Modelling and Simulation of Line Start Permanent Magnet Synchronous Motors with Broken Bars

Khalid I Baradieh* and Zakariya Al-Hamouz
Electrical Engineering Department, KFUPM University, Saudi Arabia

Abstract
LSPMSMs combine the high efficiency of the permanent magnet motors (PM) with the ease of use, simplicity in design and high starting ability of induction motors. Since there are a rapidly growing usage of this relatively new motor, studying its performance under fault conditions is necessary.

In this paper, a technique based on coupled magnetic circuit theory has been used in order to develop a mathematical model for LSPMSM under broken bar conditions. This model takes into account the rotor asymmetry due to fault in q0 reference frame. Motor’s torque, rotor speed and stator current signatures for healthy machine (with 28 bars), machine with one, five and ten broken bars are presented under no load and full load conditions. Trends obtained are in good agreement with previously reported work.

Keywords: LSPMSM; PM; Broken bar; Coupling; Fault; Signature

Introduction
Motors are the backbone of industry and manufacturing, where tens of thousands of motors are available in industry. They vary between DC, induction, synchronous, permanent magnet synchronous (PMSM), and recently, line start permanent magnet synchronous motors (LSPMSM). The motor’s name comes from its ability to start directly when connected to the source. It has permanent magnets on its rotor, and a squirrel cage starting winding. LSPMSMs combine the high efficiency of the permanent magnet motors (PM) with the ease of use, simplicity in design and high starting ability of the induction motors [1]. However, LSPMSM has a poor starting torque because of the opposite (braking) torque caused by PM [2,3].

There is a rapidly growing literature on LSPMSM focused on studying the performance and behavior of the healthy motor. The literature on studying the performance of healthy LSPMSM shows a variety of approaches. Miller [4] studied the effect of the LSPMSM rotor resistance on the synchronization of the motor. This work investigated the effect of the load moment of inertia. The same author studied and analyzed the starting performance of single phase LSPMSM by applying average electromagnetic torque, and then studied the performance of motor for different components of torque. This method is generalized to include m-phases LSPMSM with unbalance voltage on the stator [5]. Sorgrdager et al. proposed a method to design LSPMSM by dividing the whole motor into sub motors, i.e., induction motor (IM), and permanent magnet synchronous motor (PMSM); each sub motor designed using classical method of design, then both designs are combined together to have LSPMSM [6].

Under broken bar condition, there has been relatively little research work devoted for the mathematical modelling of the motor under broken bar conditions. Recently, two research articles addressed the behavior of LSPMSM under broken bar conditions. Mehriou et al. used ANSYS Maxwell® software to study the performance of this motor under broken bar fault [7,8]. The authors concentrated on the use of stator current and air-gap signatures as a possible sign to investigate the possibility of broken bar occurrence.

For other types of motors such as induction motors, some methods are based on the construction of the rotor bars where each rotor bar is represented by its RL equivalent circuit [9-13]. Hamdani et al. [14] also modeled rotor bars in induction motors based on its RL equivalent circuit where the winding function method has been used to implement the cage inductances. Chen and Zbibvanovic used the coupled circuit approach to model the rotor in induction machines [15]. The fault in induction machines represented by asymmetry in the rotor phase’s resistances and asymmetry in the rotating electromagnetic field in the airgap. Therefore, broken bar fault is represented by unbalancing in the rotor resistances.

Based on the above literature, it is quite clear that there exist no mathematical modelling of LSPMSM under broken bar conditions. As such, in this work, an attempt to develop and test such a model under different loading conditions is presented. The effect of varying the number of broken bars on the motor’s current, torque and speed will be investigated.

Mathematical Modeling
In this section, the mathematical model of LSPMSM under healthy conditions is presented followed by the proposed model under broken bar conditions.

Mathematical model of healthy LSPMSM
The line start permanent magnet synchronous motor has the characteristics of high efficiency synchronous motors with self-starting capability when connected to a fixed frequency voltage source. Synchronous excitation provided to the motor when the permanent magnets installed on its rotor. In addition, cage torque provides the motor with the induction torque for starting. Significant magnetic saliency and reluctance torque at synchronous speed resulted from the difference in permeability between the rotor core and the permanent

*Corresponding author: Khalid I Baradieh, Electrical Engineering Department, KFUPM University, Saudi Arabia, Tel: 966533591540; E-mail: Khalid.baradia@outlook.com

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magnet. At asynchronous speed, the saliency and DC excitation of the permanent magnets will cause pulsating torque components. A LSPMSM may fail to synchronize when the field strength of the magnets is too strong, because of the excessive pulsating torque component from the DC excitation of the magnet. Since the stator and rotor of the LSPMSM are magnetically coupled, coupled circuit approach is used to develop a mathematical model of the motor. Based on rotary qd0 reference frame, mathematical model of healthy LSPMSM has been developed [16,17]. For completeness, the following shows a brief description of the healthy mathematical modelling in the qd0 reference frame.

The equations of the stator and rotor voltages are defined as:

\[
\begin{align*}
V_{q0s} &= r_{ss} i_{q0s} + \frac{d}{dt} \lambda_{q0s} + \omega L_{ls} i_{d0s} + \alpha \omega \lambda_{d0s} \\
V_{d0s} &= r_{ss} i_{d0s} + \frac{d}{dt} \lambda_{d0s} + \omega L_{ls} i_{q0s} - \alpha \omega \lambda_{q0s} \\
V_{q0r} &= r_{rr} i_{q0r} + \frac{d}{dt} \lambda_{q0r} \\
V_{d0r} &= r_{rr} i_{d0r} + \frac{d}{dt} \lambda_{d0r} \\
V_{00} &= 0
\end{align*}
\]  

Where the primed quantities means the values referred to the stator side. Subscripts s, r referred to the stator and rotor, respectively. \( V_{q0s} \), \( V_{d0s} \), \( V_{q0r} \), \( V_{d0r} \) are the q, d, 0 axis of the stator and rotor voltages, respectively. \( r_s, r_r \) are the stator and rotor resistances, respectively. \( \lambda_{q0s}, \lambda_{q0r}, \lambda_{d0s}, \lambda_{d0r} \) are the q, d, 0 axis of the stator and rotor currents and flux linkages, respectively. \( \omega \) is the angular speed.

From the literature, the end-ring resistance and magnetization currents are small. Hence both can be neglected. Therefore, the equivalent phase resistance of the healthy motor can be expressed as [15]:

\[
r_e = \frac{(2NS)^2}{(N_b/3)^2} 
\]  

Where \( r_e \) is the rotor bar resistance. \( N_b \) is the number of stator winding turns. The q, d, 0 axes of the stator and rotor flux components are defined as:

\[
\begin{align*}
\lambda_{q0s} &= L_{q0s} i_{q0s} + L_{mq} i_{d0s} + L_{md} i_{q0r} + L_{mq} i_{dq} \\
\lambda_{d0s} &= L_{d0s} i_{d0s} + L_{mq} i_{q0s} + L_{md} i_{dq} \\
\lambda_{q0r} &= L_{q0r} i_{q0r} \\
\lambda_{d0r} &= L_{d0r} i_{d0r}
\end{align*}
\]  

Where \( L_{q0s} \) is the stator leakage. \( L_{q0r} \) is the rotor leakage referred to the stator side and \( L_{md} \) is the q, d axis of the magnetizing inductances, respectively.

The torque equations of the LSPMSM are expressed as:

\[
\begin{align*}
J \frac{d\omega}{dt} &= T_e - T_L - B \omega \\
T_e &= \frac{3P}{4} (\lambda_{q0r} i_{d0s} - i_{d0r} \lambda_{q0r})
\end{align*}
\]  

Where \( T_e \) is the rotor moment of inertia. \( \omega \) is the angular speed. \( P \) is the number of poles. \( T_L \) and \( T_L \) are the electromagnetic and load torques, respectively. \( B \) is the friction coefficient. Therefore, eqns. (1), (3) and (4) represent the mathematical model of healthy LSPMSM.

**Proposed mathematical model of LSPMSM under broken bar conditions**

In this subsection, modification to the mathematical model of healthy LSPMSM will be developed under broken bar conditions. In general, rotor cage consists of \( N_b \) identical bars represented as parallel RL lines and shorted at the end-rings from both sides [18]. The end-rings are also represented as an RL lines, as shown in Figure 1.

A LSPMSM is a highly symmetrical motor; any fault will cause a degree of asymmetry on its parameters. Therefore, broken bars will cause asymmetry on the rotor resistances, which leads to asymmetry in the rotating air-gap flux [15]. As has been reported for induction motors, the effect of the rotor broken bars can be represented by an unbalance on the rotor resistance matrix [19,20]. The new rotor resistance matrix can be written as:

\[
\begin{bmatrix}
r_e^* + \Delta r_{ra} & 0 & 0 \\
0 & r_e^* + \Delta r_{rb} & 0 \\
0 & 0 & r_e^* + \Delta r_{rc}
\end{bmatrix}
\]

\( \Delta r_{ra}, \Delta r_{rb}, \Delta r_{rc} \) represent changes in the rotor bar resistance. Eqn. (2) can be modified to include the effect of the broken bars as follows:

\[
\begin{align*}
r_e^* &= r_e + \Delta r_e \\
0 &= r_e + \Delta r_e \\
0 &= r_e + \Delta r_e
\end{align*}
\]  

Therefore, the incremental value \( \Delta r \) becomes:

\[
\Delta r_{ra,b,c} = r_e^* - r_e = \frac{3N_b}{N_b - 3N_b} r_e
\]

Where \( \Delta r_{ra}, \Delta r_{rb}, \Delta r_{rc} \) represent the change in the rotor
resistances in phases a, b and c, respectively and n_{bb} represents the number of broken bars [21].

The incremental value $\Delta r$ given in eqn. (7) is converted from abc to qd0 reference frame i.e., "rotary Park's transformation" and the result is represented as:

$$
\Delta r_{qd0} = \begin{bmatrix}
\eta_1 & \eta_2 & \eta_3 \\
\rho_1 & \rho_2 & \rho_3 \\
\zeta_1 & \zeta_2 & \zeta_3
\end{bmatrix}
$$

(8)

Where:

$$
\begin{align*}
\eta_1 &= \frac{1}{3}(\Delta r_a + \Delta r_b + \Delta r_c) + \frac{1}{6}(2\Delta r_a - \Delta r_b - \Delta r_c \cos(2\theta)) + \frac{\sqrt{3}}{6}(\Delta r_a - \Delta r_b \sin(2\theta)) \\
\rho_1 &= \frac{1}{6}(2\Delta r_a - \Delta r_b - \Delta r_c \sin(2\theta)) - \frac{\sqrt{3}}{6}(\Delta r_a - \Delta r_b \cos(2\theta)) \\
\zeta_1 &= \frac{1}{3}(\Delta r_a - \Delta r_b - \Delta r_c \cos(\theta)) + \frac{\sqrt{3}}{3}(\Delta r_a - \Delta r_b \sin(\theta)) \\
\eta_2 &= \frac{1}{3}(\Delta r_a + \Delta r_b + \Delta r_c) \\
\rho_2 &= \frac{1}{6}(2\Delta r_a - \Delta r_b - \Delta r_c \cos(2\theta)) - \frac{\sqrt{3}}{6}(\Delta r_a - \Delta r_b \sin(2\theta)) \\
\zeta_2 &= \frac{1}{3}(\Delta r_a - \Delta r_b - \Delta r_c \sin(\theta)) - \frac{\sqrt{3}}{3}(\Delta r_a - \Delta r_b \cos(\theta)) \\
\eta_3 &= \frac{1}{3}(\Delta r_a + \Delta r_b + \Delta r_c)
\end{align*}
$$

(9)

Accordingly, eqn. (1) is modified to include the effect of broken bars and the final expression is given as:

$$
\begin{bmatrix}
\dot{v}_{q0} \\
\dot{v}_{d0} \\
\dot{v}_{rb} \\
\dot{v}_{ob}
\end{bmatrix} =
\begin{bmatrix}
\rho_1 & \rho_2 & \rho_3 & 0 \\
\lambda'_{q0} & \lambda'_{d0} & \lambda'_{rb} & \lambda'_{ob} \\
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0
\end{bmatrix}
\begin{bmatrix}
v_{q0} \\
v_{d0} \\
v_{rb} \\
v_{ob}
\end{bmatrix} +
\begin{bmatrix}
\rho_1 & \rho_2 & \rho_3 & 0 \\
\lambda'_{q0} & \lambda'_{d0} & \lambda'_{rb} & \lambda'_{ob} \\
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0
\end{bmatrix}
\begin{bmatrix}
\delta \\
\delta \\
\delta \\
\delta
\end{bmatrix} +
\begin{bmatrix}
0 & 0 & 0 & 0 \\
\eta_1 & \eta_2 & \eta_3 & 0 \\
\rho_1 & \rho_2 & \rho_3 & 0 \\
\zeta_1 & \zeta_2 & \zeta_3 & 0
\end{bmatrix}
\begin{bmatrix}
\theta_d \\
\theta_d \\
\theta_d \\
\theta_d
\end{bmatrix}
$$

(10)

Therefore, LSPMSM mathematical model under broken bar conditions is given by eqns. (3), (4) and (10).

**Simulation Results**

To investigate the effectiveness of the developed mathematical model, a 230 V, 4-hp, 2-pole, 60 Hz, 3-phase LSPMSM has been used [17]. The motor's data are given in Table 1. Simulation has been performed using MATLAB/SIMULINK platform.

Figures 2-4 show the output torque, motor speed and stator current under no load condition and with 0 (healthy), 1 and 5 broken bars, respectively. The figure clearly shows that at starting, the motor behaves as an induction motor and after the transient period behaves as synchronous. The motor reaches synchronous speed and the torque converges to zero (No load value) in around 0.8 second. It is also clear that as the number of broken bars increases, the motor takes more time to reach the synchronous speed and the torque will have more oscillations in the transient period.

The effect of loading on the motor's performance under healthy and broken bar conditions has also been investigated as shown in Figures 5-7. It can be seen that as the number of broken bars increases, the transient period oscillations increases. When comparing the performance under loading conditions with the case of no load, the

| Parameter | Value       |
|-----------|-------------|
| $L_m$     | 0.065 p.u.  |
| $L_{sl}$  | 0.543 p.u.  |
| $r_a$     | 0.054 p.u.  |
| $L_{ms}$  | 0.132 p.u.  |
| $H$       | 0.3 s       |
| $r_s$     | 0.017 p.u.  |
| $L_{qs}$  | 1.086 p.u.  |
| $r_{ds}$  | 0.108 p.u.  |
| $L_{rs}$  | 0.132 p.u.  |
| $D_{u}$   | 0 p.u.      |
| $N_s$     | 28          |
| $r_{sb}$  | 0.00126 p.u.|

Table 1: Parameters of LSPMSM in PU.
Figure 3: Rotor speed under no load with 0, 1, and 5 broken bars.

Figure 4: Stator current under no load with 0, 1, and 5 broken bars.

Figure 5: Electromagnetic torque under full load with 0, 1, and 5 broken bars.
Figure 6: Rotor speed full load with 0, 1 and 5 broken bars.

Figure 7: Stator current under full load with 0, 1 and 5 broken bars.

Figure 8: Zoomed stator current under full load with 0, 1 and 5 broken bars.
figures shows that loading extended the transient period and the time needed to reach steady state value of torque and speed. These behaviors are in very good agreement with findings reported in the literature using a FEM [7,8].

Taking a zoom of stator current under any loading condition (as shown in Figure 8 for full load case) shows that the transients are totally different for healthy and broken bar cases. This might be helpful in developing a diagnostic tool for detecting broken bars in LSPMSM.

To check the performance of the motor when the number of broken bars exceed one third of the total bars, Figures 9 and 10 show the rotor speed and torque, respectively with 10 broken bars fault under no load conditions. The obtained results showed that the motor is unable to synchronize which is in agreement with the FEM findings reported in literature [7,8].

Conclusion

This paper presented a mathematical model for LSPMSM under broken bar fault. The effect of having broken bars is reflected in the faulty model rotor resistances. Simulation results showed the performance of the motor under healthy and broken bar conditions. The motor’s torque, rotor speed and stator current behavior under no load and loading conditions has been investigated with different broken bar values. Simulation results show that the motor took longer transient time with more oscillations as the number of broken bars increases. It also showed that the motor failed to achieve synchronism when the number of broken bars exceeded one third of the total rotor bars. These findings are in good agreement with the behavior reported in the literature when using FEM.

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