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Conceptual comparison of Line-Start Permanent Magnet Synchronous and Induction Machines for Line-fed of different conditions

Mohsen Hosseinzadeh Soreshjani*, Alireza Sadoughi

[1]Malek Ashtar Industrial University, Shahin Shahr, Isfahan, Iran

*Corresponding's Email: Hosseinzadeh.ieee@yahoo.com

Abstract *– This study presents a comparative analysis of an Induction Machine (IM) and its equal Line-Start Permanent Magnet Synchronous Machine (LSPMSM) when they are directly connected to the mains. Simulation results from MATLAB/Simulink software are presented under normal and voltage sag conditions and different load torques, to provide a comprehensive comparison. In addition, the effect of input frequency is evaluated. Different tests in no-load, motoring, and generating modes show a better steady-state response of an LSPMSM rather than its IM, if its synchronized problems could be obviated.*

Keywords*: Line-Start Permanent Magnet Synchronous Motor (LSPMSM), Induction Motor (IM), Line-fed, Voltage sag conditions.*

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INTRODUCTION

Due to their simplicity, ruggedness, reliability, and volume manufacturing, IMs have extensively been applied in different applications. Progressive increases of electrical energy turn the efficiency of IMs to a vital issue. In IMs, the existence of slip and rotor copper losses degrades the motor efficiency and Power Factor (PF) [1-4]. The rotor slip power losses are absent for Synchronous Motors (SMs), and as a result, SMs which naturally are able to provide both reactive currents and a fixed synchronous speed (for different loads with a fixed voltage supply) have a higher efficiency and PF than IMs. Nevertheless, they have a higher volume and cost than IMs. That is why, PMSMs are employed, and the decreasing price and improved performances of Permanent Magnets (PMs) make them more interesting than in the past [2-5].

On the other hand, PMSMs, produce a magnet brake torque that decreases the total torque and has a repercussion on its starting. In this regard, PMSMs are not able to start with a fixed voltage frequency, and LSPMSMs which are synchronous hybrid PM/reluctance high-efficient motors are designed to meet IE4/Super-Premium Class requirements [6-8]. They are amended from an IM, inserting PM segments, in the rotor cage, so they are able to start with the mains. In other words, LSPMSMs unite the merits of IMs (robust construction with respect to disturbance and line-starting ability) and PMSMs (high values of torque per unit current density, PF, and efficiency). However, the flux of the PM is selected based on a compromise between the operation of the motor near the unity PF and solving the starting motors.

In principle, LSPMSMs have a rotor cage for induction starting and PM materials, providing synchronous torque, and they are suitable candidates for substitution of IMs and PMSMs. Recently, research accelerated to evaluate and compare different performance aspects of three- and single-phase of LSPMSMs and equal IMs [9-16]. However, a comparison between LSPMSMs and IMs for generating mode has not been reported yet.

The main contribution of this paper is to offer an in-depth analysis, and it simulates and compares the dynamic behavior of both motors in Line-starting for the same situations of normal and voltage sag conditions. Simulation results, testing nominal and reduced voltage and frequency, confirm the fact that the aforementioned problems during line-starting that mainly caused by braking torques PM poles degrade the dynamic response of LSPMSM. Furthermore, the simulation results of the identical situations introduce the LSPMSM as a suitable candidate of Induction generators, as it produces the reactive current as well. Furthermore, the steady-state response of the LSPMSM is mainly superior rather than its equal IM.

This paper is organized as: First, modeling and description of IMs and LSPMSMs principles are provided. Then, the model of a commercially available four-pole three-phase squirrel-cage IM, made in Motogen Company, and its equal LSPMSM along with the same situations are simulated for both directly connected to the

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mains for different conditions in the MATLAB/SIMULINK software.

IM MODEL

Since LSPMSM has a squirrel cage rotor of IM and PM segments, a prototype of the original model along with rotor cross sections of IM and LSPMSM is shown in Fig. 1. In general, their stator frame and weddings are completely the same. In this paper, PMSMs are not considered, as they are not able to start in the presence of a fixed supply voltage.

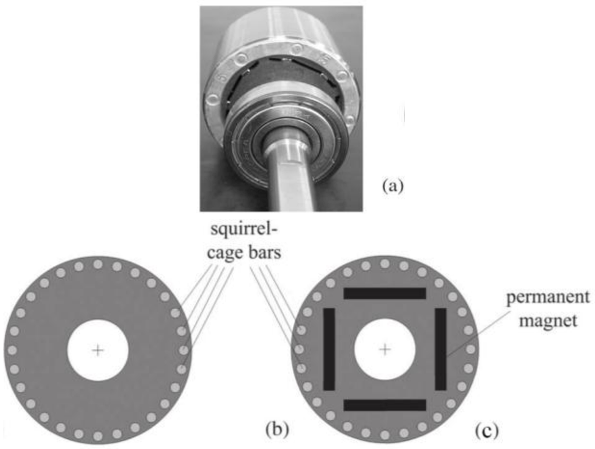

Fig. 1- a. A prototype of the original model, and rotor cross sections of b. IM, c. LSPMSM.

Equations (1-5) describe a mathematical model of a squirrel-cage IM in a rotor d-q reference frame [3]. The equations of the stator and rotor voltages are described as follows:

$$\begin{cases} V_{qs}^{r} = r_s i_{qs}^{r} + \omega_m \lambda_{ds}^{r} + p\lambda_{qs}^{r} \\ V_{ds}^{r} = r_s i_{ds}^{r} - \omega_m \lambda_{qs}^{r} + p\lambda_{ds}^{r} \\ V_{0s}^{r} = r_s i_{0s}^{r} + p\lambda_{0s}^{r} \end{cases} \quad (1)$$

$$\begin{cases} V'^{r}_{qr} = r'_r\, i'^{r}_{qr} + p\lambda'^{r}_{qr} = 0 \\ V'^{r}_{dr} = r'_r\, i'^{r}_{dr} + p\lambda'^{r}_{dr} = 0 \\ V'^{r}_{0r} = r'_r\, i'^{r}_{0r} + p\lambda'^{r}_{0r} = 0 \end{cases} \quad (2)$$

where the d–q axis variables (V_{ds}, V_{qs}),(i_{ds}, i_{qs}),and (λ_{ds}, λ_{qs}), are the stator voltage, stator current, and stator flux, respectively. The d–q axis rotor variables of voltage, current, and flux components, referred to stator side, are (V'_{dr}, V'_{qr}), (i'_{dr}, i'_{qr}), and (λ'_{dr}, λ'_{qr}), respectively. The equations of the stator and rotor fluxes are expressed as:

$$\begin{cases} \lambda_{qs}^{r} = L_{ls} i_{qs}^{r} + L_M \left(i_{qs}^{r} + i'^{r}_{qr} \right) \\ \lambda_{ds}^{r} = L_{ls} i_{ds}^{r} + L_M \left(i_{ds}^{r} + i'^{r}_{dr} \right) \\ \lambda_{0s}^{r} = L_{ls} i_{0s}^{r} \end{cases} \quad (3)$$

$$\begin{cases} \lambda'^{r}_{qr} = L'_{lr}\, i'^{r}_{qr} + L_M \left(i_{qs}^{r} + i'^{r}_{qr} \right) \\ \lambda'^{r}_{dr} = L'_{lr}\, i'^{r}_{dr} + L_M \left(i_{ds}^{r} + i'^{r}_{dr} \right) \\ \lambda'^{r}_{0r} = L'_{lr}\, i'^{r}_{0r} \end{cases} \quad (4)$$

where r_s, r'_r, L_{ls}, L'_{lr}, and L_M are the stator and rotor resistances and the stator leakage-, rotor leakage-, and magnetizing inductances, respectively. The voltage and flux equations suggest the equivalent circuits shown in Fig. 2.

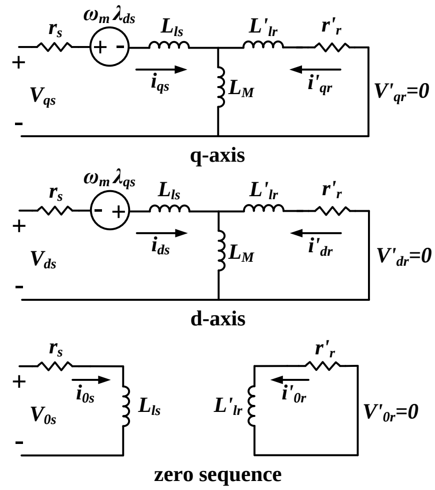

Fig. 2- Rotor reference frame equivalent circuits for a three-phase IM.

The mechanical equations are also expressed as:

$$\begin{cases} T_e = \dfrac{3}{2}\dfrac{P}{2}\left(i_{qs}^{r} \lambda_{ds}^{r} - i_{ds}^{r} \lambda_{qs}^{r} \right) \\ J\,\dfrac{d\omega_m}{dt} = T_e - T_L - B\omega_m \end{cases} \quad (5)$$

where ω_m and P are the angular speed and the pole numbers, respectively. Finally, T_e, T_L, B, and J are the electromagnetic and load torques, friction coefficient, and moment of inertia, respectively.

LSPMSM MODEL

For modeling purposes, the PM inductance (L_{rc}) can be lumped and combined with the common d-axis mutual inductance of the stator (L_{md}). Besides, the equivalent magnetizing flux of the PM (λ'_m) is defined as:

$$\lambda'_m = L_{md} i'_m \quad (6)$$

where i'm is the equivalent magnetizing current of the PM referred to the stator side. Therefore, the equations of stator voltage, rotor voltage, stator flux, and rotor flux for LSPMSM are obtained as:

$$\begin{cases} V_{qs}^{r} = r_s i_{qs}^{r} + \omega_m \lambda_{ds}^{r} + p\lambda_{qs}^{r} \\ V_{ds}^{r} = r_s i_{ds}^{r} - \omega_m \lambda_{qs}^{r} + p\lambda_{ds}^{r} \\ V_{0s}^{r} = r_s i_{0s}^{r} + p\lambda_{0s}^{r} \end{cases} \quad (7)$$

$$\begin{cases} V'^{r}_{qr} = r'_{qr}\, i'^{r}_{qr} + p\lambda'^{r}_{qr} = 0 \\ V'^{r}_{dr} = r'_{dr}\, i'^{r}_{dr} + p\lambda'^{r}_{dr} = 0 \end{cases} \quad (8)$$

$$\begin{cases} \lambda^{r}_{qs} = L_{ls} i^{r}_{qs} + L_{mq}\left(i^{r}_{qs} + i'^{r}_{qr}\right) \\ \lambda^{r}_{ds} = L_{ls} i^{r}_{ds} + L_{md}\left(i^{r}_{ds} + i'^{r}_{dr}\right) + \underbrace{L_{md} i'^{r}_{m}}_{\lambda'^{r}_{m}} \\ \lambda^{r}_{0s} = L_{ls} i^{r}_{0s} \end{cases} \quad (9)$$

$$\begin{cases} \lambda'^{r}_{qr} = L'_{lr}\, i'^{r}_{qr} + L_{mq}\left(i^{r}_{qs} + i'^{r}_{qr}\right) \\ \lambda'^{r}_{dr} = L'_{lr}\, i'^{r}_{dr} + L_{md}\left(i^{r}_{ds} + i'^{r}_{dr}\right) + \underbrace{L_{md} i'^{r}_{m}}_{\lambda'^{r}_{m}} \\ \lambda'^{r}_{0r} = L'_{lr}\, i'^{r}_{0r} \end{cases} \quad (10)$$

The equivalent circuits shown in Fig. 3 are obtained based on (6-10). It is worthwhile to note that this model and simulated parameters are applicable to interior and surface types. Furthermore, the rotor eddy-current losses in the PM material of the LSPMSM are ignored because, for instance, the value of the ohmic resistance of NdFeB-permanent magnet is 80 times larger than that of copper resistance.

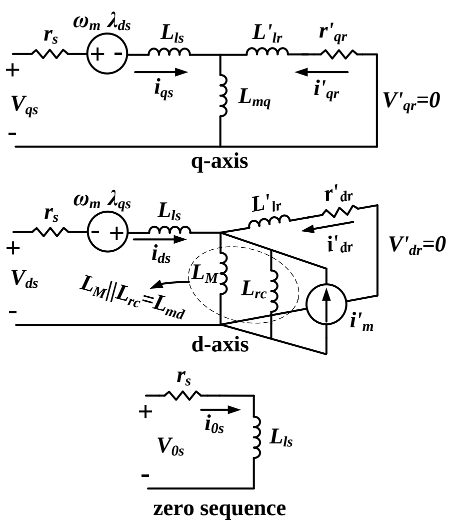

Fig. 3- Rotor reference frame equivalent circuits for a three-phase LSPMSM.

The electromagnetic torque is developed into three components: a reluctance torque which is formed due to the saliency of the motor; an excitation torque which is produced thanks to the field of PM; and an induction torque which is also called asynchronous or cage torque.

$$T_e = \left(\frac{3}{2}\right)\left(\frac{P}{2}\right)\left\{ \underbrace{L_{md} i'^{r}_{dr}\, i^{r}_{qs} - L_{mq} i'^{r}_{qr}\, i^{r}_{ds}}_{Induction\ \ Torque} + \underbrace{\lambda'^{r}_{m}\, i^{r}_{qs}}_{Excitation\ \ Torque} + \underbrace{\left(L_{md} - L_{mq}\right) i^{r}_{ds} i^{r}_{qs}}_{Reluctance\ \ Torque} \right\} \quad (11)$$

SIMULATION RESULTS

In this section, simulation results of an IEC frame size 80-4A, 0.75 (KW), four-pole three-phase squirrel-cage IM, made in mitogen company, and the equal LSPMSM, amended from the aforementioned IM, of Line-fed are provided. The simulation parameters are given in Table I, and λ'_m=1.32 is designed to gain access a high-efficiency and power factor in the nominal conditions.

TABLE 1
MACHINE PARAMETERS

Common Electrical Parameters	Common Mechanical Parameters	IM Parameters	LSPMSM Parameters
F_n=50 (Hz)			L_{md}=69.3(mH)
V_n (RMS L-L)=380 (V)	J=0.002 (Kg.m^2)	L_M=0.4721(H)	L_{mq}=0.2597 (H)
r_S=10 (Ω)	B= 0.00008 (N.m.s)	r'_r=8.5 (Ω)	r'_{dr}=8.5 (Ω)
L_{lS}=.0358 (H)	Poles=4		r'_{qr}=9 (Ω)
L'_{lr}=0.0358 (H)			λ'_m=1.32

Although the different squirrel-cage and PM materials and the different load torque and inertia, cause to yield different steady-state and dynamic line-starting transients, the effect of the amplitude voltage and input frequency on the aforementioned IM and LSPMSM is simulated. In other words, simulation results of these motors supplied by the mains with nominal frequency, and a variable load torque for nominal and 80 percent of nominal voltages (380 and 305 volts) are, respectively, presented in Figs. 4 and 7. In addition, to test the effect of the input frequency, Figs. 10 and 12 indicate the behavior of these motors for F=25 (Hz) of normal and voltage sag conditions, respectively. In this work, coefficient B is intentionally selected near the zero to ignore the friction losses and present a better comparison of both motors in no-load. The stator current of phase "*a*" ($i_{a\ Stator}$), electromagnetic and load torques (T_e and T_L), and motor speed (ω_m) for the mentioned conditions are shown in Figs. 4, 7, 10, and 12. Torque components of LSPMSM (, i.e., T_{exc}, T_{rel}, and T_{ind}) and the electromagnetic torque (T_e) of IM of Figs. 4 and 7 are shown in Figs. 5 and 8, respectively. In addition, torque-speed characteristics of both motors are depicted in Figs. 6, 9, 11, and 13.

In the first second, the tested motors are directly line-started from standstill to support T_L=5 (N.m), then the load torque (T_L) is changed to zero- and -5 (N.m) at 1 second and 2 seconds, respectively. For better performance evaluation, dynamic and steady-state information about speed and current parameters such as overshot, undershot, settling time, rise time, and steady-state speed as long as peak-to-peak (P-P) of the stator current in both transient and steady states based on mentioned situations are listed in Tables II, IV, VI, and VII. Moreover, to investigate the influence of the load torque on line-starting motors, different steady-state parameters, obtained from simulation for different load torques in No-load, motoring, and generating modes, based on tested conditions of Figs. 4 and 7, are listed in Table III, VI, respectively. Clearly, deliver power into the AC network is determined by a negative sign, and similarly positive values of power denote absorb power from the power system. In addition, leading capacitive and lagging inductive power factors are concluded from reactive power generation and consumption, respectively.

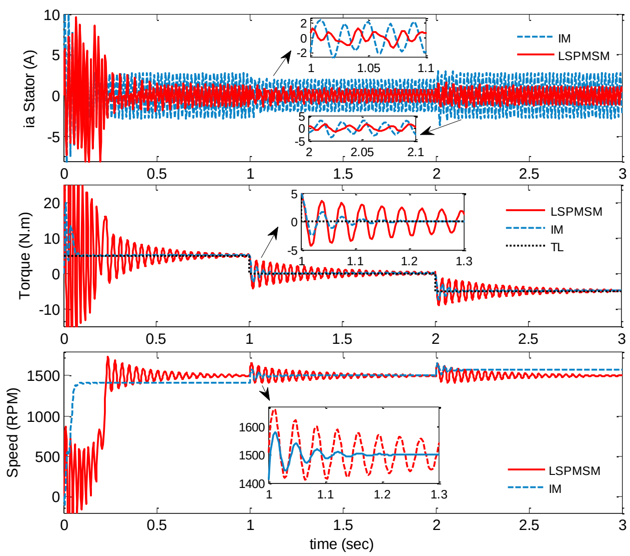

Fig. 4- The stator current of phase "*a*" ($i_{a\ Stator}$), electromagnetic and load torques (T_e and T_L), and motor speed (ω_m) of LSPMSM and IM under nominal conditions ($V_{L\text{-}L\ in}$=380 (V) and *f*=50 (Hz)).

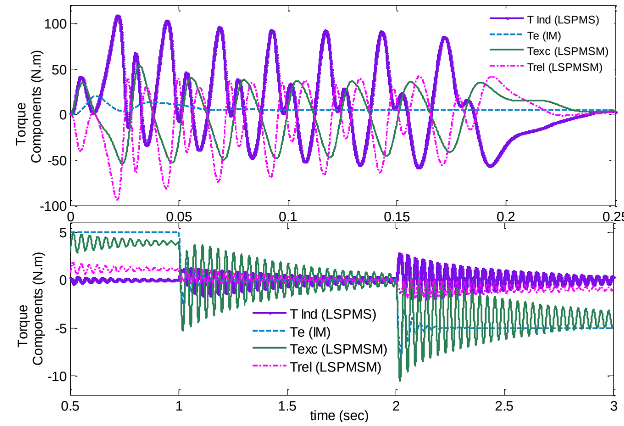

Fig. 5- Torque components of LSPMSM (T_{exc}, T_{rel}, and T_{ind}) and electromagnetic torque (T_e) of IM in the time interval (0-0.25) seconds and (0.5-3) seconds under nominal conditions ($V_{L\text{-}L\ in}$=380 (V) and *f*=50 (Hz)).

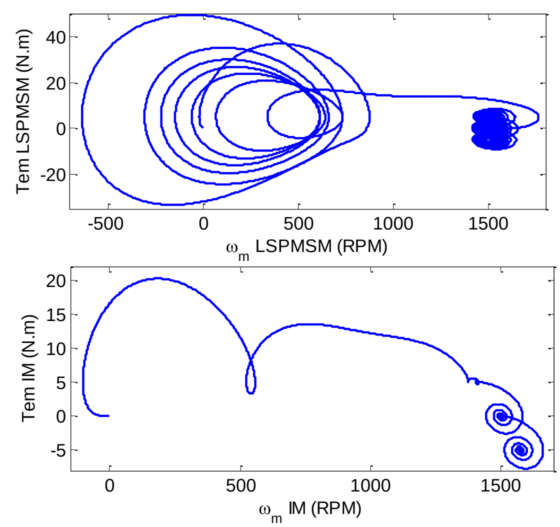

Fig. 6- Torque-speed characteristic of LSPMSM and IM shown in Fig. 4 ($V_{L\text{-}L\ in}$=380 (V) and *f*=50 (Hz)).

TABLE 2

TRANSIENT AND STEADY-STATE DATA OBTAINED FROM FIG. 4 (VL-L IN=380 (V) AND F=50 (HZ)).

		Speed					Stator Current	
	Motor	Overshoot (RPM)	Undershoot (RPM)	Steady State (RPM)	Rise time (sec)	Settling time (sec)	P-P of $i_{a\ Stator}$ in Steady State (A)	P-P of $i_{a\ Stator}$ in Transient (A)
TL=5 (0-1sec)	IM	7	-100	1407	0.08	0.25	5.5	26
	LSPMSM	240	-575	1500	0.23	0.8	2.8	19
TL=0 (1-2 sec)	IM	80	0	1500	0.004	0.25	3.9	4.6
	LSPMSM	160	-80	1500	-	0.8	1.6	2.4
TL=-5 (2-3 sec)	IM	90	0	1574	0.003	0.25	5.5	6
	LSPMSM	150	-80	1500	-	0.8	2.2	3.2

TABLE 3.
STEADY-STATE DATA OF LSPMSM AND IM FOR DIFFERENT LOAD TORQUES IN DIRECTLY CONNECTED TO THE MAINS WITH NOMINAL VOLTAGE AND FREQUENCY (VL-L IN=380 (V) AND F=50 (HZ)).

Mode	T_L (N.m)	Machine	ω_m (RPM)	$\|PF\|$	η (%)	P_{Elec} (W)	P_{Mech} (W)	Q_{in} (VAR)
Motoring	6	IM	1384	0.75	79.89	1089	869.8	968.2
		LSPMSM	Not Syn.	Not Syn.	Not Syn.	Not Syn.	Not Syn.	Not Syn.
	5	IM	1407	0.67	81.83	900.6	736.9	928
		LSPMSM	1500	0.89	92.59	848.2	785.4	-438.6
	4	IM	1429	0.62	83.11	720	598.4	901.8
		LSPMSM	1500	0.81	93	675.2	627.9	-480.6
	3	IM	1448	0.52	83.31	546.1	454.9	887.8
		LSPMSM	1500	0.71	92.97	508.8	473	-509.8
	2	IM	1466	0.39	81.27	377.9	307.1	884.5
		LSPMSM	1500	0.54	92.09	338.6	311.9	-523.1
	1	IM	1484	0.23	72.28	214.9	155.4	890.9
		LSPMSM	1500	0.33	88.27	185.6	163.8	-531.2
No-Load	0	IM	1500	0.06	-	58.8	-	906.3
		LSPMSM	1500	0.03	-	15.67	-	-519.6
Generating	1-	IM	1516	0.13	61.01	-96.9	-158.7	929.9
		LSPMSM	1500	0.28	88.57	-146.2	-165	-501.1
	2-	IM	1531	0.25	76.8	-246.3	-320.6	961.4
		LSPMSM	1500	0.52	93.10	-289.5	-311.1	-480
	3-	IM	1545	0.36	80.71	-391.7	-485.5	1000
		LSPMSM	1500	0.68	94.07	-425.6	-452.6	-455.7
	4-	IM	1560	0.45	81.63	-533.3	-653.3	1046
		LSPMSM	1500	0.86	94.34	-635.2	-673.2	-371.9
	5-	IM	1574	0.52	81.43	-671.1	-824	1100
		LSPMSM	1500	0.92	94.07	-764.2	-812.8	-330.3
	6-	IM	1587	0.57	80.71	-805.2	-997.4	1160
		LSPMSM	1500	0.95	93.81	-876.8	-934.6	-291.8

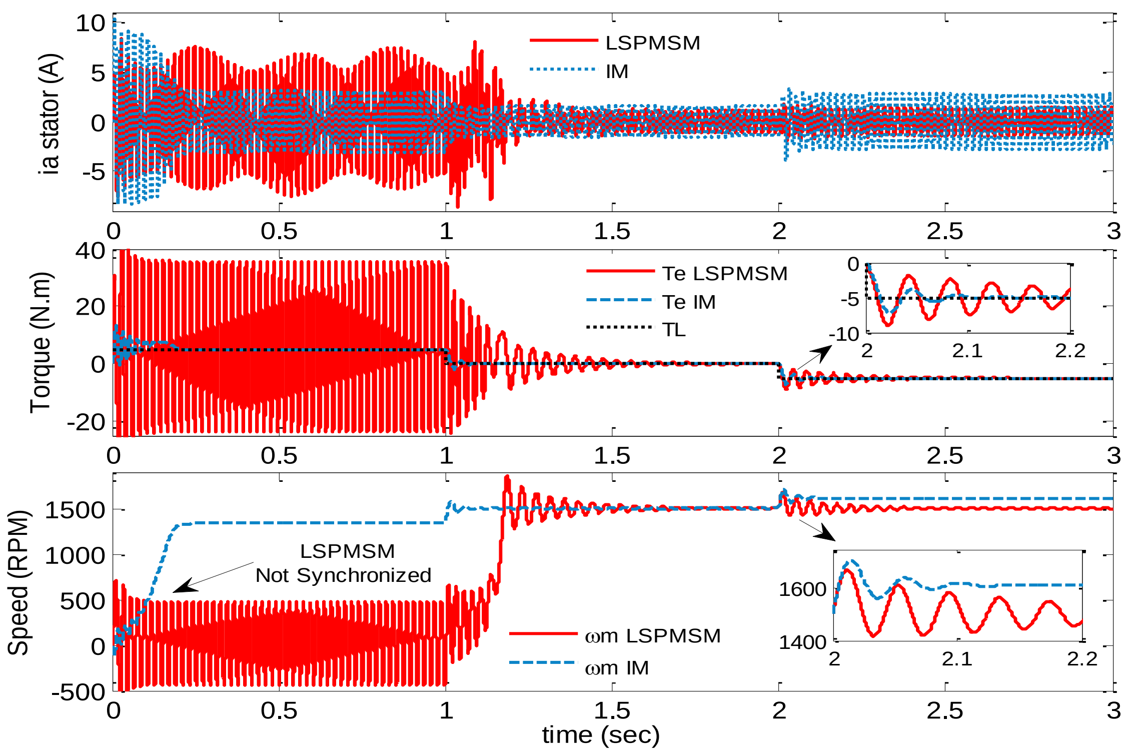

Fig. 7- The stator current of phase "*a*" ($i_{a\ Stator}$), electromagnetic and load torques (T_e and T_L), and motor speed (ω_m) of LSPMSM and IM for voltage sag conditions ($V_{L\text{-}L\ in}$=304 (V) and *f*=50 (Hz)).

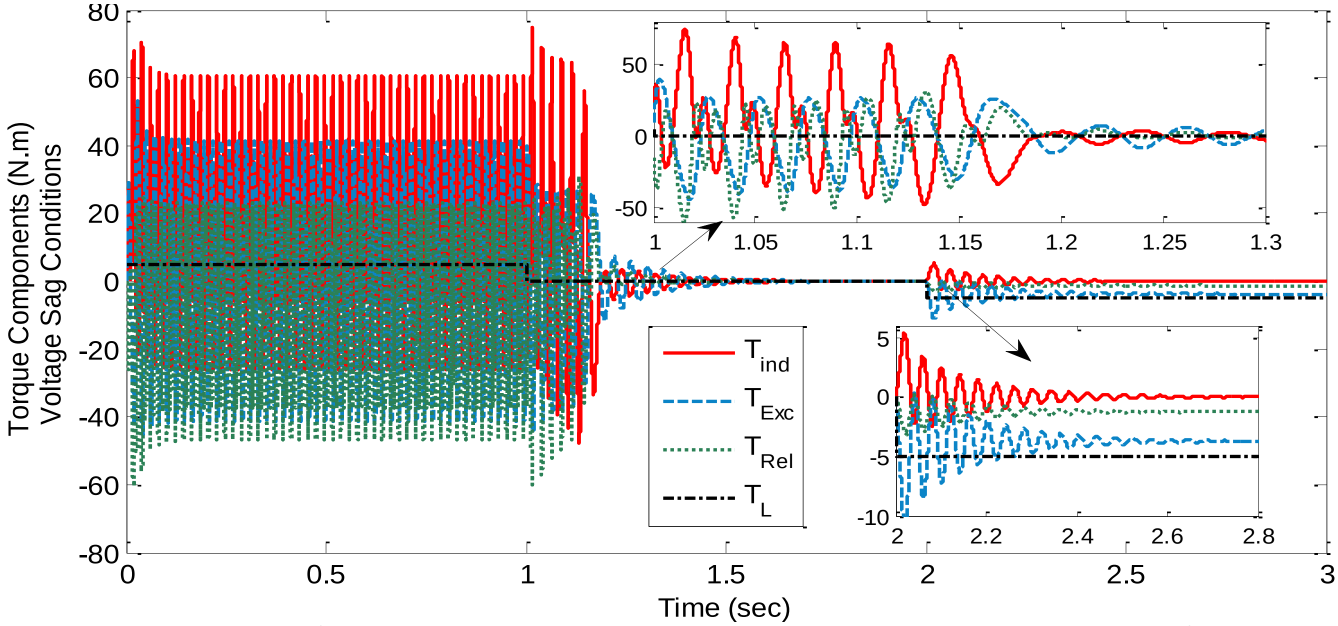

Fig. 8- Torque components of LSPMSM (T_{exc}, T_{rel}, and T_{ind}) and load torque (T_L) under voltage sag conditions ($V_{L\text{-}L\ in}$=304 (V) and f=50 (Hz)).

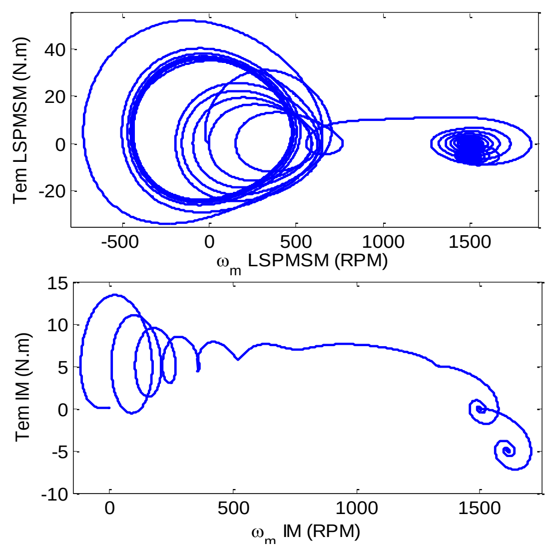

Fig. 9- Torque-speed characteristic of LSPMSM and IM shown in Fig. 7 ($V_{L\text{-}L\ in}$=304 (V) and f=50 (Hz)).

TABLE 5.
TRANSIENT AND STEADY-STATE DATA OBTAINED FROM FIG. 7 (VL-L IN=304 (V) AND F=50 (HZ)).

		Speed					Stator Current	
	Motor	Overshoot (RPM)	Undershoot (RPM)	Steady State (RPM)	Rise time (sec)	Settling time (sec)	P-P of $i_{a\ Stator}$ in Steady State (A)	P-P of $i_{a\ Stator}$ in Transient (A)
TL=5 (0-1sec)	IM	0.025	-120	1333	0.25	0.35	6.24	18.6
	LSPMSM	700	-720	Not Syn.	Not Syn.	Not Syn.	Not Syn.	15
TL=0 (1-2 sec)	IM	75	0	1500	0.008	0.27	3.1	5
	LSPMSM	355	-200	1500	0.0175	0.9	2.31	16.6
TL=-5 (2-3 sec)	IM	95	0	1612	0.005	0.27	5.67	7.16
	LSPMSM	170	-82.5	1500	-	0.9	2.85	3.72

TABLE 6.
STEADY-STATE DATA OF LSPMSM AND IM FOR DIFFERENT LOAD TORQUES IN DIRECTLY CONNECTED TO THE MAINS WITH VOLTAGE SAG CONDITIONS AND NOMINAL FREQUENCY (VL-L IN=304 (V) AND F=50 (HZ)).

Mode	T_L (N.m)	Machine	ω_m (RPM)	|*PF*|	η (%)	P_{Elec} (W)	P_{Mech} (W)	Q_{in} (VAR)
Motoring	6	IM	unstable	unstable	unstable	unstable	unstable	unstable
		LSPMSM	Not Syn.	Not Syn.	Not Syn.	Not Syn.	Not Syn.	Not Syn.
	5	IM	1333	0.8	75	931.2	698.3	693.3
		LSPMSM	Not Syn.	Not Syn.	Not Syn.	Not Syn.	Not Syn.	Not Syn.
	4	IM	1377.3	0.76	79.26	727.9	576.9	625
		LSPMSM	Not Syn.	Not Syn.	Not Syn.	Not Syn.	Not Syn.	Not Syn.
	3	IM	1414	0.68	82.28	539.8	444.1	584.8
		LSPMSM	Not Syn.	Not Syn.	Not Syn.	Not Syn.	Not Syn.	Not Syn.
	2	IM	1445	0.54	83.38	363.1	302.7	565.9
		LSPMSM	Not Syn.	Not Syn.	Not Syn.	Not Syn.	Not Syn.	Not Syn.
	1	IM	1474	0.33	78.9	195.6	154.3	564
		LSPMSM	1500	0.31	72.97	215.3	157.1	-665.5
No-Load	0	IM	1500	0.06	-	53.9	-	576.9
		LSPMSM	1500	0.08	-	36.16	-	-668.2
Generating	1-	IM	1524	0.19	72.83	-116.3	-159.6	602.8
		LSPMSM	1500	0.16	66.18	-104	-157.1	-657.2
	2-	IM	1548	0.38	80.9	-262.3	-324.1	640.6
		LSPMSM	1500	0.38	82.3	-258.6	-314.2	-633.2
	3-	IM	1570	0.5	81.57	-402.3	-493.1	689.7
		LSPMSM	1500	0.57	86.96	-410	-471.3	-596.4
	4-	IM	1591	0.58	80.45	-536.4	-666.5	749.4
		LSPMSM	1500	0.71	88.81	-558	-628.3	-546.7
	5-	IM	1612	0.63	78.74	-664.9	-844.2	819.8
		LSPMSM	1500	0.82	89.53	-702.9	-785.4	-483.5
	6-	IM	1633	0.66	76.74	-787.6	-1026	900.6
		LSPMSM	1500	0.9	89.61	-844.3	-942.5	-405.6

During the starting by a fixed frequency voltage, the excitation and reluctance torques in the LSPMSM decrease the total torque, as they operate as braking torques. Therefore, they have a repercussion on starting LSPMSM and generate torque pulsation. In other words, just the induction torque accelerates the motor and pulls it into synchronism. Moreover, owing to the starting torque, LSPMSM encounters difficulties synchronizing for a high load torque (or high load inertia), when the motor is line-started. Therefore, in general, the IM provides better dynamic operation than the LSPMSM, when they are directly connected to the mains because it has a fast response and has less variation in the speed against load torque changes.

On the other hand, LSPMSM, which operates as a usual synchronous machine, yields more superior performance in the steady-state than equal IM, because it improves power factor and efficiency, decreases the effective stator current, enhances the torque density, and eliminates the rotor losses and all the problems related to the slip, as the result of the synchronous speed. Furthermore, as can be found from Tables III and V, unlike the IM, the LSPMSM in the generating mode provides active and reactive powers, and thus it offers the possibility to replace IMs with LSPMSMs especially in generating mode applications. As can be found from Figs. 5 and 8, similar to the PMSMs, in the steady-state synchronous speed, the induction torque of LSPMSM is zero and the electromagnetic torque consists of excitation and reluctance torques. In addition, when compared to the IM, the speed of LSPMSM in its steady-state operational region for different load torques has no change (, i.e., unlike the IM, the motor speed is independent the load torque), and it is dependent on only the voltage source frequency. For this reason, the steady-state speed of the LSPSMS is changed from 1500 (RPM) to 750 (RPM) when the input frequency of the supply changes from 50 (Hz) to 25 (Hz).

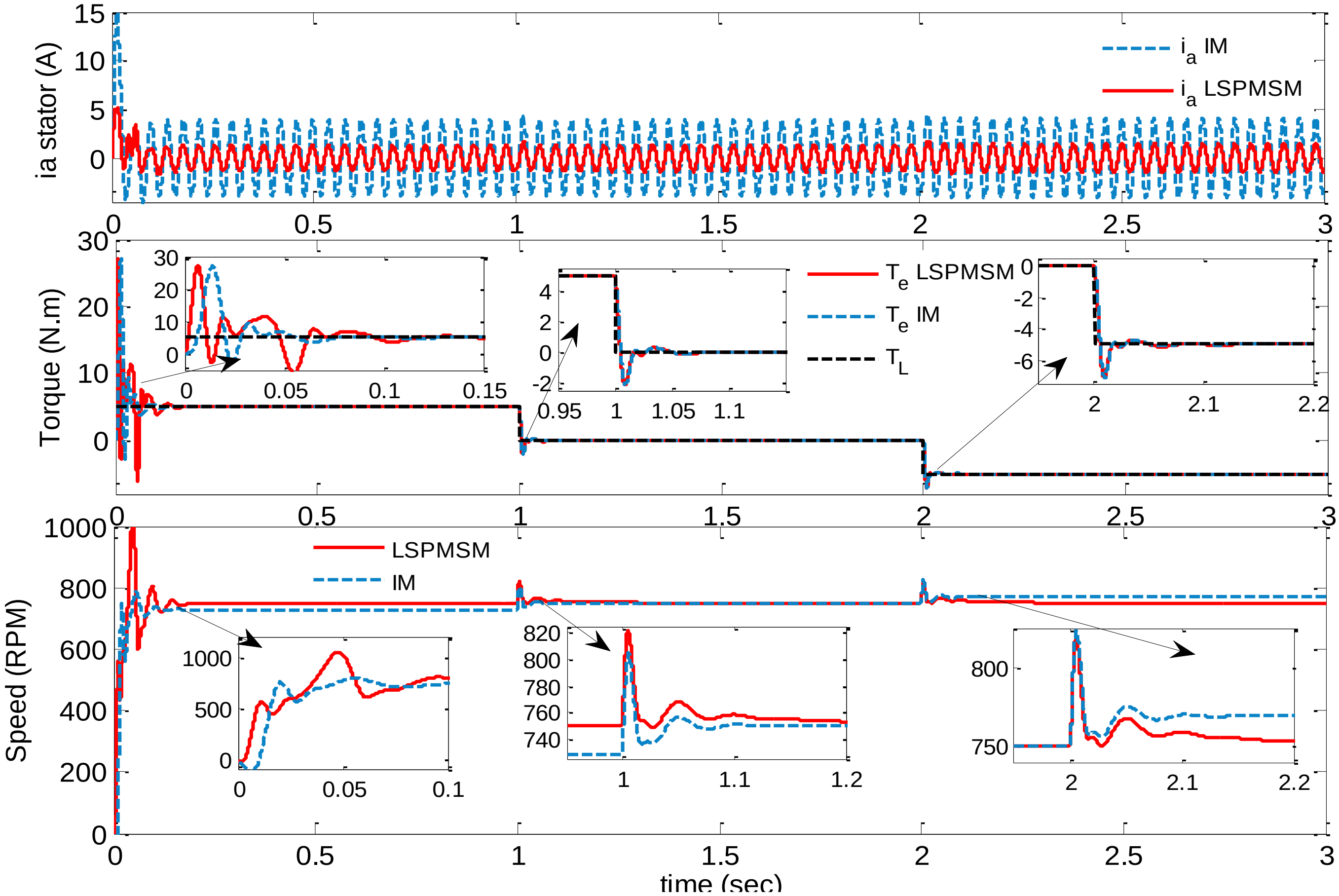

Fig. 10 - The stator current of phase "*a*" ($i_{a\ Stator}$), electromagnetic and load torques (T_e and T_L), and motor speed (ω_m) of LSPMSM and IM for ($V_{L\text{-}L\ in}$=380 (V) and f=25 (Hz)).

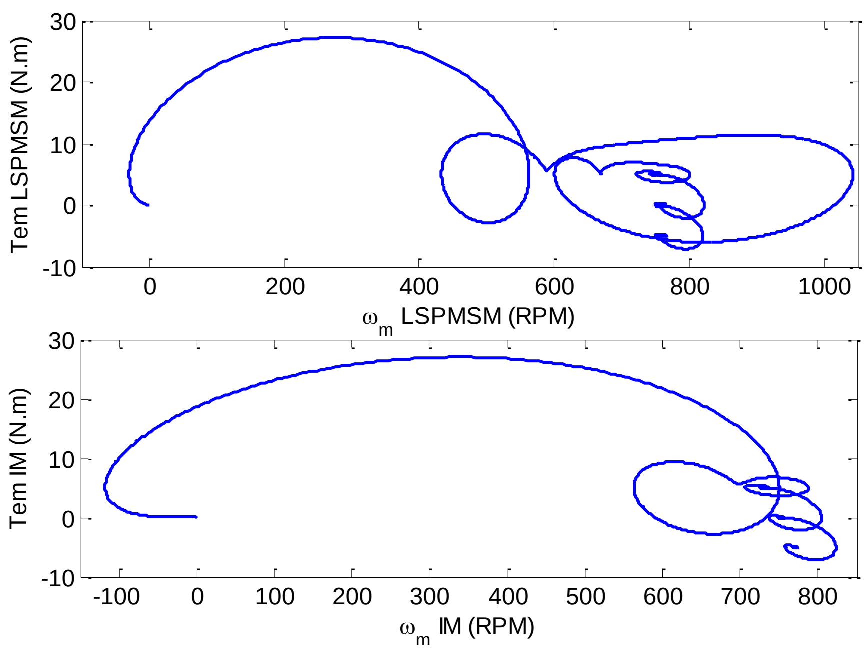

Fig. 11 - Torque-speed characteristic of LSPMSM and IM shown in Fig. 10 ($V_{L\text{-}L\ in}$=380 (V) and f=25 (Hz)).

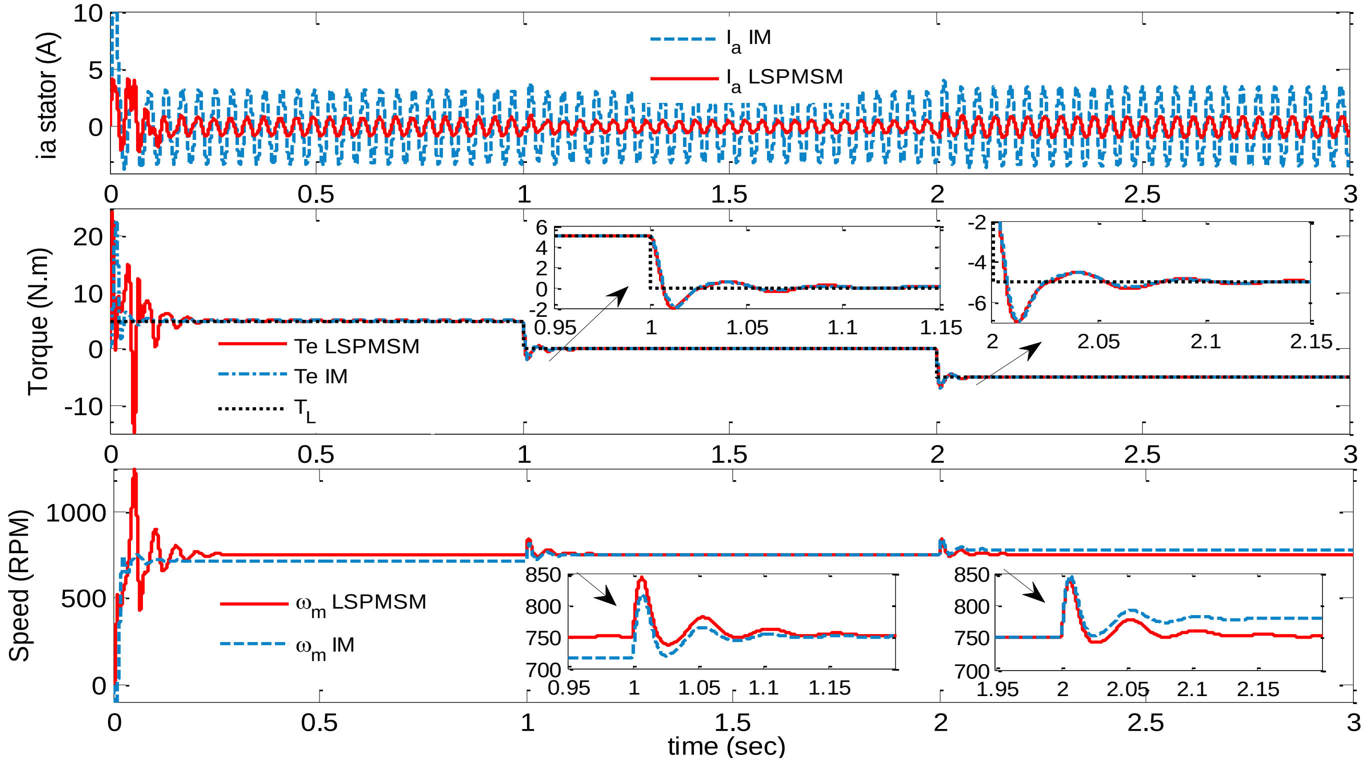

Fig. 12 - The stator current of phase "*a*" ($i_{a\ Stator}$), electromagnetic and load torques (T_e and T_L), and motor speed (ω_m) of LSPMSM and IM ($V_{L\text{-}L\ in}$=304 (V) and *f*=25 (Hz)).

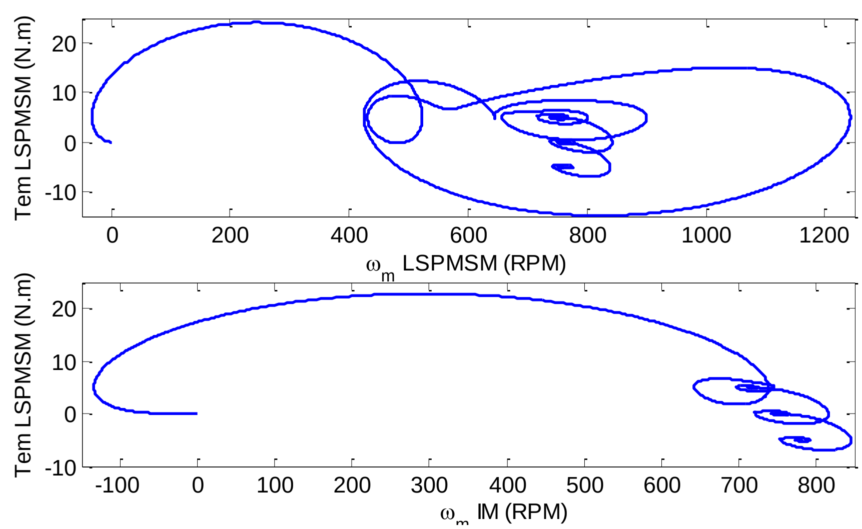

Fig. 11 - Torque-speed characteristic of LSPMSM and IM shown in Fig. 12 ($V_{L\text{-}L\ in}$=304 (V) and *f*=25 (Hz)).

Controlling the voltage and frequency provides the opportunity to the LSPMSM to obviate the aforementioned problems during the starting. In general, LSPMSM encounters difficulties synchronizing especially for higher load torques or reduced input voltage. For this reason, as shown in Fig. 7, the LSPSMS cannot reach to the synchronous speed. However, as shown in Table V, even though it is synchronized for lower loads, its steady-state parameters are no longer better than the IM. On the other hand, this problem can be solved as well by controlling the input frequency. In other words, a comparison between Figs. 7 and 12 confirm that for lower voltage and frequency the LPSMSM is synchronized as well.

TABLE 7.
TRANSIENT AND STEADY-STATE DATA OBTAINED FROM FIG. 10 (VL-L IN=380 (V) AND F=25 (HZ).

		Speed					Stator Current	
	Motor	Overshoot (RPM)	Undershoot (RPM)	Steady State (RPM)	Rise time (sec)	Settling time (sec)	P-P of $i_{a\ Stator}$ in Steady State (A)	P-P of $i_{a\ Stator}$ in Transient (A)
TL=5 (0-1sec)	IM	60	-118	728	0.019	0.25	7.78	19.8
	LSPMSM	292	-30	750	0.036	0.3	2.67	6.28
TL=0 (1-2 sec)	IM	54.27	0	750	0.001	0.14	7.73	8.27
	LSPMSM	71.7	-1.5	750	-	0.2	2.754	2.88
TL=-5 (2-3 sec)	IM	54.5	-13	769.27	0.012	0.2	8.165	8.4525
	LSPMSM	70	0	750	-	0.3	3.03	3.06

TABLE 8.
TRANSIENT AND STEADY-STATE DATA OBTAINED FROM FIG. 12 (VL-L IN=304 (V) AND F=25 (HZ)).

		Speed					Stator Current	
	Motor	Overshoot (RPM)	Undershoot (RPM)	Steady State (RPM)	Rise time (sec)	Settling time (sec)	P-P of $i_{a\ Stator}$ in Steady State (A)	P-P of $i_{a\ Stator}$ in Transient (A)
TL=5 (0-1sec)	IM	33	-134.3	715.19	0.0225	0.28	6.44	16.54
	LSPMSM	493	-33	750	0.039	0.32	1.62	6.32
TL=0 (1-2 sec)	IM	66.4	0	750	0.0015	0.2	6.2	6.69
	LSPMSM	92.7	-12.7	750	-	0.2	1.1	1.45
TL=-5 (2-3 sec)	IM	66.4	0	779.3	0.015	0.2	6.85	7.23
	LSPMSM	88.6	-8.5	750	-	0.2	1.86	2.19

CONCLUSION

The aim of the presented work was to evaluate the performance of IM and LSPMSM for different conditions. This study showed that the LSPSMS behavior is affected through large load torques or lower input voltages. On the other hand, LSPMSM problems during the line-starting can be obviated through an appropriate control of input voltage and frequency. The second major finding was that the LSPMSM machines in generating modes exhibits more superior overall performance than the IMs. Therefore, they are able to save energy if LSPMSM substituted IM. Subsequent research might investigate LSPMSM performance with a closed-loop controller to test them for adjustable speed control drive performances.

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