Simulation of line start permanent magnet synchronous motors and its performance analysis

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Abstract—**Line start permanent magnet (LSPM) synchronous motor is noted as an alternative to the induction motor because it offers a very high efficiency and unit power factor. A squirrel cage is provided in the LSPMSM to accelerate the rotor from standstill, whilst the magnets make the motor run at the synchronous speed. In this paper, the LPSM is modeling using Matlab/Simulink. The Simulink simulation then used to explore the behavior of torque component during the starting run or motor from standstill. The ability motor to synchronize with various values of magnet field strength, mechanical loading, and rotor inertia is also examined.**

Keywords: Simulation, LSPM, torque,synchrinize

I. INTRODUCTION

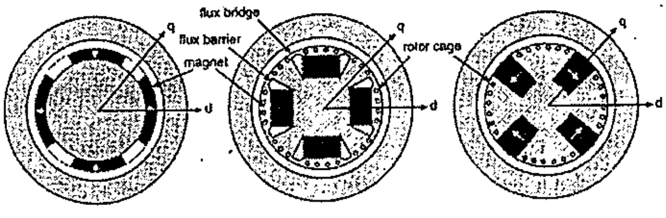
Line-start permanent magnet synchronous motor (LS-PMSM) is a kind of high efficiency synchronous motor. A squirrel cage is provided in the LS-PMSM to accelerate the rotor from standstill, whilst the magnets make the motor run at the synchronous velocity. Compared to the traditional three-phase induction motors, the LS-PMSM has typical advantages such as higher efficiency and power factor within a wide load range. This kind of motor could be a more efficient solution for general use applications than the induction motor.

The LS-PMSM has been widely studied since it was first presented. A lot of experiences have been accumulated, and the machine has been applied to some particular industrial occasions. However, due to the complexity of the magnetic circuit and the rotor structure of the LS-PMSM, the optimal design method need further study.

In this work, the simulation of LSPMSM is developed using Matlab Simulink. Then, the synchronizing process has been studied which indicates the effective parameters for reaching the starting capability, such as critical load torque, supply voltage, and back emf. The steady-state characteristics are alsomeasured by applies the step load changing. The aim of this project is to implement the simulation of LSPMSM and study its performance.

II. CONFIGURATION OF ROTOR

The dc excitation of the field winding in a synchronous machine can be provided by permanent magnet. One obvious change with replacing the electrical excitation with a permanent magnet is the elimination of cooper losses. Machines so excited can offer simpler construction, lower weight and size for the same performance, with reduced losses, and higher efficiency. The disadvantages are that present prices of permanent magnet materials (except for ferrites) are relatively high, and that magnet characteristics change with time. The choice of magnets for a motor is influenced by factors such as the motor's performance, weight, size, and efficiency, and the economic factor regarding the material and production. Machinability, tolerance, and ease of handling of various permanent magnet materials can also effect production cost significantly. Figure 1 shows the three common arrangements of permanent magnet in synchronous motors. The surface mount arrangement is popular with modern high$H_c$magnetic materials that are not easily susceptible to demagnetization. Since the leakage of the magnet with regard to air gap flux generation is small, this arrangement can result in a smaller volume of permanent magnet material being used. With material of lesser H_c and where the risk of demagnetization is high, the magnet is usually embedded in the rotor. The embedded arrangement will allow a longer length of magnet than the surface mount arrangement. Furthermore, with the material of low remanence, there is room for the flux focusing that is needed.



(a) surface (b) interior (b) interior transverse

Figure 1: Arrangement of permanent magnets in synchronous motors

In general, a line start motor will have a rotor cage to help start the motor on a fixed frequency supply. The induction motor torque component of a line start motor has to overcome the pulsating torque caused by the magnet during starting. An inverter-fed motor may or may not have a rotor cage as the inverter frequency can be synchronized to the rotor speed. Inverter -fed motor can be fed with pwm sinusoidal voltage form or quasi-square voltage waveform of 120° or 180° wide.

III. EQUIVALENT CIRCUITS

A circuit model of a permanent magnet motor, which is usedfor predicting its transient behavior, is shown in fig. 2. The equivalent *qd0* circuit representations shown in fig. 2 of the permanent magnet synchronous motor damperhave cage windings but no g winding. For modeling purpose, the permanent magnet inductance of the stator and damper winding, L_{rc}, that is associated with its recoil slope, can be lumped with the common d-axis mutual inductance of the stator and damper winding and the combined d-axis mutual inductance denoted still by L_{md}.The current i'_m, is the equivalent magnetizing current of the permanent magnets, referred to stator side. The corresponding *qd0* equations for the above equivalent *qd0* circuit of the permanent magnets, referred to the stator side.

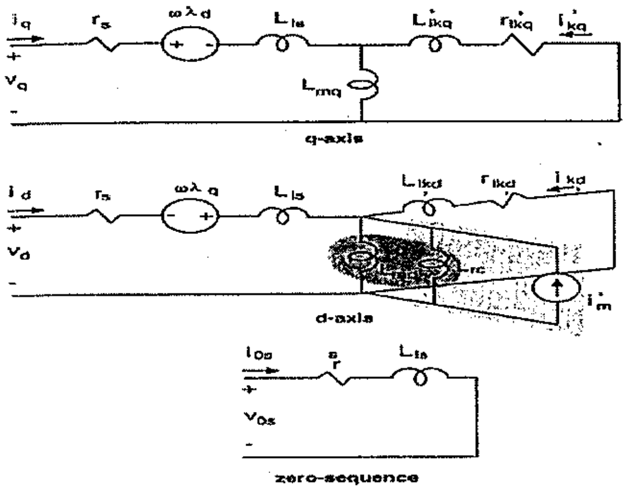


Figure 2: Equivalent qdo circuits of a permanent magnet synchronous motor

In equation 1,the development electromagnetic torque is separated into three component: a reluctance component, which is negative when Ld<Lq; an inductance component which is an asynchronous torque; and an excitation component from the field of the permanent magnet.

$$T_{em} = \frac{3}{3}\frac{P}{2}\left(\mathrm{L}_d - \mathrm{L}_q\right)i_d i_q + \frac{3}{3}\frac{P}{2}\left(L_{mq}i'_{kd}i_q + L_{mq}i'_{kq}i_d\right) + \frac{3}{3}\frac{P}{2}\mathrm{L}_{md}i'_m i_q (1)$$

The mutual flux linkages in the q- and d axes may be expressed by

$$\lambda_{mq} = L_{mq}(i_q + i'_{kq})$$
$$\lambda_{mq} = L_{md}(i_q + i_m + i'_{kq})(2)$$

As before, the winding currents can be expressed as

$$i_q = \frac{1}{L_{ls}}(\lambda_q - \lambda_{mq})$$
$$i_d = \frac{1}{L_{ls}}(\lambda_d - \lambda_{md})$$
$$i'_{kq} = \frac{1}{L'_{lkq}}(\lambda'_{kq} - \lambda_{mq})$$
$$i'_{kd} = \frac{1}{d}(\lambda'_{kd} - \lambda_{md}) \qquad (3)$$

With the above relations for the d-axis winding current substitutedinto Eq.2 and simplifying, we will obtain

where

$$\frac{1}{L_{MD}} = \frac{1}{L_{ls}} + \frac{1}{L'_{lkd}} + \frac{1}{L_{md}} \quad (4)$$

Similar expression for $\lambda_{mq}$and L_{MQ}can be written for the q-axis.

For steady state condition, where $\omega=\omega_e$, as in the case of E_f in a wound field machine, $\omega_e\lambda'_m$ or $x_{md}i'_m$can be obtained by E_m, the magnet's excitation voltageon the stator side. And if stator resistance is disregarded, replacing $E_f$by E_m *in* Eq. 5, the developed torque of a permanent magnet motor in terms of the rsm phase voltage $V_a$at its terminal is

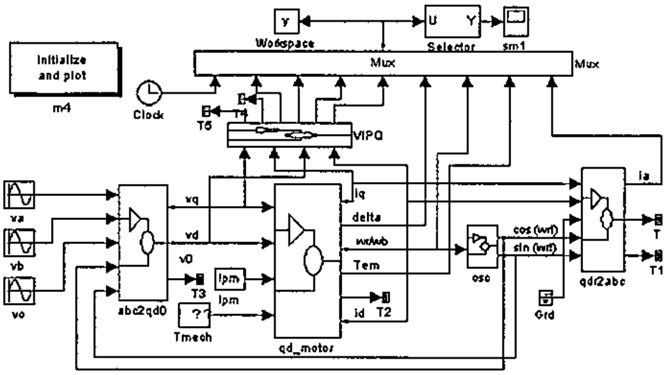
$$T_{em} = -3\left(\frac{2}{P\omega_e}\right)\left\{\frac{V_a E_m}{X_d} sin\delta + \frac{V_a^2}{2}\left(\frac{1}{X_q} - \frac{1}{X_d}\right) sin2\delta\right\}(5)$$

IV. SIMULATION ANALYSIS

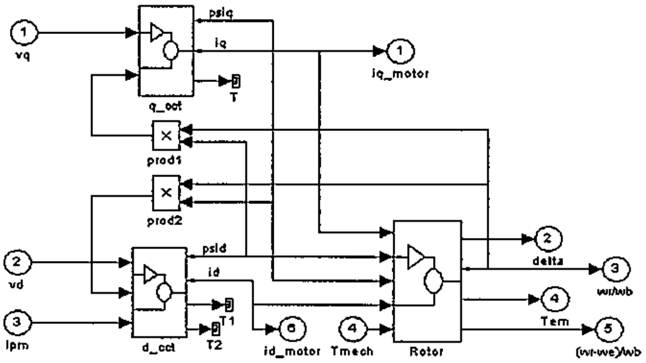
Figure 3 shows the Simulink simulation, s4 of a line-start permanent magnet motor connected to a fixed frequency supply sources.The Simulink file s4 contain an implementation of a line start, three phase permanent magnet synchronous motor connected directly to a 60 hz, three phase supply voltage rated magnitude. The matlab file m4, has been programmed to work with s4, it willset up in the matlab workspace the parameter of the 230-V, 4-hp, two pole, 60-hz, three phase line start permanent magnet given in Table 1below.

Table 1: Parameters of line start motor in per unit

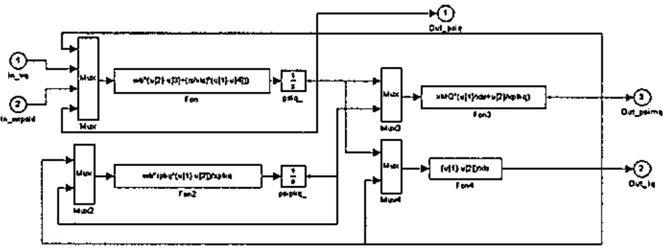
x_{ls}=0.065 per unit	r'_{kq}=0.108 per unit
r_s=0.017 per unit	x'_{lkd}=0.132 per unit
x_d=0.534 per unit	x'_{lkq}=0.132 per unit
x_q=1.086 per unit	H=0.3s per unit
r'_{kd}=0.054 per unit	D_ω=0 per unit



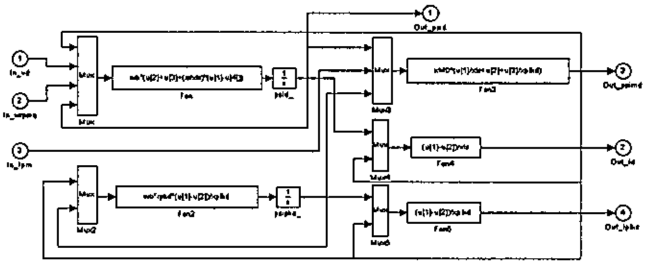
(a) Overall diagram of s4



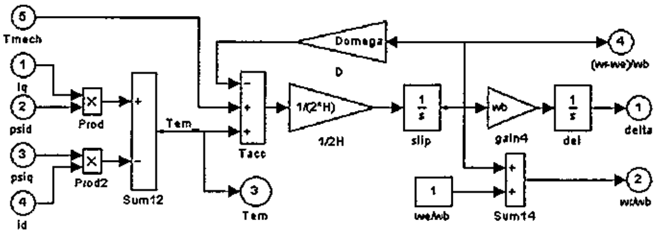
(b) inside the abc2qd0 block of s4



(c) inside the qd_motor block of s4



(d) Inside the q_cct block of s4



(e)Inside the rotor block of s4

Figure 3: Simulation s4 line-start permanent magnet motor.

The matlab script file m4, will prompt the user to input the desired equivalent magnet current i'_m, or the terminal inputpower condition for it to establish the equivalent magnetizing current.It also allow the user two option to initialize the integrator in s4: that with steady state current, flux,and rotor speed corresponding to the terminal condition specified by the user, and that with just the magnet's d-axis field flux, zero stator current,and rotor speed as in startingfrom standstill. As programmed, it will allow the user to repeat a new calculation to determine the equivalentmagnetizing currentfor fresh terminal condition or to make repeated simulations with changes in parameter, external loading, or stop time. The file m4, is also set up to provide a plot of the input real and reactive power P_m and Q_m, the power angleδ, the per unit speedof the rotor,ω_r/ω_b,the electromagnetic torqueT_{em}, and the stator a-phase current i_a, in one figure. In a separate figure, it will plot T_{em} along with its reluctance, induction and excitation components.

In the table there is 8 condition of the terminal that can be test to the block simulation to get the result.

Table 2: Magnet strength for the given terminal conditio

case	Rotor inertia, h	External loading,tmech	Im for sm to br	remark
1.	nominal	0pu	Set im=0	Im=1.6203
2.	nominal	0pu	Sm=0.9+j0.436	Im=2.6985
3	nominal	0pu	Sm=0.9+j0.436	Im=2.2223
4	nominal	0pu	Sm=1+j0	Im=2.2223
5	nominal	-0.5pu	Sm=1+j0	Im=2.2223
6	2×nominal	-0.5pu	Sm=1+j0	Im=2.2223
7	2×nominal	0pu	Sm=1+j0	Im=2.2223
8	2×nominal	-0.5pu	sm=0.9+j0.436	Im=1.6203

V. RESULT AND DISCUSSION

The result of figure 4 and figure 5 is obtained based on thecase no. 8 in table 2 that Simulink s4 was simulated in the matlab simulation.

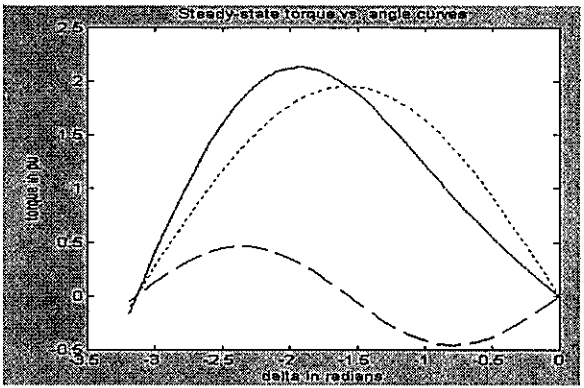
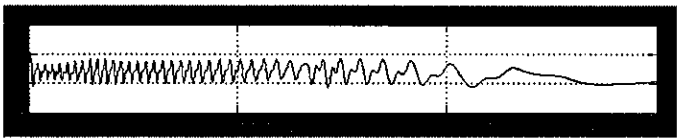
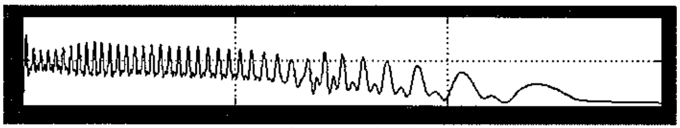


Figure 4: Steady-state torque vs angle curve permanent magnet motor



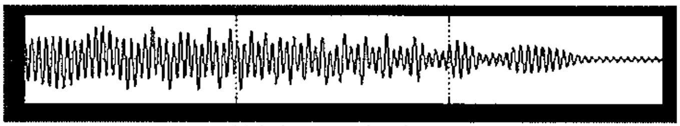
(a) Pm in pu vs. time in sec



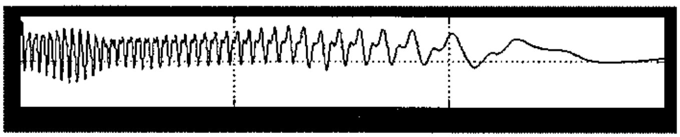
(b) Qm in pu vs. time in sec

(c) Delta in rad vs. time in sec

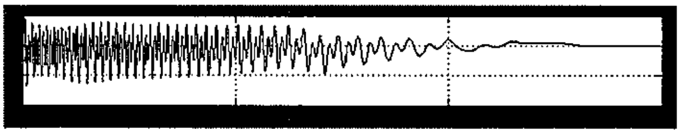
(d) wr/wb in rad vs. time in sec



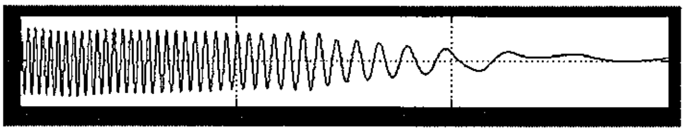
(e) ia in pu vs. time in sec



(f) Tem in pu vs. time in sec



(g) Trel in pu vs. time in sec



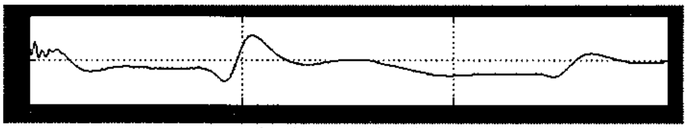
(h) Text in pu vs. time in sec

Figure 5: Starting transient of permanent magnet motor

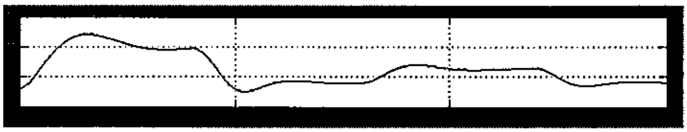
The results show the motor synchronous with after experience of transient at starting. When the torque value is change the time of motors to synchronous is longer. It's also same with rotor inertia, when the value is added the time is longer to motors synchronize. Higher torque and higher inertia the synchronization take long time and vice versa.

The effects of changes in mechanical or shaft load on armature current, power angle, andpower factor can be seen from the phasor diagram. Phasor diagram showing effect of changes in shaft load on armature current, power angle and power factor of a synchronous motorof lag relative to the rotating magnetic field, thereby increasing both the angle of lag ofthe counter EMF phasor and the magnitude of the stator current. It is interesting to notethat during all this load variation, however, except for the duration of transient conditionswhereby the rotor assumes a new position in relation to the rotating magnetic field, theaverage speed of the machine does not change. As the load is being increased, a final pointis reached at which a further increase in δfails to cause a corresponding increase in motortorque, and the rotor pulls out of synchronism. In fact as stated earlier, the rotor poles atthis point, will fall behind the stator poles such that they now come under the influence oflike poles and the force of attraction no longer exists. Thus, the point of maximum torqueoccurs at a power angle of approximately 90° for a cylindrical-rotor machine.

(a) Pm in pu vs. time in sec



(b) Qm in pu vs. time in sec



(c) Delta in rad vs. time in sec

(d) wr/wb in rad vs. time in sec

(e) ia in pu vs. time in sec

Figure 5: Response to step change in mechanical loading

Figure 5 is the result of simulation to obtain the dynamic response of permanent magnet motor to a sequence of step-load changes. The the file m4 is used to initialize the simulation in s4 with condition corresponding to Case 2 in Table 2. Before performing the simulation, the repeating sequence signal source for mechanical loading is set up as below

$$Tmech\_value = [0\ 0\ -1\ -1\ -0.5\ -0.5\ -1\ -1]$$

$$Tmech\_time = [0\ 0.4\ 0.4\ 0.8\ 0.8\ 1.2\ 1.2\ 1.5]$$

From the figure 5 its show permanent magnet response to the change of step-load sequence. From the graft, it show the transient happen when step changing load is set up. The transient effect is different with different loading and compared to normal steady state condition which is just street line in the graft.

VI. CONCLUTION

The performance predictions of line start permanent magnet synchronous motor canbe performed by using matlab Simulink. Important information about the motor torquecapability is obtained through the study of different torque component. The of motor to synchronizedis also depend on magnetic field strength, mechanical load, and rotor inertia.

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