Network effects of line start permanent magnet synchronous motors as replacements for induction motors

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Abstract

The line-start permanent-magnet synchronous motor (LS-PMSM) has permanent magnets in its rotor, along with a squirrel cage starting winding. It can be contacted directly to the supply for starting and running. Its main advantage over an induction machine is that its efficiency can be considerably higher: losses during normal running can be halved, due to the reduction of magnetising current in the stator and the absence of copper losses in the rotor. Pure permanent-magnet machines can be driven from inverters to achieve comparably high efficiency, but the line-start motor has the advantage of simplicity and consequent lower cost.

Electric motors account for about half of global electricity consumption, and are increasingly being required to have high operating efficiencies. Within industry, a lot of energy is consumed in driving pumps with induction motors of the order of tens of kilowatts. Where variable-speed operation is not required, the LS-PMSM is a suitable replacement, and offers lower running costs for a rather higher initial cost.

If LS-PMSMs are to be used to replace induction machines (IMs) on a large scale, it is important to know whether there are differences in behaviour that will affect the electrical network. Adverse effects of LS-PMSMs are particularly important as they could lead to problems with the supply voltage, or to excessive loading of the system. It is useful to know any favourable effects too, as these can be used in marketing the motor and in designing the local distribution system. The effect of power quality on losses must be known if realistic efficiencies and maximum ratings are to be calculated. When motor parameters have an important effect on the motor's interaction with the network, an understanding of this interaction will allow a better choice of motor to be made.

For these reasons, this study has considered ways in which a LS-PMSM fundamentally differs from an IM in its behaviour during starting and running. In particular, the effects of supply voltage change on active and reactive power consumption have been examined. Higher starting transients, different harmonic impedance, and increased regeneration into faults are among the other differences considered. Dynamic simulations have been performed in Matlab Simulink of some representative machines and systems.

The most significant findings are that the synchronous operation and permanent field can respectively cause a LS-PMSM to increase its active power consumption as the supply voltage decreases, and to raise system fault levels by its regeneration. The reactive power responds to voltage reductions in a way that is helpful to realistic distribution systems. There is reason to suppose that harmonic voltages in the supply will be of more detriment to a LS-PMSM than to an IM, but simulations of harmonic effects were not possible in this work.

The project task

Original task

> “ …. There are though some features with permanent magnet motors that might be important for their possibility to be integrated in the power system. These include:
>
> - Low resistance that might increase the harmonic currents in the motor if there are harmonic voltages in the connection point.
> - Increased consumption of reactive power when the terminal voltage is decreased. This causes increased currents in the motors, and might decrease the voltage level even more.
>
> The aim of the project is to study the importance of these features. To be more specific the aim is to study the performance of the system, including permanent motors, when:
>
> **1**. A motor starts which increases the currents which lower the terminal voltage of the permanent motor during the start-up.
> **2**. There are harmonics present in the system.
> **3**. There is a fault in the feeding system which lowers the voltage in the system.
>
> The aim is to build up a model of a test system in EMTDC and simulate interesting cases… ”

Alterations

During the course of this project a different simulation program was chosen. The reactive power consumption was found not to be a problem, but other important concerns were studied. Harmonics were not examined by simulation because of the complexity of suitable machine modelling and the inadequacy of necessary motor data.

These changes to the initial description are explained further in the relevant parts of this report.

List of tables and figures

A glossary of abbreviations and some terms

P and Q – active and reactive power

d and q – direct and quadrature (axes) - see Park's transform, page 31

PM – permanent magnet

B and H – magnetic flux density (Teslas) and magnetising force (A/m)

IM – induction machine
SM – synchronous machine
PMSM – permanent magnet synchronous machine
LS-PMSM – line-start PMSM

Eo – the open circuit emf of a PMSM rotating at rated speed

HEM – higher efficiency motor, usually meaning a higher efficiency IM

VSD – variable speed drive; an inverter-fed motor

PWM – pulse width modulation

MOSFET – metal oxide semiconductor field effect transistor

IGBT – insulated gate bipolar transistor

CEMEP – European committee of manufacturers of electrical machines and power electronics

EPACT – Energy Policy Act (U.S.)

EMTDC – electromagnetic transients simulation program developed by Manitoba Hydro particularly for High Voltage Direct Current simulations. Power Systems Computer Aided Design (PSCAD) is a graphical user interface for the core program.

Pole-slipping – the effect of a SM being out of synchronism and the induced and supply voltages being in phase then in antiphase as the rotor field 'slips' past the stator field.

Load-angle – the angle between the induced and supply voltages of a SM

Swing – the oscillation of load angle about an equilibrium position

1 Modern practice and future changes in drive systems

The aim of this chapter is to show that there is the potential for enough installed motor capacity to be replaced by LS-PMSMs as to alter considerably the network behaviour.

The large proportion of electricity consumed by motors, in particular by those driving pumps and fans, is described. Recent attention to higher efficiency motors is explained, along with developments of permanent magnet materials that have resulted in lower prices and better performance. Common types of motors are compared to show that the LS-PMSM is likely to have an advantageous total lifetime cost for some mundane applications.

- A background to motor use
- Permanent magnets for motors
- Consequences on LS-PMSM uptake
- Comparison of a.c. machines

Energy consumption by motors

Electric motors account for a large part of worldwide electricity consumption. For example, in the U.S. just over half of the total electricity consumption is by electric motors [13], while in the U.K. this figure is just under half [8]. Similar situations exist in many countries [15], as pumps in particular are necessary even for basic water supply and sewerage systems as well as for industries. Within worldwide industry, motors consume about 70% of the electricity [14].

Since motors are such a major electricity consumer, a general change in efficiency of the drive systems used will have a marked effect on the environmental effects of electricity generation, and on the costs of energy to companies and nations. Electric motors can consume many times their capital cost during their lifetime, although the exact relation of capital and running costs of course depends upon the duty of the motor and the material and energy costs in the country in question. For example, a U.S. source [13] quotes annual energy costs of a constantly running 15kW motor as nine times the capital cost. Although it can be tempting for companies to minimise initial costs, the savings possible from an efficiency increase can often be seen to warrant a more expensive motor.

Taking the U.K. as an example of industrial drive applications, a third of the energy use is by motors in the low power range of 1.1 to 15 kW, while another third is in the range 15 to 150 kW [11]. Motors in these power ranges are usually induction motors running from standard low-voltage supplies such as 400V.

The drive losses

From the chart (right) of U.K. industrial motor consumption [8] it can be seen that over half of the energy is used in applications that move fluids. Although some pumps have to move liquids against gravity, for example in water supplies, a lot of energy is used in forcing fluids through their networks of pipes and ducts. Large improvements to flow can be made through the use of even slightly wider paths and smoother bends. Air leaks in systems of fans and ducts can also considerably reduce the system's efficiency. Where flow control is required, the use of motor speed control gives far higher efficiency than throttling of the flow, and motor life is longer than with repetitive stop-start operation.

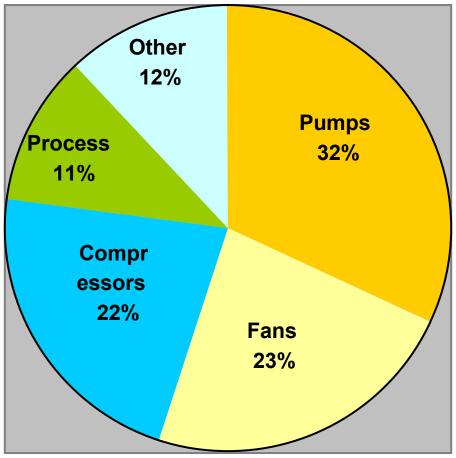

Figure 1 UK motor energy consumption

An IM in the low to medium power range can be expected to have an efficiency in the region 80 to 95% (see table 2 on page 18). Given that pumps operating against no static pressure are putting all their output into pipeline resistance, there is often a lot more potential for energy saving in the load than in the motor.

However, there is still a saving to be made by reducing motor losses, and a high efficiency motor that can directly replace the existing one is a straightforward way to reduce the wasted energy in the system. When the load is already constrained in efficiency, improvements to the motor efficiency are the only way to make further energy savings.

High efficiency motors

Efficiency improvements are made to conventional IMs by reducing constant losses in the iron and cooling fan, and load-dependent losses in the windings. Low resistance rotor bars are used increasingly. Reduction of iron or copper losses is effected by using more material or higher quality materials, either of which will increase the motor cost. If HEMs become much more popular it may not be worthwhile to continue manufacturing the lower efficiency range for the few consumers whose motors are used too infrequently for efficiency to matter.

One possible problem of HEMs is the reduced slip that results from lower rotor resistance [11]. The consequent increase in load consumption could reduce the overall efficiency of the drive. Alteration of the load would be needed in such a case.

Variable speed drives

In the last decade, inverter drives have become widely available. Fast switching of devices such as MOSFETs and IGBTs has allowed PWM synthesis of sinusoidal waveforms, with quite low harmonic content. The voltage magnitude and frequency can be varied according to programmed sequences, and motor speed or position may be fed back or estimated to allow IMs or SMs to be closely controlled. As well as soft-starting the motor, with good effects on motor life and the supply voltage, inverter drives allow efficient operation at variable speed. When a speed reduction can be used in place of throttling the fluid flow, very large energy savings can be made [2].

In spite of the improvements in inverter drives, a motor that operates efficiently and without any power electronics is likely to have the advantage for simple, single speed applications, as long as enough such motors are produced to keep the cost lower than a motor with an inverter.

Increased standards for efficiency

Governments are increasingly concerned about energy consumption and can intervene to penalise manufacturers or users of low efficiency equipment, or to legislate about efficiency requirements. Any further efficiency improvements in motors are likely ultimately to cause such legislation to be tightened to meet the new possibilities.

In 1992 the U.S. Energy Policy Act specified efficiency minima for general purpose motors from 0.75 to 150 kW [13]. These were required of most manufacturers by 1997.

In the E.U. such legislation has not come about, but market forces are intended to achieve the same effect. Three motor classifications, Eff1, 2 and 3 (see right) have been specified for motors throughout the lower and medium power ranges [14].

The classifications are the result of a cooperation between the E.U. and the European committee of manufacturers of electrical machines and power electronics, CEMEP. Since 2000, motor manufacturers have been free to use this classification, and it is hoped that consumer awareness of the savings possible even for a small efficiency increase will result in a need for manufacturers to use the classification and to make their motors fall into the higher categories.

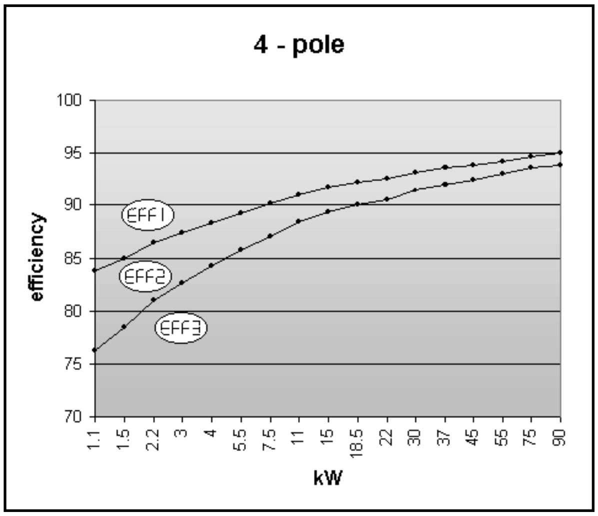

Figure 2 European energy efficiency classes for 4-pole motors

The Eff1 class can be difficult to achieve by alterations to IMs, and this could prompt companies to look to other types of motor to give the most economic solution.

Changing to high efficiency motors

The main limit on a motor's lifetime is insulation degradation [2], so re-winding of motors is a common way to get an old motor back in service at less cost than a replacement. The disadvantage of this method is that re-wound motors tend to have lower efficiency. New motors have in the last two decades been designed far more for efficiency than previously; the difference in efficiency between a new high-efficiency motor and a re-wound motor of the older type can be more than 4% [9], which, combined with the greater life expectancy of a new motor can make this the better option.

As motor life-times are generally less than 20 years [2] a general efficiency improvement of new motors will percolate into the operating population of motors far more rapidly than it would if new installations were the only reason for motor purchases.

Permanent magnets for motors

PM materials have been used since the earliest days of electrical engineering, but only quite recently have the high performance rare-earth magnets become available, with a sufficient energy density to be used in demanding applications. Reduced magnet costs and advantages of size and efficiency make PM motors ever more popular.

PM specifications

Important properties for the motor application are:

- Energy density: the maximum magnetic energy (proportional to B and H) able to be produced outside the magnet per unit volume of the magnet. This gives an indication of the size of magnet required to magnetise the airgap.

- Remanent flux density (B_r): the maximum flux density of the magnet, this being the absolute maximum that can be obtained in the magnetic circuit if its area is no bigger than that of the magnet. Any reluctance in the circuit will of course reduce this flux density.

- Coercivity (H_c): the magnetising force needed to demagnetise the remanent flux. Low coercivity requires more care in using the magnets, in order not to demagnetise them with the fields from motor currents.

- Temperature dependency: increased temperature can reduce B_r and H_c, making demagnetisation more easily possible. The effect of temperature on the maximum permissible field strength must be allowed for in the design.

- Curie temperature: the temperature at which all magnetisation ceases. The high Curie temperature of common PM materials means that the effect of temperature on the coercivity is the dominant constraint on permitted magnet temperature.

Common PM materials

Ferrites have been known of for longest, and the availability of the ingredient Fe_2O_3 as a by-product from steel manufacture gives them a low price. Their main disadvantages are the low remanence (0.4T) and low energy density.

Samarium-Cobalt magnets were developed in the 1970s and have a far higher energy density than ferrites. They can operate over a very wide temperature range, their main disadvantages being the high price and rather lower energy density and remanence than Nd-Fe-B magnets.

Neodymium-Iron-Boron magnets were developed in the early 1980s partly in response to the large price increase of Cobalt at the time. They have a better energy density and remanence but a lower Curie temperature than Sm-Co. Protection against moisture is needed because of the neodymium content. This is usually achieved by a thin layer of metal oxide.

Table 1 Comparison of rare-earth magnets

Material	Sm-Co	Nd-Fe-B
Energy density [kJ/m^3]	240	385
Remanence [T]	1.15	1.4
Coercivity [kA/m]	2400	3260
Curie temperature [°C]	800	350

PM motors have consequently been made more attractive in the last two decades by the availability of much improved PM materials. Although Sm-Co has the advantage for withstanding high temperatures, the lower price and required volume of Nd-Fe-B make it a likely choice for a commonplace motor.

Consequences of the foregoing upon LS-PMSM uptake

Several aspects of the previous sections indicate good reasons for the future acceptance of the LS-PMSM as a replacement over a large amount of the installed IM power.

PM price reductions

Increased knowledge of PM materials, possible further developments, and greater use are likely to provide cheaper magnets. The consequent reduction in cost of PM motors will make LS-PMSMs and inverter-supplied PMSMs more competitive with IMs in terms of total lifetime costs.

The drive for higher efficiency

Given that a large proportion of global electricity consumption is by motors, there are national and global advantages to be obtained by the use of HEMs. International moves towards energy saving will make the requirement for high efficiency ever stronger.

If another type of motor, for example the LS-PMSM, becomes available in a form that can directly replace IMs, and that offers a higher efficiency even than a high efficiency IM, there may be advantages of lifetime cost for some applications, depending on the capital cost of the new motor. Government intervention in the name of energy conservation, such as energy taxes or grants for efficient equipment, could help to make the new motor economic even if its capital cost were high.

The importance of pump loads

The LS-PMSM has more of a problem than the IM at starting, as will be explained later. This feature makes it best suited to loads such as centrifugal pumps, whose inertia is quite low and whose torque is in proportion to the square of the speed so is lower at sub-synchronous speeds than it would be with a direct proportionality. Low-inertia fans would also be suitable loads, but fans generally have higher inertias than pumps [2].

By happy chance, pumps and fans are responsible for more than half of industrial motor consumption. Even taking away those loads that require or are improved by variable speed and are consequently buffered from the supply by an inverter, there can be expected to be large amounts of load that would be well suited to the LS-PMSM.

The less obvious consequences of replacing IMs

The large amount of installed IM capacity that could be changed to LS-PMSMs means not only that large energy savings can be made for users and nations, but also that a difference in behaviour between the machines will have an impact on the behaviour of, potentially, all levels of the supply network.

In a local distribution system of an industry that chooses to adopt LS-PMSMs, these machines may make up much or all of the load, with pronounced effects from any unhelpful behaviour of the LS-PMSM in response to steady or transient variations of supply voltage.

On the much larger scale of the power system, a significant change in the behaviour of the connected load could result from large use of LS-PMSMs. Effects at this level are not so important for this project as such a ubiquitous use of LS-PMSMs is a long way away and may indeed never happen if a different technology takes hold. Nevertheless, some consideration is given to power system effects.

Different tolerance of supply harmonics and imbalances, and the need to limit the magnet temperature, may mean that a poor quality supply that was sufficient for IM operation is harmful to a LS-PMSM that has been installed as a replacement.

Synchronous machines

The traditional, electrically excited SM has the useful feature of controllable var production or consumption, but has rotor copper losses and needs a means to transmit magnetising current to the rotor. Starting can be achieved by an inverter supply or by using another motor to get the SM to synchronous speed. In some cases, damping or starting windings or unlaminated rotor iron can be used along with zero excitation current in the field, to get the machine near to synchronous speed. These motors are used mainly for large loads with constant speed, continuous operation, where the var generation and good efficiency offset the other difficulties.

Asynchronous machines

The IM solves the mechanical problem of current transfer to the rotor, but generally has higher losses due to the active current flow in the rotor, extra stator current to supply the inevitable var consumption, and rotor iron loss from the rotor's relative motion to the stator flux. Efficiencies can be improved to some extent by the use of better materials, or by working the iron and copper less hard, but these methods increase the cost of the motor, and in the latter case the size and weight will be increased too. Larger IMs have a much increased efficiency, but there is still room for improvement. The following table gives some typical efficiencies for standard modern IMs.

Table 2 Some 4-pole IM efficiencies (from ABB)[1]

Rated kW	1	10	25	50	75	100
Efficiency %	78	90	93	95	95	96

PM synchronous machines

The rotor of a PMSM has PM material instead of a winding, to produce the magnetic field. The reactive power is then not so directly controllable, and removal of the field while starting is not possible. There is the considerable advantage that the lack of magnetising current reduces losses and obviates the need to transfer current to the rotor. The problem of thermally or magnetically inflicted demagnetisation, and the possible mechanical weakening of the rotor still make the machine less robust than the IM. A very good efficiency, no brushes, and potentially smaller size are the advantages.

A pure PMSM is unable to start directly from the supply, so it requires an inverter or a means of getting it near synchronous speed before connecting it to the supply. An inverter has the advantage of buffering the motor from supply transients. It may however increase the total losses of the drive. This depends on the magnitude of inverter losses and motor copper losses; high copper losses in the motor could be reduced by control of the inverter to give maximum torque for the applied current. If the motor had quite low resistance, the inverter losses may be higher than the reduction in motor losses achieved by using an inverter. When variable speed is not required the losses are not reduced considerably, so an inverter introduces greater complexity and cost with no further advantage than making possible the use of a pure PMSM.

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[1] 4-pole, 400V 50Hz, basic models.

Line-start PMSMs

As with a SM, addition of a starting circuit in the rotor allows the PMSM to be connected directly to the network both for starting and running. The efficiency advantages are then available together with simplicity, although control of reactive power is not possible. As will be described later, starting problems arise from the PM field and rotor saliency, so the LS-PMSM is not quite the panacea it may sound.

To allow for the weak starting performance and the need for a jump to synchronous speed from the maximum speed of the asynchronous characteristic, the load inertia must be limited, and a high order torque/speed characteristic is desirable. Centrifugal pumps are of quite low inertia and have a second order characteristic, besides being a large part of the installed capacity of medium power motors. They are therefore a very suitable application for the features of a LS-PMSM.

There are not many specifications available to indicate typical performance of a LS-PMSM as this machine is still under development. A 15kW version built in 1995 as a prototype achieved 94% efficiency [1], but higher values may well be reached within the same frame size as refinements are made. If the presence of extra rotor windings does not affect the magnetic properties of the machine too much, values from pure PMSMs could be used as a guide to LS-PMSM efficiency during synchronous operation.

2 Description of the LS-PMSM

In this chapter the construction, means of torque production, and the starting and running of the LS-PMSM are described. The design using a buried-magnet rotor with a squirrel cage winding is the main subject of this whole project since it is highly suitable to replace IMs in applications requiring a rugged motor. Nevertheless, some other possible constructions are mentioned too.

- ☐ Construction
- ☐ Sources of torque in the LS-PMSM
- ☐ Synchronous operation
- ☐ Starting and synchronising

Construction

The rotor of a LS-PMSM contains permanent magnets to produce the field for normal operation, and an electrical circuit to carry currents for asynchronous torque production when starting. Some common options are described below.

Rotor electrics

For small machines with easy starting conditions it may be practicable to leave the rotor unlaminated so that the iron forms the electrical circuit for starting. This is very convenient for manufacture, but gives less control over the parameters than with a separate electrical circuit. In the cases where the magnets are outside the iron, a conductive cylinder may be put around them to protect them from flux transients. Such a cylinder may be sufficient as a starting winding in a very small, light motor [4].

A conventional induction motor cage complicates the mechanical structure of the rotor, unless the magnets are surface-mounted. Larger motors and those with harder starting conditions will require a properly designed cage, with a low enough X/R ratio to provide good torque during the start. Skin effect in the bars can be used as in an IM to boost the rotor's power factor at high slips, but as there is no rotor current in steady operation it is possible touse the skin effect less, using bars with a higher resistance to give the desired starting performance as well as good damping of oscillations during synchronised operation.

Rotor magnetics

PM material must be incorporated in the rotor so as to provide flux in the airgap. Magnets mounted on the surface of the rotor are exposed directly to air-gap flux transients propagated from the supply, and pose the problem of how to attach the magnets if the motor is made for high speeds. Sometimes bands of strong fibres are used to hold the magnets in place. Different coefficients of expansion between the magnet and rotor iron could cause further problems for magnets attached with adhesive in a larger machine. The magnets can otherwise be inset below the rotor surface, and a mechanical restraint applied around them.

Burying the magnets into the rotor removes the problems of making them stick and protecting them from flux transients, but also has drawbacks since there must be enough iron in the region of the magnets to hold the rotor together under all the mechanical stresses. This iron will make something of a short circuit path for the flux, which effect should be minimised. Provided that the path is quite narrow, its iron will soon saturate and so will greatly limit the leakage. A useful feature of buried magnets is that the greater flux-emitting area of magnet than surface area of rotor can achieve a higher air-gap flux than the magnet could produce when used directly.

If it is feasible to vary the airgap around the rotor, the airgap flux density can be made closer to the fundamental sinusoid than would be possible with the quite square wave-shape produced by permanent magnets. The advantages will be lower iron losses and a purer supply current. Such pole shaping is often applied to salient-poled machines, but may not be worth the extra complexity for the motor applications considered here.

PM materials generally have μ_r of around unity, and certainly much less than for the iron. Depending on the positioning of the PM there can be different reluctances through the d and q axes (for d and q definitions, see page 31).

Inset or buried magnets (right) will give a higher reluctance to the d-axis, but surface magnets will give very little difference. This difference in reluctances is referred to as saliency, as it occurs in machines that have salient poles and thus airgaps in between the pole-pieces. The different reluctances make the synchronised motor act as a hybrid of a PMSM and a reluctance motor; these effects are discussed in later sections.

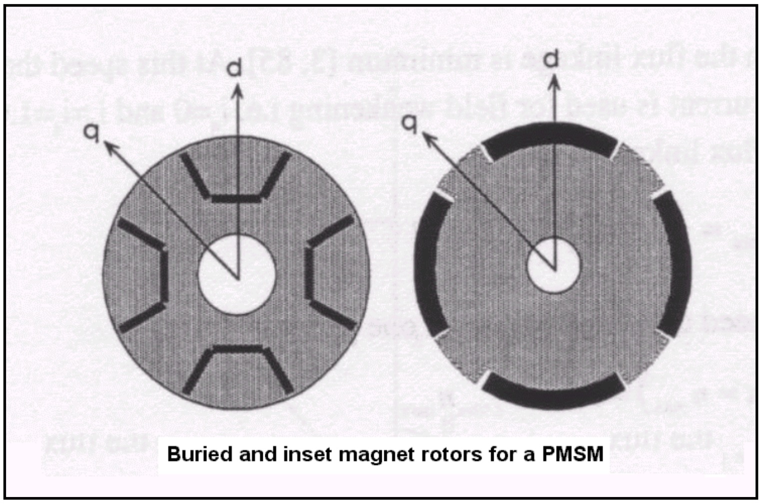

Figure 3 Saliency effects on the d and q axes of PM rotors

Many different compromises of field strength, reluctance and starting/damping circuit are possible, depending on the application. For the simulations in this project the buried magnet design was used as this gives the best protection of the magnets while leaving enough space for proper rotor bars, these points being important in a motor designed for direct network starting and running.

Stator

The LS-PMSM's stator is of conventional three-phase type. Prototypes have commonly used existing IM stators, and it is also preferable for a company to be able to produce standard stators that can be used both for its IM and LS-PMSM product lines. The airgap is normally larger than for an induction machine, in common with SMs in general, leading to lower reactances than those of a similar IM.

Sources of torque in the LS-PMSM

There are several ways in which electrical torques occur between the stator and rotor.

Main sources

- Synchronous torque is the obvious first way for a PMSM; it is developed by the interaction of the PM field and the stator current. If the rotor is synchronised with the stator field it will reach a steady operating load-angle where the electrical power into the induced voltage equals the mechanical power produced. When not in synchronism the rotor is constantly rotating past the stator flux, so no net torque is produced.

- Asynchronous torque is produced as in an induction motor whenever there is relative motion of the rotor windings and the stator field.

Torques due to asymmetries

- Reluctance torque arises from the saliency of the magnetic circuit. If the saliency is large, the reluctance torque can provide a considerable amount of the running torque, and can increase the peak available torque of the motor.
  This effect can be thought of in terms of patterns of stretched flux 'lines', where alignment of the stator flux between the rotor axes produces torque because of the flux's 'desire' to align the easy q-axis with the stator flux. Alignment of the d-axis gives no torque but is an unstable equilibrium. Alternatively, consideration of the change of stator reactances with varying rotor position shows that the stored energy is changed as the rotor moves; hence there is a force on it.

  The reluctance torque is dependent on the difference in axis reluctances (the degree of saliency) and the angle between the rotor position and the stator field. It goes through a complete cycle when moving from the positive to the negative end of an axis, so has half the period of the synchronous torque. Thus it can be combined with the synchronous torque to give the overall angle-dependent torque. The effect in the PMSM is to flatten the torque/angle response around the directly aligned position, and to sharpen it past ±90°. The flatter response means a greater change of angle for any given disturbance, so the stability is reduced when within this normal range of load angle. This is quite the opposite effect from that in an electrically exited synchronous machine, whose q-axis reluctance is usually the higher due to the presence of the excitation winding in the magnetic path.

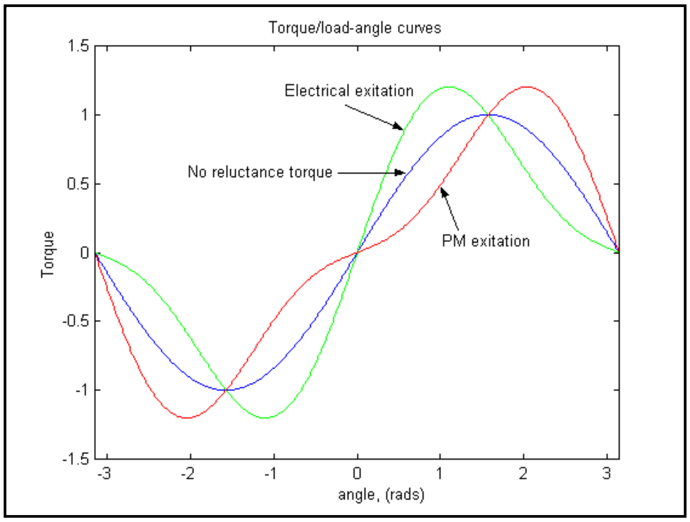

Figure 4 Torque/load-angle with a salient rotor

- Görge’s phenomenon is the name of the torque dip that happens when the rotor speed passes half of the synchronous speed. It is explained by asymmetry in the electric or magnetic part of the rotor, which causes the induced rotor currents not to be sinusoidally distributed. The resulting positive and negative sequence flux components then move around the rotor at slip frequency, in the forward and backward directions relative to the rotor’s motion. At half of synchronous speed, the negative sequence flux is stationary relative to the stator, while before and after this point it is rotating – it rotates in the positive stator direction when the rotor speed exceeds this turning point. Its rotation induces sub-harmonic currents through the stator and supply impedances, producing a torque between rotor and stator; this of course acts on the rotor in the opposite direction to that in which the flux is travelling. Hence there is an extra accelerating torque that peaks a little before half of synchronous speed, and as the speed further increases, it falls to a similar size of negative torque which then decreases. This is like a two-quadrant IM torque/speed curve with its synchronous speed at half of the positive sequence synchronous speed of the motor.

Magnet braking torque

Magnet braking torque is the last significant electrical torque, and is due to the presence of the permanent magnetic field. This too induces sub-harmonic currents in the stator during the start-up, which flow through the stator and supply and dissipate energy. The peak torque occurs at low speed, as the braking-torque/speed curve is rather like that of an induction machine with the speed axis reversed. Such an analogy sounds a reasonable guide as the constant rotor field moving at increasing speed during run-up will appear to the stator as would the induction machine’s fairly constant rotating stator field appear to its rotor as the rotor speed falls to a stall. The braking torque is dependent on the synchronous reactance as presented to the frequency at which the rotor is moving, and is in proportion to the square of the rotor magnetisation. This produces design conflicts with the benefits of a high PM induced voltage for high synchronised stability, reduction of magnetising current, and provision of reactive power.

Other torques

There are of course other torques present, such as cogging torques that occur as the flux moves between teeth. Such torques can be adjusted by various means such as skewing of stator slots, but they are more of importance to the smoothness of the drive than to the network power quality aspects of the starting and running of the motor.

Steady running

This is predictably the easiest state to describe. Simplistically, the motor is operating as a synchronous machine with constant excitation. Since the rotor is at steady synchronous speed there is no induced voltage in the windings or iron from the fundamental flux wave that is dragging the rotor with it. In reality the space harmonics of the stator, and any harmonics in the supply, will produce fields moving around relative to the rotor. The harmonic flux will not produce a net torque from the synchronous or reluctance action, but positive sequence components will contribute torque, though inefficiently, through the induction motor nature of the rotor. Negative sequences will produce an unhelpful torque, while triplen harmonics will not produce torque, but will cause more losses. This is all just as for a pure induction machine**,** although as described in the previous section there are other torques present due to electrical or magnetic asymmetry.

The phasor diagram for steady operation is shown on the right. The difference between the supply and induced voltages, *Vz* and *Eo*, appears across the stator's series impedance and causes the supply current *I* to flow. The power dissipated by *I* in *Eo* is converted to mechanical power.
The load angle between the supply and induced voltages is denoted by δ, while the angle of the series impedance is α.

In order to include saliency in this model the series impedance would need to be made dependent upon the orientation of the current relative to the rotor, complicating the model considerably. On page 32, a more convenient rectangular representation is given.

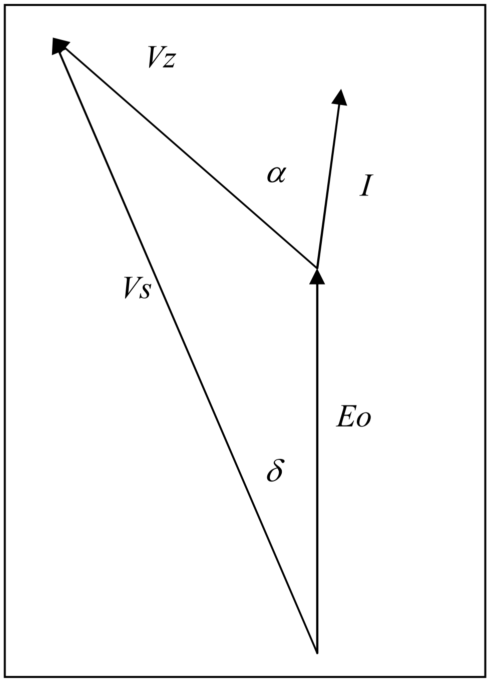

Figure 5 Phasor diagram of a pure (non salient) synchronous motor

Disturbances while synchronised

Any disturbances from the load or supply will affect the three torque sources: synchronous, reluctance and asynchronous. The angle-dependent synchronous and reluctance torques can be combined as in fig. 4, and the motor will oscillate along its torque/angle curve after a disturbance. This is where the presence of the rotor windings is helpful, as even when synchronised they act as damping windings. The previously mentioned feature of low rotor X/R ratio is of help here to dissipate as much energy as possible when swinging. Disturbances of the supply are one of the subjects of this project, and their effect on drive shocks and swinging will be considered along with their other consequences.

Starting and synchronising

The asynchronous run-up

The normal asynchronous torque accelerates the rotor from standstill, but is altered by the torque build-up and dip of Görge’s phenomenon, and the magnet braking torque whose peak is at a quite low speed. Both of these extra torques need consideration when choosing machine parameters as either could cause an otherwise adequate run-up to become stuck at a speed too low for synchronisation. Choosing the rotor magnetisation level is a difficult compromise as a higher value helps the synchronism but brakes the early run-up more. The torque dip only happens with rotor asymmetry, but PMSM designs - particularly with embedded magnets - are by nature magnetically asymmetrical.

The initial angle of rotor field and supply voltage at turn-on can have a large bearing on the initial current surge, saturation, and initial torque smoothness. If at the time of connection to the supply the voltage vector is 90° lagging the PM field orientation, the sum of fluxes will reach a higher value than in normal running, and saturation of the magnetic circuit will cause high current flows. The rotor torque in such a case will have an initial negative component from the PM interaction with the stator field. An electrically and mechanically superior start comes from a turn-on leading the rotor flux. This difference from the asynchronous machine means that several tests are needed if studying LS-PMSM transients’ effects on the rest of a system.

The synchronisation

The synchronous and reluctance torques will give an alternating torque on the rotor when out of synchronism. This will cause the rotor speed to oscillate around the value determined by the asynchronous torque. In a successful synchronisation the oscillation will carry the rotor to synchronous speed during the positive half of a torque cycle. Unless the synchronisation is only marginally achieved, the rotor will exceed the synchronous speed then oscillate around it until smoothly synchronised at the steady-state load angle. The torque/speed curves of the asynchronous torque production and the load will have an effect on the synchronisation, not just because they define how close to synchronism the rotor would become without the synchronous torques, but also because they determine how much help and hindrance is given to the synchronising torques to pull the rotor up to synchronous speed.

There is thus a minimum asynchronous speed from which a particular motor-load combination can get into synchronism. If the run-up characteristics of the combination cannot reach this speed, the final state will be some lower equilibrium speed with a constant oscillatory component from the synchronous torques. This is a worrying state since the rotor’s windings will have high current flows, its iron will have unaccustomed losses, and the lower induction motor efficiency will increase the supply current. If such a condition is not detected and stopped, the heating of the rotor may allow the PM material to become permanently demagnetised. A higher order torque/speed load characteristic gives better starting and less likelihood of synchronisation failure as the torque is lower at sub-synchronous speeds. Second order characteristics are a likely application for the LS-PMSM, and strong torque components of lower orders pose a risk to the start-up.

Simulation of synchronism

To give an idea of the synchronisation process, and to confirm that the pulsating torque has zero mean when unsynchronised, a basic simulation was run in Matlab. The synchronous and reluctance torques were modelled as pure sines of the angle between stator and rotor fields, and the load by a quadratic function of speed and an inertia. The most unrealistic part was the modelling of the asynchronous torques; only the induction torque was considered, and it was made linearly dependent on the slip. This makes the model an approximation of a real machine over a small speed range.

The following plots show the importance of inertia on the synchronisation. Here, the load has a combined 1st and 2nd order torque/speed characteristic, and an asynchronous torque that can only support the load at a considerably lower speed than the synchronous speed – the motor could in this case not reach the critical speed by itself. The simulations were started with rotor speed of a little less than synchronous. In a real case, the asynchronous torque would have to carry the rotor to a high enough speed for synchronism, and if the inertia happened to be too high for synchronism then the speed would oscillate about the asynchronous speed, never quite reaching synchronous speed. The artificial situation of a low asynchronous speed has been used here in order to make the loss of synchronism very obvious. Between the two plots, the only difference is a tiny change (<1%) in the inertia.

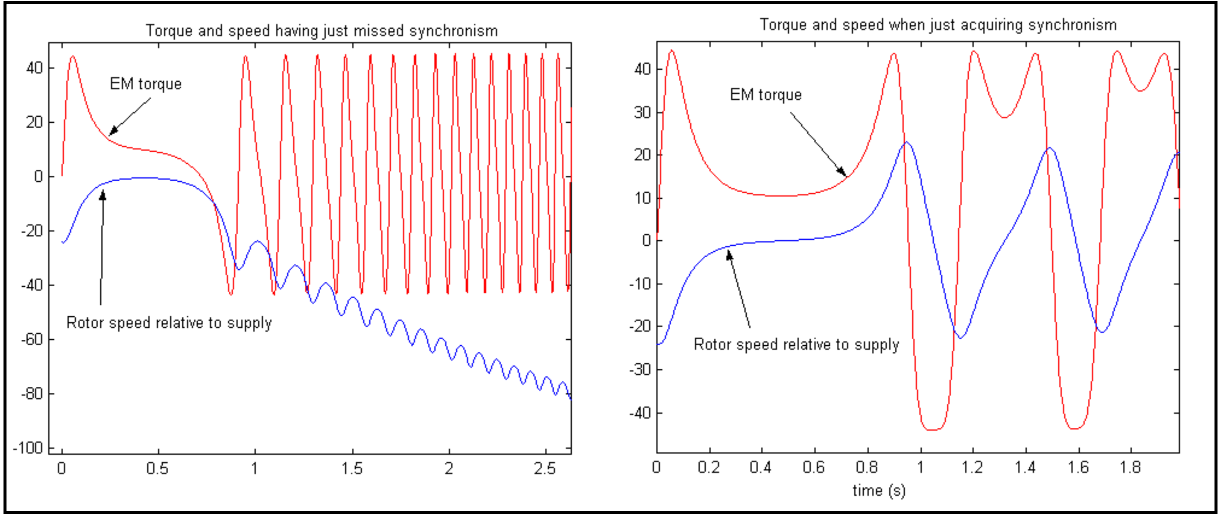

Figure 6 Successful and failed LS-PMSM synchronisation

It can been seen that critical point is the reaching of synchronous speed before the load angle changes enough to make the total resultant torque on the rotor become negative.

In the first case this is just missed, so when the speed difference has caused the load-angle to change sufficiently, the torque is reversed and carries the rotor away, its speed falling rapidly as the synchronous torque has zero mean and the chosen asynchronous torque constant is in this case too low to attain the critical speed.

In the second case, synchronous speed is reached at a point where the load angle is still producing a little more than the load torque; this is seen from the small positive derivative of the speed. Then the load angle starts moving back to where it was, running up over the positive torque peak again, and swinging to the negative side (generator quadrant) until the consequent deceleration brings the speed down again. The oscillation is damped, in this case slowly, by the asynchronous torque. The dips in the positive peak of the torque appear to be caused by the rotor position oscillations passing the pull-out angle on their swing into the motoring quadrant: the swing is asymmetric because its mean is the load torque, hence the generating quadrant is not similarly affected.

3 Modelling the test system

This chapter explains the reasons for the choices of motor model and simulation program, and describes the transform used to simplify the motor model. Brief descriptions are given of the other component models that were used to make the simulated systems. Parameters are quoted for the representative motors that were used in the simulations.

Important limitations of the motor and meter models are explained. An understanding of these limitations is essential for good interpretation of the results from some of the simulations.

Finally, simplified equivalent circuits are given for both types of motor when in steady state, to aid explanations of simulation results in the next chapter.

- The necessary models
- Park's transform
- The simulation program
- The motor models
- Descriptions of other modelled components
- Simplified steady-state equivalent circuits

The necessary models

A lot of the project could have been done with steady-state models - for example, study of the effects of reduced voltage on power and current flows and supply voltage. However, proper study of the interactions of starting and running motors, and of the whole system in a collapsing situation, required dynamic models. The dynamic models were then also used for simulations of steady state situations, but simplified equivalent circuits have been used for explanation in such cases.

Dynamic models of an IM, LS-PMSM, inductive-resistive three-phase supply, and mechanical loads were made, along with metering for rms values and active and reactive power flows. All three-phase connections used vectorised lines to simplify the diagrams. The modelling and simulation methods used are described in the following paragraphs.

Appendix B on page 75 contains a list of the blocks written for this project.

Park's transform

Condensing to one phasor

In the analysis of three phase machines it is possible to define the self and mutual inductances of all the coils as functions of rotor angle, then to simulate the machine in steady and transient conditions from the interactions of these flux linkages [6]. The difficulty is that as the rotor moves, the mutual inductances change, as will some of the self inductances if the rotor has a salient magnetic circuit. Thus a lot of matrix manipulation is needed in each step.

An old and much used simplification is to assume that each of the three evenly spaced phase windings produces a sinusoidal a flux in the airgap, so the fluxes can be summed as vectors. This will give a rotating flux vector of 3/2 the individual phase magnitudes, and this vector can therefore be described by real numbers on two perpendicular axes, α and β. Zero sequence components of the flux sum instantaneously to zero so they do not appear in these axes; they can be transformed into the third dimension, γ. With three-wire connections there are only two independent variables, so only two transform axes are required. The three-wire connection clearly means there can be no zero-sequence components, so it is the γ component of the transform that is removed in this situation. The transformation from phases a, b and c to axes α, β and γ is by a matrix of coefficients. All the variables – currents, voltages and fluxes – can be transformed to the new system, since the currents directly produce the flux, and the emfs directly relate to the derivatives of currents.

$$\begin{bmatrix} V_\alpha \\ V_\beta \\ V_\gamma \end{bmatrix} = s \bullet \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix} \bullet \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix}$$

(where s is the scaling factor, as described below)

Instead of modelling the motor by three phase-circuits for the stator and rotor, with all the associated mutual inductances and possibly varying self inductances, circuits can now be drawn for the components of the transformed system, ignoring the γ circuit in the cases where the γ component cannot exist. The electrical components keep the same resistances and inductances as the original phase values, but mutual inductances between the perpendicular circuits are zero. The problem remains that the changing relative positions of the rotor and stator coils causes time-variance in the stator to rotor inductances, while the saliency of the rotor causes time-variance in the stator self-inductances.

Scaling can be applied to make the transformed variables have either the same magnitude or the same total power dissipation as the phase variables - scaling factors of 2/3 and $\sqrt{(2/3)}$ respectively. Magnitude invariance was used for the simulation models, and use of the same scaling factor for converting back to phase values of course makes the choice of scaling unimportant when seen from outside a machine model.

The discrete windings of a realistic machine make the assumption of sinusoidal fluxes unrealistic. However, experience of the LS-PMSMs being considered here [1], and of machine modelling in general, has shown this to have little practical effect for the purposes intended.

Rotation transform

In many cases a further useful transformation is to consider the α β system in another reference frame. A rotation matrix is applied to the α and β values to give the values on a chosen rotating axis (**d**irect) and a perpendicular one (**q**uadrature). The transformation from three-phase quantities to perpendicular rotating axes is 'Park's transform'.

$$\begin{bmatrix} V_d \\ V_q \end{bmatrix} = \begin{bmatrix} \cos(\Theta) & \sin(\Theta) \\ -\sin(\Theta) & \cos(\Theta) \end{bmatrix} \bullet \begin{bmatrix} V_\alpha \\ V_\beta \end{bmatrix}$$

(where θ is the electrical angle of the chosen reference frame with respect to the reference zero angle, usually the axis of phase A)

Referencing to the rotor will remove time-varying inductances, and for synchronous machines in general will allow the field flux to remain on one axis regardless of swings or loss of synchronism. SMs are often modelled in this way, and PMSM control systems can operate easily in the rotor dq frame. Park used this transform in the analysis of synchronous generators, thus the original Park's ransform is with rotor position as the reference. As long as the mutual inductances between the rotor and stator vary as the sine of the rotor angle, and the self inductances of stator windings vary as the sine of twice this angle as the d and q reluctances are presented to the windings, then the transform is valid even when the fluxes produced by the windings are not sinusoidally distributed in space [7].

With the supply as the reference the transform has useful applications in three-phase systems other than machines, with the advantage that steady-state values are d.c. terms so facilitating control design, and only reactances couple the axes, which effect can be compensated in a control system.

dq phasor representation

For steady-state operation Park's transform allows the machine's phasor diagram to be rewritten with all quantities expressed on the d and q axes. The diagram on the right shows the stator voltage drops due to the d and q currents through the series impedance. These are added to the emf Eo the sum giving the same phasor as the supply voltage. Working backwards from the currents was used in this example to allow simple use of complex impedance.

Saliency can now be included by the use of different inductances in the d and q axes, a very useful feature of the transform. As the PM field is defined as the d-axis, the emf induced by the PM field is always on the q-axis.

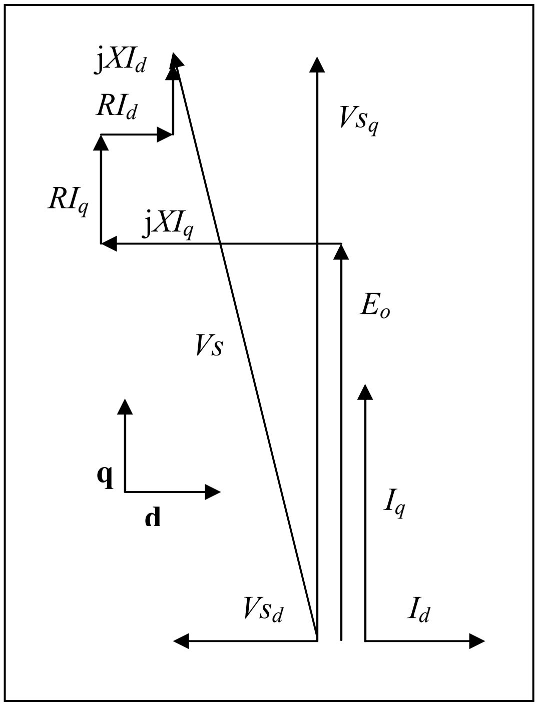

Figure 7 dq phasor diagram of a salient SM

The simulation program

Several possibilities were considered, out of the available simulation programs. Some programs had models available of IMs and PMSMs, but no modifications could be made to these, and there is no valid way of externally combining these models to represent the hybrid.

EMTDC/PSCAD is a dedicated power system transient simulation program with built-in machine and system models and good output visualisation. The LS-PMSM would have to have been modelled either as a new component in C language, or as a set of the built-in control system blocks interfaced through current sources to the electrical part of the system. The lack of familiarity, and the experience of more frequent error reports and crashes than with Matlab, decided against this option. Matlab m-files could have been used, and such models were written but not fully debugged before this option was abandoned in favour of Simulink.

Simulink has the disadvantage that some systems which could be described in a few lines of Matlab code require quite a long time to put together as Simulink blocks, even with the use of sub-systems and vectorised lines. There are however several advantages: the models can be put into sub-blocks to allow the whole system to be displayed and altered in concise block diagram form, aiding understanding and minimising mistakes; the blocks can have parameters changed easily from the outside; the simulation can be paused or prematurely stopped but still gives the graphical outputs while running, unlike normal Matlab simulations.

A "power system blockset" addition to Simulink is available, which allows wires to carry voltage and current information with Kirchhoff's laws applied at the junctions, instead of just representing one control variable or vector. Machine models are included, so only the LS-PMSM would have needed to have been written. This blockset was acquired on free trial from the suppliers, and some simulations were made to gain familiarity with it. It was found impracticable to use the blockset for the project as the method used to interface its machine models to the system's 'wires' is to have them measuring the input voltages, and generating the currents from controlled current sources. When these sources are fed from an inductive supply, there is of course a problem as an attempt to change the current significantly in any time step will produce a large induced emf. The solution of putting a resistor across the source is not viable as resistances high enough to have negligible effect on the solution slow the simulation down colossally.

Method of modelling and simulation

The rotor-referenced dq model was used, to simplify the effects of the PM field and saliency. The induction motor model was also referenced to the rotor to keep the models similar. Such modelling of IMs and SMs is very well documented, so the IM model was easily drawn [1,6].

Each machine model uses the αβ transform on the three phase voltages, and the dq transform is then made from knowledge of the rotor angle. The dq voltages are applied to a model of the electrical part of the motor, where sources of winding voltage are equated to yield the time rate of change of winding flux-linkages Ψ.

Small changes were made to the IM model to include the PM field of the LS-PMSM [1]. In the final version of the model the constant PM contribution to stator flux-linkages is added onto the flux-linkage values used for calculating torque and rotation-induced emf, but not onto the values used for calculating winding currents.

In the following equations, the subscripts *m, s, r, d* and *q* refer to mutual, stator, rotor, direct and quadrature components respectively. Ψ denotes flux linkages (unit V·s), and ω denotes electrical angular speed.

$$U_{ds} = R_{ds} i_{ds} + \frac{d\Psi_{ds}}{dt} - \omega_r \Psi_{qs}$$

$$U_{qs} = R_{qs} i_{qs} + \frac{d\Psi_{qs}}{dt} + \omega_r \Psi_{ds}$$

$$U_{dr} = R_{dr} i_{dr} + \frac{d\Psi_{dr}}{dt} = 0$$

$$U_{qr} = R_{qr} i_{qr} + \frac{d\Psi_{qr}}{dt} = 0$$

where:

$$\Psi_{ds} = L_{ds} i_{ds} + L_{dm} i_{dr} + \Psi_{PM}$$

$$\Psi_{qs} = L_{qs} i_{qs} + L_{qm} i_{qr}$$

$$\Psi_{dr} = L_{dr} i_{dr} + L_{dm} i_{ds} + \Psi_{PM}$$

$$\Psi_{qr} = L_{qr} i_{qr} + L_{qm} i_{qs}$$

and:

$$L_{ds} = L_{dm} + L_{leakage\_ds}$$

and similarly for L_{qs}, L_{dr}, *and* L_{qr}.

The values of $d\Psi/dt$ are integrated and used to find the dq currents and to calculate the mechanical torque, the currents being passed to the output transform and the torque to a mechanical model:

$$T_{em} = p \cdot s \cdot \left\{ i_{qs}\Psi_{ds} - i_{ds}\Psi_{qs} \right\}$$

where 'p' is the number of pole pairs and 's' the reciprocal of the scaling transform used between the abc and dq values.

Verification of the motor models

The IM and PMSM blocks were tested against those from the Simulink power system blockset, and matched perfectly. The combined model for the LS-PMSM was verified by simulations with the field set to zero, and others with the rotor resistances at high values, to check that the results still matched those of the IM and PMSM respectively.

Limitations of the models

No account was taken of the effect of temperature changes on the resistances and PM field strength: the changes of resistance are considerable between cold and maximum temperature, but there are so many different experimental machines that it would be pointless to worry about this change when another similarly rated machine may have quite different winding resistances anyway. Where good detail was given in specifications the resistances at normal operating temperature were used.

Skin effect in the windings was not included, although it could improve the start-up [1]. The main limitation of this omission would be if harmonic impedances were considered.
Saturation and iron losses were not included, with the effect that transient currents may be higher than the simulation suggests, and losses - particularly in the presence of harmonics - will also be higher.

Modelling of the temperature, skin and saturation effects would have required more complexity, and would have reduced the speed of the simulations. There was insufficient information available to model these effects properly in the machines whose parameters were used in the simulations, so even an excellent model of all the effects would have been hindered by the inaccuracy of its inputs.

The skin effect may be used to a different extent on other similar machines, so its inclusion in the model would not necessarily help to fulfil the project aim of studying general differences between IMs and LS-PMSMs. Saturation and iron loss modelling would have been very helpful in the simulations of starting and transients, but are extremely complex and beyond the scope of this project.

Motor parameters for the simulations

Parameter values had to be obtained for both types of motor. For the IMs this was easy to do, but for the LS-PMSM it was a lot less simple as these machines are not in common use. Some values were found for motors of 5 to 20kW, and the most detailed information concerned models around the middle of this range. These are designs being researched within the Permanent Magnet Drive research group at KTH. The LS-PMSM models used for simulations were based on this information, while the IM model used parameters from an IM in the same model range and of the same power.

Because of possible commercial sensitivity of such information the parameters used are included here in pu form. Base values are rated power (7.5kW), line voltage and electrical and mechanical synchronous frequencies. The torque required to produce the rated power at synchronous speed is used as a base when torques are quoted as pu later in the report.

In the following table, the PM field strength is quoted as the induced line voltage from the permanent magnet alone at synchronous speed. The machines are all 4-pole. All rotor values are referred to the stator.

Table 3 Per-unit parameters of the motors used in the simulations

Motor	**Induction**	**LS-PMSM**	**LS-PMSM**
Name used	IM	LS-PMSM 1	LS-PMSM 2.2
H (inertia) s	0.056	0.056	0.056
R stator	0.141	0.038	0.044
R rotor	0.061	0.020	0.11
L leak stator	0.088	0.074	0.056
L leak rotor	0.081	0.088	0.052
L mutual (d)	1.91	0.39	0.32
L mutual (q)	1.91	0.93	1.06
Eo (PM strength)	(0)	0.7	1.0

Although these motors are specific cases, they are used in the simulations to produce results that distinguish the two species from each other. Variations of machine parameters are used in some simulations, but the species remain distinct.

Descriptions of other modelled components

Supplies

The supply models had frequency and phase given as inputs to the model mask. To model its resistance and inductance, the supply block had an input into which the summed current values from the loads were fed back. This current was used as the input to a gain and a derivative with gain then their outputs were subtracted from the supply's output voltage. The effect of the discrete solution of the system was to give large transients of voltage at time-steps where changes happened in the system. To avoid this problem a rate limiter was used before the derivative, and a rate limit greater than the peak di/dt for full load was found to give good suppression. This was found to give a similar effect to that of a lag-lead filter, but with less processing required.

An harmonic injection generator block was also made, to produce simultaneously up to five harmonics of specified harmonic order, amplitude and phase. This generator was a stiff source intended to be summed with the supply voltage before feeding to the system.

Metering

All values within the system were instantaneous three-phase quantities. There was a need to know P and Q flows, and a gain in understanding from having rms values of current and voltage over all phases.

A P and Q meter was made to integrate over a period the three-phase products of voltage and current, with a 90° phase shift in one of the inputs for the Q measurement. An rms meter was made, using integration of the square of each phase value over a supply period and dividing the sum by the number of phases to give the average rms value per phase.

Because any reading of P, Q or rms I or V is dependent on values from the previous 20ms, it is necessary to view fast-changing plots in later sections with care: torques, speeds and instantaneous phase currents are immediate, but these other metered values are not.

Loads

Two mechanical load models were used, each with an input of rotor speed and an output of torque.

The normal model allowed a quadratic torque characteristic to be specified in terms of the zeroeth, first and second order torque components at synchronous speed. This was generally used as a pure second order torque, e.g. a centrifugal pump or fan. Where load inertia was included it was modelled by increasing the motor's inertia. The masked model allowed two step changes of a superimposed zeroeth-order torque to be included for easy simulation of supply disturbances.

For some of the simulations a speed-control load was used to apply torques to hold the motor's speed to a reference.

Simplified steady-state equivalent circuits

Derivation

When the LS-PMSM is steadily synchronised its rotor circuit has no current flow, so can be disregarded. Hence its equivalent circuit becomes that of a PMSM.

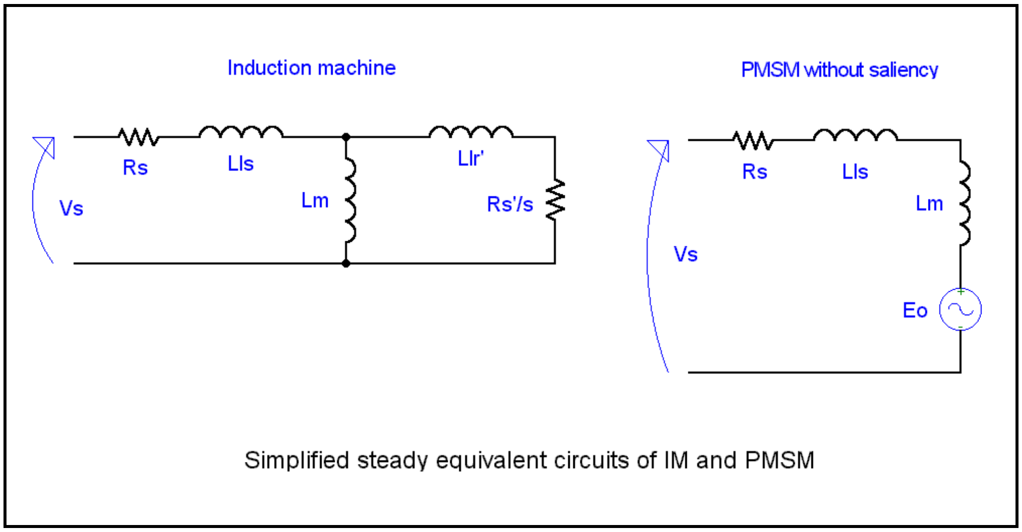

Figure 8 Simple steady equivalent circuits for induction and synchronous machines

To include saliency in the PMSM model it would be necessary to allow for the angle between the stator currents and the rotor in determining the induced voltage. This destroys the simplicity, so the easier model will be used where explanations are needed of the machine's behaviour.

The steady state IM model is purely passive. The rotor currents are coupled to the stator through the transformer action between the windings, so all the referred rotor current in the stator is really passing through the primary of this mutual inductor. The field from this stator current opposes the equal field from the actual rotor current, so no induced voltage results. A further, magnetising, current flows in the stator side to cause the induced voltage to equal the applied voltage. Consequently the mutual inductance can be replaced by a single self inductance of the same value, into which the difference between stator and referred rotor currents flows. The leakage inductances are kept separate.

The slip is modelled by changing the value of the rotor resistance so that the dissipation in the modelled resistance allows for the heating of the true resistance and the power converted to work.

The PMSM is simplified here by neglecting the effect of saliency. In the real machine, the field has a constant magnitude, so its rotation at a fixed speed within the stator coils makes them behave like the secondary winding of a transformer whose primary is supplied by a constant a.c. current source. The induced voltage in the open circuited secondary is then constant, but when secondary current is drawn it passes through one side of the mutual inductor, and is not able to be mirrored because of the constant source on the opposite side.

For this reason the current in the PMSM has to be regarded as passing through an inductor of the leakage *and* mutual inductances combined.

The PMSM is thus modelled as a constant voltage source of the same frequency as the supply, but with a phase angle that changes with the rotor load angle, and separated from the supply by the combined inductances and the resistance.

The larger airgap of a PMSM means that its magnetising reactance is lower than that of the IM. For the motors used as examples in the simulations, the IM had Lm as twice the Lmq magnitude of the LS-PMSMs. So although the current in the steady state LS-PMSM equivalent has the mutual inductance included in its path, this has less effect than it would if the LS-PMSM had the same construction as the IM. When it is considered that the induced voltage may be equal to the supply voltage it becomes apparent that high current flows into the LS-PMSM are possible if the load angle becomes large. During a pole slip there will be a period in which the voltage across the stator impedance is the sum of both magnitudes, leading to high currents also. On the other hand, with a zero load angle it would be possible to have no current at all from the supply, as the magnetisation would be done by the PM field. Although the possibility of zero magnetising current does not exist for an IM, an IM's transient behaviour is quite like that of a PMSM since the rotor currents are in a high inductance circuit and cannot change quickly. This means that for brief disturbances after steady running the rotor behaves as a permanent magnet field that can become out of phase with the supply. The effect is discussed in the simulation section, page 49.

For the IM, the equivalent situation of increased load angle is that of increased slip. The effect is to reduce the modelled rotor resistance, so increasing the current flow. The current is ultimately limited by the impedance of the purely passive components, but the series inductance is lower than in the LS-PMSM so these current may still be quite high.

Use of the equivalent in analysis of the LS-PMSM

Equations of complex power input through an impedance $|Z|e^{j\alpha}$ from a voltage source at zero phase (V_s) to another at phase δ (E_o) give:

$$S_{in} = \frac{|V_s|^2}{|Z|} e^{j\alpha} - \frac{|V_s| E_o}{|Z|} e^{j(\alpha-\delta)}$$

Taking just the active power input to the internal emf, E_o, requires rearrangement to give:

$$P_{em} = \frac{E_o V_s}{Z} \cos(\alpha + \delta) - \frac{E_o^{\;2}}{Z} \cos(\alpha)$$

The second term is completely defined by the motor parameters, while only V_s and δ in the first term are variable. As the power input to the emf is the mechanical output of the motor, and this is known to be constant as long as the speed remains constant, P_{em} is also known. Therefore the equation links changes in the supply voltage to changes in the load angle.
Since the stator's reactance is typically many times its resistance, it is a good approximation that only the reactance affects the current flow, which simplifies the output power equation by making cos(α) = 0.

Unfortunately it is not always definite how a change in supply voltage or a parameter such as E_o or Z_s will affect the power or current consumption of the motor.

The polar phasor diagram (right) shows the supply voltage *Vs*, composed of the induced voltage *Eo* from the rotor field, and the voltage dropped in the stator impedance, *Vz.*

To know what effect a change in some value, for example *Vs*, will have on other quantities such as active and reactive power, it is necessary to know the particular operating situation and machine parameters, bearing in mind that the output power to the load must be constant as long as the motor remains synchronised.

In the case of the effect of *Vs* on active power, the initial effect of a reduction of *Vs* is to reduce *Vz* and consequently the current *I* too. The angle of *Vz* is also moved anti-clockwise, so if the initial case was as shown in the figure, the current may have a greater component in phase with *Eo*, unless it moves so far as to lead *Eo* as much as it lagged it before.

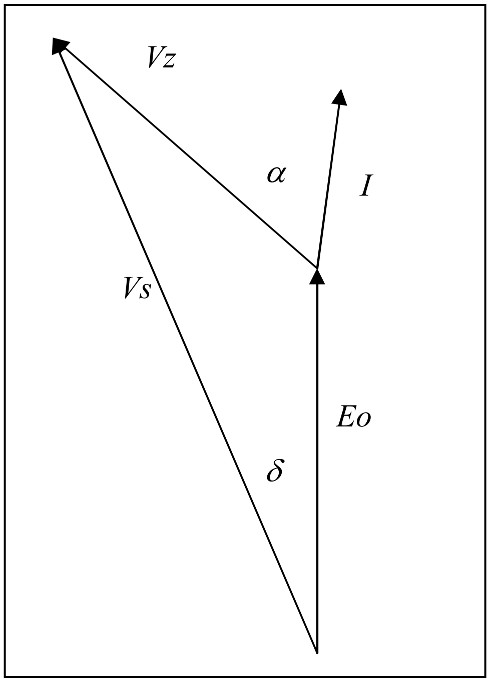

Figure 9 Polar phasor diagram of a pure (non salient) synchronous machine

Therefore, depending on the initial angle of *I* with respect to *Eo* the power into *Eo* may be increased or decreased by a reduction of supply voltage. Then the difference in electrical and mechanical powers will cause the rotor to decelerate or accelerate and therefore the load-angle to change, this also having an effect on the phase and magnitude of the current.

The complexity of the interactions of variables in the machines and between the machines and system means that simulations are the best way to find out how the various values affect each other. Simple models are useful mainly for understanding of the outcomes of simulations.

4 Simulations

This chapter describes the simulations performed with the motor models, and contains some plots of results. As well as the main points of the project description, other situations were studied where it was felt that the differences between an IM and a LS-PMSM could produce a change in machine and network behaviour.

Dynamic models of the three motors described on page 36 were used for the simulations. Unless otherwise stated, the total inertia was just the motor inertia, and the load was the full rated value with a square torque/speed characteristic. The intention was to model a light pump, this being the most suitable type of load for the LS-PMSM's performance.

All plots shown in this part of the report have time in seconds on the horizontal axis, and values in pu on the vertical axis, unless marked to the contrary. Each plot is relevant to the text on its left or immediately above it.

- ❑ Effects of a PM rotor on current waveform
- ❑ Starting transients
- ❑ Disturbances of steady operation
- ❑ Undesirable regeneration

- ❑ Steady-state response to voltage changes
- ❑ Effects on a weak supply system
- ❑ Harmonics

(this subject is mainly just discussed, as the motor models and specifications were inadequate for proper simulation)

When out of synchronism, the salient rotor and the presence of a PM field produce different supply current waveforms from those of a pure IM. Phase currents can be offset or imbalanced, at frequencies from zero to the supply frequency. To allow separate study of these effects, motor LS-PMSM 2.2 was altered to have first no saliency, then to have saliency but without the PM field. The non-salient rotor was achieved by setting the d-axis inductance equal to that of the q-axis, thus making it as though the PM material had the same permeability as the rotor iron.

To make the effects of saliency and PM field more obvious in the plots, Rr was multiplied by fifty, making the rotor circuit draw much less current than normal. Feedback of speed to load torque was used to force the speed to follow a ramp from zero to synchronous speed after letting the turn-on transients settle.

The figure below shows the currents for this modified motor in its two forms, with the speed increasing linearly from zero at 0.75s to synchronous speed at 2.75s.

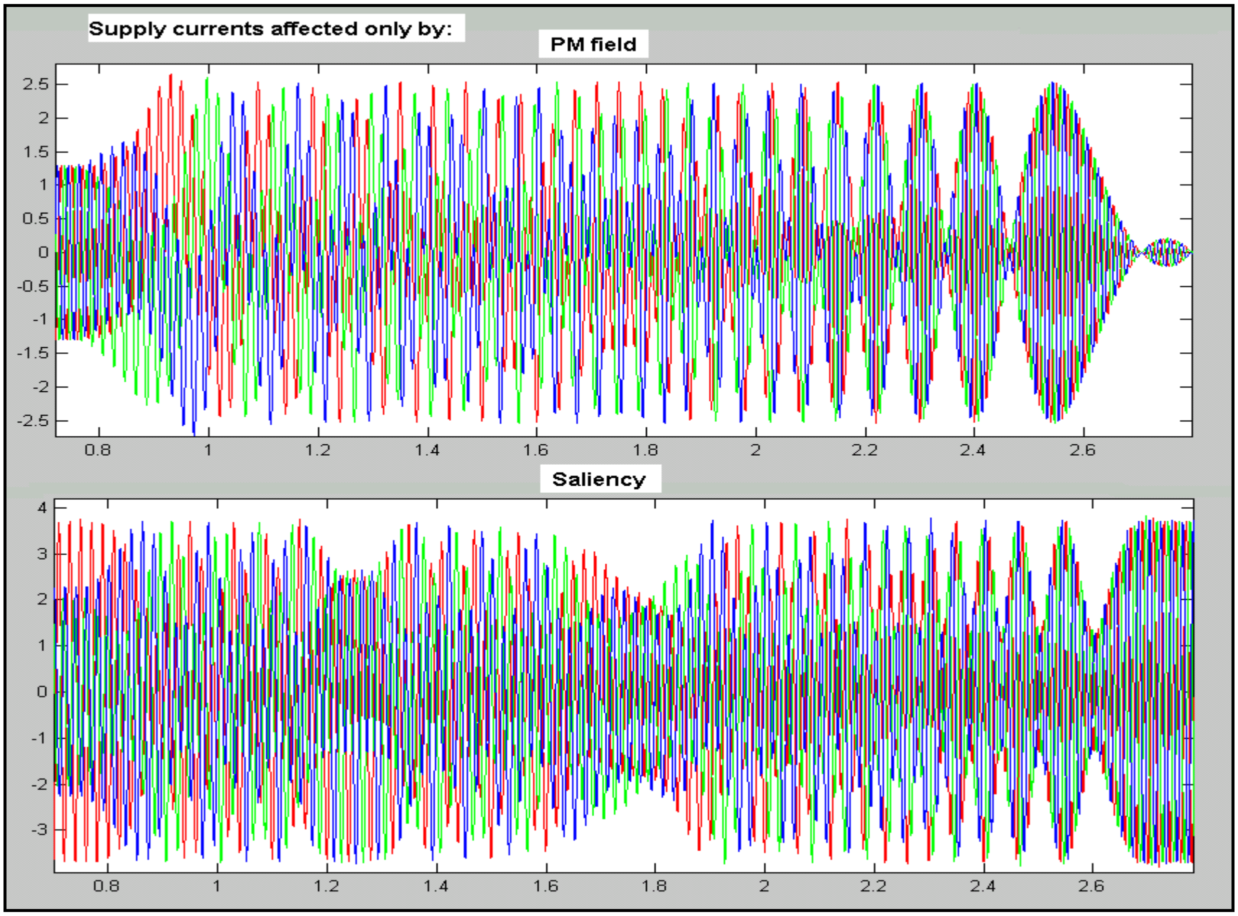

Figure 10 Supply current waveforms over the full speed range with a purely PM and a purely salient rotor

PM field alone

Without the rotor windings - e.g. when steadily synchronised - this is very simple to consider; the supply is a fixed source, and the phasor difference between it and the internal emf acts across the stator impedance to cause the stator current flow. The load-angle for any given supply voltage is determined by the mechanical load, so the load then determines the current.

When out of synchronism, the rotor circuit must also be taken into account. The moving PM field alters the magnetising current required to maintain the airgap voltage. Added to this magnetising current is the rotor current, scaled by the effective turns ratio between rotor and stator. The stator's series impedance of resistance and leakage reactance allows the PM-induced emf to affect the airgap voltage, so the rotor current can also differ from the case of the IM.

At low speeds, the induced voltage is also low, but as its period is long there is enough time for the induced voltage in a phase to produce a large offset in the supply current. So all the phase currents have a sinusoidal offset, a positive sequence sub-harmonic current. As the rotor speed approaches synchronism the two frequencies are so similar that the interaction is seen a beating; the currents have an intermediate frequency, and their envelope changes magnitude as the phase difference between the voltages varies. In the plot, the chosen reduction of the IM effects and the use of LS-PMSM 2.2 with its 1pu Eo allow the envelope to come down nearly to zero when the supply and internal voltages are in phase.
With the normal rotor impedance resumed, the difference is just that the offset effects are seen as smaller changes to the usual IM current.

Saliency alone

Movement of the rotor causes each phase-winding to experience changing inductance, so the behaviour over the speed range is very interesting. The rate of change of current at any time then depends upon the resultant voltage in the circuit, *and* on the instantaneous inductance for that winding.

At standstill the phase with the lowest inductance presented to it has the highest current magnitude. As the rotor begins to move, the phase magnitudes change at twice the rotor frequency because of the symmetry of the axes; that is, the –d axis has the same reluctance as the +d axis. Thinking of the rotor as presenting a 'waveform of reluctance' to the stator windings, there are two cycles of this wave over the rotor's surface, so the reluctance wave has twice the frequency of the rotor. With low rotor speeds the effect is just this changing of the phase magnitudes, while their frequency remains that of the supply.

At half speed the effect of the reluctance waveshape passing the stator windings at supply frequency is to make all phases perfectly balanced. In the range of a quarter to three-quarters of synchronous speed the interaction of voltage and inductance causes the currents to have an offset level at the frequency difference between the rotor and half of synchronous speed.

Approaching synchronous speed the inductance presented to each winding is only changing slowly with time, and the reluctance wave matches up in the same way with the voltage wave in each phase, causing all the phases' currents to grow and shrink together at the difference frequency.

The combination

In the real LS-PMSM the PM and saliency features are combined, and are moderated by being added to the normal three-phase loading of the rotor circuit.

The plot on the right shows the currents into the IM and LS-PMSM 2.2 during a startup from a stiff 1pu supply, with the usual load of full rated power square characteristic and only the motor's inertia.

It can be seen that the rapid start-up and the addition of the rotor bar currents make the offset of the LS-PMSM currents the only significant difference. Saturation in the real LS-PMSM, due to the combination of stator and PM fields, could make imbalanced phase-current magnitudes large also.

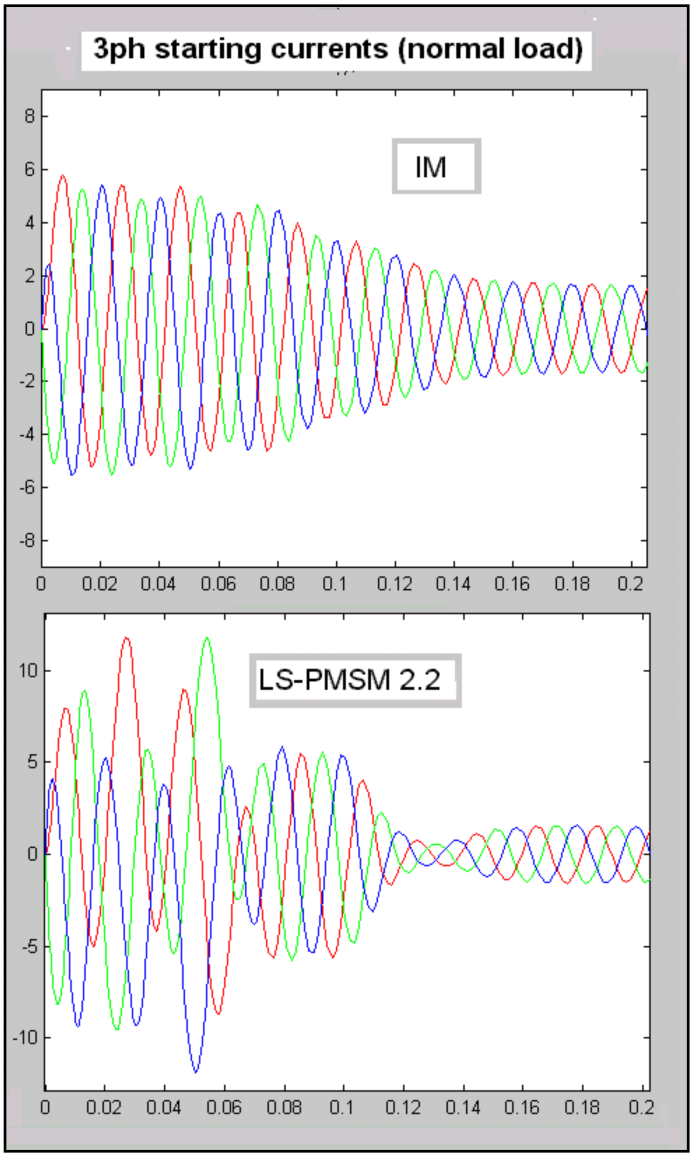

Figure 11 Three-phase starting currents

The three-wire connection makes zero-sequence components unable to flow, so all the observed cases of imbalanced phase-current magnitudes indicate the presence of negative-sequence components. The offsets of the waveforms also must balance across the phases, but are at lower frequencies than the supply – they are sub-harmonic components.

These imperfect current waveforms will work through the supply impedance to introduce negative-sequences and sub-harmonics in the supply voltage. Sustained negative-sequences would cause higher losses in parallel motors. As the rotor reaches synchronism very quickly in normal start-up conditions it is unnecessary to worry about the effects on supply current purity at these intermediate speeds. In the case of a failed start, or a stall from excessive load or reduced voltage the effects could persist, but even in an extreme case of a weak system and large imbalances or offsets there is a lot more risk to the stalled motor from its unsynchronised operation than there is to other motors from the negative-sequences in the supply voltage.

Starting transients

If there are considerably higher currents flowing in the supply to a LS-PMSM during start-up than there would be for a comparable IM, the network voltage will have worse sags. In this section the starting behaviours of the two motor types are compared.

The current waveforms are not studied, but just the rms current, as this makes the interpretation of the plots simpler. Because the extent of voltage drop in a weak system is strongly dependent on the phase as well as the magnitude of the current, the P and Q components are also noted. The integration of current due to the rms metering should be considered if resolution of a single supply-period is desired when rapid changes in current are occuring. Examination of the instantaneous currents as well as the rms values showed that the initial transients lasted long enough for the rms value to indicate well the magnitude of the transient. The plot on the previous page shows instantaneous phase values, and may be compared to rms plots in this section.

In these tests the realistic situation of normal mechanical loading was applied, since the pump or fan duty would not be disconnected for starting. The effect of the load is of course to slow down the increase of speed, and the square characteristic makes the load torque become much more significant at higher speeds than during the early part of the start. Without load the last 0.5pu speed can be gained in a cycle even after several cycles have been needed for the first 0.5pu speed increase, due to the lower relative speed of field and rotor, while in bad starting conditions with initial negative torque, the load can be helpful by producing a braking torque that combines with the asynchronous torque to get the rotor back to positive speeds. Other load characteristics such as direct proportionality or constant torque will have much more effect on the synchronisation, easily reaching the point where the asynchronous torque cannot get the rotor to a high enough speed to synchronise.

No allowance was made for load inertia, although this would be very significant for a fan and could be quite a lot for a robust pump designed to cope with solids passing through. Higher inertias would prolong the run-up or even prevent synchronism, but the case used indicates the nature of the consumption throughout the speed range, so can be stretched in time to approximate other permissible inertias.

The symmetry of the IM's rotor makes the starting transient independent of the initial rotor angle. The supply angle at the moment of switching does have an effect on the initial offset and magnitude of each phase current; any phase that is around voltage zero at turn-on will have a strong initial d.c. component, leading to higher peak current and flux. Saturation effects will increase the current still further. The LS-PMSM of course shares this feature, fundamental to all inductive-resistive loads, but its PM field makes the initial rotor position important too. This is described on page 27.

Throughout the starting of the LS-PMSM there are unhelpful effects from the PM field (page 27). These slow down the run-up, causing the supply disturbance to last longer than for a similar IM. The imperfect current waveforms discussed in the previous section will also happen for a longer time if starting is slow.

Rotor position

With all three motors connected to a stiff 1pu voltage source the start-ups were simulated. The IM's peak starting current was only 4pu, which is on the low end of IM starting currents. The LS-PMSMs both had a sharp current rise to about 6pu, changing little for various starting angles.

The worst situation was when turn-on happened with the PM flux leading the applied voltage vector by 90º. In such a case the currents growing in the windings cause the initial torque to be in the reverse direction. This was seen as a large negative torque and consequent longer time before synchronisation.

In the best case, with the PM flux lagging the applied voltage by 90º, there is an initial positive torque. There is the added advantage that as the rotor is now following the supply rather than moving the other way this period of positive torque now lasts for longer – indeed a light rotor and strong field could result in synchronisation in one bound, although this is not a likely situation in practical drive systems of this size.

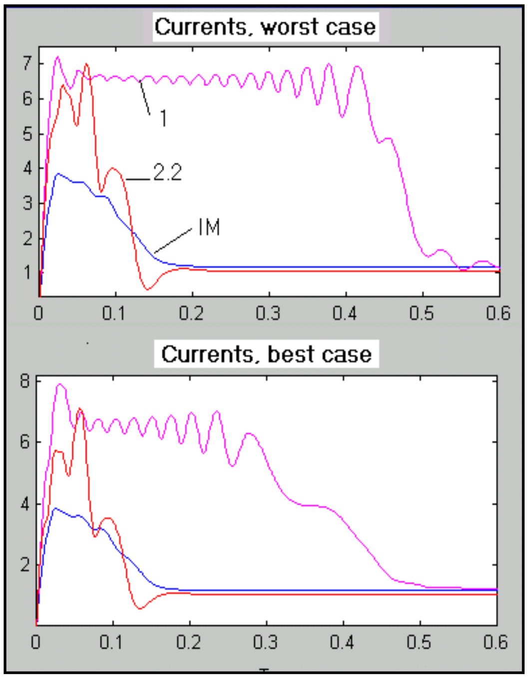

Figure 12 Starting currents

The neglect of saturation on the model is very important here: in the bad starting condition there is the further problem that during the negative torque period the flux from the stator current is added to the PM flux, surely causing great saturation in a real machine. The supply currents could therefore be far higher than indicated here. Such an extreme case could not happen with an IM, and is important in considering protection settings and the effects on power quality.

After this initial surge, the simulated behaviours differed; the much lower rotor resistance of LS-PMSM 1 caused reduced asynchronous torque, due to the poor phase of the rotor current. For this reason the rise to synchronism was much slower, taking 0.5s with the normal load, rather than 0.15s for motor 2.2 which is on a par with the IM.

The low rotor circuit resistance of LS-PMSM 1 also caused a large reactive power flow of 6pu from the supply, staying quite consistent throughout the unsynchronised operation. This was twice the peak value of motor 2.2, while the peak active power of 1 was only half as much as that of 2.2.

In steady state the very low reactive power consumption of LS-PMSM 2.2 can be seen; it is in fact slightly negative here.

The plots on the right show P, Q and I for all three motors during starting.

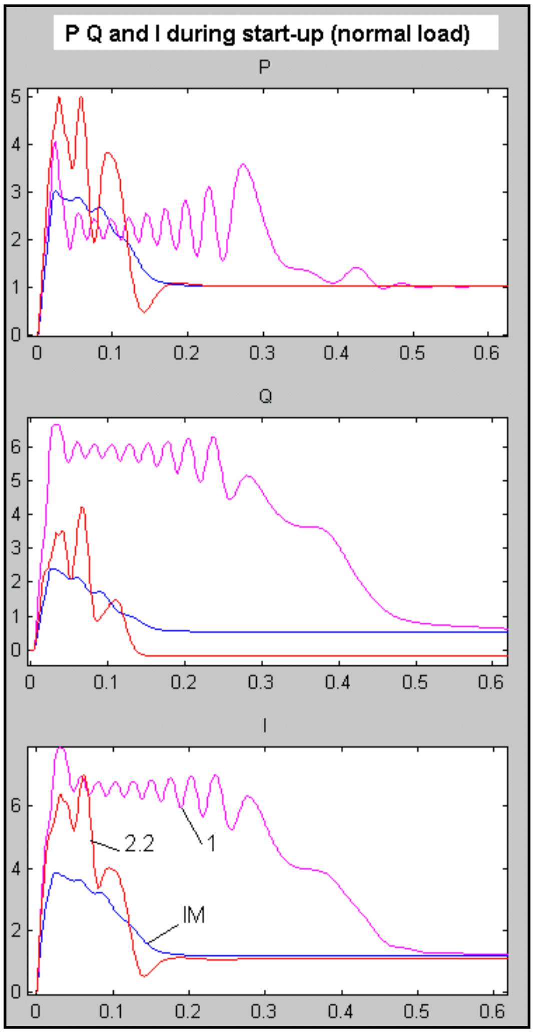

Figure 13 P, Q and I during a loaded start

Parameter effects

The starting problem and the high reactive power consumption of motor 1, besides the reduced damping when in synchronism, suggest it would benefit from a higher rotor resistance. To confirm this, Rr was tripled and the test repeated. The behaviour was then very similar to that of motor 2.2, except for the effects arising from the lower PM field strength, as in the figure below.

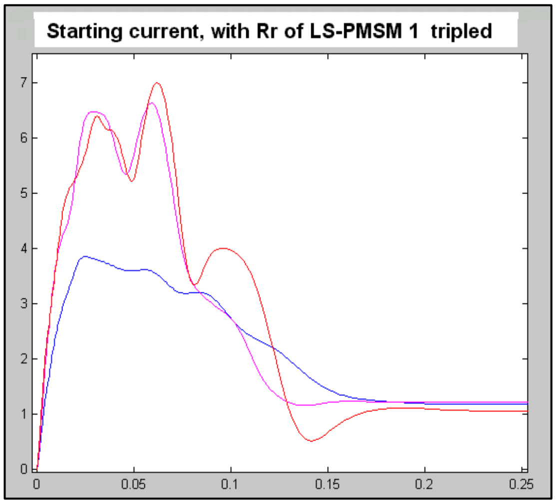

Figure 14 Starting current, with Rr of LS-PMSM 1 tripled

The primary determining factors of the power and reactive power inputs when out of synchronism are those related to the IM part: Rs, Xls, Rr, and Xlr. Since the rotor values are likely to have been chosen on the basis of sufficient starting torque, and for damping when synchronised, there may have been little consideration of the power quality effects of large reactive power consumption during the short start-up period. This makes a check on these parameters a good idea when considering such a motor for use in a delicate system. An IM's rotor values will naturally have been chosen for good performance as an IM, so are not as likely to be a problem.

The effect of supply voltage on starting

When the motors were started with reduced voltage available the PM braking torque of the LS-PMSMs was very detrimental to starting. Simulations were made with a stiff supply at voltages down to 0.75pu.

The poor asynchronous torque of LS-PMSM 1 caused it to start slowly even on full voltage, and voltage reductions slowed it still more. At 0.75pu voltage LS-PMSM 2.2 took about five times as long to start as it did on 1pu, while the IM had not quite doubled its starting time.

Table 4 Starting time (s) with varied voltage from a stiff supply

Motor	IM	LS-PMSM 1	LS-PMSM 2.2
V = 1.0pu	0.15	0.45	0.15
V = 0.9pu	0.20	0.75	0.2
V = 0.8pu	0.25	STUCK	0.3
V = 0.75pu	0.25	STUCK	0.7

When LS-PMSM 1 was unable to synchronise, its rotor became stuck at an oscillation near zero speed. This suggests that the magnet braking torque is preventing the speed from increasing. The use of weaker magnets may help the early run-up, but would also hinder the synchronisation. The main problem with this motor is the asynchronous torque, as described in the previous section.

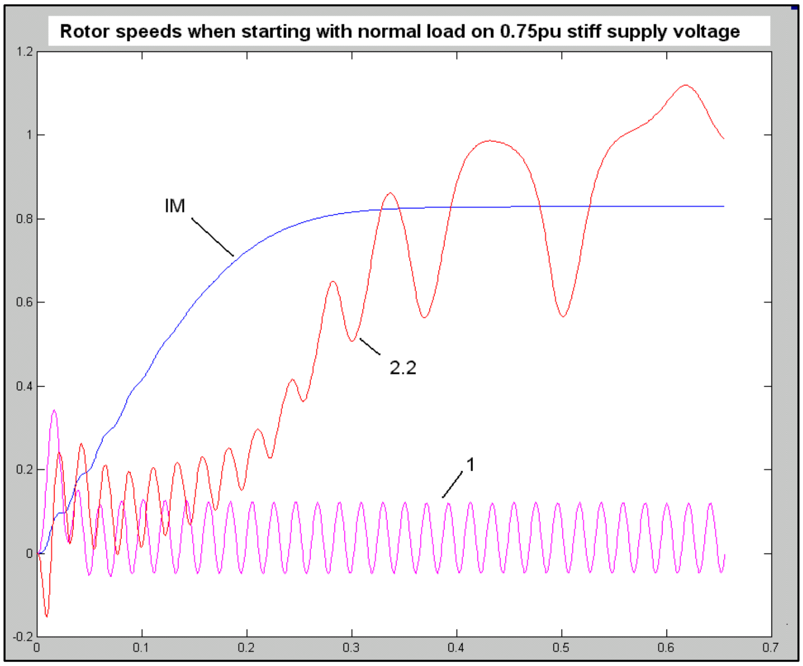

Figure 15 Rotor speeds during starting with normal load and stiff 0.75pu voltage

Low supply voltages will therefore have a very bad effect on the starting of a LS-PMSM, and its heavy starting currents will make the voltage even worse. Ensuring good asynchronous torque at a moderate power factor is a good way to help the LS-PMSM start well in these bad conditions, so the good asynchronous torque described in the previous paragraph is especially important.

A difference may exist in the extent to which the LS-PMSM and IM pass supply disturbances to the load and vice versa. While a typical load for a network connected motor will not require very smooth torque, load shocks could have an effect on supply quality in a weak system. Both directions of transfer have been briefly simulated.

The rotor currents of an IM in steady-state operation alternate at the slip frequency, so keeping the rotor field in phase with the stator field. When a disturbance makes the rotor field orientation swing quickly in comparison to the electrical time constant of the rotor, the rotor field can no longer follow the stator field. In an extreme case the rotor could be considered to behave as a SM rotor, since its field follows the physical rotor. With slower swings of the rotor field, the rotor currents change sufficiently to keep the rotor and stator fields together.

The larger airgap of the LS-PMSM gives it a reduced reactance, so when there is a phase difference between its rotor and stator fields, the effect upon current is greater than in an IM. Higher rates of change of current during transients are also permitted by the low inductance.

Load disturbance

Simulations were run to give an idea of differences between IMs and PMSMs at feeding back load disturbances to the supply. The effects on I, P and Q were observed for steps of load torque. In a real situation the shock load could be caused by solid objects entering a fan or pump, or some process load with sudden changes of torque. It is desirable that the motor driving such a load should filter the transient considerably, rather than passing it rigidly into the supply and so affecting the power quality.

As an example of a large shock, a torque of 4pu was superimposed on the normal load torque for 20ms. If this loading had persisted, all the motors would have been stalled, but here the rotors had swung by less than one electrical revolution before removal of the extra torque.

During the recovery from the shock (0.77s onwards) the IM's rotor currents were able to alter sufficiently to keep the rotor and stator fields synchronised, making the current quite smooth. The LS-PMSMs appear to have slipped poles once during this same period. The higher impedance of the IM played a part in reducing its current consumption at all points.

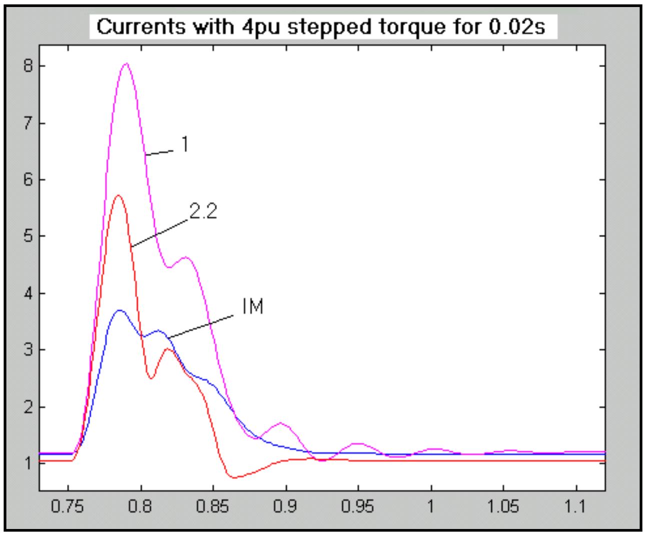

Figure 16 Effect of load shock on supply current

With a torque of 0.5pu applied in the same way for a longer time, the slow rate of swing allowed all the motors to adjust their angle or speed to supply the new torque, without any pole-slipping. The effect on the supply was then quite similar for the IM and the LS-PMSMs, but with much more damping on the current response of the IM.

With this smaller torque, the rotor current of the IM was able to change quickly enough to follow the deceleration and keep the fields synchronised. Steady operation was reached at a greater slip. The required increase of the load angle of the LS-PMSMs involved some swinging, which is why there was overshoot and more oscillation in their currents.

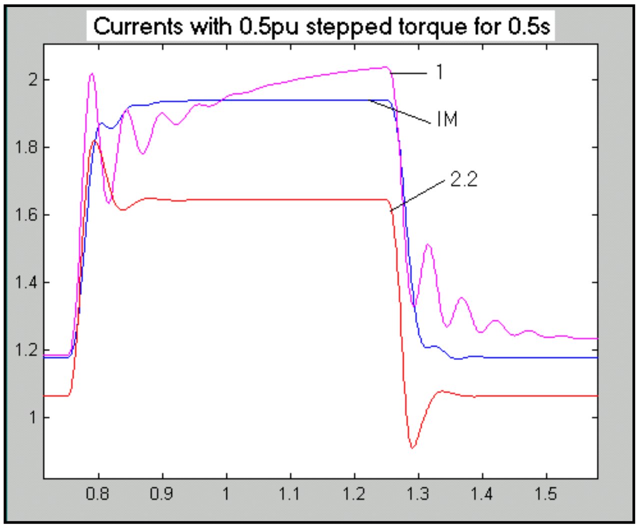

Figure 17 Effect of a moderate load change on supply currents

Supply disturbance

Supply transients of a duration less than the stator's electrical time constant will be filtered well from passing into the mechanical load. Longer voltage reductions of several cycles' duration may be caused by faults on the network, or starting of local machines, and can be transferred to the load.

The supply voltage was stepped down for five cycles, to simulate fault clearance on a branch elsewhere in the system. The supply was kept stiff so as to study just the primary effects of the stepped voltage, and not the further effects of increased voltage drop with higher load current.

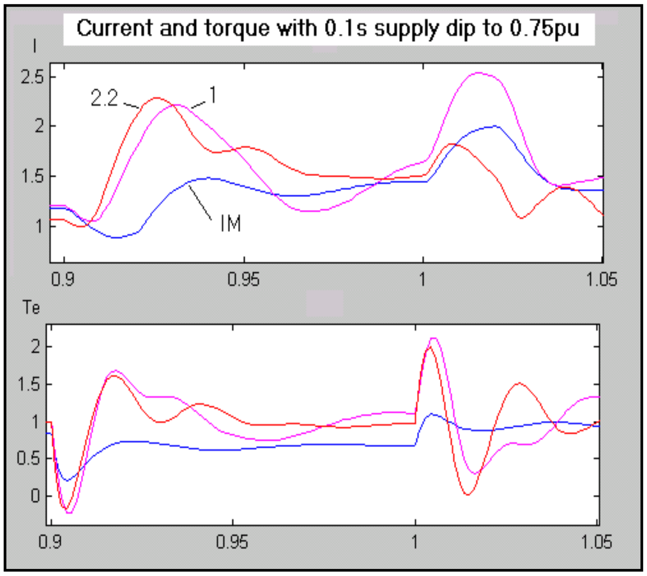

Figure 18 Effect of a voltage dip on current and torque

From the current plot (upper plot on the right) all the motors show an initial dip in current as the applied voltage drops. For the LS-PMSMs, the reduced electrical torque causes the speed to fall, and the increased load-angle quickly makes the current increase. The swing of the rotor causes the currents to peak considerably before settling to lower values. The IM also has a drop in current, but as the speed has to fall to reach a steady state again this drop lasts for longer and there is much less overshoot on the recovery (see the plot of currents at 0.94s). The overshoot here is due to the electrical inductances rather than the mechanical swinging. When the voltage is restored to normal there are large peaks in the torques of the LS-PMSM as the load angle is initially too high. Swinging then causes a large overshoot on the return. The lower Eo of LS-PMSM 1 leads to a high reactive power and current rise after resumption of normal voltage.

There are definite differences in the behaviours, with the LS-PMSMs transferring voltage transients more readily into currents and torques. Further tests with a short-circuit at the motor terminals also showed a much greater rate of rise of current, and higher peaks of currents and torques than for the IM.

In the case where a voltage dip is caused by another motor starting, the large transient increase of supply current of the LS-PMSM will depress the supply voltage further, making the newly connected machine have a worse start. The transient current lasted only 50ms in the case shown, but this could vary between machines, and is a lot bigger than the increased steady-state current draw of a LS-PMSM running with reduced supply voltage (discussed later in this chapter).

Undesirable regeneration

The LS-PMSM's permanent field allows it to generate current even into a short circuit, as long as it keeps turning. The IM requires magnetising current to be supplied in order to function as a generator, so its rotor currents will quickly decay even if it was running normally before a supply fault, and its output can thus become zero while it still rotates. From this comparison, the currents from the motors into a fault and the braking of the load in such a case can be expected to be increased by the use of a LS-PMSM.

Short circuits

LS-PMSM 2.2 and the donor IM were used as examples, in the situation of a local short-circuit bringing the supply voltage to zero. The usual mechanical loading was applied, and just the motor inertia was used. The LS-PMSM had a higher current (right), but the consequently greater braking caused the speed to fall quickly to zero, while the IM was still moving after all its regeneration had ceased (below).

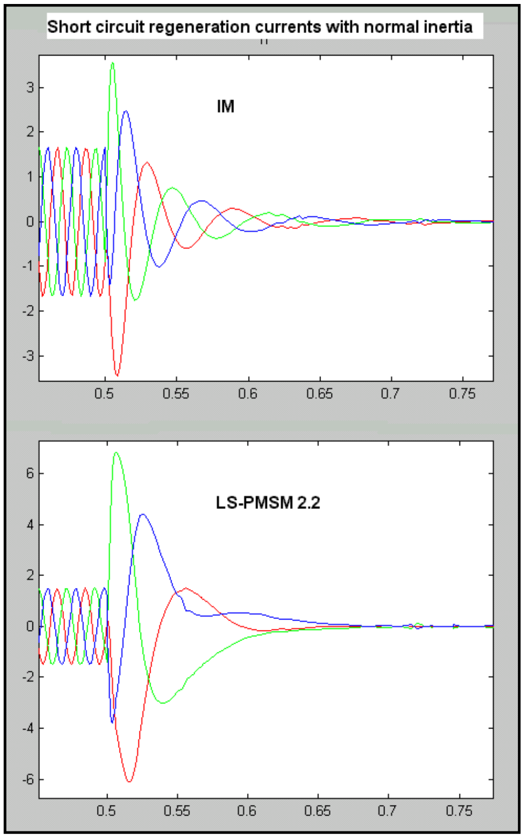

Figure 19 Regeneration into a short-circuit

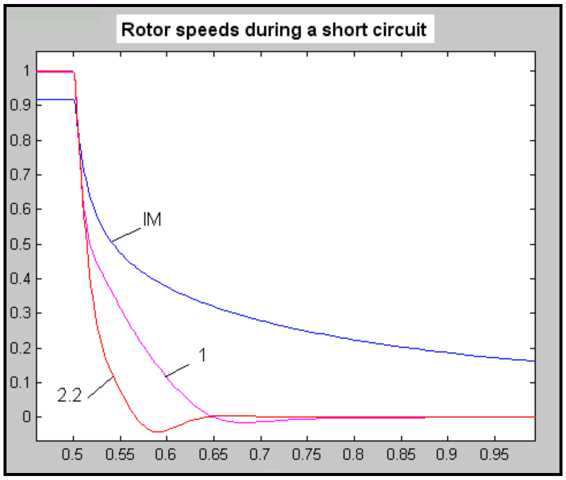

Figure 20 Rotor speeds during a short circuit

To confirm the effect of the IM rotor's electrical time constant on its regeneration time, the self inductance was increased and the resistance decreased, with the effect of a prolonged regeneration period. It is at clear that regardless of the drive inertia an IM will only be able to supply current into a short circuit for a short time. Although different IM designs will have a range of time constants, it is obvious that anything greater than a few hundreds of milliseconds would lead to very nasty transient behaviour, and would be hard and pointless to realise anyway.

The behaviour of the LS-PMSMs was studied more closely by simulating a short circuit at the terminals of a motor with a very high inertia – much higher than would be able to synchronise in a real case. Both motors had sub-transient peaks of 5pu current, decaying in a little over one cycle to 2.5pu for motor 2.2 and 1.5pu for motor 1. The initial peak is caused by currents in the rotor circuit resisting the reduction in flux that the high stator currents are producing. The PM field is not affected by the short circuit current as a normal excitation could be, so there is no further decay of currents – the synchronous reactance is reached directly from the sub-transient reactance. After settling to steady values, the output currents were reduced only by the falling rotor speed.

Isolation

When the supply is isolated rather than short-circuited, there is no braking effect from the regeneration. The induced voltage from the rotor field then appears at the terminals and on any parts of the supply system to which the motor is still connected. The presence of loads in parallel will produce some braking, dependent on the magnitude and phase of the load impedance. Again, the necessarily low inertia of LS-PMSM drives will limit the time for which significant voltage is generated. IM drives will have a quick decay of rotor field, causing regeneration to stop regardless of the inertia. With an open-circuited stator it was seen that the decay of rotor current was slower than with a short-circuit, but it still took only 200ms to fall to a small proportion of its original value.

A LS-PMSM therefore can have the interesting effect of maintaining a voltage on its terminals after a disconnection. If a normal contactor were used to connect the motor to the supply, a motor with Eo similar to the supply voltage could hold its own contactor on until its speed dropped below a critical value. Thus, other parts of the system could be kept live.

Conspiracy in the system

Where an IM with a high drive inertia is in parallel with a LS-PMSM in part of a system that has been isolated, an interaction using their respective load energy and the permanent field seems plausible. The LS-PMSM would be able to supply magnetising current to the IM, while its low inertia will cause its speed to fall more rapidly than that of the IM. Thus, the IM would be magnetised with a lower frequency than its mechanical frequency, so it would be able to generate power into the system. If this power could be used in the LS-PMSM to prevent it from falling in speed as rapidly as it would when alone, the presence of a LS-PMSM with high inertia IM loads in parallel could result in a longer period of regeneration after a loss of supply than would be possible with either motor alone.

Some simulations were made of this situation using an IM with a large inertia, and various parallel electrical loads. It was found that the presence of the LS-PMSM caused the IM currents to remain around 1pu for much longer than in the system of only IMs. From the P and Q measurements it was observed that there was indeed a Q flow from the LS-PMSM to the IM, and a P flow in the other direction. Low-resistance loads in parallel with the machines reduced this effect because of the LS-PMSM's internal impedance. The speed of the LS-PMSM still did fall a lot more rapidly than the speed of the IM, so it appears that there was not sufficient active power flow to supply the LS-PMSM load at a speed anywhere near the rated speed. Other choices of motors may have more interaction.

This situation was cited mainly as an example of the many possible effects from the introduction of a different motor. If regeneration is a problem, the motors will be equipped to isolate them from the system, so such interactions will not occur.

Steady-state response to voltage changes

The response to voltage changes is one of the fundamental differences caused by the synchronous nature of the LS-PMSM. A drop in the supply voltage to an IM initially causes less power to flow into it, and less to emerge as shaft power. The slip thus increases, until the combined effect of reduced load torque and increased EM torque allows equilibrium to be regained, provided that the motor is not pushed into stalling. The important point about this change in slip is that even a constant-torque load will draw less power at this lower speed, while more usual loads have a first or second order torque characteristic, leading to very quick reduction in load power as the slip increases.

Therefore, depending on the load characteristic and the motor parameters it is even possible for an IM to be helpful by drawing less current during a voltage reduction. More usually there is an initial mild increase, then a decrease as the voltage drops further. The Q consumption for magnetising is reduced, but there can be higher currents if the increased slip has more effect than the decreased voltage, so the extra current in the leakage reactance may increase the overall Q consumption.

The PMSM has the inherent feature of fixed speed and angle-dependent torque, so a drop in voltage will initially cause a deceleration of the rotor, until a new (larger) load angle is reached where the power output is maintained. The rotor will then pass and oscillate about this new point, damped by the various losses such as any start-up or damper windings, and iron losses. The steady-state situation can be considered as the induced voltage at a variable load angle connected to the supply through the stator resistance and inductance. The induced voltage stays constant as long as the rotor stays in synchronism and the iron stays unsaturated. The rotor windings are ineffectual in steady-state synchronised operation, simplifying the situation a lot.

Steady-state speed, then, is constant, and until the voltage drops enough to lose synchronism the mechanical load is unchanged. Getting the same output but with a reduced voltage will normally increase the currents, and thus the losses in the series impedance. The only situation where this will not be the case is if the consequent change in load angle and power-factor causes a reduced current over some small operating range, which is even less likely when the machine is optimised for the original voltage. So by its increased active power consumption with reduced voltage the LS-PMSM obtains an advantage for fussy mechanical loads, but at the expense of a disadvantage for an already labouring supply system. It will be seen in this section that there is a potentially helpful effect of voltage reductions on reactive power consumption, which may well outweigh the disadvantage of the active power consumption.

Voltage reduction up to loss of synchronism

The three motors were tested by ramping the supply voltage down until synchronism was lost, and observing the behaviour.

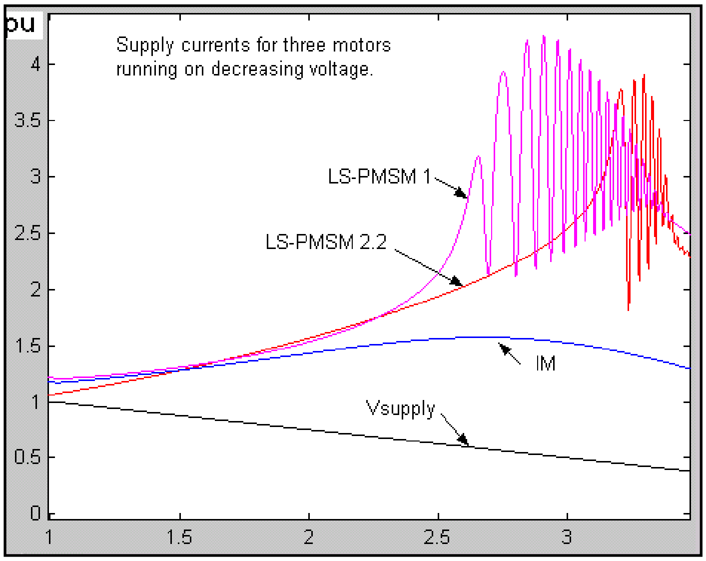

Figure 21 Supply currents with slow voltage reduction

The mechanical load was of square proportionality, with 1pu torque at 1pu speed. From the plot (right) it can be seen that the IM current increases only a quite small amount at any voltage. LS-PMSM 2.2 starts with little over 1pu current, but this rises more rapidly as the voltage falls. 0.5pu is the limit for retention of synchronism – even when operating at this voltage, a small disturbance (0.025pu step down) will lose synchronism. In spite of the lower impedance of LS-PMSM 1, the smaller Eo gives it a lower power transfer capability causing earlier loss of synchronism. This would be a disadvantage in a weak system, as the high current rise near loss of synchronism, and the quick change from Q production to large Q demand from the induction machine operation, would be worse for the voltage than a motor which kept drawing active power but at a favourable power factor.

There is a large difference between the IM and LS-PMSMs at extremely reduced voltage where the curves go in opposite directions. In the more normal range the IM current rises less sharply but this could be partly to do with the parameters used. The difference between the motors is much less clear for small voltage reductions, and will be examined more closely later by studying P and Q consumption instead of just current magnitude.

More moderate voltage changes while synchronised and loaded

To show the differences in reaction to voltage change, the representative LS-PMSMs 1 and 2.2 and the donor IM were loaded so as to have a square torque/speed characteristic with 1pu load power at synchronous speed, then the supply voltage from a stiff source was altered. The effects were only examined down to 0.75pu voltage since this is already a very severe reduction that would be reached only transiently during a fault, or in other very unusual circumstances.

Efficiencies allow for only the copper losses that were modelled here, not for iron, windage, and stray losses.

LS-PMSM 1 and the IM had very similar values and behaviour of Q and I, although the IM's slip led to the output power and efficiency being rather lower. The IM's current did increase when the voltage dropped, since the increase in slip was great enough to overcompensate for the decrease in required magnetising current. The consequent increase of reactive power consumption in Xs and X'r was less than the decrease in magnetising current, so the reactive power consumption dropped too. Active power consumption was reduced as the lower demand of the load at the greater slip speed had a greater effect than the extra copper losses from the increased current.

The LS-PMSMs' power consumptions of course increased as the supply voltage fell. 2.2 has 1pu Eo as opposed to the 0.7pu of 1, so at 1pu supply voltage its reactive power flow was smaller: 0.2pu generation, rather than 0.6pu consumption. Thus the current input was less, and the copper-loss and total P input less also. With the supply dropping below 0.92pu the increase of Q out of 2.2 and the decrease of Q into 1 caused the reactive current of 2.2 to be greater, and this combined with the greater resistance of 2.2 to make this motor have the higher power consumption.

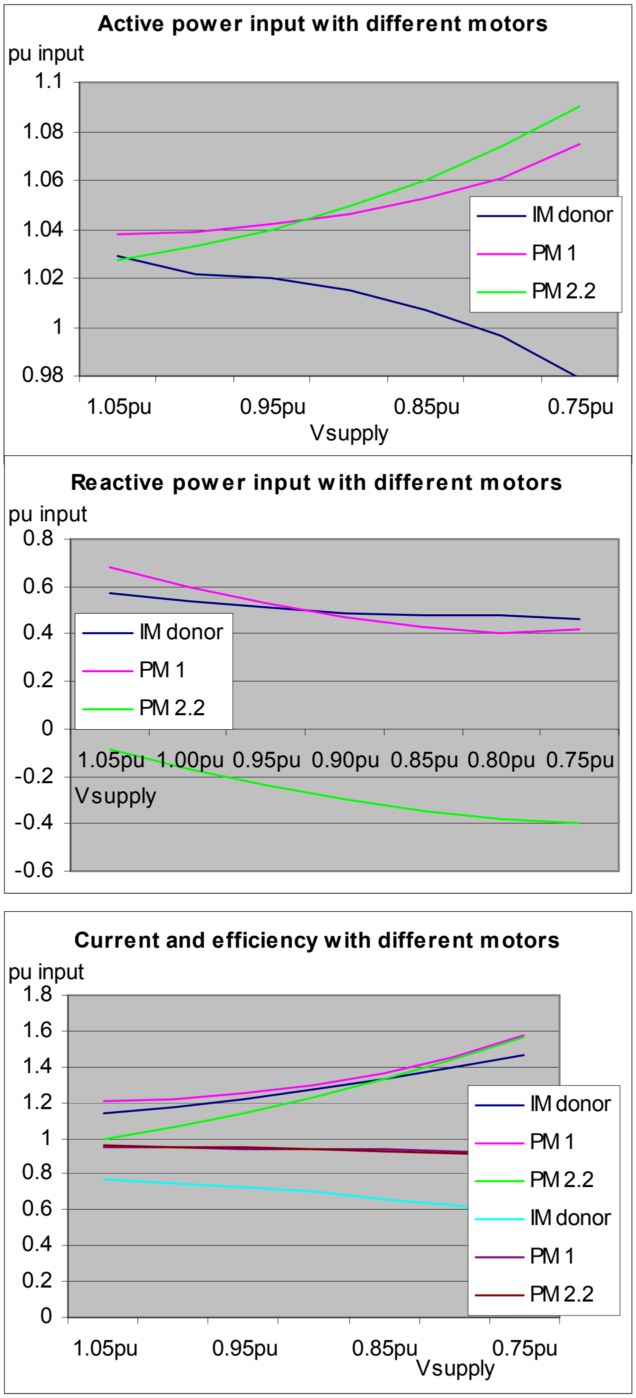

Figure 22 P, Q, I and efficiency with voltage reduction down to 0.75pu

Voltage changes on low load

The previous tests were all done with rated load. This is the most natural value to choose for the basic applications for which small and medium LS-PMSMs are being considered here. In general, lower loading means more effect on Q than P consumption. Different responses to voltage change and parameter alteration would be possible at the different load angles of lower loadings. The use of such a motor for long periods at much less than rated load would suggest a bad choice for the application, but would nonetheless be possible in if extra power were required for periods greater than the motor's thermal time-constant. If it were important to optimise the voltage response of a motor for such a situation, it may be necessary to select which operating condition is considered the more important.

The effect of motor parameters

Parameters of motor LS-PMSM 2.2 were varied, and the effects were studied as the supply voltage was changed. With a 1pu mechanical load of square speed/torque characteristic, the supply voltage from a stiff source was varied over the range 1.05 to 0.75 pu. The model parameters were varied to study their effects upon P, Q, I and η. Since this was all done with the motor in synchronism, the rotor electrical parameters Rr and Xr were ignored. They could be important if worrying about the loss of synchronism that could happen at rather lower voltage levels, or recovery when the supply returns.

As the LS-PMSMs have series reactances many times greater than their resistances they are considered as having α ~ 90° for simplicity of explanation.

An increase of Rs increases the power dissipation in the copper, besides producing more voltage drop in the q-axis. Since the dissipation in Eo is constant and the stator resistance is the only other modelled component with power dissipation, a very low Rs will give very little rise in power consumption as the voltage drops. There is the further advantage that normal operating efficiency will be even better.

Low Rs leads to low damping of the supply current, and this was evident in the start-up currents.

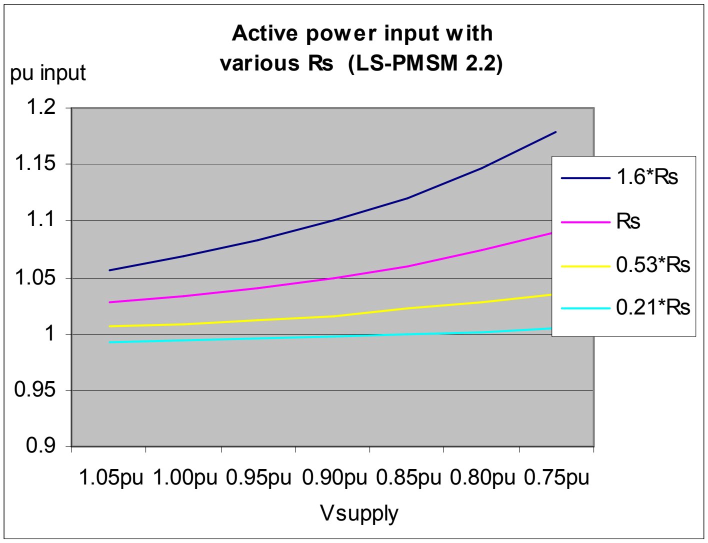

Figure 23 Variation of P with Rs, LS-PMSM 2.2

For any synchronised PMSM with fixed frequency, *an increased current draw implies increased active power consumption and vice-versa*. This is due to the constant output power while synchronised. Whether increased resistance will have this effect too depends on whether the increased resistance decreases the current input for the particular operating situation, but such an effect could only happen over a small operating range. This motor had an increased current at all voltages tested when given a higher resistance.

An increase in Rs also led to an increase in reactive power production, the effect diminishing as the voltage reduced. This increase would be helpful in most cases, but is certainly not a good reason for having extra losses in the machine.

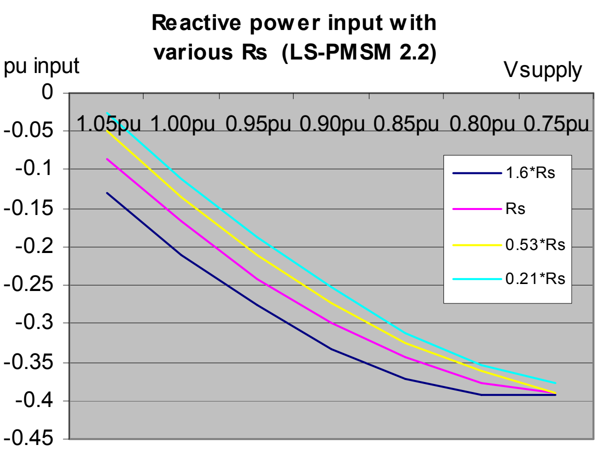

Figure 24 Variation of Q with Rs, LS-PMSM 2.2

Increased inductance had the effect of increasing reactive power consumption – in fact, this was shown as a reduction of reactive power production. The effect of this change is more pronounced than with the resistance, since the reactance is the greater component of the stator impedance. It can be seen that the effect is most prominent at lower voltages. When the reactance is doubled (right), the extra load angle required to maintain power output causes the reactive power production to diminish and turn to consumption as the supply voltage falls.

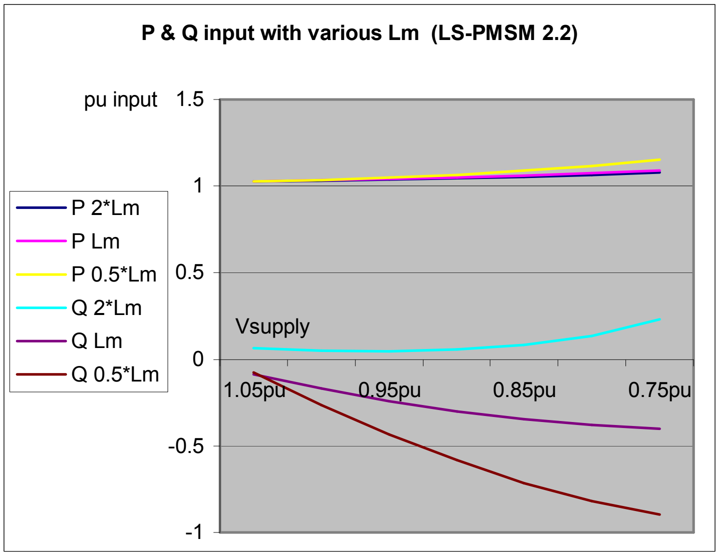

Figure 25 P and Q input with Lm variation

Lower values of reactance allow operation at a smaller load angle where the effect of a small increase of load angle is to increase the var production. Lower supply voltages show this off to the best effect, but a very low voltage will increase the load angle to the point where the var production decreases again. The lower reactance causes in this case more current to flow, and thus the power input to increase and the efficiency to drop.

Variation of Eo had the most simple and notable effect. As the impedance is mainly reactive, the change in full-load δ needed to keep the power constant after a change in Eo has negligible effect on the active power flow into the motor. The change in Eo does however cause a change in the reactive power flow, and the input current is thus the phasor sum of the nearly constant active and the varying reactive parts. So when Eo = Vs, and Q = 0, the current is at its minimum and the efficiency at its maximum. Taking the series resistance into account, this point is not so easily calculated, but most machines will have a high X/R ratio.

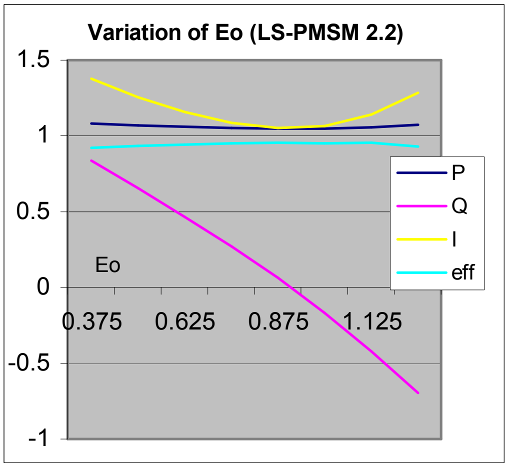

Figure 26 Effects of varied Eo

Parameter choice is of course complicated: taking Eo as an example, a high value will normally be advantageous for steady operation because of the helpful increased generation or reduced consumption of reactive power. Under reduced voltage operation the high Eo will lead to more Q production, giving higher currents and losses, but being helpful to the voltage in a typical system with lagging loads. During start-up the high Eo will be a hindrance, increasing the start-up time and the torque and current oscillation. In typical cases where operation is as one of many loads in a system with considerable Q consumption, the ability to generate Q is likely to be preferable to a higher starting current of just one of the loads.

Effect on a weak supply system

The previous tests studied various features of the motor's performance in succession. Although they tell a great deal about the behaviour of the motors in a weak system, they do not account for the interactions between motors in the system during transient loading.

Comparison of motor behaviours when an IM starts

To examine the effects of such interactions, the supply system was given an impedance of 0.0047 + j0.0117 pu per phase, corresponding to a conveniently round number of Ohms, giving 4% drop at rated load of three motors. With the three usual motors connected and running steadily, a further induction machine with a high load inertia (5*Jm) was started, and the effect on the other motors and the system voltage studied. Note that the current may increase while P and Q decrease or stay constant, since the voltage has reduced.

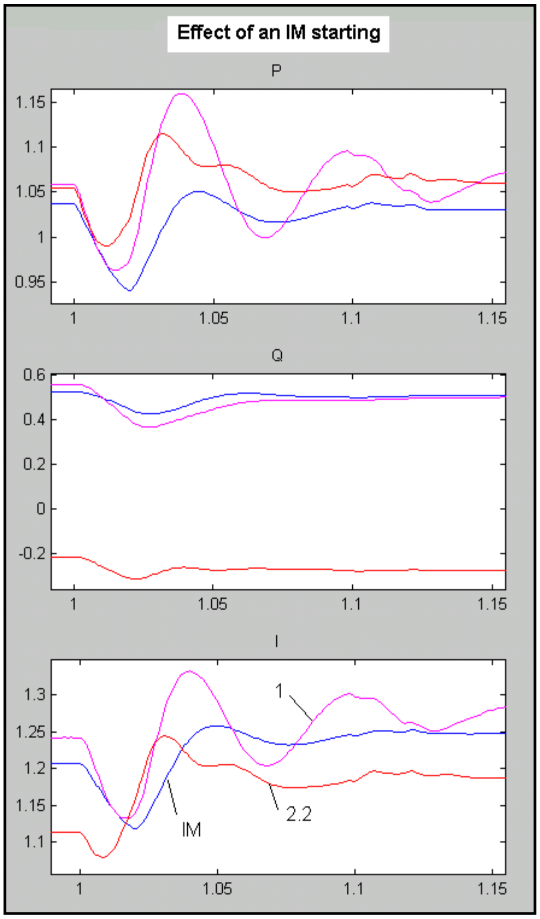

Figure 27 P Q and I when a parallel motor starts

From the plots (right) the most significant change of current is for LS-PMSM 2.2, due both to its output power constancy and its higher stator resistance causing the input power to rise more than that of the other two motors, and to its increase of reactive power *production* with decreased terminal voltage. The important point to note here is that the reactive part of this seemingly bad current increase is in fact a good thing, since it reduces the total current from the supply when there are lagging loads in parallel, and makes the phase of the supply current better as concerns voltage droop and stability. It is also notable here that the reactive power behaviour of the motors is more similar than that of the active power. The LS-PMSMs have a much more oscillatory response to the voltage transient, due to the rotor angle-dependence and swinging of the rotor after the disturbance.

Supply voltage with various motor combinations when a motor starts

Different combinations of motors were put into the same system, and the same IM was started, still with the large load inertia.

There was really very little difference in behaviour between LS-PMSM 1 and the IM, apart from the slight oscillation of voltage apparent when all machines were of type 1. The effect of changing IMs for motors of type LS-PMSM 2.2 was to improve the system; the initial voltage was higher due to the good power factor and efficiency, and the starting IM had therefore an easier task, beside the useful extra reactive power production of the LS-PMSMs during the voltage sag. The change in voltage was almost exactly the same in all cases.

Variation of PM field strength of either LS-PMSM led to a shifting of the curves, higher Eo giving higher system voltage. Doubling and halving of the stator resistance and reactances led to *very* little effect on the supply voltage change.

In the plot (below) of the system voltage for each combination, the light rise in voltage, e.g. at 0.95s for the all-IM system, is where the starting IM gets over the oscillatory part of its start-up. Hereafter the system voltage rises to the new, lower level due to the extra IM's current demand.

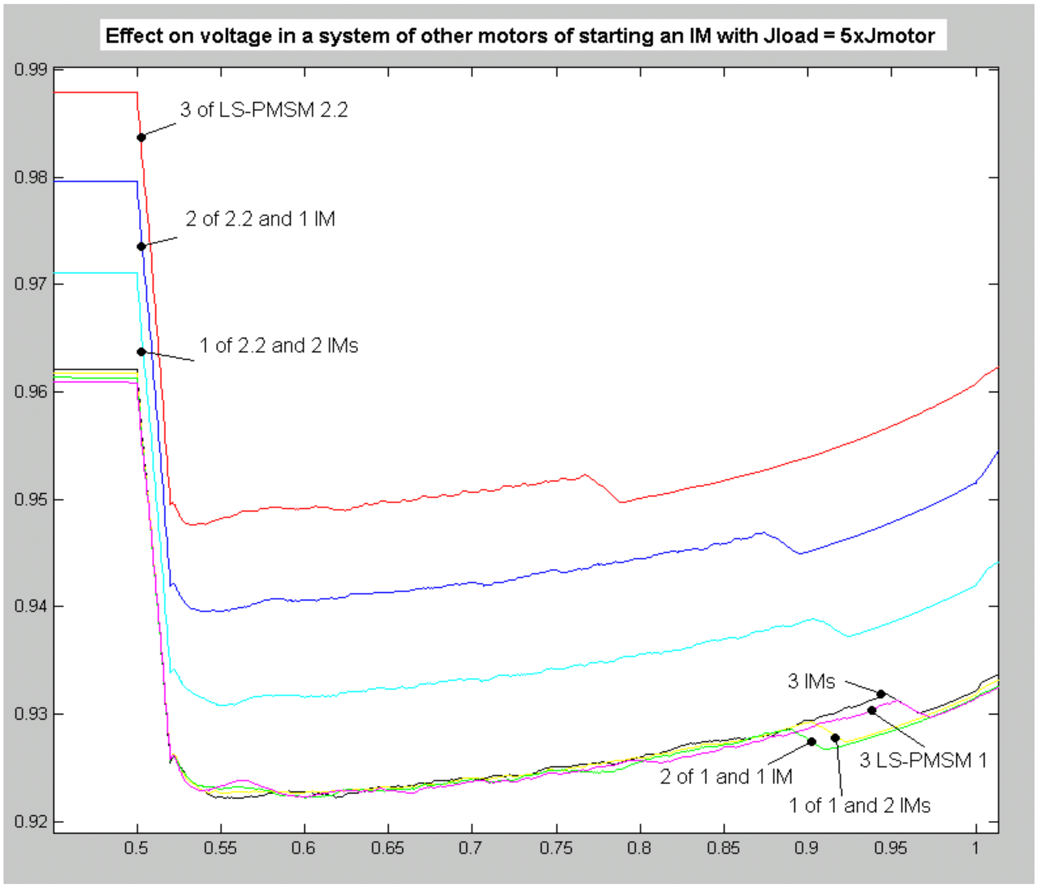

Figure 28 System voltage with various combinations of motors when an IM starts

Supply voltage with various motor combinations as the system is loaded

With a system of three of LS-PMSM 2.2 or of three IMs driving the standard load, increasing resistive and inductive loads were applied in parallel with the motors, using the same supply impedance as previously.

LS-PMSM 2.2 was markedly better for the system voltage than the IM, while maintaining full load speed too. As anticipated, the increasing real power consumption was less significant than the increased var production.

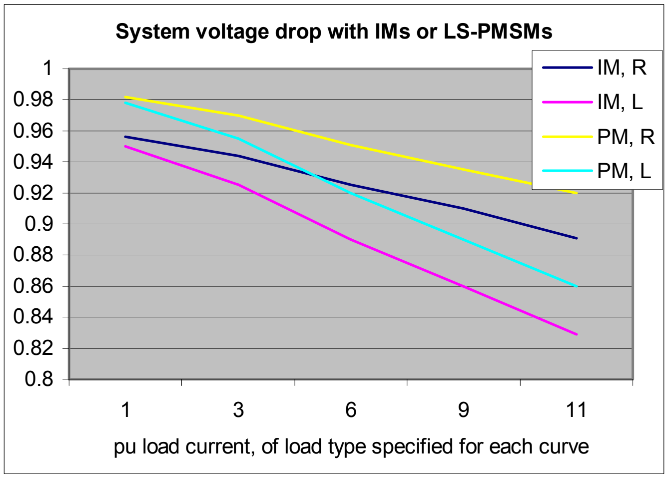

Figure 29 System voltage with parallel static loads

Harmonics

Triplen harmonic[1] currents are zero-sequence so are not possible with the three-wire connection of this motor. Harmonics whose orders are one below a multiple of three will produce negative-sequence flux components moving backwards at multiples of synchronous speed relative to the rotor. They generate negative torques, so requiring a higher fundamental current. Harmonics of one above a multiple of three are positive-sequence and produce helpful torque, but at a low efficiency because of the iron losses and the asynchronous nature of the torque production.

The purpose of this brief section is to point out features that could make the LS-PMSM's behaviour different from that of the IM in the presence of harmonic supply voltages.

Stator

The PMSM's larger airgap leads to considerably lower reactance. This will have the effect of reducing the impedance to harmonics, especially as the reactance is a lot more significant to harmonics than is the resistance.

The stator resistance will also have an effect on the power dissipation by harmonic currents, but this parameter is not fundamentally different between the motor types. To enhance the high efficiency claims of the LS-PMSM and to reduce its excessive P consumption at reduced voltages it may be that a typical LS-PMSM will be designed with a lower stator resistance than a normal IM, so giving less need for worry about the dissipation from harmonic currents.

Rotor

Since the rotor cage is not intended to have current flows during normal running, it may well have a different design from that of an IM made for the same application. For example, an IM is likely to have quite low resistance bars for the sake of reduced dissipation during running, but may utilise skin effect for improved starting. A LS-PMSM could sensibly be designed for good starting *and* damping by having higher resistance bars. The high dissipation is then used advantageously. However, a further increase in resistance through skin effect at low speeds may increase the resistance beyond its optimum value for torque production, suggesting that use of a low skin effect design is more likely for a LS-PMSM.

As the reactance presented to harmonics will be high, it will have a much greater effect on rotor current than the resistance will. Therefore, higher resistance or greater skin effect will increase the harmonic losses. A rotor design with considerable skin effect will then have higher harmonic losses, so there may be a slight advantage here for a LS-PMSM, which can use the skin effect less.

Iron losses

Stator iron losses will be increased by the harmonic components in the magnetising flux. The higher currents drawn with harmonics present will cause more loss in leakage-flux paths too. Their higher frequencies will cause harmonic currents to dissipate more power in the iron. All of these effects are the same as with a normal IM, and are not of great concern.

The rotor, however, has no iron losses in normal operation, but the presence of harmonic fluxes could cause considerable loss. This would be particularly important if the rotor design has taken advantage of the synchronous operation by using less lamination or higher-loss iron.

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[1] Harmonics at multiples of three

The effects

Harmonics cause losses in the rotor iron and copper, both of which are loss free when operating in steady synchronous conditions with pure supply waveforms, and ignoring space- harmonics. An advantage of the low rotor loss of a LS-PMSM is that there is not such a need to design the motor for heat transfer from the rotor. However, the rotor is more delicate because of the temperature sensitivity of the PM material. If not designed for use in the presence of harmonics, these two points together could cause dangerous overheating.

The conditions for the stator are less worrying since the harmonic dissipation is a smaller part of the normal dissipation. There is still the potential for more copper and iron losses than in a comparable IM.

Simulations

It is important to note that the lack of iron-loss and skin-effect modelling makes the dynamic models used for the other simulations very inadequate for studying harmonic impedances and heating effects. To see if there was any noticeable difference between the motor types even when modelled very simply, some simple tests were done with the usual dynamic models. The rms and PQ meter blocks were made for use at 50Hz, but harmonics will work just as well.

Harmonic voltages were injected into the stiff supply feeding the three different motors. Odd harmonics up to the 11th were used, at 10% and 30% of the supply voltage, then a mixture of all was used. There was very little effect in any case; the 5th harmonic had the greatest effect for all the motors, and this was seen as a change of about 1% in the active power input for a 30% 5th harmonic. Since the harmonic mmfs travel at nearly the same speed with respect to the IM or PM rotor, both machines have similar rotor-bar losses from the harmonics. As it was clear that the models had not produced interesting results, no further mention is made.

To make any meaningful simulations and studies of harmonic losses and impedances a lot more information about the motors would be needed. This would be complicated by the many different slot shapes of IMs and LS-PMSMs, and various qualities of iron and lamination. Examination with full modelling of each proposed LS-PMSM design in comparison with a range of common IM specifications would be needed in order to know whether there is an important effect from supply harmonics.

5 Conclusions

This chapter contains a summary of the main differences between the motor types, as discovered in the previous chapter. The possible effects of replacing IMs with LS-PMSMs are considered for the motor, the mechanical load, the local supply system, and the whole power system.

Finally, the original questions of the project description are addressed.

- ☐ Summary of results of motor behaviour
- ☐ The effects of replacing IMs with LS-PMSMs
- ☐ Conclusions about the original project aim

(All these points are comparing LS-PMSMs to IMs)

Starting

The braking effect of the PM field during starting, and the braking after half-speed by the saliency (page 24) cause the starting time and consumption to be higher. There are large variations of current as the motor approaches synchronous speed. The choice of rotor electrical parameters will have a great effect on the system power quality during starts, as a resistance which is too low will not only draw more current at a lower power factor, but can also reduce the torque so making the start take a lot longer. Increased saturation from bad field orientation at turn-on can increase the starting currents further, and is an effect not present at all in IMs.

The only thing in defence of the LS-PMSM is that high efficiency IMs tend to have reduced resistance in their stators and rotors, besides reduced leakage reactance. These features make starting currents of HEMs higher than those of the basic IMs. Although clever use of the skin effect may increase the rotor resistance of high efficiency IMs a lot during starting, the LS-PMSM can be designed with quite high rotor resistance anyway, in the knowledge that it has no effect upon the efficiency during steady, harmonic free operation. Still, the inherently poor starting due to the PM field makes the LS-PMSM a heavy consumer during starting.

Transient response of supply current and voltage

The lower reactance and the effect of rotor swinging after a change in supply voltage cause much higher transient currents in a LS-PMSM after a change in voltage. The effect of a motor starting is to depress the supply voltage, and the resultant high current surge of a parallel LS-PMSM will make the voltage become lower still. A further effect is that the motor which is starting will then have a longer starting time.

After a short period (about three cycles for the LS-PMSMs studied) the currents will settle and the steady-state response of the motor to voltage changes will determine the currents drawn and the consequent effect on the supply. As the current peak is caused by swinging it can be prolonged by higher load inertias; the simulation was done with just the motor inertia. Fortunately for the supply system, the starting problems of the LS-PMSM preclude its use with particularly high inertias.

Disturbance transfer

Rapid changes in the mechanical load are more readily propagated back to the supply system, with the potential to cause flicker if shock loads are a common feature of the particular drive application. Using a higher-inertia drive to combat the feedback of shocks may not be practicable because of the starting troubles of high inertias. Only in cases of remarkably frequent and fierce load disturbances would the supply be affected to an important extent; the effect of a motor starting is much greater, although it only happens occasionally.

Supply disturbances also more strongly propagated to the load, even as much as to give 1pu peaks of torque change in the simulation of a 0.25pu voltage change. A direct network-connected motor is unlikely to be used for any load where this matters, and the likely pump loads of the LS-PMSM will not be affected by such short torque shocks.

Fault contribution

The PM field allows the motor to provide current to a fault for as long as it is driven by the mass of the drive. From the perspective of the load this means a quicker reduction in speed when there is either a short-circuit or an isolation of a section containing the motor and other loads that can use the produced current. For the supply it means that a further current source of decreasing frequency and magnitude will feed into a short-circuit, while an isolated section will continue to be supplied for a while, again with decreasing voltage and frequency.

Active power variation with supply voltage

While synchronism is maintained, the power to the load stays constant regardless of the load characteristic as the supply voltage changes. In general this causes a rise in current for a reduction in voltage, and a consequent rise in active power consumption due to the increased dissipation in the stator resistance.

This effect is less in an IM as the load speed can fall, but the torque characteristic of the load then determines the resulting power requirement. The load characteristic of a LS-PMSM has no effect on the power variation until synchronism is lost.

When the voltage drops severely (e.g. <0.7pu) the different behaviours become very marked. The IM begins to take less power even if it was initially taking an increased input as the voltage dropped, while the PMSM's active power input rises sharply to several pu before synchronism is lost, at which point the consumption remains high.

A low Rs is therefore a very important feature for the motor and supply. Its only disadvantage in use is in the reduced damping of transients, but it may well be that no more copper can be put into the motor without an increase in the size.

Reactive power variation with supply voltage

With the typically large X/R ratio of the stator, reactive power flow is the main consequence of differences in magnitude between the supply and induced voltages.

A reduction in supply voltage thus leads to a reduction of Q consumption, or an increase in Q generation. For Eo less than 1pu there will initially be a reduction in magnetising current, until the supply voltage is the same as Eo. For Eo about 1pu, a supply voltage reduction will cause the current to increase as the Q generation increases. Higher values of Eo are unlikely, due to the increased braking during start-up.

Eo has a very direct effect on the Q generation. Where other constraints allow, Eo should be chosen to give a suitable reaction of Q to the supply voltage for system in which the motor will operate. In some cases Q generation at rated voltage will be desirable for the system power factor, while in others this is not necessary. It should be borne in mind that any flow of Q means that an extra current in the motor is producing heat but not torque.

The effect of changes to the values of X and R is much dependent upon Eo and the operating load-angle in the particular case. For LS-PMSM 2.2 an increase in R led to an increase in Q production, due to the smaller α and increased δ moving the current phasor further forward than the supply voltage moved forward with δ. Consideration of the simplified phasor diagram (page 26) will show that this is not a universal result! Decreasing X also increased Q production, so in this case the change in load angle was having a greater effect than the change in α.

Protection of the motor

If a load problem causes a loss of synchronism while the supply voltage remains normal, the motor current will be very high and the motor's protection will soon disconnect it. A loss of synchronism caused by low supply voltage would result in less current draw, but still much more than usual (see page 56) unless the voltage collapses almost entirely, at which point the contactor would disconnect the motor anyway.

Protection against sustained overloads is more of a problem than for an IM. Overloads may happen through mechanical overload or reduced supply voltage. As the starting current and time are greater in a LS-PMSM, but the normal running currents are usually lower, the protection needs to operate on small overloads but to endure large surges. This is a harder discrimination task than for an IM. Good documentation is therefore needed about the motor, to allow the selection of appropriate fuse-links or relay settings for the load type.

One good point about the LS-PMSM's constant speed operation is that the cooling fan will remain at its intended efficacy, while an IM will have less cooling available at lower voltages.

When more active power is drawn during a voltage reduction all the extra dissipation is in the stator windings, and with the motor (2.2) used for the simulations the stator power loss more than doubled with a supply drop to 0.75pu. A higher value of Rs will lead to a higher current flow through this higher resistance, giving far more loss. This heightened effect is exacerbated by the considerable increase in resistance that will occur as the winding temperature increases with the extra dissipation.

Repeated starts could heat the rotor enough to weaken the Nd-Fe-B magnets. If there is a need to protect against the situation of excessive numbers of starts, a thermal relay with a long time constant could be used to simulate the rotor temperature. Normal load currents would then need to have no effect on the relay, as they do not heat the rotor considerably. Directly sensing the temperatures in the motor would be a good way to protect it from all thermal overloads, but this would detract from the intended simplicity.

Consumption of harmonic currents is discussed on page 63, and threatens higher losses, in the rotor as well as the stator.

Effects on the load

Supply disturbances will be transmitted more strongly into the load. Likely applications should not be affected by this.

The synchronous operation has an advantage that the load performance will not deteriorate with supply voltage fluctuations. However, if a LS-PMSM has been used to replace an IM directly, the higher speed will mean that more power is put in to the load. If the load is a centrifugal pump, it will have a large increase of power for a small speed change, due to the square characteristic described in the introduction. This higher speed may have the effect that the drive using the new, efficient motor actually has a higher consumption than the original system, even though the higher pump speed is not needed.

The local system

The starting currents can be expected to be higher, longer lasting, and more oscillatory than with an IM. Reductions in supply voltage have more of an effect on starting performance. The transient response to voltage changes is sharper, and can reach higher peaks as the rotor swings.

It can therefore be expected that the presence of LS-PMSMs in place of IMs will increase the voltage fluctuations of the supply when either an LS-PMSM or an IM starts. If some other disturbance occurs such as a fault clearance, the LS-PMSMs will cause increased voltage disturbance by their resultant swinging.

All that can be done to allow for these effects is to ensure that the supply is stiff enough for the voltage sags to be kept within limits for motor starting and for other equipment on the local system. Over-current protection settings may need to be raised to prevent tripping when several LS-PMSMs respond to a voltage fluctuation.

If a group of LS-PMSMs were to be started, or re-started after an interruption, it would be advisable to connect them individually or in small groups. If a large group were connected together, the higher starting currents would reduce the supply voltage, causing further problems from the increased influence of supply voltage reductions on starting ability.

Systems with series inductive reactance in the supply have a much flatter relation between P consumption and voltage, and a higher peak P transfer, when the load contains some Q generation. The presence of a LS-PMSM that can reduce the system's Q consumption, or even generate Q into the supply, will be of great help to a system. The increased generation when voltage is reduced will outweigh even a strong tendency to require more P. Therefore, even if a LS-PMSM draws more current with reduced voltage, the effect on the supply may well be favourable. The LS-PMSM's reaction of Q to voltage change is, then, very desirable and will normally be greater than with an IM, which is always a consumer of Q.

With particularly large voltage reductions, there may be a danger of thermal damage to the LS-PMSM if it remains connected. An adverse effect on the system from the current draw is possible in the case where there is not much parallel lagging load for the Q production to compensate, or where the P consumption is a strong disadvantage. As over-current protection will take a long time to disconnect moderate over-currents, under-voltage protection could be set to disconnect the motor at whatever voltage is considered to give unacceptable behaviour or danger to the motor. Some time-delay would be needed to allow for supply dips caused by fault clearances or motors starting.

The PM field provides a source of emf even when the supply is removed. In a basic system it should be no problem if, on loss of supply to the area containing the PM motor, there is a generated voltage from the PM machine. Because of the starting difficulties of the LS-PMSM, the load is unlikely to have a very high inertia, so will stop quite rapidly anyway. If there were a quite high load inertia and not much electrical load in the rest of the isolated system, the PM machine may remain near their rated speed for more than the required time for isolation of the supply from an earth fault. This isolation requirement may for example occur where sensitive earth-leakage protection is used to protect people against electric shock. The presence of loads connected from phases to neutral, and of breakers on only the phase conductors, would keep the phases ground referenced in spite of the motor's three wire connection, making it impossible to get an instant removal of voltage from the system while the PM machine is running. To solve this problem the PM machine's contactor could be linked to the cut-off, or the machine run on a separate circuit, or shorting of the whole system be effected along with supply isolation.

If an LS-PMSM were used in a situation with plug and socket connections, e.g. a mine or building site using pumps, it may be necessary to take measures to avoid the dangers of a motor being unplugged and a person contacting the pins of its plug. Such a situation is also likely to be one where quick isolation of the supply is required in the event of an earth fault.

The larger system

In the extreme case where a considerable amount of IM load on a system is replaced by LS-PMSMs, several changes may occur in the system's behaviour.

The increased regeneration ability will make the load circuits on bus-bars less passive, and the fault contribution from these circuits could then be important. In industrial areas particularly, a large proportion of the load could be motors (see first chapter).

The increase in active power when the terminal voltage is reduced will be bad for the active power control if 'brown-outs' are used as a method of controlling consumption. The LS-PMSM will make the active power problem even worse than will constant-power loads such as those having voltage regulation. A tap-changing transformer would in this case be helpful to the system during brown-out, by keeping the motor load constant until the final tap is reached. The technique of reducing voltages to control power consumption is not common in Europe, where eventual disconnection is preferred in extreme cases of active power imbalance.

Active power response to frequency may be mildly different between the two motor types. This has not been studied here, but would be a useful subject for investigation. The maintenance of active power balance is determined not just by some generating plant having governors set for response to system frequency, but also by how much the load power falls for a drop in frequency. This latter effect is less well defined, but is relied upon to make up some of the natural control of active power balance. The change in power of a motor will depend on the characteristic of its load, and the electrical behaviour of the motor. A SM can be known to follow the system frequency, while an IM may have a change of slip so its speed will not have to change in proportion to a change in supply frequency. A significant difference in the response to frequency could be important to the system even at the national level if a large amount of IMs were converted to LS-PMSMs.

It must be observed that a normal SM will have the same effect of contributing to faults and staying synchronised through small voltage dips. The important difference is that these SMs will be in use for special applications, while LS-PMSMs could replace many small IMs and take over a significant amount of the installed capacity without an individual machine appearing to have any effect. This potential for insidious integration of large amounts of synchronous plant is the important feature of the LS-PMSM.

Increased harmonic currents

There is good reason to consider that harmonic voltages in the supply will cause a higher harmonic current consumption for an LS-PMSM than for an IM. Motor losses will therefore be greater.

The most important reasons are considered to be the lower reactance and the possible design belief that there is no rotor dissipation during normal running.

Analysis will be needed of new motors to see if they can tolerate the effects of likely harmonic currents. Such analysis was beyond the scope of this project, and would have been specific only to the two LS-PMSMs used herein.

See page 63 for a discussion of possible effects of supply harmonics, and page 35 for the reasons why modelling suitable for harmonic studies was not attempted.

Increased reactive power consumption

There is no basis to suppose that an LS-PMSM will have worse reactive power consumption than an IM, when running on reduced voltage. In fact, an LS-PMSM will almost always perform in a way that is much more helpful to the network. Suitable choice of parameters, particularly the induced voltage (PM field strength) can enhance this effect.

See page 55 for the steady-state reactive power requirements of the representative motors with various parameter ranges and supply voltages, and page 61 for the voltage response to an IM starting of supply systems with different combinations of motors. Page 68 gives a summary of reactive power effects.

For further pursuit

The work of this project could be extended by concentrating on harmonic studies with a range of IM and LS-PMSM designs, to see how big the differences in harmonic impedance are. Much more extensive models and motor data would be needed. Some conclusions may then be found about the LS-PMSM designs best able to survive poor supply quality.

The reaction of active power to supply frequency would have a bearing on the national level of the power system if a large capacity of LS-PMSMs were to develop in place of IMs. Regeneration into a short circuit could also be a matter of importance to the system as concerns fault levels near buses with a high motor load.

6 Appendices

- **Acknowledgements**
- **The Simulink files**
- **References**

Appendix A *acknowledgements....*

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Appendix B *The simulink files*

All the files listed below, together with the complete systems used in the simulations, are on a CD in case further tests or verifications are desired.

Supplies
Constant voltage 3-phase RL supply (constant frequency and phase)
Controlled voltage 3-phase RL supply (constant frequency and phase)
Harmonic voltage generator
Timed switches to give changes in supply and load values

Loads
Quadratic mechanical load
Mechanical speed controller with reference input
Electrical RLC parallel load
Electrical PQ parallel load (RLC load with values defined to give P&Q at specified voltage)

Motors
IM
PMSM
LS-PMSM
All the above, adjusted to suit the simulink power-system blockset
All the above, with parameters of the motors used in the simulations

Metering
3-phase P & Q meter
Polyphase 50Hz true rms meter (could be adjusted in freqency by changing integrator delay)
Three-machine meter block to convert all values of three machines to rms pu, and vectorise
Send parameters from meter block to matrices of time, motors 1, 2, 3 for each parameter
  Display on 'scope the above information
  Display on digital read-out the same information

Appendix C ***References:***

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