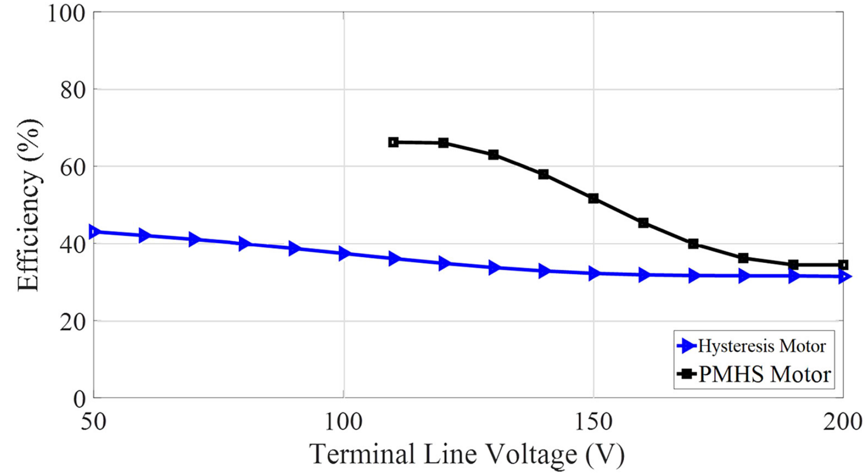

Fig. 9. Variations of motor efficiency versus input line voltage for hysteresis motor and PMHS motor.

the synchronous speed, the maximum synchronous torque can be calculated. This value at nominal voltage is equal to 0.095 N m and 0.223 N m for hysteresis motor and PMHS motor, respectively. Because the range of torque variations in synchronous speed in both hysteresis and PMHS motors is very small, the loading test of these motors is very difficult and requires high-tech equipment. Therefore, by increasing the terminal voltage (10 Volt per step), the performance parameters of the machine are evaluated. In this paper, the frictional load is used to achieve the maximum load, and by performing several experiments, the maximum load at each terminal voltage is obtained. In these experiments, it was not possible to apply a wide range of input voltage due to limitations such as the maximum allowable current and the minimum torque required for synchronization.

Fig. 5 shows the changes in stator current relative to stator terminal voltage variations. As can be seen from this figure, at a constant voltage, the PMHS motor has less current than the hysteresis motor. The reason for this can be explained by the equivalent circuits presented in Section III of this paper, which shows that the presence of internal voltage of magnets in the equivalent circuit will reduce the motor current.

The variation curve of the power factor relative to the input voltage variations is shown in Fig. 6. A higher power factor of the PMHS motor than the hysteresis motor was also expected according to the analysis presented in Section III.

Figs. 7 and 8 show the variations of input power and copper losses of motors relative to variations of input voltage, respectively. From these figures, it can be seen that at a constant voltage, the PMHS motor has fewer losses than the hysteresis motor. However, the output torque of the PMHS motor is the sum of the torques caused by the magnets and the hysteresis disc and is much higher than the output torque of the hysteresis motor, which leads to a significant increase in the efficiency of the PMHS motor compared to the hysteresis motor. This can be clearly seen in Fig. 9.

Examination and comparison of the experimental results show that the addition of a permanent magnet to the hysteresis motor can significantly improve the performance of the hysteresis motor. It should be noted that this combination also has two drawbacks. One is that the balance of axial forces in this hybrid machine (PMHS motor) is disturbed, but this problem can be solved to a desirable level by adopting a suitable assembly mechanism and bearing. In

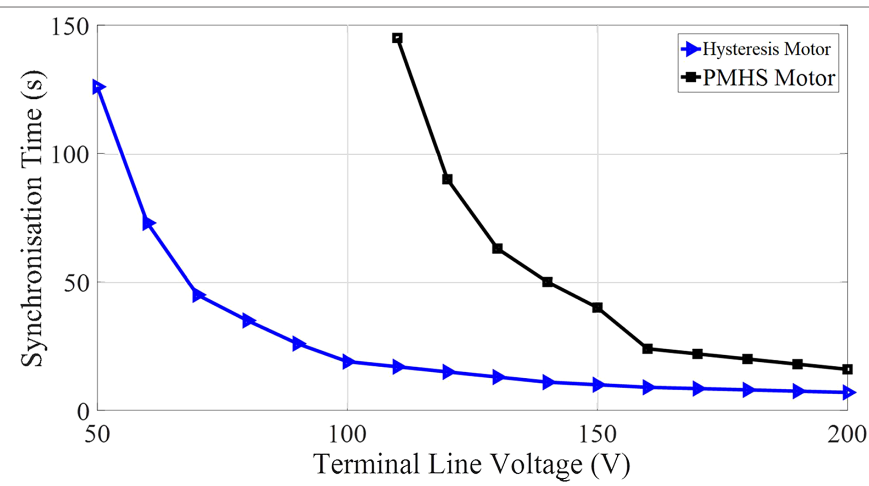

Fig. 10. The synchronization time variations curve with respect to the input line voltage for hysteresis motor and PMHS motor.

this article, due to the small nominal power of these motors, the presence of suitable washers and bearings prevent axial forces. Another disadvantage is that the synchronization time of the PMHS motor is increased compared to the hysteresis motor. This is also due to the annoying torque caused by the magnets in the asynchronous regime. The difference in synchronization time between the two hysteresis and PMHS motors can be seen in Fig. 10. It should be noted that in applications where the motor is powered by the drive, this defect will not matter much.

V. CONCLUSION

Hysteresis motors have disadvantages such as low power factor, low output torque, and low efficiency, which have severely limited their related industries. One way to improve the performance of a hysteresis motor is to add a permanent magnet to it. In this paper, two hysteresis and PMHS motors were manufactured and tested. Examination of the test results shows that the addition of a permanent magnet significantly improves the performance parameters of the hysteresis motor such as input current, power factor, output torque, and motor efficiency. On the other hand, this combination increases the synchronization time of the motor and also disturbs the balance of its axial forces. It should be noted that in situations where these motors are powered by the drive (which is often the case), the synchronization time is controlled by the drive and the mentioned fault is not important. Also, by using the appropriate and robust assembly process, the unbalance of the axial forces can be overcome.

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REFERENCES

1. C. P. Steinmetz, *Theory and Calculation of Electrical Apparatus, New York, McGraw-Hill book company, inc.*, 1917.
2. H. C. Roters, "The hysteresis motor-advances which permit economical fractional horse power rating," *AIEE*, vol. 66, pp. 1419–1430, 1947.
3. M. A. Copeland, and G. R. Slemon, "An analysis of hysteresis motor: I-Analysis of the idealized machine," *AIEE*, pp. 34–42, 1963.
4. M. A. Copeland, and G. R. Slemon, "An analysis of hysteresis motor: II-the circumferential flux machine," *IEEE Trans. Power Apparatus Syst.*, vol. 83, no. 6, pp. 619–625, 1964. [CrossRef]
5. M. A. Rahman, M. A. Copeland, and G. R. Slemon, "An analysis of the hysteresis motor part III: Parasitic losses," *IEEE Trans. Power Apparatus Syst.*, vol. 88, no. 6, pp. 954–961, 1969. [CrossRef]
6. T. Kataoka, T. Ishikawa, and T. Takahashi, "Analysis of a hysteresis motor with overexcitation," *IEEE Trans. Magn.*, vol. 18, no. 6, pp. 1731–1733, 1982. [CrossRef]
7. G. Cannistra, and M. Sylos, "*A model for the hysteresis motor analysis*," Electric Energy Conference Adelaide, October 1987, pp. 648–654.
8. H. Papst, "Electric rotary-field system." United States Patent US2834895A, May 1958.
9. G. Wakui, "Hysteresis motor with reaction torque and its analysis," *Electr. Eng. Jpn*, vol. 98, no. 5, pp. 58–67, 1978. [CrossRef]
10. A. Darabi, H. Tahanian, Shayan Amani, and Mohammadreza Sedghi, "An experimental comparison of disc-type hysteresis motors with slotless magnetic stator core," *IEEE Trans. Ind. Electron.*, vol. 64, no. 6, pp. 4642–4652, 2017. [CrossRef]
11. R. Nasiri-Zarandi, M. Mirsalim, and A. Tenconi, "A novel hybrid hysteresis motor with combined radial and axial flux rotors," *IEEE Trans. Ind. Electron.*, vol. 63, no. 3, pp. 1684–1693, 2016. [CrossRef]
12. V. I. Perov, "Synchronuos motor with excitation by permanent magnet with hysteresis loop," *Vestn. Elektropomyshlennosti*, vol. 3, p. 32, 1959.
13. M. A. Rahman, A. M. Osheiba, and T. A. Little, "Effects of Samarium Cobalt Permanent Magnet on the performance of Polyphase Hysteresis-Reluctance Motors," *IEEE Transaction on Magnetics*, vol. 20, no. 5, pp. 1765–1767, 1984.
14. A. Behniafar, and A. Darabi, "Analytical modeling of disc-type permanent magnet hysteresis motor in steady-state operational conditions," *COMPEL Int. J. Comput. Math. Electr. Electron. Eng.*, vol. 36, no. 4, pp. 991–1007, 2017. [CrossRef]
15. R. Galluzzi, N. Amati, and A. Tonoli, "Modeling, design, and validation of magnetic hysteresis motors," *IEEE Trans. Ind. Electron.*, vol. 67, no. 2, pp. 1171–1179, 2020. [CrossRef]
16. S. F. Rabbi, P. Zhou, and M. A. Rahman, "Design and performance analysis of a self-start radial flux-hysteresis interior permanent magnet motor," *IEEE Trans. Magn.*, vol. 53, no. 11, 1–4, 2017. [CrossRef]

Ali Behniafar was born in 1987. He received his M.S. and Ph.D. degree from Shahrood University of Technology, Shahrood, Iran, in 2011 and 2017, respectively. He joined the Gonbad Kavous University, Gonbad Kavous, Iran, in 2018. His research interest is designing and manufacturing of electrical machine.