Generic optimised torque control of marine PM propulsion machines

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In recent times there has been an increased interest expressed towards the use of advanced power-dense PM (permanent magnet) motors as an alternative to traditional excited synchronous machines in terms of marine power generation and utilisation. This relates specifically to AFM and TFM (axial and transverse flux machines), since they potentially offer a higher torque per unit mass than more traditional technology. Consequently, much design work is being carried out to maximise the power to weight ratio of these machines although, in order to harness their full potential, their control also needs to be optimised. This paper describes a generalised approach to electromagnetic torque control that utilises the motor's magnetic flux characteristic in order to ensure that maximum torque is produced for minimal input power. The method is generalised for any separately-excited synchronous, permanent magnet or reluctance machine, including AFM and TFM. A TFM motor is used to illustrate the performance of this control algorithm and was chosen because of its highly non-linear nature.

INTRODUCTION

In recent years there has been much motor design and control work published with respect to generic electrical machine applications. The overriding thrust for this electric machine and controller research has come about for several reasons, these criteria also being the main driving forces for replacing 'conventional' technologies with electrical technologies:

- It must provide a cost advantage with respect to running and initial capital outlay.
- It must offer a performance advantage in terms of stability and transient response.
- Maintenance must be minimised.
- Ideally the machine and controller must be survivable in the event of a system fault.

The latter requirement is of particular importance for marine applications and especially when considering Naval vessels having a high degree of automation onboard. Increased motor and controller performance coupled with improved reliability, as well as the marine industry's continued demand for improved performance, reliability and environmental impact, has led to the development of highly specialised large marine induction[1] and PM machines[2] for marine propulsion and generation.

The maturity of these technologies has led to further initiatives in terms of the AES (All Electric Ship) concept[3]. The overall power generation and propulsion system in the AES can be sub-divided into four major areas of technology:

- The electric machines, in terms of generation and propulsion.
- The power electronic converters[4] that enable the transfer of power around the distribution system in an efficient and safe manner.
- The distribution system itself including, power protection[5] system.
- The control and automation of the entire power system.

This paper will concentrate on the first area of technology, ie the optimal control of electric machines. Specifically it will describe a generalised optimal torque control strategy, which is applicable to many synchronous machines, ie separately excited, permanent magnet and switched reluctance machines.

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Dr. CD French is presently a lecturer in Marine Electro-Technology within The Department of Marine Technology at Newcastle University. He has been involved in both commercial and academic research of electrical power systems for a number of years. His main interests include real-time control of advanced electric machines for vessel propulsion and generation systems, as well as a strong interest in Marine Renewable Energy Technologies.

The scheme is designed to always maximise the torque:current ratio, and has previously been proved to be effective through extensive simulation and experimental evaluation[7]. In terms of recent developments more emphasis is placed on multi-pole direct-drive permanent magnet machines used for propulsion, although the control scheme is equally applicable to generation systems. The approach is illustrated with the aid of a propulsion case study using a Transverse Flux Motor model. The motor is a star connected three-phase machine, although it will be shown that the presented techniques are not limited to this configuration.

Torque estimation

The general equations for a PM machine can be written as;

$$V_x = i_x R + \frac{d\Psi_x}{dt} \tag{1}$$

$$\Psi_x = Li_x + Mi_y + Mi_z + \lambda_x(\theta_x) \tag{2}$$

where the subscript x refers to the phase, and in considering a three-phase system y and z refer to the other two phases. R is the phase resistance. I and $d\Psi/dt$ are the resulting stator phase current and the open-circuit back-emf that results from the application of stator voltage V, and where the back-emf is a function of the rate of change of flux-linkage, Ψ_X. Equation 2 describes the flux-linkage with respect to phase self and mutual inductance, L and M respectively; together with the magnetic flux-linkage λ, which in turn is a function of phase position. It can be shown that in a balanced three-phase system that the effects of mutual inductance cancel out[5], thus equation 2 can be simplified;

$$\Psi_x = Li_x + \lambda_x(\theta_x) \tag{3}$$

Thus, flux-linkage is a function of phase current and position. Substituting equation. 3 into equation. 1;

$$V_x = i_x R + L_x \frac{di_x}{dt} + \frac{d\lambda_x(\theta_x)}{dt} \tag{4}$$

$$\therefore V_x = i_x R + L_x \frac{di_x}{dt} + E_x$$

where E_X is the open circuit back-emf voltage, whose instantaneous magnitude is a function of rotor speed and position. If the second term, which represents the effects of self-inductance, is neglected, then in order to calculate the rms torque equation 4 can be considered as an energy balance equation;

$$P_x = i_x^2.R + i_x.E_x \tag{5}$$

The first power term refers to stator losses and the second power term to the electromagnetic torque-producing component. Thus;

$$T_x = \frac{P_x}{\omega} = \frac{i_x.E_x}{\omega} \tag{6}$$

Since the calculation is to be rms based, then the back-emf is a linear function, K, of rotor speed, ω thus;

$$\therefore T_x = \frac{i_x.K_T.\omega}{\omega} = i_x.K_T \tag{7}$$

where x represents the phase number, i, T and E are the stator phase current, phase torque and back-emf respectively. Thus it can be seen that if the above assumptions are made then the phase torque can be easily found independently of rotor speed. This method of electromagnetic torque estimation is very simple to implement, since the motor controller only needs to consider the motor to be a linear torque producer.

Traditionally, the torque produced by a synchronous electrical machine can be controlled by regulating the armature current with respect to the field current. In the case of permanently excited machines, such as a TFM or AFM this would imply that the electromagnetic shaft torque would be a function of the stator current, equation 7.

The relationship between the applied stator current and the resulting shaft torque can thus be assumed to be linear, if the self inductance of the stator windings is neglected. Therefore, if the rms current and back-emf of the motor are known, equation 8 can be used to ascertain the rms shaft torque produced by each phase of the machine. The same equation can be expanded to produce the instantaneous phase torque;

$$T_x(\theta) = \frac{P_x(\theta)}{\omega} = \frac{i_x(\theta).E_x(\theta)}{\omega} \tag{8}$$

This method is a widely accepted way of predicting a machines electromagnetic torque, although the assumptions made make it only valid for certain operating parameters, that is, where the change

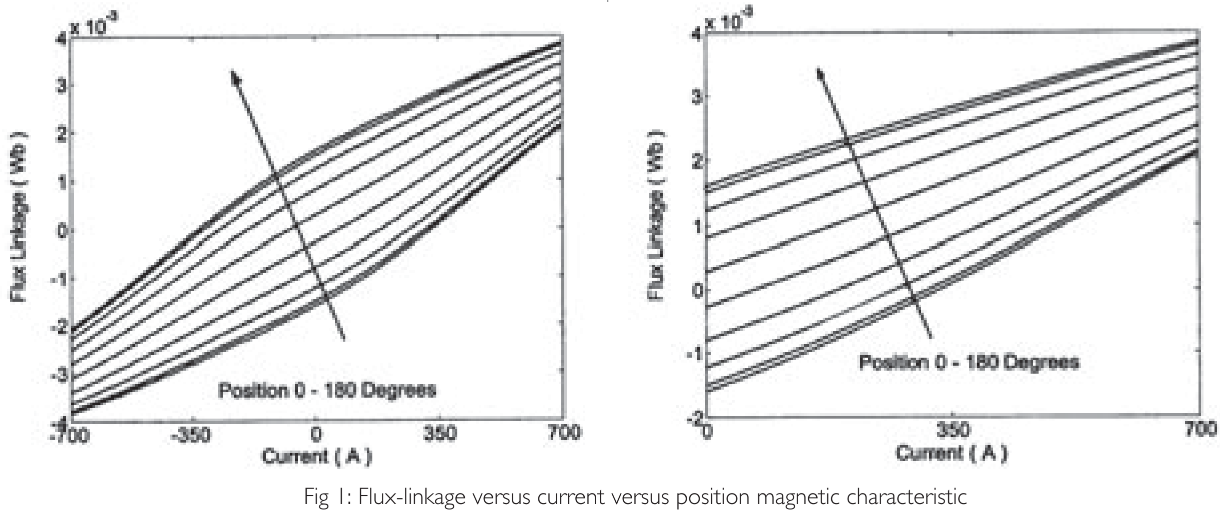

Fig 1: Flux-linkage versus current versus position magnetic characteristic

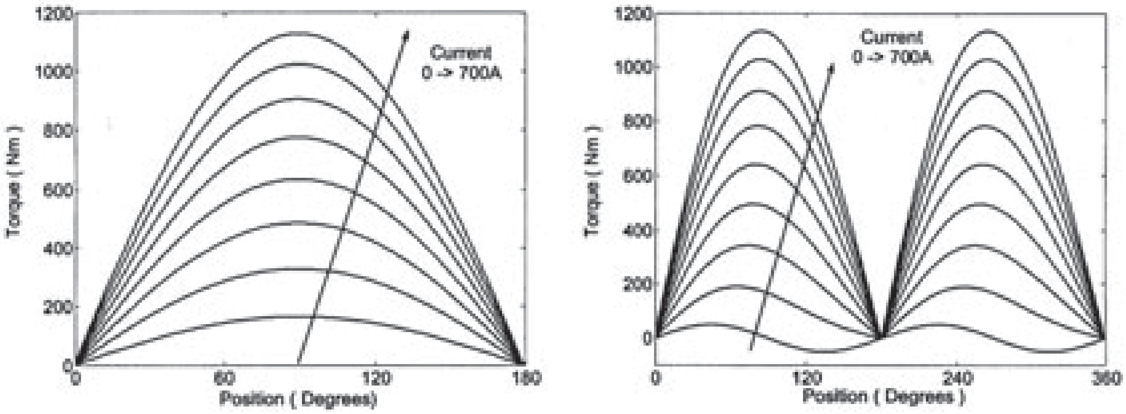

Fig 2: Torque versus position versus current characteristic

of inductance with respect to position and current is zero, or at least minimal. In the past, with only simple controller technology available, this situation has influenced the design of electric machines, for example machines with relatively large magnetic circuits were developed so that the effects of magnetic saturation can be neglected. Ideally this scheme does not produce any torque ripple, but to sub-optimal alignment of magnets, non-uniformity of magnetic material and current controller limitations this is not always so. Thus they are not optimised in terms of cost and their power:weight ratio.

Fig 1 shows the phase flux-linkage versus applied current characteristic of a TFM with respect to position, this was obtained from locked rotor tests of the Rolls-Royce TFM representative machine[2]. The slope of each flux-linkage curve represents the phase self-inductance and, as can be seen, the relationship is far from linear, thus the assumptions made in the above equations are not valid.

If the motor is to produce ripple-free shaft torque then the mechanics of torque production must be fully considered. There are three methods of electromagnetic torque production within such a machine:

- Reluctance torque is produced in machines where the self-inductance of the stator winding changes significantly with position, ie where the magnetic field produced by the phase currents is a function of position.
- Cogging torque is produced in PM machines containing slots and it is due to the magnet flux seeking a minimum reluctance path[7].
- Alignment torque is produced by the mutual coupling between the rotor magnetic and the stator winding magnetic field.

$$W_0' = \int_0^{i} \Psi di => T = \frac{\Delta W_0'}{\Delta \theta} \quad (9)$$

A more generic approach is to derive the phase torque with respect to position and current directly from this practical characteristic. This can be achieved by first calculating the co-energy with respect to current and position; this represents the amount of energy being transferred, as shown in equation 9.

From the co-energy characteristic it is thus possible to derive the torque versus position versus current characteristic[6]. Fig 2a shows this relationship developed from the flux-linkage relationship of Fig 1 for a single pole of the machine. Figure 2a takes account of alignment and reluctance torques; it is possible to acquire this information required from motor static locked rotor tests. For many machines this would be sufficient, but for a TFM the effects of cogging torque are significant[2], thus the zero current component needs to be added to the characteristic, Fig 2b illustrates this.

Fig 3 shows how this technique can be further developed to include the non-linear region of the flux-linkage characteristic, ie, where the effects of magnetic saturation become dominate. As can be seen from Fig 3, the resulting characteristic is highly non-linear with respect to current and position.

Conventional torque control

The conventional method of torque control is to compare a demand with an estimate or measurement of output torque and thus derive an error that can drive the control system. As already discussed, the first method relies on the fact that the phase current

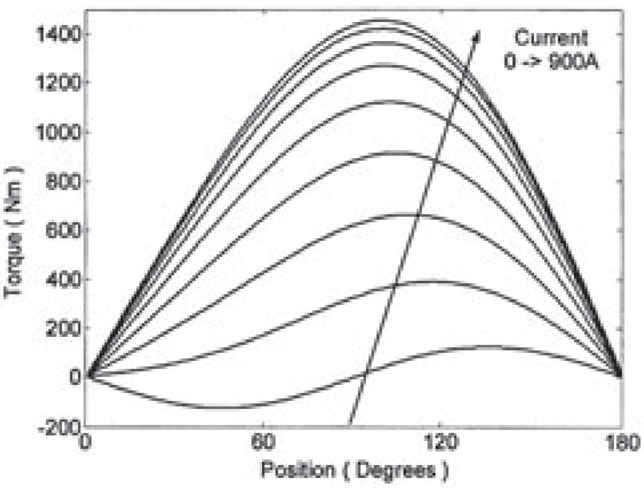

Fig 3: Torque versus position versus current characteristic including saturation effects

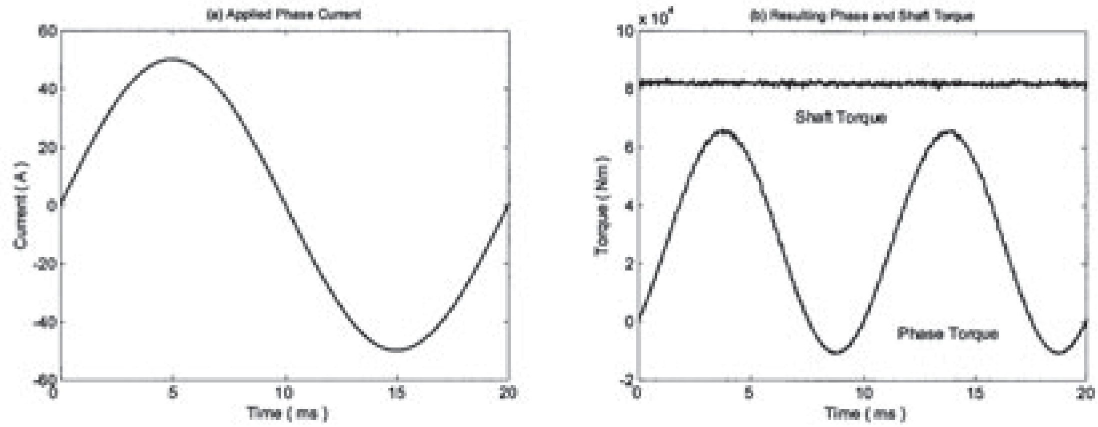

Fig 4: Cogging torque: applied phase current, and resulting phase and shaft torque

is proportional torque, thus the assumption made is that current flowing in the windings directly represents the torque being produced by the machine. This is a linear interpretation, although it is possible to use a lookup table to model the effects of saturation, and without complex compensation algorithms it can only account for alignment torque. Shaft torque feedback is usually based upon utilising a torque measurement transducer. If a torque transducer is used it is generally possible to get all the torque information with sufficient bandwidth, typically 20kHz, the system could operate well but would add cost and decrease system reliability.

The first method is the most popular, since if a machine with sufficient tolerance is constructed then the system could perform well, ie, the normal operating region exhibits no or little effects of saturation, reluctance torque or cogging torque. The classic illustration of these is the widespread use of field-orientated controllers for induction and synchronous machines[8]. The following figures illustrate the consequence of using this strategy throughout the operating regions of the example TFM.

Fig 4 shows the performance of the system at low currents, ie in the region where cogging torque dominates the torque production process. Fig 4a shows the applied sinusoidal current and Fig 4b shows the resulting phase torque and shaft torque, that is, the electromagnetic torque being produced by the alignment torque is swamped out in magnitude by the cogging torque. Notice the instantaneous negative torque produced by the phase torque, this implies that in order for the phase to generate a net zero torque, there will need to be a stator winding current.

Fig 5 shows how the relationship operates between the phase current and torque at medium current levels. It is noticeable in this particular machine that the cogging torque still swamps out the alignment torque at certain points in the operating cycle, ie at low current levels present at the zero crossings, this implies that the cogging torque is slightly out of phase with the electrical cycle.

Fig 6 shows how the motor responds when it starts to operate in the region of magnetic saturation. The torque produced by the machine is no longer a linear function of current, to the point that some points are so saturated that a torque ripple on the shaft is now present.

It can, therefore, be seen that the conventional method of torque estimation would appear to be sufficient during the non-saturated regions, with respect to shaft electromagnetic torque, although when closer inspection is given – ie the relationship between the phase current and its resulting electromagnetic torque production – the method is not valid.

Thus the requirements of the control scheme would appear to dominate the design requirements of the motor itself. If issues of size and weight are not a problem, then this may be acceptable if the economics are convincing. However, within the marine industry these over-designed technologies result in larger

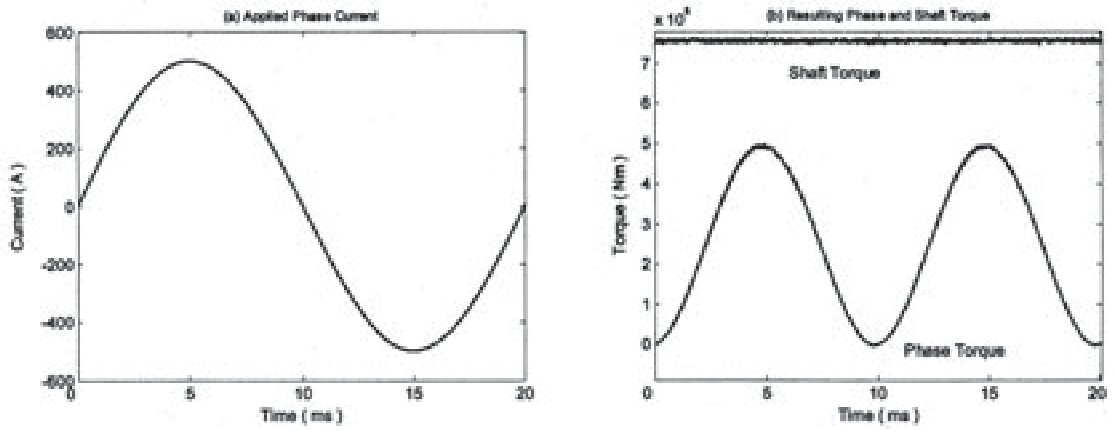

Fig 5: Linear torque region: applied phase current, and resulting phase and shaft torque

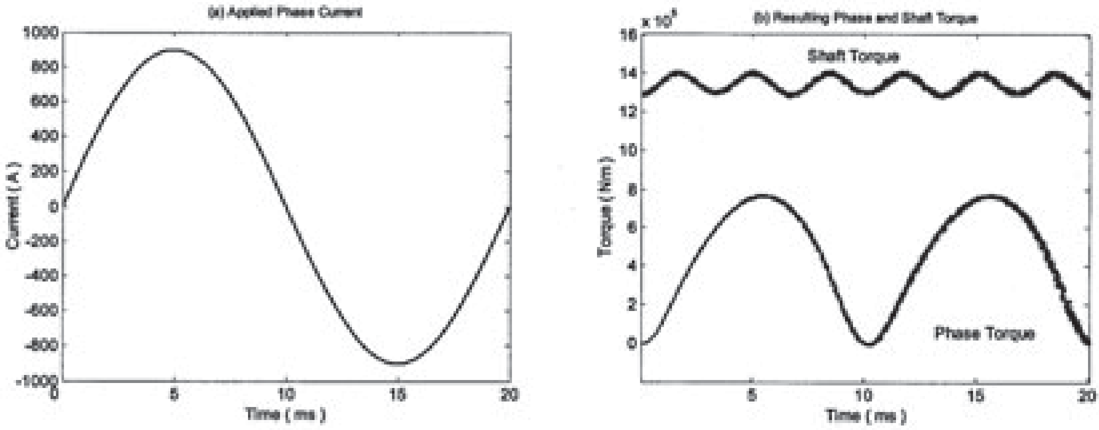

Fig 6: Saturated torque region: applied phase current, and resulting phase and shaft torque

machines, in terms of size and weight, than are optimally possible.

The advantage of using the described method of torque estimation is that no assumption is made about the machine's electromagnetic characteristics, therefore it can account for variations in mechanical and electromagnetic tolerances within the machine, ie the motor can be controlled within its true capabilities and not what the controller assumes it can do.

The method of torque estimation described will thus be able to track accurately the electromagnetic torque produced by the machine, even when operating in a highly non-linear manner. This premise becomes even more important when it is considered that direct-drive electric marine propulsion systems will, in order to achieve low rotational speed, require a large number of electromagnetic poles. Achieving the electromagnetic and mechanical tolerances in order to allow the conventional method of torque control will inevitably lead to machines with large magnetic circuits and high-tolerance engineering technologies.

Generic optimised torque control algorithm

Although if the above electromagnetic torque estimation method was used in conjunction with a conventional feedback loop a more accurate torque control system would result, it can be improved upon. Consider the situation illustrated in Fig 4, where the cogging torque swamps the alignment torque and yields areas where there is a negative shaft torque produced. Generally, it is not desirable for any of the phases to be producing negative torque. Also the system does not guarantee that the machine is being used in the most efficient manner, ie that the ratio between the torque produced and the stator I^2R losses is maximised.

The following algorithm[6] uses this generalised torque estimation scheme to generate instantaneous motor current demands, that are optimised in terms of the torque:current ratio. This implies that the performance is optimised, but also the losses will be minimised.

The optimised direct torque control algorithm shown in Fig 7 is designed to optimise the machines performance, by realising the true capabilities of the motor and matching them to the capabilities of power controller. In order to maximise the performance, the ratio between torque and current is maximised, thus the maximum torque for a given current is realised and also the I^2R stator losses are thus minimised, see equation 10. This is achieved by the application of the torque versus position versus current characteristic, ie, by the application of the motor's true characteristics, thus, the method does not have any preconception of the current waveform shape, it is calculated in an optimal manner. Note, that if this direct torque scheme is applied to a machine with a sinusoidal emf profile, in the linear operating region the current waveform will indeed be a sinusoid[9]; and similarly, a machine with a trapezoidal profile would yield the expected 120° current shape.

The first significant feature of the algorithm to note is the lack of a conventional feedback loop. The algorithm directly regulates the torque by a predictive, or feed forward, method using the machine's torque versus position versus current characteristic. The torque characteristic is calculated at start-up from the flux-linkage versus current versus position characteristic, via the co-energy characteristic.

The optimised control system consists of five distinct stages, where the first two determine the optimal current profiles and the

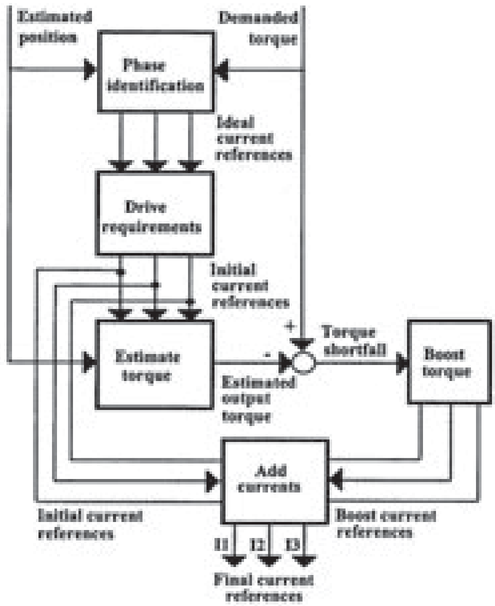

Fig 7: Optimised direct torque algorithm

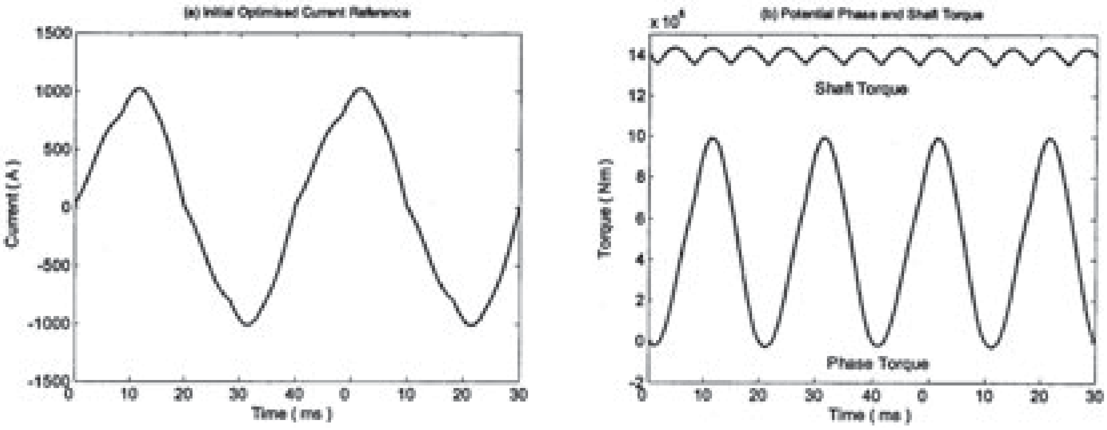

Fig 8: Initial current reference — Optimised current waveform generation and potential torque production

remaining three take account of machine and drive limitations. The following sections explain the overall operation of the algorithm, stage by stage:

Stage 1 - Phase identification. Using the torque characteristic together with the measured rotor position and phase current the torque-producing weighting factor for each phase is determined. This factor is found by comparing the torque-producing capabilities of each phase with respect to the copper losses[8]. Therefore the weighting factor can be expressed as;

$$T(\theta, i) / i^2R \qquad (10)$$

Stage 2 – Ideal reference generation. Using the torque weightings, the algorithm then divides up the demanded torque into the percentage weightings for each phase. The optimal current references are then obtained by applying the individual phase torque demands and the position information to the torque characterisation table. This results in the phases with the highest torque-producing capabilities providing more torque then the lower phases, although phases with lower torque capabilities may well produce torque so that the overall losses can be minimised while still achieving the demanded torque.

Stage 3 – Motor and drive realities are taken into account by determining the limitation of the system and modifying the current waveforms from stage 2. The two major limitations modelled are current limit and the limitations of a finite dc-link voltage. The first is mainly a thermal limit from within the drive and the motor, so with appropriate modelling this too could be improved[10]. The second effect limits the rate of change of current, which in turn can be determined by phase inductance.

Stage 4 – Boost torque demand. By using the torque estimation algorithm of the last section and applying the modified current references, a measurement of what the torque shortfall will be if these references were applied to the machine can be obtained. This torque shortfall would essentially be the torque ripple.

Stage 5 – Optimal current demands The boost reference currents are added to the initial current references to produce the final optimised references. These currents can then be applied to the drive's current controller. Note that the final references are also checked to see if they are achievable by the next sampling interval, in terms of using the limits generated in the third stage.

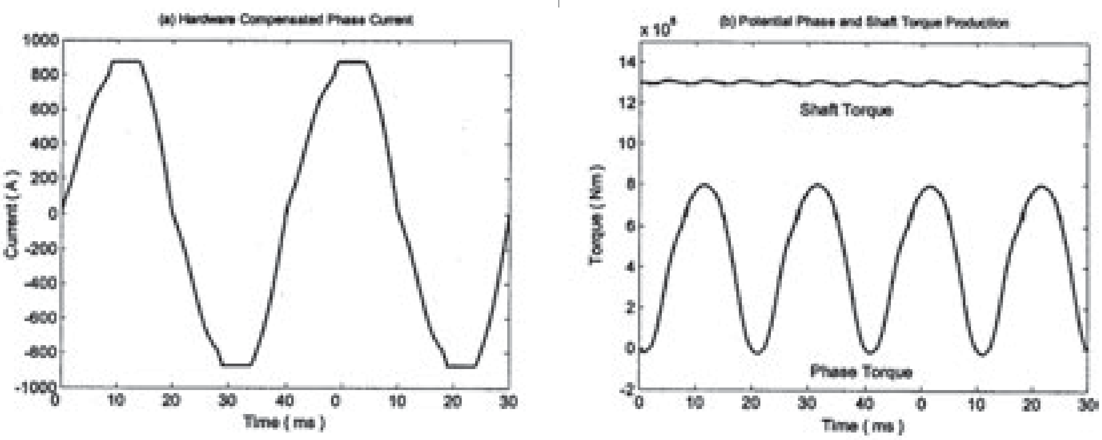

Fig 9: System reality compensation — Optimised current waveform generation and potential torque production

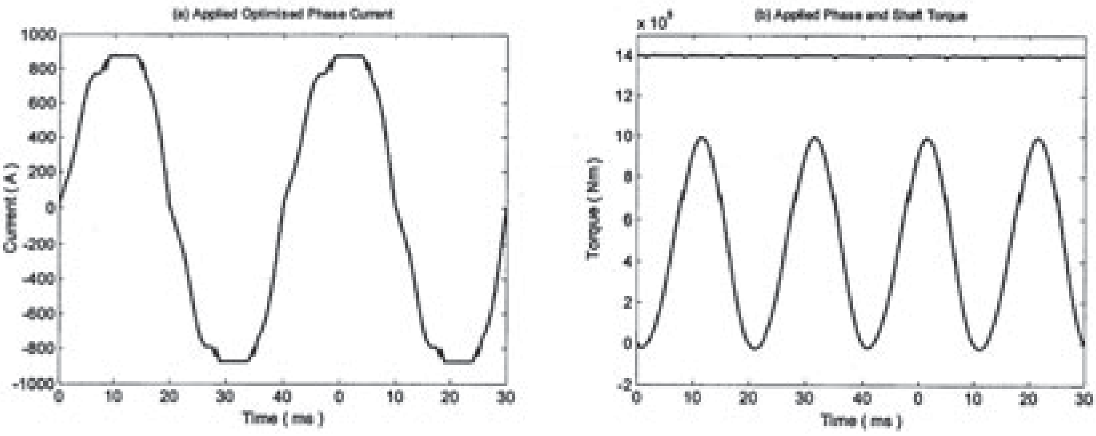

Fig 10: Applied current references — Optimised current waveform generation and potential torque production

Optimised torque control of a TFM

By way of illustration of this method of torque control, the example TFM is now considered. A torque demand of 1.4MNm is demanded from the machine. Note that if the upper saturation region of this machine's characteristic were ignored, ie torque control in the linear region only, then the machine would be limited 1.2MNm, see Fig 6b.

The two algorithm stages of phase identification and initial current waveform generation are shown in Fig 8. Fig 8a, shows the phase current waveform shape, as can be seen this far from sinusoidal, although the waveform shape is optimised in terms of its torque:current ratio with respect to position. Fig 8b shows the phase and shaft torque that would result if this waveform shape was demanded from the motor and, as can be seen, the result would be a torque ripple due to the operation of the motor in the saturation region.

The effect of the third stage is illustrated in Fig 9. That is, the system realties are taken into account, in this particular case the maximum current that the power controller can supply to the motor is 900A, as can be seen from Fig 8a, the initial current references implied a peak demand of just over 1000A. Fig 9b shows how the peak capping of the current affects both the phase torque waveform shape and the resulting shaft torque, if these currents were applied to the motor.

Fig 10 illustrates the last two algorithm stages, ie the boost phase and the production of the final current demand that will be actually demanded from the motor. The adjusted currents from the last stage are used to estimate what the potential torque would be, and compared with the actual demanded torque, which results in a torque shortfall; this is manifested in the torque ripple in Fig 9b. The torque production ratios calculated in the first stage are then used to make up for the torque shortfall, ie the phases that have not been current limited. This results in the final current demands shown in Fig 10a, which are far from sinusoidal, and the resulting phase and shaft torque are shown in Fig 10b. Note that due to this technique it is possible to accurately control the motor well into the saturation region, an area which would have been avoided with conventional control methods. This has resulted in a 16% increase in the potential operating region of the machine, the main restriction now being thermal performance.

Advanced control strategies

As can be seen this method allows the electromagnetic shaft torque to be accurately controlled to within the tolerances of the machine, the power controller and the supply regardless of whether the machine is working in it linear or non-linear magnetic region of operation. Consequently up further possibilities for more advanced control techniques are opened up.

Generally, synchronous machines require position information to regulate the phase currents in the correct manner. The algorithm described is no exception to that, although since the system utilises flux-linkage versus current versus position characteristic, it is possible to use the same data to produce a rotor position estimation signal[11].

- One application of this technique would be, if a position sensor was used, to provide a continual update to the flux-linkage data table as the machine operates. Thus the real magnetic characteristics of the machine could be continually monitored and modified, so that the controller can operate optimally under all conditions and throughout the machine's lifetime.
- The information given by the estimated rotor position signal could also be used to back up the physical sensing system, in order to provide position information under fault conditions. It could also be used to improve the accuracy of the data provided by the position sensor.

One further illustration of advanced control scenarios that become possible with this technique is that it could be used in conjunction with a mechanical torque observer system[12] to compensate for static and transient mechanical torques imposed on the shaft of the machine to the extent that overall torque control of the machine could be placed in the frequency domain, possibly allowing the control of shaft vibrations also to be compensated for. Fig 11 shows the performance of the algorithm when a frequency component of 250Hz with a magnitude of 300kNm on top of a steady-state demand of 900kNm is demanded. Fig 11a represents the optimised current waveform for this particular situation; note that the current is limited by the converter's internal 900A limit during some points in the cycle. Fig 11b shows the torque performance in terms of electromagnetic phase and shaft production. Clearly, one of the limiting

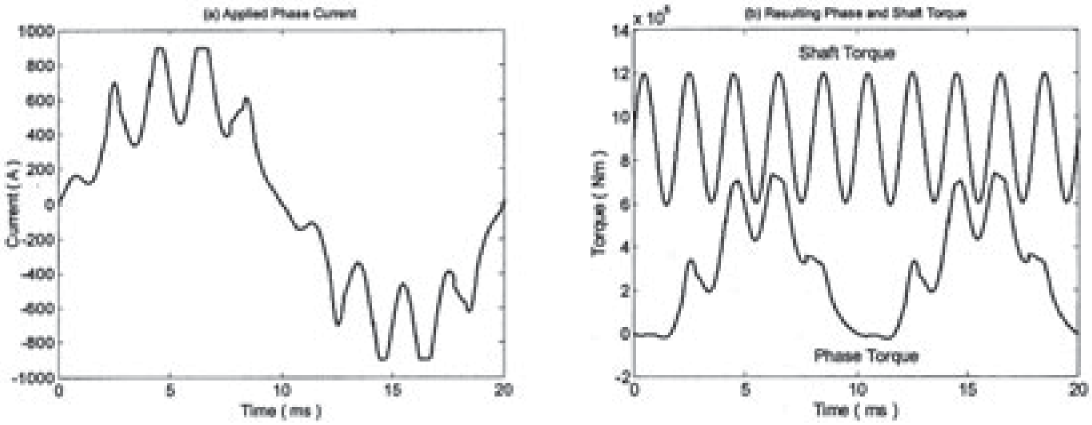

Fig 11: Variable torque demand — Optimised current waveform generation and potential torque production

factors of implementing such a frequency control strategy is the high performance requirements of the converter, ideally a high switching frequency will be required in order to meet the transient current demands. Although with the continued rapid development of modern power electronics, this practical limit for large power systems will continue to increase. If this frequency-domain control approach is taken further, it may be possible to directly control the acoustic transmission of power down the shaft and onto the propeller of the vessel.

CONCLUSIONS

This paper has described a generic method of torque estimation that is valid for most types of synchronous machines. It has shown, through illustration of an example of a highly non-linear three-phase TFM, how conventional methods of torque control would not be able to extract the full potential of such a machine. The optimised direct torque control scheme described will ensure that the maximum amount of torque is produced for the minimum amount of current for a given machine throughout its operational region. It has also been shown how the operational region can be expanded, to such an extent that the full capabilities of both the electric machine and power converter, with respect to the power supply, can be exploited. The key characteristic of the technique is that no assumptions are made about the electromagnetic torque production capabilities of the motor thus ensuring that the power:weight ratio of machine can be fully optimised both at the design and operational stages of the machine's lifetime.

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