Network effects of line-start permanent magnet motors

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Abstract: **Advances in permanent magnet technology, combined with stringent requirements on efficiency that are being implemented in various countries, suggest the line-start permanent magnet motor as a suitable high efficiency replacement for IMs driving fixed speed loads. The considerable proportion of the system load that could be affected, and the lack of any supply buffering in the direct-connected motor, raise the question of how much effect such a change would have on the behaviour of the supply system. In the work reported here, simulations have been made to compare the behaviours of induction and permanent magnet motors under conditions such as supply voltage changes and starting transients. The effects of permanent magnet motors on a supply system have been considered in the light of the simulations.**

It has been found that there are some very positive effects of a change to permanent magnet machines, although the starting currents are higher and low supply voltages could cause more overheating than in an IM.

Introduction

Environmental and economic concerns are causing higher energy efficiency to be required of electrical loads. Motors make up a large proportion of the installed load in power systems, typically 70% of industrial loads and 50% of the total system load in an industrialised country [1,2].

The induction motor (IM) has been by far the most common motor in industry and some lighter applications for the last hundred years. Its good features include very sturdy construction and low maintenance. Recent development of semiconductor switches and controllers for inverters has allowed IMs to be used even when close control over speed and position is required. However, the IM has an inherently lower efficiency than the permanent magnet motor as its torque is produced by the interaction of the currents in the stator windings and the large induced currents flowing in the rotor windings, and current is required at all loads to magnetise the airgap.

A typical efficiency of a 10kW IM is around 90%; there is thus the potential for worthwhile reduction of the total system consumption by efficiency improvements to motors. The large proportion of motor loads means, however, that changes in motor behaviour may change considerably the system behaviour.

Permanent magnets allow there to be no rotor currents in steady operation, and some or all of the airgap magnetisation can be done by the magnets rather than extra stator current. During the past decade there has been a much increased use of permanent magnets, as better materials have become available at lower prices. As increased efficiency requirements push the IM to the peak of its realisable efficiency, permanent magnet motors become a good way for manufacturers to produce high efficiency motors of a reasonable cost and size.

In many cases a load may require its motor to be driven from an inverter, which can buffer the motor and supply from each other as well as providing precise control of the motor for various drive applications. For some other drives such as simple pumps, there will be no need to vary the speed from the supply frequency; in this case the drive system can be expected to be simpler and cheaper if the motor used is able to connect directly to the supply for starting and running.

The replacement of IMs would be encouraged if permanent magnet motors were available as a direct substitute, being of the same size and connecting directly to the same supply without any additional controls. The types of loads that are suitable for this constant speed operation are also those that could be a large proportion of the motor load in a system, such as pumps and fans [1]. There is thus a good reason to consider the case of considerable amounts of IM load being replaced by line-connected permanent magnet motors.

Changes to the operational structures of power systems have occurred recently in many countries, leading to commercially operated systems with equipment operating nearer its limit. If a consumer with many motor loads is supplied at a weak point in a network, it will be particularly important to know the effects of changing the type of motor used. Even within a local distribution system, a change from IMs to permanent magnet motors may require upgrading of switchgear and cabling, or alternatively may allow more motors to be run on the existing system, depending on the relative behaviours of the motors. The behaviour of the motor towards the load may also be different.

The type of motor considered

In this work the line-start permanent magnet synchronous motor (LS-PMSM) has been considered, which has the desirable feature of starting and running directly from the supply as a direct replacement for an IM. A LS-PMSM is usually manufactured from an existing IM stator, for ease of production. Its rotor contains permanent magnets, whose permeability is usually much less than that of the surrounding iron; the magnets thus cause the axis on which the permanent magnet flux lies to have a higher reluctance than the electrically perpendicular axis. The airgap is larger than that of an IM, leading to lower reactance. When the rotor is synchronised with the stator field, the permanent magnet field and the saliency both contribute to the torque, the saliency sometimes producing nearly as much torque as the field does. A squirrel-cage is included in the rotor; this provides an asynchronous torque for starting, and also damps the synchronised operation. As the function of the cage is different from that in an IM, the electrical properties may differ.

During starting, the permanent magnet field causes braking of the rotor by inducing sub-harmonic currents in the stator. There is also a speed-dependent component of torque due to the rotor saliency, causing a sharp drop in torque when passing half of synchronous speed (Görge's phenomenon) [3].
When out of synchronism the rotor's speed has an oscillation due to the interaction of the stator field with the permanent magnet field and saliency. This oscillation is superimposed on the speed produced by the asynchronous torque from the currents in the cage. During a successful starting and synchronisation of a LS-PMSM the asynchronous torque accelerates the rotor against the load torque and electromagnetic braking torques until its speed is near enough to synchronous speed for the superimposed oscillation to carry the rotor into synchronism.

The modelling method

For the dynamic modelling of the machines, a rotor-referenced d-q model of an induction machine was made in Matlab Simulink. Stator and rotor circuits were modelled on the d and q axes, and to extend the model to the LS-PMSM the field was modelled as a further winding in the d axis, supplied by a constant current source [3].

No account was taken of the effects of magnetic saturation and iron losses, as these would have made the model far more complicated.

In the phasor diagram, Fig. 1, the steady-state result of the d-q transform of a LS-PMSM is shown. The supply voltage Vs is composed of the components aligned with the d and q axes. This is matched by the sum of the induced voltage from the field, E_o, and the resistive and reactive voltage drops in both axes due to the currents I_d and I_q. In transient conditions there will be voltages induced by changes of currents in the axes' inductances, and E_o varies with the speed of the rotor.

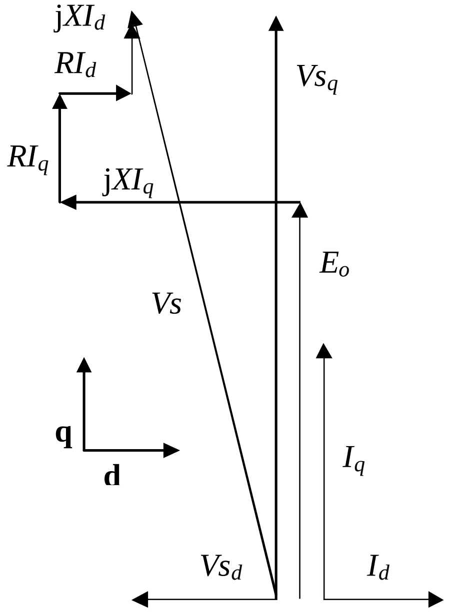

Fig. 1 *Phasor diagram of operation*

The effects of rotor saliency are included in the transform by using different values of reactance, X, for the two axes.

Simple models were also made of mechanical loads, with inertia and a quadratic relationship between speed and torque. The supply system was modelled as series inductive-resistive with a controllable voltage source.

Simulations

The simulations whose results are described here were made using the parameters from 4-pole 7.5kW models of an LS-PMSM and IM.

A stiff supply was used for simulations of starting currents and active and reactive power responses to voltage changes, then supply impedance was modelled to show the effect of the presence of LS-PMSMs in a system.

The possible effects

Taking a wide view of what problems may arise from the proposed direct replacement of IMs by LS-PMSMs, four categories of effect were identified:-

Effects *on* the motor from:

the load; successful synchronisation requires a load of moderate inertia, and reduced load torque at low speeds.

the supply; differences in design of the rotor cage, and the larger airgap, may give different harmonic losses when the supply has harmonic voltages.

since the motor operates synchronously, its speed cannot fall even if the supply voltage decreases; therefore the output power is maintained, at the expense of a higher current and increased losses.

Effects *of* the motor on:

the load; the synchronous operation means that the speed will be rather higher than with an IM. This may cause the load to operate above its rating, with consequently increased power consumption.

during starting there may be much higher torques due to the oscillating component from the permanent magnet field.

the supply; a drop in supply voltage will cause an increased current input to maintain the load power; this implies that the active power consumption will rise due to increased copper loss.

as the rotor speed is constant, the steady state induced voltage from the permanent magnet field can be considered as constant. A drop in the supply voltage will then cause the motor to consume less or generate more reactive power. This effect can be described by the classic situation of two voltage sources – the induced voltage and the supply – connected by a reactance, although the series resistance and the change in load angle make this only an approximation. This change in reactive power consumption is the most useful network-related feature of the LS-PMSM.

Starting

During starting, the LS-PMSM has a much greater oscillatory torque than the IM. The supply current has a strong variation when the speed is getting near synchronous speed, as the supply and induced voltages move slowly in and out of phase.

A simulation was made of an IM and LS-PMSM starting on a stiff supply, driving the full rated load with a square torque/speed characteristic, and with a load inertia of twice that of the motor. Fig. 2 shows the rms currents and the torques.

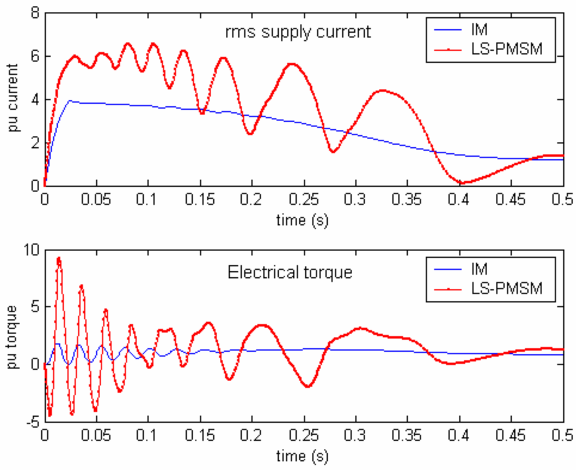

Fig. 2 *Current and torque during motor starting*

The actual magnitudes may be made closer than is shown in fig. 2, by different selection of machine parameters. The oscillating currents and torques, and the naturally worse starting performance arising from the presence of braking torques, do however make the LS-PMSM the worse motor in its effect on the supply when starting.

The starting currents of a real LS-PMSM are very dependent on the relative positions of the rotor field and the supply voltage at the moment of switching. The worst case is when the build up of stator field adds to the permanent magnet field for the first half period of relative motion of the supply and rotor. In this case the flux may be a lot higher than usual, causing saturation of the iron and consequently far higher supply currents, which extreme situation can not occur in an IM.

Active power variation with supply voltage

A large difference in the natures of the two motor types is the reaction to variation of the supply voltage. When an IM is run on a decreased voltage, its torque/slip operating point changes, and a new operating speed is reached at which the slip has increased enough for the motor to supply the load power. The power requirement of a load with a square torque/speed relation will be in proportion to the cube of the speed, so a small change in slip can make quite a large reduction in the load power requirement. Even if the motor's efficiency drops due to the voltage reduction, the active power consumption may increase very little if at all.

A LS-PMSM will remain at synchronous speed until the voltage falls so far as to cause a loss of synchronism, such a loss causing a high and oscillatory supply current. Constant speed operation means that the same mechanical power must be provided in spite of the reduced voltage, so more current is drawn and there are higher losses. Fig. 3 shows the quite small effect of a supply voltage reduction on active power consumption.

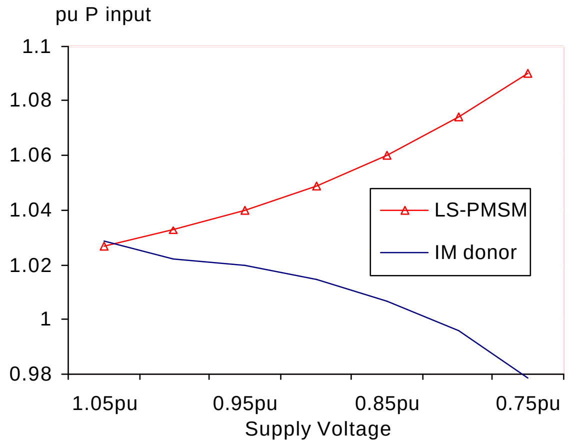

Fig. 3 *Steady state active power (P) input with varied supply voltage*

It should be noted that although the change in active power is small compared to the total consumption, it increases the motor losses considerably.

Reactive power variation with supply voltage

As regards the reactive power response, the main difference between the motor types is the active nature of the LS-PMSM, whose induced voltage from the permanent magnet field is an internal voltage source.

A simple model, for the sake of understanding, is to treat the motor as a voltage source connected through its internal impedance to a fixed supply voltage – Fig. 1 with equal d and q reactances.
Since the impedance is mainly reactive, the angle between the sources mainly determines the active power transfer, and the active power into the induced voltage E_o is the fixed load power. The reactive power is therefore mainly determined by the difference in voltage magnitudes rather than the load angle

Since the speed is constant as long as the motor remains synchronised, the steady state induced voltage is constant, so changes in supply voltage have a direct effect on reactive power consumption by the motor. The saliency of the rotor complicates this analysis, but the general behaviour of the motor is well explained by it.

A reduced supply voltage causes a reduced reactive power consumption if the induced voltage was already lower than the supply voltage, or an increased reactive power generation if the induced voltage was higher than the supply voltage. As a typical supply system contains inductive loads and has series inductive reactance in the supply, the response of a LS-PMSM to voltage variations will help to maintain the voltage.

The variation of reactive power is proportionately more than the variation in active power, and reactive power generally has the greater effect on the voltage. For this reason, a LS-PMSM is likely to be very helpful to the system as it can either provide more or consume less reactive power than an IM would, and this reactive power varies if the voltage changes. The LS-PMSM's induced voltage is the main parameter determining the normal level of reactive power flow.

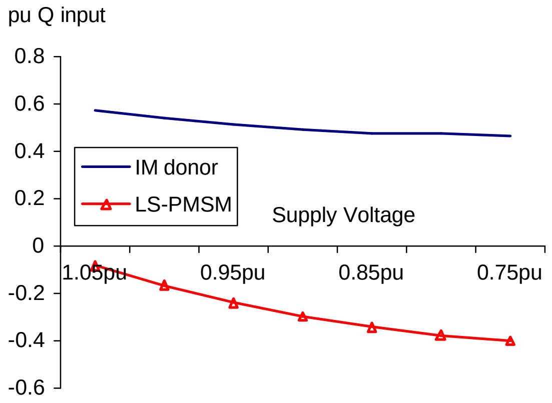

Fig. 4 *Steady state reactive power(Q) input with varied supply voltage*

Transient behaviour

A matter of interest was the effect on transient behaviour of a system of motors. The supply was given an impedance of 0.1 + j0.25 ? , a little over 1% impedance on the base of one motor's power.

The three running motors were all IMs in the first simulation, then they were changed one by one to LS-PMSMs. It was found that the lower active and reactive power consumptions of the LS-PMSM caused the steady state voltage to be higher as each IM was replaced. The drop in voltage during the transient was almost the same in all cases, so the consequence of using LS-PMSMs was to increase the voltage at all times, see fig. 5. This indicates that any effect of higher current draw during disturbances was easily offset by the good response of reactive power.

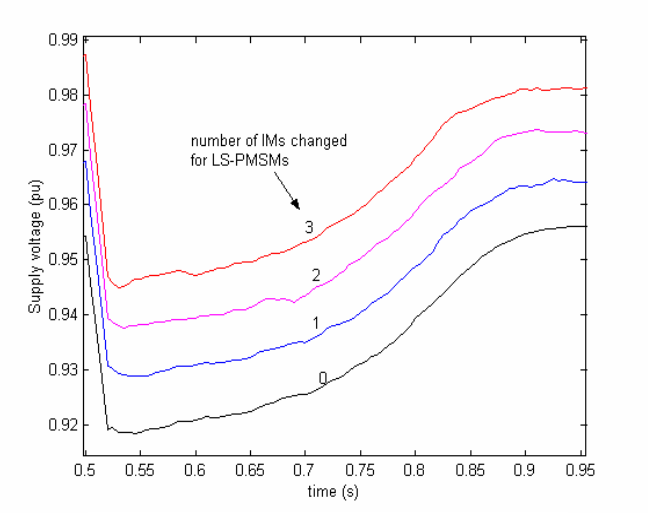

Fig. 5 *Supply voltage when starting a parallel IM with various motor combinations already running.*

Supply disturbances, such as another motor starting, have a greater effect on the torque of the LS-PMSM, although for likely applications this would not be a problem. Fig. 6 shows the result of a similarly rated IM being started.

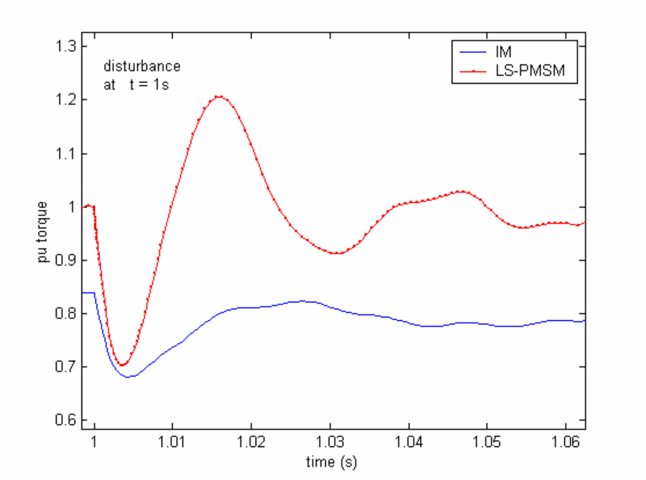

Fig. 6 *torques after a small supply-disturbance*

Regeneration

An IM that has been short-circuited after normal running can generate current for a short time while the currents in the rotor circuit decay. A LS-PMSM can generate current as long as it keeps rotating. Its initial current into a fault will fall due to the sub-transient reactance changing to the synchronous reactance, and the decreasing mechanical speed. If the motor is open-circuited, the permanent magnet induced voltage will be maintained at the terminals as long as the speed is still high; this may hold on a simple mechanical contactor, causing a large current to flow when the supply is resumed.

Summary

The main network-related points that are of importance when IMs are changed for LS-PMSMs are the starting transients and reactive power consumption.

The starting transients can be expected to be worse since starting is more difficult with the additional braking of a LS-PMSM rotor, and the induced voltage slipping in phase past the supply voltage produces a large oscillation on the current. The response when recovering from voltage disturbances such as short losses or large dips (e.g. a cleared fault elsewhere in the system) can also be expected to be worse, again due to the swinging or loss of synchronism of the rotor.

The reactive power consumption or generation is determined mainly by the magnets' field strength, which is constrained by the requirements on braking, synchronising and running torques. The potential for a good power factor and helpful response of reactive power to voltage changes makes a LS-PMSM very helpful to the system in steady state and in moderate disturbances that do not cause large swinging or loss of synchronism. It must be noted that when synchronism is lost the reactive power demand can be just as bad as for an IM.

A LS-PMSM has a lower active power consumption than an IM when in steady operation, unless its slightly higher speed causes a considerably higher load consumption. A reduction in supply voltage makes the LS-PMSM's active power consumption rise, causing increased losses in the motor and an unhelpful effect on the supply system. The local system will almost always be more affected by the change in reactive power, which has a good effect on the voltage.

The active nature of a LS-PMSM suggests that it would supply more current than an IM into a fault, particularly a fault lasting more than 100ms or so. This could be important at buses all the way up to the highest levels in areas where there is a lot of motor load.

The overall network effect of the proposed change is very good in steady state and with small disturbances. The currents during starting, large swinging, and loss of synchronism, warrant consideration of controls to prevent the motors all being started together or remaining connected to the supply during a brief interruption.

The induced voltages may hold-on a contactor during a short interruption, and this effect would need to be prevented in order to avoid large currents on restoration of the supply

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Biography: Nathaniel Taylor studied for his undergraduate degree at Imperial College, London, and spent his final year on exchange at the Royal Institute of Technology in Stockholm, on the MSc Electrical Power Engineering course. His MSc thesis project involved the study of LS-PMSMs and their interactions with supply systems, and the main results of simulations are summarised in this article.