Instantaneous Power Control - an Alternative to Vector and Direct Torque Control?

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Abstract— **This paper presents a new algorithm for the control of AC machines based on the concept of controlling the instantaneous real and imaginary power. This strategy, called Instantaneous Power Control (IPC), allows decoupled control of the torque and flux in the machine.**

This paper outlines the basic algorithm and then presents simulation results of its performance.

I. Introduction

FIELD Oriented Control (FOC) has been developed and refined since the early 1970s to obtain high performance control of AC machines. Most of the work has concentrated on the induction machine. Approximately 10 years ago the concept of direct torque control (DTC) was invented [1], and this technique has also been refined and developed, and is now being applied to a variety of different AC machines. Both these techniques have their strengths and weaknesses, which we shall briefly examine in order to place the technique presented in this paper in context.

The FOC technique, as the name implies, relies intimately on accurate knowledge of the spatial position of the flux space vector in the machine. The control technique is based on decoupling the flux and torque axes of the machine by transforming the machine variables to a rotating reference frame aligned with the flux vector. One can align with the rotor flux, stator flux or magnetising flux vectors using either direct or indirect FOC. Since it is undesirable or impractical to directly measure the flux position, it is generally estimated using machine terminal measurements, coupled with knowledge of some of the machine's parameters. For example, in indirect FOC the rotor time constant is crucial in obtaining the flux position. Similarly, for direct FOC an accurate flux model of the machine is required. Over the last 15 years, much of the research in FOC has concentrated on developing robust on-line parameter identification techniques capable of identifying the required parameters so that high performance can be maintained, despite parameter variations and uncertainty.

The rotating frame principle of the FOC strategies imply that all the measured parameters have to be converted to and from a three phase stationary reference frame to a two phase rotating frame. These coordinate transformations involve sine and cosine functions.[1] The outputs from FOC are the reference currents. These are then passed to a current controller which usually uses a current regulated PWM or current hysteresis technique to impose the desired currents on the machine.

Whilst commercial FOCs have been available for a number of years, the performance of this control strategy is still compromised, to some degree, by the requirement for accurate estimates of parameters in the machine. The requirement for a parameter estimator coupled with the coordinate transformations results in a fairly complex algorithm.

DTC, in contrast to FOC, is a control strategy that operates in a stationary reference frame. Its other main distinguishing feature is that it is not as reliant on knowledge of machine parameters. The position and magnitude of the machine flux is estimated using knowledge of the terminal voltage integral. Using a table of switching vectors versus flux and torque outcomes, DTC chooses an inverter voltage vector to vary the torque and flux in the desired manner. Note that there is no explicit current controller or PWM generator in this scheme. The PWM generation occurs implicitly as the inverter vectors are chosen, and the current is implied via the resultant switching pattern. Whilst this leads to simplicity many implementations work on a hysteresis principle and consequently the inverter switching rate is uncontrolled.[2] Techniques have been developed to overcome this problem, but at the expense of parameter dependence [2]. It should be noted that the use of voltage to estimate flux means that DTC performance deteriorates in very low speed applications, and it is not suitable for zero and low speed operation.

This paper proposes a new alternative drive control technique to the two outlined above, known as instantaneous power control (IPC). It is based on control of instantaneous real and imaginary power into the machine. It is motivated by the fact that real power (ignoring losses) controls the torque produced by the machine, and the imaginary power controls the flux. The technique has some characteristics similar to DTC, namely that it requires voltages, operates in a stationary reference frame,

[1] These transformations are usually achieved using look-up tables.

[2] It is possible to have a constant switching frequency with large excursions of the current and torque.

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and is simple to implement. The outputs of IPC are two reference currents which are then passed to a predictive current controller (PCC) [3, 4]. The PCC has an integrated symmetric switching PWM generator, therefore the switching frequency is a user specified constant, and the current harmonics are well defined and minimised. The IPC technique appears to be suitable for medium performance drives systems which do not require zero or low speed operation.

The concept of power control was applied to reactive power compensator applications some 15 years ago [5]. However, the use of similar techniques in electrical machine control applications is *new*. IPC intimately depends on the underlying PCC for back emf voltage estimates. It should also be noted that the IPC technique can be used for the control of PWM rectifiers and photovoltaic interfaces, but these tend to be simpler applications and will not be considered further in this paper.

The remainder of this abstract will develop the basic expressions for IPC, show the structure of a drive system based on the technique, and present simulation results to demonstrate the performance.

II. ALGORITHM BASICS

The IPC algorithm has three main components – the power reference generator (PRG), the current reference generator (CRG) and the PCC. We shall look at each of these, starting with the CRG firstly.

The CRG, as the name implies, accepts as inputs the required instantaneous real and imaginary powers, and then generates the required currents for the PCC. This is achieved essentially using the inverse of the complex power expression.

Assuming that the voltage vector is used as the reference for the determination of leading and lagging, we can write the complex power expression for a machine in space vector notation as:

$$\underline{S} = \underline{i}\,\underline{v}^* \tag{1}$$

which can be written in two phase stationary frame variables as:

$$\underline{S} = [i_{\alpha\beta}][v_{\alpha\beta}]^* \tag{2}$$

where:

$$[i_{\alpha\beta}] = i_\alpha + j i_\beta$$
$$[v_{\alpha\beta}]^* = v_\alpha - j v_\beta$$

Expanding (2) we get the expressions for the instantaneous real and imaginary power as defined in [5]:

$$\underline{S} = v_\alpha i_\alpha + v_\beta i_\beta + j(v_\alpha i_\beta - v_\beta i_\alpha) \tag{3}$$

Therefore:

$$P = v_\alpha i_\alpha + v_\beta i_\beta \tag{4}$$
$$Q = v_\alpha i_\beta - v_\beta i_\alpha \tag{5}$$

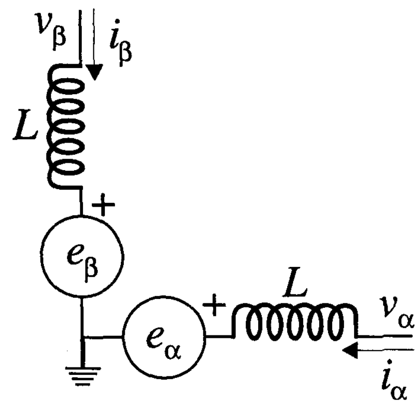

Fig. 1. Two phase representation of an induction machine.

where P is the instantaneous real power, and Q is the instantaneous imaginary power.

It is well known that an induction machine can be modelled as a voltage behind a total leakage inductance when driven by an inverter [6]. Therefore, after a three to two phase power variant transformation, the induction machine model becomes that of Figure 1. The voltages relevant to the power absorbed by the machine are the back emf voltages, e_α and e_β. These voltages are related to the flux and electrical frequency applied to the machine. Therefore (4) and (5) are:

$$P = e_\alpha i_\alpha + e_\beta i_\beta \tag{6}$$
$$Q = e_\alpha i_\beta - e_\beta i_\alpha \tag{7}$$

The instantaneous real power P is effectively the real power being consumed in the slip modified rotor resistance of the machine – i.e. R_r/s, (ignoring the losses in iron and the stator resistance), plus any power stored in the field. The imaginary power, Q, is related to the *instantaneous* rate of magnitude change or vector acceleration of the flux vector in the machine.[3] In steady state Q becomes equal to the conventional reactive power in a machine.

If one controls P, and the flux in the machine is constant, then one is approximately controlling the torque produced by the machine, as $P \approx \tau\omega_m$, where $\tau \triangleq$ the electromagnetic torque, and $\omega_m \triangleq$ the shaft angular velocity.[4] Similarly the imaginary power controls the flux in the machine. This can be seen from the space vector diagram of Figure 2. Considering the system to be in steady state the real power is ei_p and the imaginary power is ei_{mr}. These expressions are also valid in transient states (this is a property of two and three phase systems – see [5]). Clearly the i_{mr} current component is in phase with the flux vector of the machine, and therefore its magnitude controls the flux magnitude.

[3] In an electrical machine the instantaneous imaginary power is the space vector current component coincident to the flux vector multiplied by the voltage vector magnitude.

[4] As we shall see this approximation for the real power needs some compensation added in order to achieve satisfactory performance.

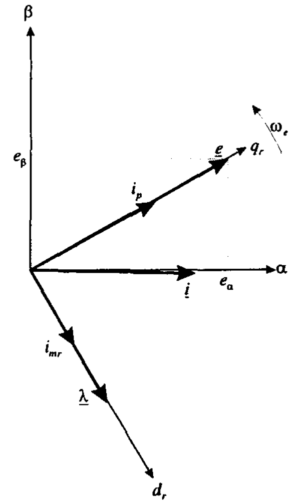

Fig. 2. Approximate vector diagram of a machine

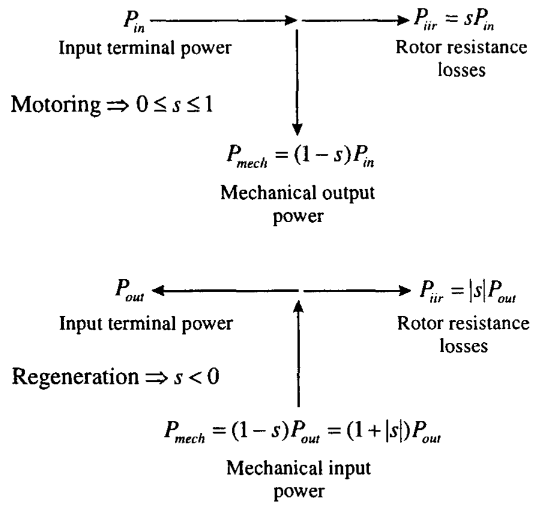

Fig. 3. Power flows in an induction machine under motoring and regeneration

If we supply a reference instantaneous real power, P_{ref}, and a reference instantaneous imaginary power, Q_{ref}, together with the back emf voltages e_α and e_β, then we can solve simultaneously for the currents in the machine that will give the desired powers. From (4) and (5) we can get:

$$i_{\alpha_{\text{ref}}} = \frac{e_\alpha P_{\text{ref}} - e_\beta Q_{\text{ref}}}{e_\alpha^2 + e_\beta^2} \tag{8}$$

$$i_{\beta_{\text{ref}}} = \frac{e_\beta P_{\text{ref}} + e_\alpha Q_{\text{ref}}}{e_\alpha^2 + e_\beta^2} \tag{9}$$

As mentioned previously the voltages e_α and e_β are not normally available.[5] However, the PCC estimates the back emf voltages as part of its normal operation.[6] It is these estimated values that are used in (8) and (9).[7]

The $i_{\alpha_{\text{ref}}}$ and $i_{\beta_{\text{ref}}}$ reference currents are then fed to the PCC which generates the firing times for the inverter legs to drive the currents in the machine to the desired currents.

A. Power Reference Generation

The first of the key components of the algorithm mentioned previously was the PRG. Oddly, this turns out to be the part of the algorithm that is dependent on knowledge of parameters.

Of the two references the easiest one to generate is the real power reference, since this is directly connected to the torque one wishes to produce from the machine. However, even with the real power reference there are a few traps one can easily fall into.

The most obvious way to generate the real power one desires from the machine is:

$$P_{\text{ref}} = \tau_{\text{ref}}\omega_m \tag{10}$$

where τ_{ref} is supplied from some outer loop such as a speed control loop, and ω_m is the actual mechanical shaft speed at a particular instant of time.

Equation (10) works to some extent, but it gives values of real power which are insufficient to generate the torque τ_{ref}. This is due to the fact that not all the real power at the input to the machine contributes to the production of output power. Clearly some power is lost in the stator resistance and iron losses of the machine. However, in addition to this there is a significant amount of power that is lost in the rotor resistance. In fact the power lost here is dependent on the slip of the machine. Whilst we can assume that the stator resistance power and the iron losses can be ignored (under many practical situations), the power in the rotor resistance cannot be ignored, especially under heavy load conditions when the slip of the machine can be large.

An approximation of the power flows under motoring and regeneration for an induction machine[8] are shown in Figure 3. As can be seen from this diagram, under the motoring condition the input power divides into two, some of it going into the rotor resistance losses (depending on the degree of slip), and some of it going into the shaft mechanical power.

Similarly, under regeneration the input mechanical shaft power divides between the rotor resistance losses and power being fed back into the supply.

Both the motoring and regeneration cases indicate that the shaft power can be significantly different from the terminal power. For example, when regenerating the slip s can have an arbitrary value for a given desired terminal output power, meaning that the rotor resistance losses can be extremely large.

[5] In PWM rectifier and photovoltaic applications these voltages are associated with the connected grid and therefore can be measured.

[6] Note that the PCC only requires knowledge of the leakage inductance of the machine.

[7] The fact that $e_\alpha^2 + e_\beta^2$ are in the denominator of (8) and (9) mean that these expressions cannot be calculated when these voltages are zero or very near zero.

[8] We are ignoring the stator resistance and iron losses in Figure 3.

The losses in the rotor resistance are being supplied from extra input mechanical power. Consequently the regenerative torque on the shaft of the machine can be significantly larger than the desired torque. It should be noted that this situation does not occur if both the real and imaginary powers are being controlled, since this implicitly places a limit on the slip in the machine.[9]

To make the shaft power equal to the desired shaft power we must compensate for the power that is being diverted away from the shaft. This implicitly means that we must have some knowledge of the slip of the machine. Assuming for the moment that we do know the slip then we can compensate the power expressions as follows for the motoring/regenerating situation:

$$P_{\text{ref}} = \frac{P_{\text{shaft}}}{1-s} = \frac{\tau_{\text{ref}}\omega_m}{1-s} \tag{11}$$

where P_{shaft} is the desired shaft power, and P_{ref} is the terminal reference power as defined previously.

To generate the slip for compensation we firstly need to consider the imaginary power reference generation, as the two are related.

Consider Figure 2 which shows an approximate vector diagram of the voltages, currents and fluxes of an induction machine. We know that the imaginary power is the back emf voltage in one axis of the machine multiplied by the current in the other axis. If the axes are d_r, q_r in Figure 2 we can write:

$$|Q| = i_{mr}e \tag{12}$$

$$= i_{mr}\omega_e\lambda_m \tag{13}$$

where λ_m is the flux magnitude, i_{mr} is the magnetising current, and ω_e is the applied electrical frequency.

Rearranging (13) one can write:

$$\omega_{sl_{\text{ref}}} = \frac{-|Q_{\text{ref}}|}{i_{mr_{\text{ref}}}\lambda_{m_{\text{ref}}}} - \omega_r \tag{14}$$

realising that:

$$\begin{aligned}
\omega_e &= \omega_r + \omega_{sl} \\
\omega_r &= p_p\omega_m \\
\omega_{sl_{\text{ref}}} &\triangleq \text{the desired slip frequency} \\
|Q_{\text{ref}}| &\triangleq \text{the desired imaginary power} \\
i_{mr_{\text{ref}}} &\triangleq \text{the desired magnetising current}
\end{aligned}$$

Note that the negative sign in (14) results from the sign of Q_{ref}, the reference imaginary power, derived later in the paper.

Given (14) we can now write the expression for the slip:

$$s = \frac{\omega_{sl}}{\omega_r + \omega_{sl}} = 1 + \frac{\omega_r i_{mr_{\text{ref}}}\lambda_{m_{\text{ref}}}}{Q_{\text{ref}}} = 1 + \frac{\omega_r L_m i^2_{mr_{\text{ref}}}}{Q_{\text{ref}}} \tag{15}$$

[9] This is also the case under FOC and DTC.

This expression can be substituted into the real power slip compensation term $1/(1-s)$. The $i_{mr_{\text{ref}}}$ and $\lambda_{m_{\text{ref}}}$ terms in this expression are reference values. Clearly i_{mr} and λ_m for an induction machine are related – i.e. $\lambda_m = L_m i_{mr}$. Hence we have written the numerator of (15) as $L_m i^2_{mr_{\text{ref}}}$. This means that knowledge of the magnetising inductance of the machine is required.

Now let us consider the Q_{ref} used in (15). The imaginary power is the crucial variable to maintain the flux in the machine. It is also required to prevent the real power positive feedback situation that can occur in regeneration.

As can be seen from (13), the imaginary power expression can be written as:

$$|Q| = i_{mr}\omega_e\lambda_m = i_{mr}\lambda_m(\omega_r + \omega_{sl}) \tag{16}$$

Therefore one concludes that the imaginary power is crucially dependent on the slip frequency of the machine. One implication of the dependence is that the imaginary power can undergo step changes, since the slip frequency changes as a step when there is a sudden torque demand.

The slip frequency of the machine is intimately related to the torque of the machine. The logical extension to this is that the desired slip frequency is related to the desired torque. The torque and slip frequency expressions of an induction machine can be written as (using the standard expression from FOC):

$$\tau = \frac{3}{2}p_p\frac{L_m^2}{L_r}|i_{mr}|\,i_p \tag{17}$$

$$\omega_{sl} = \frac{i_p}{T_r|i_{mr}|} \tag{18}$$

where $T_r = L_r/R_r$, $L_r \triangleq$ the rotor inductance, and $R_r \triangleq$ the rotor resistance. Therefore T_r is the rotor time constant.

Rearranging (17) one can write:

$$i_p = \frac{\tau}{\frac{3}{2}p_p\frac{L_m^2}{L_r}|i_{mr}|} \tag{19}$$

Substituting (19) into (18) gives:

$$\omega_{sl} = \frac{\tau}{\frac{3}{2}\frac{L_m^2}{L_r}|i_{mr}|^2 T_r} \tag{20}$$

The denominator in (20) can be simplified by assuming that the leakage inductance of the machine is very small in relation to L_r, and hence $L_r \approx L_m$. Therefore (20) can be written as:

$$\omega_{sl} \approx \frac{2\tau}{3p_pL_m|i_{mr}|^2T_r} = \frac{2\tau}{3p_p|i_{mr}|\lambda_mT_r} \tag{21}$$

We are now in a position to write an expression for the reference imaginary power. Substituting (21) into (16) and simplifying we get:

$$\begin{aligned}
Q_{\text{ref}} &= -\left[|i_{mr}|_{\text{ref}}\,\omega_r\lambda_{m_{\text{ref}}} + \frac{2\tau_{\text{ref}}}{3p_pT_r}\right] \\
&= -\left[L_m\left[|i_{mr}|_{\text{ref}}\right]^2\omega_r + \frac{2\tau_{\text{ref}}}{3p_pT_r}\right]
\end{aligned} \tag{22}$$

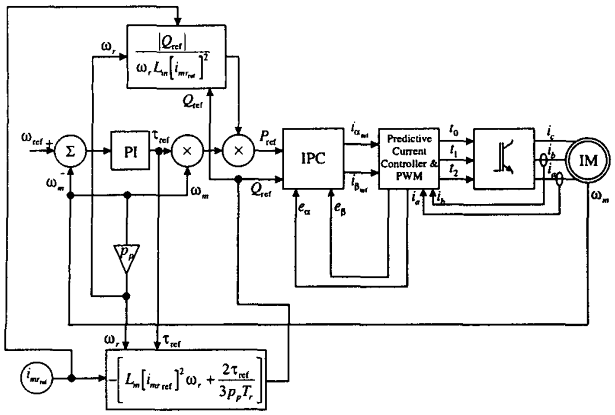

Fig. 4. Block diagram of a drive system using an instantaneous power controller (IPC).

Remark 1: Clearly (22) involves parameter knowledge of L_r, R_r, and L_m. Therefore, whilst the current reference generation part of the algorithm does not require any knowledge of parameters, the generation of the reference values for the power controller does.

Remark 2: The negative sign for the Q_{ref} expression is to give the correct sign for inductive imaginary power given the original definition of complex power in (2).

An alternative way of deducing the imaginary power is using its fundamental definition in (12). This allows us to write:

$$|Q| = i_{mr}\sqrt{e_\alpha^2 + e_\beta^2} \tag{23}$$

However, this expression is not much use from a control viewpoint since the e_α and e_β voltages are the result of the applied currents, voltages from the previous control interval as well as the current speed of the machine. In other words these voltages are not the desired back-emfs in the next control interval.

Figure 4 shows a block diagram of a controller based on the IPC control strategy. One important point that should be emphasised is that the controller is dependent on knowledge of the L_m, T_r and L_l parameters of the machine (the latter is the total leakage inductance, which is required by the current controller).

One other point that is very important in the operation of the control algorithm is the determination of the back-emf estimates. These are generated as a byproduct of the predictive current control algorithm. However, the algorithm as originally proposed [4] does not take into account the voltage drop across the stator resistance, R_s. This omission does not cause any significant problems with the current controller, but if IPC is being used then the controller becomes unstable under regeneration[10] if the voltage drop across the stator resistance is not taken into account when calculating e_α and e_β. It turns out that R_s does not have to be accurately known – in fact any value equal to or larger than the actual value appears to stabilise the system. The theoretical reasons for this are still to be investigated.

[10]The control system appears to be stable under motoring even when R_s is ignored

Parameter	Value
L_m	0.0693H
L_r	0.0713H
L_s	0.0713H
R_r	0.816Ω
R_s	0.435Ω
Poles	4
J	0.089 kgm^2

TABLE I
MACHINE PARAMETERS

The equations for defining the back-emfs used in (8) and (9) are:

$$\begin{aligned} e_d[k,k+1] &= \alpha[k,k+1]V - \frac{2L_l}{T}(i_d(k+0.5) - i_d(k)) \\ &\quad - i_d(k+0.5)R_s \end{aligned} \tag{24}$$

$$\begin{aligned} e_q[k,k+1] &= \beta[k,k+1]V - \frac{2L_l}{T}(i_q(k+0.5) - i_q(k)) \\ &\quad - i_q(k+0.5)R_s \end{aligned} \tag{25}$$

where:

$L_l \triangleq$ the total leakage inductance
$V \triangleq$ the voltage vector magnitude
$R_s \triangleq$ the stator resistance value
$[k, k+1] \triangleq$ denotes over the interval $k \rightarrow k+1$
$(k+0.5) \triangleq$ denotes in the middle of the interval $[k, k+1]$

Remark 3: The back emfs are also crucial to the correct determination of the current references via (8) and (9). Therefore erroneous estimates of these will adversely affect the performance of the controller. As can be seen from (24) and (25), e_d and e_q are determined using derivatives of the current and knowledge of the applied voltage. Therefore, if the measurements are noisy the back emf estimates will be very noisy. Furthermore, practical effects of inverter dead-time could adversely affect these estimates due to applied voltage errors.

III. SIMULATION RESULTS

This section presents some preliminary simulation results of the IPC algorithm as outline in the previous section.[11] The machine is initially started under conventional FOC, and the IPC algorithm is switched on after 250msec of operation. Note that the first 200msec is used to establish the flux in the machine, and there is no control action during this time. The parameters of the machine used appear in Table I.

[11]The simulations were carried out using the Saber® simulator. The machine parameters used are the default parameters for the induction machine simulation model in the simulator.

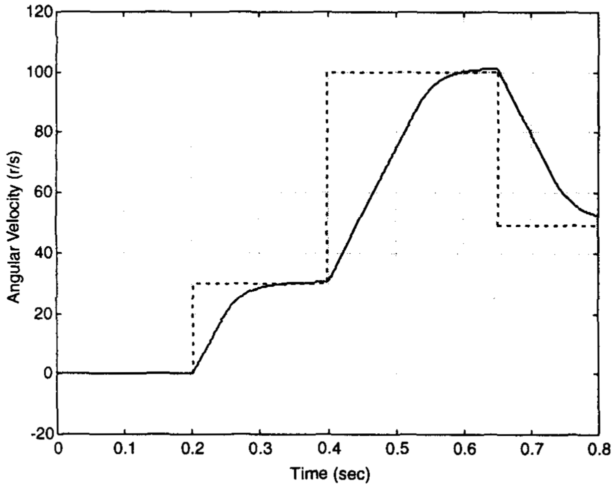

Fig. 5. Speed performance of an induction machine under IPC.

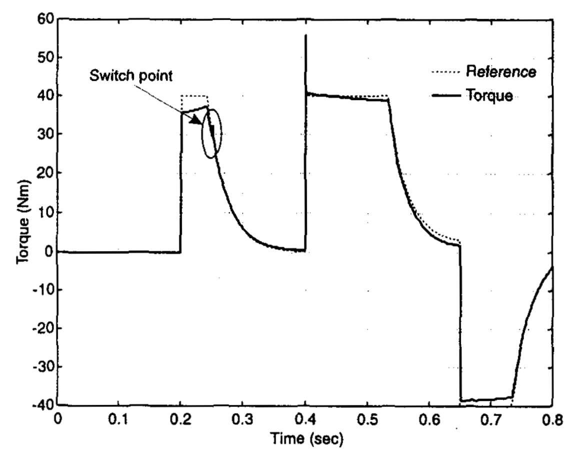

Fig. 6. Electro-magnetic torque during the angular velocity transients.

Figure 5 shows the speed performance of the machine under IPC. The torque generated by the machine during the angular velocity transient is shown in Figure 6. One can see from this figure that the transient torque performance is very good. It is believed that the error in the torque under high load conditions is due to some of the approximations made in the development of the imaginary power reference. This is the subject of further research. The error in the torque from time 0.2 to 0.25sec is due to the flux not being at the correct level when the control is first applied – the FOC algorithm assumes that the flux has reached the nominated value at 0.2sec.

Figure 7 is a closeup of the torque transient at 0.4sec. One can see that the torque rises from near zero torque to 40Nm in approximately 0.5msec. The overshoot exhibited in this transient needs further investigation. From Figure 6 one can see that there is no overshoot at the 650msec transient.

One of the key performance aspects of the system is its ability to follow the powers. Figures 8 and 9 show the estimated

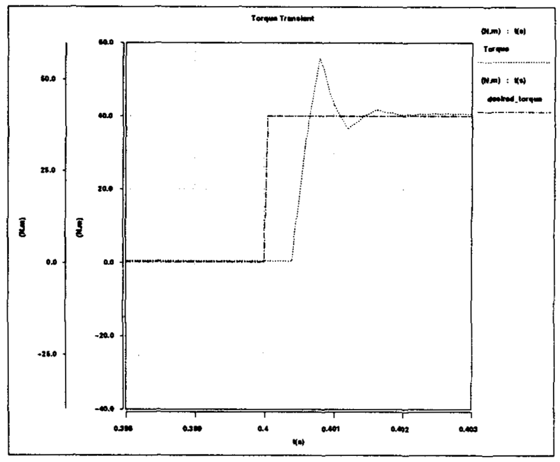

Fig. 7. Closeup of the 0.4sec torque transient.

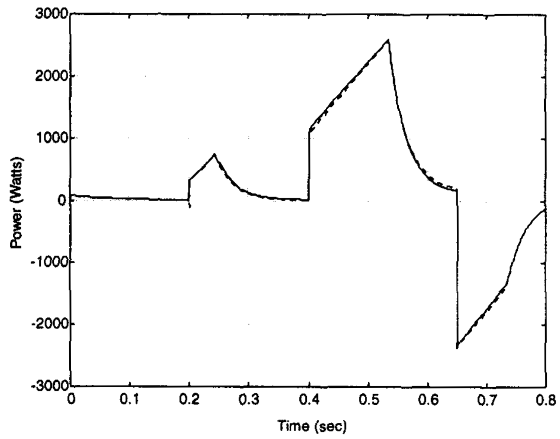

Fig. 8. The estimated real power and reference real power.

real and imaginary powers and the respective reference powers. As can be seen from these figures the reference value for the real power is closely followed. The imaginary power on the other hand shows a deviation from the desired value at higher angular velocities. The reasons for this are still being investigated.

Note from Figure 9 that the imaginary power can undergo step changes. The imaginary power magnitude can increase for essentially two reasons – an increase in the frequency of the system which increases the energy being transferred between the phases per unit time (and hence $|Q|$), or an increase in the amplitude of the flux, and hence the stored energy.[12] This too will result in more energy being transferred between the phases per unit time, and consequently an increase in the $|Q|$. In the particular case of Figure 9 the imaginary power reference is designed such that $|Q_{\text{ref}}|$ increases to accommodate the change in frequency caused by the variation in slip required to produce

[12]The extra stored energy means that real power is also transferred into the system.

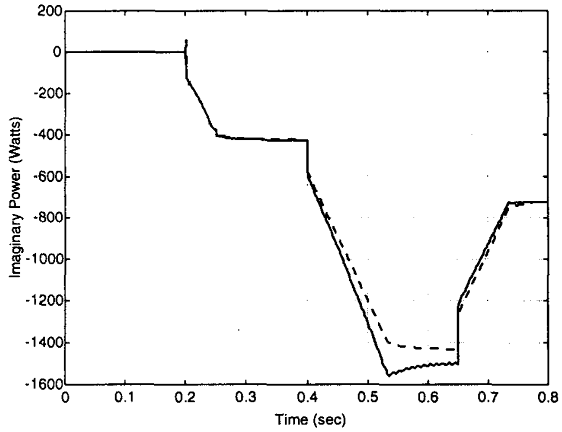

Fig. 9. The estimated imaginary power and reference imaginary power.

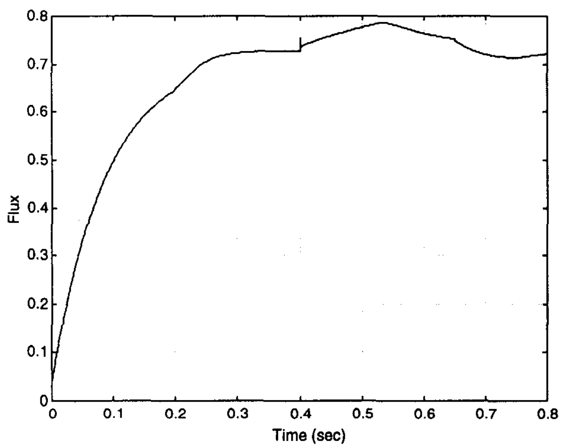

Fig. 10. The flux in the machine.

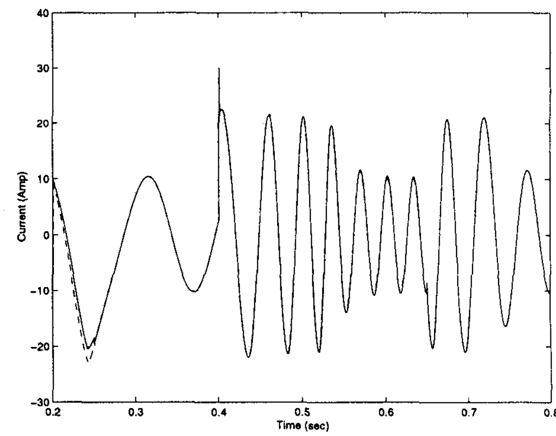

Fig. 11. d-axis actual and reference current under IPC.

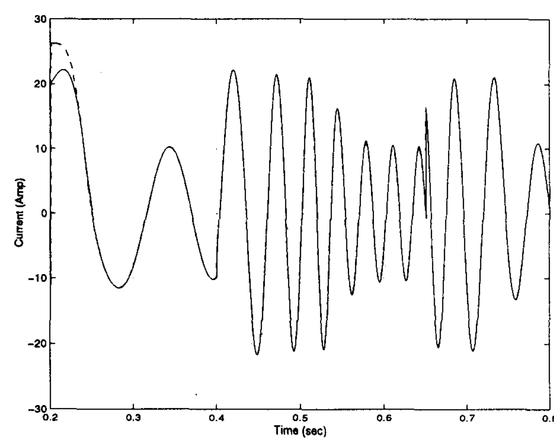

Fig. 12. q-axis actual and reference current under IPC.

the desired real power. Therefore the flux should ideally remain the same.

The term *estimated* used in the captions of Figures 8 and 9 indicates that the powers are calculated using measured currents and estimated back-emfs as per (24) and (25), since the actual two phase equivalent back-emfs are not directly available from the machine simulation model.

Figure 10 shows the flux in the machine. The increase in the flux from 0 to 0.2sec can be seen. As noted previously FOC control starts at 0.2sec before the flux has reached its nominated value of 0.72 Weber, and IPC starts at 0.25sec. The other significant points to note from this figure are:

- The flux varies from the nominated value after 0.4sec.
- The flux is being controlled by the IPC, although this control is not as tight as one would desire.
- The variation in the flux corresponds to the error between the reference and estimated imaginary powers in Figure 9.

Remark 4: The correspondence between the errors in the reference flux and errors in the imaginary power indicate that if the imaginary power can be made to accurately follow its reference then the flux will be accurately controlled.

For completeness we shall finally look at the currents and the back-emf estimates. Figures 11 and 12 show the d and q axis currents of the machine together with the references. As can be seen the references are closely followed which indicates that the PCC is working very well. When there is a sudden torque requirement, the current and torque transients are accurate and fast.

Figures 13 and 14 show the back-emf voltages of the machine. There are no reference voltages to follow, so it is difficult to say whether the estimated back-emfs are the actual back-emfs. However, the good performance from both the power controller and the current controller indicate indirectly that the estimates must be satisfactory. The other point to note is that the estimates are smooth and don't display noisy characteristics.[13]

Finally, Figure 15 shows the magnitude of the back-emf voltages. One may recall from (23) that the imaginary power mag-

[13] It should be noted that the simulation does not include the effects of inverter dead-time or noisy current measurements.

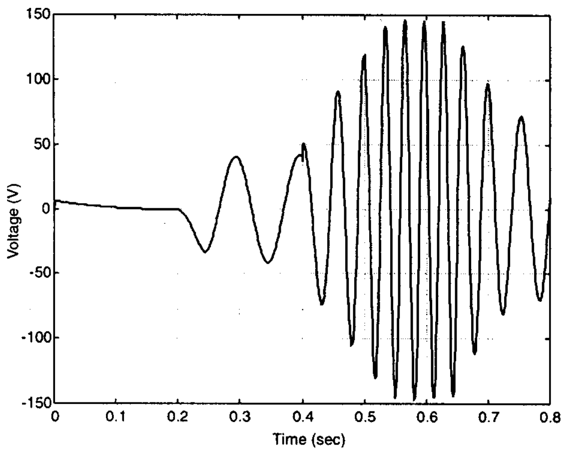

Fig. 13. d-axis estimated back-emf voltage.

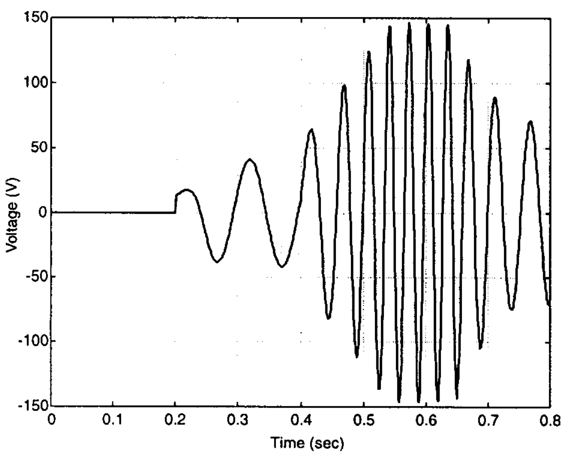

Fig. 14. q-axis estimated back-emf voltages.

nitude can be approximated by the voltage magnitude multiplied by i_{mr} (which equals 10 Amp in this example). Examination of Figure 9 and Figure 15 shows that this assertion is true. How this correspondence can be used to improve performance and to identify parameters is the subject of current research.

Studies have also been carried out to investigate the effects of inaccurate knowledge of the rotor time constant (T_r). Comparisons of IPC and FOC show that the performance of IPC is much less sensitive to inaccuracy in T_r compared to FOC. In the case of FOC, flux control is essentially lost with a $\pm 50\%$ error in T_r, whereas the effects are minimal for both the torque and flux with IPC.

IV. CONCLUSIONS

This paper has presented a *new* control algorithm for induction machines based on the concept of controlling the instantaneous real and imaginary powers into the machine. Similarly to FOC and DTC, IPC allows decoupled control of the flux and real power (and hence torque) of the machine.

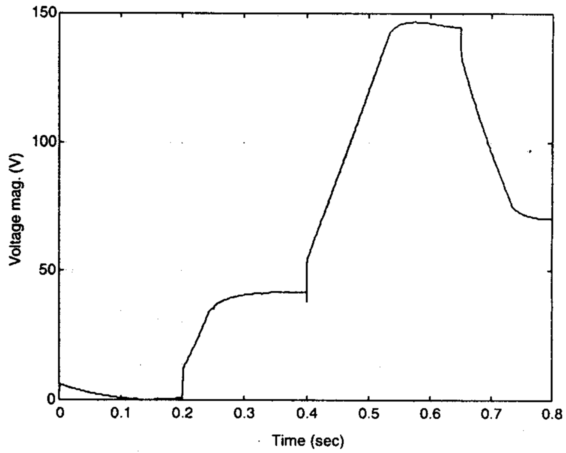

Fig. 15. Back-emf voltage magnitude.

It is interesting to note that the IPC algorithm, and particularly the control of instantaneous imaginary power, is in some ways more general than either FOC or DTC in that it can be applied to static systems without reactive elements such as compensators [5], as well as to systems with reactive elements such as machines and PWM rectifiers. Furthermore, the IPC concept generates a different way to view the operation of electrical machines.

Simulation results have been presented to confirm the theoretical viability of the algorithm and to demonstrate performance under ideal simulation conditions. At the time of writing the paper preliminary experimental studies are being undertaken. One of the important issues to arise from the experimental studies thus far is the importance of inverter dead-time on the performance of the algorithm. If the dead-time is not accounted for, the PCC does not generate estimates of the back emf that are accurate enough for the power controller equations. Details of the experimental studies will be presented at the conference and published in a future paper.

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