Dynamic Modelling and Analysis of Electric Motor with Integrated Magnetic Spring Driving Weaving Loom Application

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Abstract—This paper presents the dynamic modeling and analysis of an electric motor with integrated magnetic spring (EMMS) when it is coupled to a weaving loom application. The EMMS can provide the majority part of the oscillating part of the load in a passive way by the magnetic spring. The electric motor provides the average torque and the remaining oscillating part in an active way. This reduces the energy consumption. To create an accurate dynamic model for the EMMS, lookup tables are generated from a finite element model (FEM). Further, a 4-bar linkage mechanism is employed to emulate the behavior of the shedding mechanism of a real weaving loom application. Eventually, the whole system dynamic model was created in Matlab environment. Moreover, a complete experimental setup was constructed to validate the effectiveness of the proposed dynamic model and the EMMS behavior. It is shown that the proposed dynamic model effectively predicts the performance of the EMMS system. Besides, it is proved that the EMMS can effectively reduce the energy consumption of the weaving loom application. The amount of reduction in the energy consumption depends on the designed magnetic spring. For the considered application, it can reach 57%.

Index Terms—Double stators, Energy consumption, Electric machines, Magnetic spring, weaving looms

I. INTRODUCTION

Electric motor systems are the main load of the industry. They consume the major part of the generated energy, which is about 40% of the generated energy worldwide. This means that a small reduction in the energy loss will save a huge amount of money as well as it will reduce the impact on the environment [1]-[5]. Therefore, the energy analysis of the electric motor system and how to reduce the energy loss is a critical and essential research topic. Consequently, an accurate fast dynamic model of the electric motor system is always necessary particularly when there is high dynamics in the system [6]-[12].

In the literature, several dynamic models have been proposed for the electric motor system. The main components of the electric motor system are the electric motor, the power electronics converter, the load and the control system. The electric motor represents the main core of the system and its dynamic model is more complex. This is due to the fact that the electric motor is a multiphysics (electrical, magnetic, thermal and mechanical) device. Therefore, there are a lot of efforts to create a fast and high-fidelity dynamic model for the motor to be used to investigate the performance of the electric motor system [6]-[8]. For example, in [11], the design and modelling of an interior PM traction motor for driving railway vehicle was presented. The dynamic model employed a static finite element analysis to obtain the flux linkage of the phases and the torque as functions of the current of the phases and rotor position. This way the effect of the slot harmonics can be included as well as the magnetic saturation and cross coupling. In [12], a modelling method using the 2D FEM for the hybrid rotor synchronous machine was introduced. The rotor consists of two parts; one is a surface mounted PM rotor and the second one is a reluctance rotor. Lookup tables (LUTs) for the flux and torque were generated using 2D FEM. It was found that the proposed model can estimate the performance of the machine with a sufficient accuracy; compared to the 3D FEM the error is less than 7.3%.

The shedding mechanism in a weaving loom application is a highly dynamic industrial load. The load torque varies strongly from a high positive value to a high negative value in a cyclic manner, with an average torque that is much smaller than the peak. This highly cyclic load variation not only affects the energy consumption but also the system sizing [13]-[18]. In the modern looms, high speed is a key element hence, the power consumption becomes an essential factor. In the literature, there is a lack of research about the weaving loom driving system [13]. In [13], the instantaneous input power of the driving motor of the weaving loom was measured. It was observed that the load profile of the weaving loom is impulsive with a non-uniform shape. Further, it was noticed that the loom does not run in a perfectly cyclic manner. For this type of loads, mechanical or magnetic springs can be employed to store energy and release it when needed i.e. supporting the electric driving motor. Magnetic springs are preferred over mechanical springs thanks to their long life time and power density [19]-[20]. In [20], a magnetic spring assisted PM motor for high dynamic industrial applications was reported. It was observed

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that the energy consumption and the peak torque of the magnetic spring assisted motor are about 6 and 3 times respectively lower than using the conventional PM motor. However, the presented drivetrain uses the magnetic spring as a separate component between the motor and the load. This leads to some challenges such as: 1) there should be enough space between the motor and the load to insert the magnetic spring; 2) separate cooling for the magnetic spring is needed.

To this end, recently, integrating the electric drive system components obtained a great interest towards increasing the reliability and compactness of the system [21]-[26]. Therefore, an integrated magnetic spring inside the electric motor could be an attractive solution. The electric motor with integrated magnetic spring (EMMS) is a novel proposed machine to be used as a driving motor for the weaving looms application. The main advantage of the EMMS is that part of the oscillating load torque can be provided by the magnetic spring in a passive way while the electric motor provides the average torque in an active way. Consequently, the EMMS consumes lower energy compared to the conventional electric motors.

In this paper, the performance analysis of a novel electric machine (an electric motor with integrated magnetic spring, EMMS) when it is coupled to a weaving loom application is presented. The electric motor and the magnetic spring share same rotor. The EMMS was not reported in the literature before. Therefore, an accurate dynamic model for the EMMS is proposed. Then, the whole system dynamic model is introduced to investigate the performance of the EMMS. Eventually, experimental measurements are reported to validate the theoretical analysis.

II. DYNAMIC MODEL OF THE SYSTEM

The main components of the system are the EMMS, power electronic converter, weaving loom shedding frame load as well as the control system. Fig. 1 shows a schematic diagram of the complete system. It is evident that the EMMS is directly driving the weaving loom application i.e. without using a gearbox.

A. The weaving loom

In the weaving loom application, the shedding mechanism load torque and inertia are affected by several factors such as the width and speed as well as the rotating and oscillating masses. Substantial amounts of the power of the looms are consumed in operating the picking, shedding, and other mechanisms. For the simulation and experimental research work, the weaving loom shedding mechanism is emulated by a 4-bar linkage, as shown in Fig. 2. The dimensions (a, b, c and d) and rocker mass of the 4-bar linkage (Fig. 2) are selected to reflect exactly the behavior of a given real weaving loom.

Based on the dynamics of the 4-bar linkage, the relation between the absolute peak torque value and speed can be obtained as shown in Fig. 3 [26]. At a given speed, the torque varies in an alternating way with respect to the rotating position. For example, at 600 rpm the peak torque varies from +90 N.m to – 90 N.m every 90 mechanical degrees as shown in Fig. 4. The total moment of inertia of the 4-bar linkage system is about 0.65 kg.m².

Consequently, the load torque ($T_l$) of the 4-bar linkage can be approximately represented by:

$$T_l = T_{pl} \sin(n \cdot \theta_i)$$  \hspace{1cm} (1)

where $T_{pl}$, $n$ and $\theta_i$ are the peak load torque, periodicity number per one mechanical revolution and rotating position angle. Notice that, for 4-bar linkage under study, $n$ in (1) equals 2.

![Fig. 2. EMMS coupled to 4-bar linkage.](image)

![Fig. 3. Peak load torque versus speed of the 4-bar linkage.](image)

![Fig. 4. Load torque of the 4-bar linkage versus rotating position at 600 rpm.](image)

B. The EMMS

As mentioned before the EMMS is an electric motor with integrated magnetic spring. The electric motor is a surface mounted permanent magnet (PM) motor. The magnetic spring is a set of magnets in the rotor and stator. Fig. 5 shows the geometry of the EMMS. Besides, several geometrical and electromagnetic parameters are listed in Table 1. It is clear that the rotor is concentrically between two stators. The rotor contains two layers of PMs. The outer layer has a high pole number (22 pole) that interacts with the outer stator windings to form an electric motor. The inner layer of the rotor has a low pole number (4 poles) that interacts with the poles (i.e. 4) of the inner stator to form a magnetic spring [24]-[25]. Consequently,
the output torque of the EMMS has two main components: An average torque component that is provided by the motor and an oscillating component that delivered by the magnetic spring. The peak torque value of both the motor and the magnetic spring depends on the designed geometry that is based on the load torque profile. The number of poles of the motor is freely to be selected while the number of poles of the magnetic spring is selected based on the number of periodicities of the load torque. The number of pole pairs of the magnetic spring equals the number of periodicities of the load i.e. \( n \) in (1) =2. The EMMS geometry of Fig. 5 is designed based on the load profile of Figs. 3 and 4 so that the peak torque of the magnetic spring is 45 N.m i.e. 50% of the peak torque of the load. Notice that, typically weaving looms work at a fixed speed e.g. 450 rpm or a limited variable speed range e.g. 400 rpm to 600 rpm. The electric motor should deliver the required average torque as well as the difference between the required oscillating load torque and the delivered magnetic spring torque.

![Fig. 5. Geometry of the EMMS.](image)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inner stator yoke thickness</td>
<td>8.5 mm</td>
<td>Number of phases</td>
<td>3</td>
</tr>
<tr>
<td>PM thickness of the magnetic spring</td>
<td>3 mm</td>
<td>Number of motor/magnetic spring poles</td>
<td>2/4</td>
</tr>
<tr>
<td>PM coverage ratio of the magnetic spring</td>
<td>0.75</td>
<td>Number of stator slot</td>
<td>36</td>
</tr>
<tr>
<td>Rotor yoke thickness</td>
<td>10 mm</td>
<td>RMS rated phase current</td>
<td>6 A</td>
</tr>
<tr>
<td>PM thickness of the motor</td>
<td>3.50 mm</td>
<td>Steel</td>
<td>M330-35A</td>
</tr>
<tr>
<td>PM coverage ratio of the motor</td>
<td>0.85</td>
<td>Motor PM type</td>
<td>NdFeB 42SH</td>
</tr>
<tr>
<td>Outer diameter</td>
<td>192 mm</td>
<td>Magnetic spring PM type</td>
<td>NdFeB 42EH</td>
</tr>
<tr>
<td>Stack length</td>
<td>110 mm</td>
<td>Rotor inertia</td>
<td>0.006 kg.m²</td>
</tr>
</tbody>
</table>

In order to build a dynamic mathematical model for the EMMS, it is essential to understand the behavior of the machine. Therefore, a 2D transient finite element model (FEM) is constructed in Ansys Maxwell. First, the rotor is rotated at a fixed speed (600 rpm) without connecting the outer stator coils to the supply i.e. no load. This way the behavior of the magnetic spring can be understood. At rotor position 0°, the magnets of the magnetic spring (see Fig. 5) with identical polarity are aligned. Hence, the produced torque equals zero. This rotor position is called the stable equilibrium rotor position. When the rotor moves from 0°, the magnetic spring produces a torque until it reaches a peak value and then it decreases again. The rotor position, at which the peak torque occurs, depends on the design of the EMMS. At rotor position 90°, the poles of the magnetic spring are aligned but the magnet polarity is opposite. Hence, the delivered torque equals zero. This rotor position is called the unstable equilibrium rotor position. Fig. 6 shows the output torque of the EMMS as a function of time at 600 rpm. The peak torque varies from about +45 N.m to -45 N.m with a sinusoidal shape containing harmonics. This torque waveform is the delivered torque of the magnetic spring and the cogging torque of the motor. To check the value of the cogging torque of the motor, the magnetic spring components in Fig. 5 are replaced by a non-magnetic material. It is found that the peak-to-peak value of the cogging torque of the motor is about 140 mN.m with a higher frequency. This means that the torque in Fig. 3 can be assumed as the torque of the magnetic spring. Fig. 7 reports the flux linkage and induced voltage in the windings versus time at 600 rpm. It is obvious that the flux linkage waveform is sinusoidal and similar for all the phases which is similar to the conventional motor behavior. Thereby, it can be understood that the flux of the magnetic spring does not affect the electric motor flux. The various losses components are shown in Fig. 8. It is clear that the core loss is about 3 times the magnet loss.

![Fig. 6. Torque of the EMMS as a function of time at no load and 600 rpm.](image)

![Fig. 7. Flux linkage (left) and induced phase voltage (right) of the EMMS as a function of time at no load and 600 rpm.](image)

![Fig. 8. Losses of the EMMS as a function of time at no load and 600 rpm.](image)
The flux density plot of the EMMS at 3 relevant rotor positions is reported in Fig. 9. It is obvious that the flux distribution inside the EMMS varies dramatically with the rotor position. This is because of the magnetic spring. When the polarity of the poles of the magnetic spring are similar i.e. position 0°, there is a high flux passing through the rotor and the inner stator cores resulting in saturation, see Fig. 9a. However, when the rotor moves from 0° to 90°, the flux of the poles of the magnetic spring start to cancel each other until it is completely cancelled at rotor position 90°. This reduces the core saturation as seen in Fig. 9b. It is worth mentioning that the rotor position 0° is a stable position because there is attraction force between the magnetic spring poles and rotor position 90° represents the unstable position because there is a repulsion force between the magnetic spring poles.

To produce an average torque from the EMMS, the current in the windings should be controlled in a similar way as the conventional surface mounted PM motor. The total output torque of the EMMS depends on the injected current waveform which depends on the load profile.

Based on the previous analysis, the dynamic mathematical model of the EMMS can be formulated in the dq rotor reference frame as follows [6], [27]. The voltage equation can be represented by:

\[
\begin{bmatrix}
\psi_d \\
\psi_q
\end{bmatrix} = \begin{bmatrix}
R_s & 0 \\
0 & R_s
\end{bmatrix} \begin{bmatrix}
i_d \\
i_q
\end{bmatrix} + \begin{bmatrix}
0 & \omega_r \rho \\
\omega_r \rho & 0
\end{bmatrix} \begin{bmatrix}
i_d \\
i_q
\end{bmatrix} + \begin{bmatrix}
\psi_d(i_d, i_q, \theta_r) \\
\psi_q(i_d, i_q, \theta_r)
\end{bmatrix}
\]

(2)

where:

- \(v, i\): Voltage and current respectively
- \(\theta_r, \omega_r\): Rotor mechanical position and speed respectively
- \(\psi, L\): Flux linkage and inductance respectively
- \(R_s\): Stator phase resistance
- \(m, d, q\): Subscripts of magnet, direct and quadrature axis components respectively
- \(P\): Pole pairs number

The torque of the EMMS can be expressed by:

\[
T_{EMMS} = T_{EM} + T_{MS}
\]

\[
T_{EM} = \frac{3}{2} P \left( \psi_d(i_d, i_q, \theta_r) + \psi_{pm} i_q - \psi_q(i_d, i_q, \theta_r) i_d \right)
\]

\[
T_{MS} = C_m \cdot MMF_r \cdot MMF_q \cdot \sin(\delta)
\]

\[
T_{EMMS}(i_d, i_q, \theta_r) = \int \frac{d\omega_r}{dt} + B \omega_r + T_I(\theta_r)
\]

(3)

(4)

where:

- \(T_{EMMS}, T_{EM}, T_{MS}\): EMMS, motor, magnetic spring and load torque respectively
- \(C_m\): Torque constant of the magnetic spring
- \(MMF\): Magento-motive force
- \(J, B\): Moment of inertia and viscous coefficient of the system respectively
- \(r, s\): Subscripts of rotor and stator respectively
- \(\delta\): Angle between the stator and rotor MMF

The main core of the mathematical model of the machine is the magnetic flux model. From the FEM analysis presented before, besides the dependency of the flux on the current, it is evident that the flux inside the machine varies with the rotor position as well. Therefore, to create the flux model, it is easier and accurate to use the FEM to generate lookup tables for \(\psi_d(i_d, i_q, \theta_r), \psi_q(i_d, i_q, \theta_r)\) and \(T_{EMMS}(i_d, i_q, \theta_r)\) [6], [11], [12]. The lookup tables are created from the FEM for various \(i_d\) and \(i_q\) and \(\theta_r\). The \(i_d\) and \(i_q\) vary from ±2 times rated current and the \(\theta_r\) varies from 0 to 180°. The 180° is one complete cycle for the magnetic spring torque which corresponds to 5.5 electrical cycles for the electric motor. The copper loss can be computed simply based on the resistance of the phase winding and the current that flows inside it. However, the magnet and core losses require obtaining the flux inside the machine. Therefore from FEM, the power losses \(P_{loss}\) are computed and lookup tables are generated for copper loss \(P_{cu}\), magnet loss \(P_{ms}\) and core loss \(P_c\). Fig. 10 shows a block diagram for the EMMS dynamic model.

**C. Inverter model and control**

The 3-phase inverter is modelled based on the state of the power electronic switches \((w_1, w_2\text{ and } w_3)\). The output phase
voltage can be computed from the input DC voltage as follows. In this paper, the switches are assumed ideal.

\[
\begin{bmatrix}
    v_{an} \\
    v_{bn} \\
    v_{cn}
\end{bmatrix} = \frac{V_{dc}}{3} \begin{bmatrix}
    2 & -1 & -1 \\
    -1 & 2 & -1 \\
    -1 & -1 & 2
\end{bmatrix} \begin{bmatrix}
    w_1 \\
    w_2 \\
    w_3
\end{bmatrix}
\]  

where:

- \(v_{an}, v_{bn}, v_{cn}\): Output three phase voltages
- \(w_1, w_2, w_3\): Status of the switches (1 = ON, 0 = OFF)
- \(V_{dc}\): DC bus voltage

The inverter switches are controlled by space vector modulation (SVM) technique based on the field-oriented control method [28], [29]. The EMMS speed is controlled as well as the \(d\)-axis current component is set to 0 A because the torque in surface mounted PM motor is generated by the \(q\)-axis current and the PM flux. This way, the copper loss is minimized.

III. DYNAMIC PERFORMANCE OF THE EMMS

In this section, the complete system (Fig. 1) dynamic model based on the previous section is modelled in Matlab. The dynamic performance of the EMMS under two cases is investigated. The first case is when the EMMS works under no load and the second case is when the EMMS is coupled to the load.

1) No load case (i.e. with no external load)

As mentioned before, the EMMS is an electric motor with integrated magnetic spring. At no load, the EMMS is not connected to the load. However, in this situation the electric motor of the EMMS is inherently loaded by the magnetic spring. Various set points for the speed controller are given i.e. 300 rpm, 420 rpm and 600 rpm as shown in Fig. 11. It is evident that the speed controller works well since the feedback speed follows accurately the reference speed.

![Speed versus time in case of no external load](image1)

Fig. 11. Speed versus time in case of no external load.

![Torque versus time in case of no external load](image2)

Fig. 12. Torque versus time in case of no external load.

![Loss versus time in case of no external load](image3)

Fig. 13. Current versus time in case of no external load.
2) Load case

The EMMS is coupled to the 4-bar linkage which represents the load profile of the weaving loom application. Similar as the no load case, the EMMS is working under speed control. Various speeds are considered to show that the behavior of the EMMS depends on the load operating point. Nevertheless, for this type of loads (i.e. weaving loom), the rotating speed of the electric motor that is driving the shedding mechanism is fixed.

![Fig. 15. Speed versus time in case of load.](image)

Fig. 15 shows the reference and feedback speed of the EMMS versus time for 300 rpm, 420 rpm and 600 rpm. Since the speed varies, the load torque of the 4-bar linkage will vary as well, see Fig. 3. Fig. 16 is a key figure in this paper, proving that the spring delivers most of the load torque at a given speed. The figure reports the different torques versus time. At 300 rpm, the load torque is lower than the magnetic spring torque (i.e. having a fixed amplitude value) and therefore, the motor counteracts the difference in the torque between the load and the magnetic spring. At 420 rpm, the load torque is approximately similar to the magnetic spring torque, hence the magnetic spring provides the required load torque. This is why the provided motor torque is very low. At 600 rpm, the load torque (Fig. 4) is higher than the magnetic spring torque (Figs. 6 and 12) and thus the motor supports the magnetic spring to provide the load torque. Compared to the conventional electric motor, the EMMS can deliver approximately the full load torque (at 420 rpm) or a part of it (above 420 rpm) in a passive way. Fig. 17 shows the dq axis current components and the phase current of the EMMS as functions of time. It is obvious that the current value varies based on the speed due to the variation of the required motor torque. In addition, when the load torque equals approximately the magnetic spring torque (at 420 rpm), the motor delivers a very low torque and hence requiring a very low current. This results in a reduced energy consumption. This is evident in Fig. 18 where the various losses are reported. It is evident that the copper loss is very low at 420 rpm resulting in low total losses.

![Fig. 16. Torque versus time in case of load.](image)

![Fig. 17. Current versus time in case of load.](image)

![Fig. 18. Loss versus time in case of load.](image)

From the previous analysis, it is clear that the EMMS can be considered as an attractive solution to reduce the energy consumption of weaving looms.

IV. EXPERIMENTAL VALIDATION

To validate the theoretical analysis presented before, a complete experimental test bench was constructed as shown in Fig. 19. The main components of the setup are the EMMS which is coupled directly to the 4-bar linkage, a 3-phase inverter...
connected the EMMS, a DC source connected to the inverter and a microlabbox to control the inverter switches. Two cases are measured as follows.

1) No load case (i.e. with no external load)

As mentioned before, at no load, the EMMS is not connected to the external load. Hence, the motor of the EMMS is inherently loaded by the magnetic spring. Fig. 20 shows various speeds operating points of the EMMS versus time i.e. 300 rpm, 400 rpm, 500 rpm and 600 rpm. It is clear that the motor speed follows the reference one with some oscillations due to mainly acceleration and deceleration of the magnetic spring. Fig. 21 reports the current of the machine versus time. The $q$-axis current amplitude varies with the speed due to the load torque variation.

Fig. 21. Measured current versus time in case of no external load.

Fig. 22. Measured torque versus time in case of no external load.

Fig. 23. Measured speed versus time in case of load.

2) Load case

In the load case, the EMMS is coupled to the 4-bar linkage. Here, it is important that the coupling position of the 4-bar linkage is correct. Any error in the coupling position will negatively affect the power consumption of the EMMS. Fig. 23 shows the speeds of the EMMS versus time. It is noticed that the oscillations in the speed are reduced when the EMMS is coupled to the load. Fig. 24 shows the current of the EMMS versus time at various speeds. It is clear that the current amplitude varies with the speed due to the load torque variation.
At 400 rpm, the EMMS provides the majority of the load torque by the magnetic spring as seen in Fig. 25. This is why the EMMS current at 400 rpm is at the lowest value compared to other speeds. Besides, it is found that 400 rpm is approximately the optimal speed at which a minimum torque is delivered by the motor of the EMMS: 20 rpm lower than the simulation. This slight difference may be due several reasons: 1) inaccuracy in the simulated load torque of the 4-bar linkage; 2) a slight error in the coupling position of the 4-bar linkage. At 600 rpm, about 50% of the load torque is provided by the magnetic spring in a passive way while the motor provides the remaining torque to achieve the load torque in an active way. This results in a reduced energy consumption. Similar observations as simulated results are clear in the measured results.

Fig. 24. Measured current versus time in case of load.

Fig. 25. Measured torque versus time in case of load.

Fig. 26 shows a comparison between the DC input power of the EMMS and the conventional PM motor when they are coupled to the same 4-bar linkage. It is found that the EMMS consumes about 57% and 36% lower input DC power at 450 rpm and 600 respectively. However, the cost of the EMMS is high as well as the manufacturability is complex compared to the conventional PM motor. Nevertheless, the higher cost of the EMMS will be paid back by lower energy consumption.

V. CONCLUSION

In this paper, the dynamic model and analysis of an electric motor with integrated magnetic spring (EMMS) for weaving loom application is presented. The EMMS can provide part of the oscillating load torque in a passive way by the magnetic spring. The electric motor can provide the remaining torque in an active way. This reduces the energy consumption. To emulate the load profile of the weaving loom’s shedding mechanism, a 4-bar linkage was used. Besides, the complete model of the whole system was presented. Experimental test bench was constructed to validate the theoretical findings.

Key findings of this paper can be listed as follows.

1) It is shown that the presented dynamic model can effectively predict the behavior of the EMMS system.
2) It is proved that the proposed EMMS can effectively reduce the required power consumption to drive the weaving loom application.
3) The amount of reduction in the power consumption depends on the designed magnetic spring.
4) For the considered study in which the magnetic spring is designed to provide 50% of the peak load torque at the rated speed, it is found by simulations and measurements that the EMMS reduces the power consumption by about 36% at rated speed (600 rpm) compared to the conventional motor.
5) Nevertheless, the amount of reduction in the power consumption can reach 57% when the EMMS runs at 450 rpm for the considered application.

REFERENCES


