Instantaneous Power Control of Induction Machines

Using a Novel Filtering Approach on the Back-EMF Estimates

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Abstract—The instantaneous power control algorithm (IPC) has been presented recently as an alternative to field oriented control (FOC) and direct torque control (DTC) for induction machine drive systems. However, implementation issues have prevented experimental results from achieving the results obtained in simulation.

This paper addresses the main issue that causes a disparity between the simulation and experimental results—the quality of the back-emf estimates used in the IPC algorithm. In addition, a sensorless control strategy that naturally arises from measurements available in IPC will be briefly discussed.

I. INTRODUCTION

Field oriented control (FOC) and direct torque control (DTC), introduced in the early 1970s [1] and 1980s [2] respectively remain as the main algorithms for control of high performance induction machine drives. Field oriented control relies on knowledge of a rotating reference frame to convert the complex equations of the induction machine into those of a DC machine. This approach allows DC servo like performance levels to be achieved, if the position of the frame is known. Unfortunately knowledge of the reference frame position in the machine at any instant of time is model parameter dependent. Considerable research over the last 30 years has been devoted to solving the parameter estimation issues associated with FOC.

Direct torque control (DTC) differs considerably in concept from FOC in that it operates in a stationary reference frame. Therefore the issue of knowing the position of the reference frame is completely bypassed. Furthermore, in its raw state the algorithm is essentially parameter independent. This algorithm is also simple from an implementation viewpoint because it does not have a current controller and separate PWM generator, but “directly” generates the PWM from the desired control objectives. However, DTC does have deficiencies—it will not operate at low rotational speeds (due to the fact that it is reliant on knowledge of back-emfs), and as originally conceived it has a variable PWM switching frequency. Research on DTC since its inception has focussed on solving these issues. Generally the solutions have involved making the algorithm more parameter dependent and more complex, which to some degree negates the initial incentive for using the algorithm.

A novel alternative control algorithm, known as instantaneous power control (IPC), was first published in 2000 [3]. The IPC algorithm makes use of a current controller and an essentially conventional PWM algorithm, and therefore has the predictable switching and spectrum characteristics of FOC. Similar to DTC, the IPC algorithm operates in a stationary reference frame and makes use of back-emf estimation. This means that frame alignment issues are avoided. However, similarly to DTC, IPC cannot operate at zero speed without special measures because it uses machine back-emf to operate. In some sense IPC lies somewhere between DTC and FOC in its operational principles.

Published simulation results have shown that the IPC algorithm seems to be more robust with respect to parameter variation as compared to FOC [4]. Until now though the experimental results presented have not been able to match those obtained in simulation studies, mainly due to issues associated with accurately estimating the back-emf in the machine. This practical problem with IPC implementation is addressed in this paper through the use of a phase locked loop (PLL) based filtering approach which severely attenuates dead-time induced distortion without introducing phase shift or amplitude attenuation. These back-emf measurements can also be used to implement a sensorless speed control strategy for IPC [5].

The remainder of this paper will outline the structure of the IPC algorithm and PLL filter, present some simulation and experimental results demonstrating the operation of the algorithm and the PLL, compare the robustness of IPC to FOC with respect to parameter changes, and finally briefly look at sensorless control using imaginary power.

II. DESCRIPTION OF IPC ALGORITHM AND PLL FILTER

A. IPC Algorithm

The IPC algorithm and practical issues associated with its operation, have already been published [3], [4]. A brief description is only included here for completeness and immediate reference. For more detail refer to [6].

The IPC algorithm for an induction machine has three main components as shown in Figure 1: the power reference generator (PRG), the current reference generator (CRG), and the predictive current controller (PCC).
It should be noted that if both the real power and imaginary power will be in error by the rotor resistance power loss. If this is not done then the shaft losses in the rotor resistance. If this is not done then the shaft losses in the rotor resistance. If this is not done then the shaft losses in the rotor resistance. If this is not done then the shaft losses in the rotor resistance.

This expression can be written in real and imaginary components, and after some straightforward manipulations one can end up with the current references for the current controller given reference real and imaginary powers:

\[ i_{c-r} = \frac{e_p P_{ref} - e_q Q_{ref}}{e_p^2 + e_q^2} \]

\[ i_{c- \phi} = \frac{e_q P_{ref} + e_p Q_{ref}}{e_p^2 + e_q^2} \]

where \( i_p \) and \( i_q \) are two phase stationary frame currents, \( P_{ref} \) and \( Q_{ref} \) are the reference instantaneous real and imaginary powers, and \( e_p \) and \( e_q \) are the two phase back-emfs (which have to be estimated).\(^1\)

The PRG generates real and imaginary power references which are fed to the CRG. The power references can be shown to be [3], [4], [6]:

\[ P_{ref} = \frac{P_{mech}}{1 - s_{comp}} = \frac{\tau_{ref} c_{lm}}{1 - s_{comp}} \]

where \( s_{comp} \) is the compensating slip (defined below), \( \tau_{ref} \) is the reference torque, and \( \omega_m \) is the mechanical shaft speed.

Using \( \omega_e = \omega_m + \omega_sl \), where \( \omega_sl \) is the slip frequency, one can, after a little manipulation, write [3], [6]:

\[ s_{comp} = 1 + \frac{\omega_r L_m^2 \tau_{ref}^2}{Q_{ref}} \]

This slip expression is known as the compensating slip because it compensates the reference power to account for the power losses in the rotor resistance. If this is not done then the shaft power will be in error by the rotor resistance power loss.

The imaginary power reference is:

\[ Q_{ref} = L_m i_{lm \omega} + \frac{2 \tau_{ref}}{3 P_p T_r} \]

where \( T_r \) is the rotor time constant, \( i_{lm \omega} \) is the reference magnetising current (similar to the reference flux producing current in FOC), \( P_p \) is the machine pole pairs, and \( \omega_r = \omega_m + \omega_sl \). It should be noted that if both the real power and imaginary power into the machine are being accurately controlled then the slip of the machine is implicitly controlled. This is especially important during regeneration, where the slip can take on any arbitrary value if not controlled, for a given output shaft power [6].

It can be seen from (4), (5) and (6) that the reference generation is highly parameter dependent. Furthermore, one can also see that flux is controlled by \( Q_{ref} \). Hence, \( Q_{ref} \) and \( \tau_{ref} \) are the reference real and imaginary powers, and \( e_p r, e_q r \) are the reference instantaneous real and imaginary components, and after some straightforward manipulations one can write the real power reference and the imaginary power reference via the \( \tau_{ref} \) term in (6).

The final section of the IPC controller is the PCC. Considerable work on PCCs has been carried out [8], [9], [10], [11] over recent years, demonstrating that it is a viable and high performance current control technique. A PCC was chosen for incorporation into the IPC controller because it implicitly generates the estimates of the machine back-emf required for the PRG, and its simple computational requirements are consistent with the objectives of the IPC algorithm. In addition the particular PCC structure used has an integrated PWM generator that ensures a constant switching frequency, and has well known and good quality harmonic properties due to its symmetric switching pattern.

B. PLL Based Filter

The equation for the back-emf estimate in each of the two phases generated in the PCC, can be shown to be [8], [10]:

\[ \hat{e}_k = v_k - \frac{2 L_r}{T} (i_{k-0.5} - i_{k-1}) \]

where \( \hat{e}_k \) is the estimated back-emf over the \( k \)th interval, \( v_k \) the voltage applied over the \( k \)th interval, \( L_r \) is the total machine leakage inductance, \( T \) the period and \( i_{k-0.5} \) and \( i_{k-1} \) are the currents measured at times \( t = (k - 0.5)T \) and \( (k - 1)T \) respectively where \( k \) is an integer.

Inverter dead-time effects severely distort the back-emf estimates as shown in the \( e_d \) estimate in Figure 2. This then distorts the current references via (2) and (3). This effect on the current references has made the algorithm practically unusable in the past, with the drive only able to operate poorly over a narrow speed range. In order to minimise the distortion in the back-emf estimates a PLL based filtering system has been developed.

The obvious approach to fix the problem shown in Figure 2 is to filter the back-emf estimates. This approach has been tried and is not very successful. The main problems are that it is difficult to filter out distortions of the type that occur in the back-emfs, and secondly the amplitude attenuation and the phase shift in the filtered back-emfs gives unacceptable performance from the algorithm.

The PLL approach is very appealing because it allows the filtering to be divided into two sections - firstly low pass filtering of the estimated back-emf magnitude, and secondly a software phase locked loop (PLL) to phase lock a normalised back-emf estimate to the distorted back-emf from the current controller. The division of the filtering and phase locking into two sections allows very low pass filtering of the magnitudes, since these only change at the rate of change of the angular velocity of the machine. The filter bandwidths to handle phase

1Note that there are no parameters in the CRG section of the algorithm.
EXPERIMENTAL RESULTS SHOWING A RAW $e_d$ ESTIMATE FROM THE PCC ALGORITHM.

Errors and amplitude errors can be individually set. The phase locked loop section is effectively a very narrow band pass filter, with the narrow pass band tracking the approximate electrical frequency of the machine. Once the filtered back-emf magnitude and phase are obtained, then the $e_d$ and $e_q$ two phase back-emf's can be reconstituted. These can then be used in equations (2) and (3) to give the current references. Figure 3 shows a conceptual block diagram of the PLL filtering system for the $d$ axis. A PLL of this design is applied to the $d$ and the $q$ axis raw back-emf estimates. The two separate sections of the algorithm can be easily identified. The digital implementation is more elegant than that shown in the figure since the phase comparison can be carried out without the use of multiplication and the consequent double frequency terms that have to be filtered out of the phase error. This allows larger flexibility in the design of the loop filter, and hence better control over the lock range of the software PLL. The PLL in software form still contains trigonometric functions, but these can be handled either by look-up tables, or directly if a floating point DSP is being used.

A analogue PLL normally has a centre frequency associated with the voltage controlled oscillator, and a lock range around this particular frequency. The back-emf waveform frequency varies over a large range corresponding to $\omega_c$. In order to lock onto the back-emf waveform the PLL needs a variable centre frequency that is approximately the frequency of the back-emf. Without this the PLL could never maintain lock. Fortunately an estimate of the applied electrical frequency is easy to obtain from the algorithm, and this is used as the centre frequency of the PLL. This input can be seen in Figure 3 as $\omega_c$.

The PLL technique used is not only applicable to this application, but can clearly be applied to machines using FOC and other control strategies. One serendipitous consequence of the PLL filtering is that the back-emf information can be used to extract speed estimates for the machine [5]. These estimates can be used as part of the feedback speed control.

An example of the performance of the PLL can be seen in the simulation results of Figure 4. In this figure the frequency and amplitude of the waveform to be identified are smoothly changing, plus the amplitude of the signal is corrupted with very large pulses. The true $e_d$ and the PLL estimated $e_d$ virtually lie on top of each other. Figure 5 shows a more detailed view of the area in the waveform where the corruption pulses occur. Whilst there is some deviation of the estimated back-emf form the uncorrupted version it is only very slight, and the feedback of the PLL quickly brings the phases of the waveforms together. Many other tests that have been performed have shown the technique to be very robust.

The PLL filtering technique has been implemented in a drive system for both the FOC and IPC algorithms. Of the two algorithms IPC is the one to benefit most from the use of the PLL because of its the sensitivity to back-emf accuracy as shown in Equations (2) and (3). Figure 6 shows preliminary experimental results of the performance of IPC on a 7.5kW induction machine. The inverter control interval was 256μssecs, and the dead-time was 4μssecs. The induction machine was connected to a load machine with an inertia of 0.141kgm², giving a total inertia of $J = 0.23$kgm².

Figure 6 shows that the performance of the IPC algorithm is very good, with it quickly and accurately following the reference speed. The very small oscillations in the speed are currently the subject of further investigation. The machine is producing approximately 30Nm of torque (the software torque limit) to generate the angular accelerations shown in this figure. The inclusion of the PLL has made the IPC algorithm a viable and competitive algorithm with FOC and DTC.
SIMULATION OF PLL ESTIMATION OF $e_d$ IN THE PRESENCE OF NON-PERIODIC PULSE CORRUPTION.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>$L_m$</td>
<td>0.0693H</td>
</tr>
<tr>
<td>$L_r$</td>
<td>0.0713H</td>
</tr>
<tr>
<td>$L_s$</td>
<td>0.0713H</td>
</tr>
<tr>
<td>$R_r$</td>
<td>0.8196Ω</td>
</tr>
<tr>
<td>$R_s$</td>
<td>0.4351Ω</td>
</tr>
<tr>
<td>Poles</td>
<td>4</td>
</tr>
<tr>
<td>$J$</td>
<td>0.089 kgm²</td>
</tr>
</tbody>
</table>

TABLE I
SIMULATION MACHINE PARAMETERS

bottom diagram in Figure 6 shows the performance of the PLL estimator for one of the two phase back-emfs when the machine is running at 50 rad/sec. One can readily see the dead-time induced distortion in the original estimates from the PCC. The PLL filter estimates are smooth, and accurately follow the phase of the raw waveform.

III. PARAMETER SENSITIVITY ISSUES

A valid question to ask about IPC is whether it is more or less parameter sensitive as compared to algorithms such as FOC. If one considers Equations (2), (3), (4), (5) and (6) one can see that parameters play a prominent part in the determination of the control. However, as with DTC, the fact that this algorithm operates in a stationary reference frame may afford it some advantages over FOC with respect to parameter sensitivity.

In order to carry out preliminary investigations of the parameter sensitivity issue simulation studies were carried out under the condition of inaccurate knowledge of the rotor time constant. This parameter was chosen since it varies considerably during machine operation, and its estimation has been the subject of much of the research on FOC. Simulation plots for accurate parameters appear in [3] and will not be repeated here. We consider the case where there is a +50% error in $R_s$, which means that the rotor time constant is in error by -50%. Therefore the $T_r$ value used in the controller is 50% larger than the actual machine rotor time constant.

Figure 7 shows the simulated performance of the IPC algorithm under this condition. Note that in this simulation it is assumed that the inverter does not have any dead-time. The machine parameters are those in Table I. One can see that the torque does not exactly follow the desired torque, and the flux wanders away from the desired flux of 0.72 Weber. However, neither the torque or flux error is extreme.

Figure 8 shows the simulated performance of the FOC under the same conditions. The torque shows larger excursions from the desired torque as compared to that in Figure 7. The flux undergoes an extreme error, varying from the desired 0.72 Weber by approximately 0.43 Weber. These results hold for a number of different values of $T_r$. Therefore IPC appears to have significant advantages over FOC with respect to sensitivity to $T_r$ knowledge.

In order to verify the simulation results IPC and FOC were experimentally tested on a drive system. Similar speed changes were made, and the speed performance noted. Currently we do not have an independent way of measuring the flux in the system. We hope to fix this soon by using search coils in the machine. The experimental results consider two situations – $T_r$ in the controller is 50% of the nominal value, and $T_r$ in the controller is 150% of the nominal value. The results of these studies for the FOC are shown in Figure 9. Note that there is a noticeable difference between the two experimental runs when the controller $T_r$ value was altered. The overshoot evident in the $T_r = 150\%$ figure is indicative that there are
EXPERIMENTAL RESULTS. TOP: IPC PERFORMANCE UNDER SPEED CONTROL WITH PLL BASED FILTERING ON THE BACK-EMF ESTIMATES

Fig. 6

Fig. 7
SIMULATED IPC TORQUE AND FLUX WITH 50% \( T_r \) ERROR.

Fig. 8
SIMULATED FOC TORQUE AND FLUX WITH 50% \( T_r \) ERROR.

The IPC algorithm is almost totally insensitive to the value for \( T_r \). The overshoot in the speed is due solely to the gains chosen for the speed feedback loop. They were kept the same as those used for the FOC plots. Clearly the IPC algorithm has a higher gain than FOC.

IV. IMAGINARY POWER SPEED ESTIMATION

Imaginary power is an integral part of the IPC algorithm. It has been shown that imaginary power can be used as a technique to estimate the rotational speed of an induction machine [12], [5]. The basic expression for the estimated speed derived in [5] is:

\[
\omega_{\text{est}} \approx \frac{1}{p_p L_{sr}^2} \left[ Q \frac{2\omega_{\text{rot}}}{3T_r} \right]
\]  

As can be seen from this expression the machine torque and the rotor time constant have a significant effect on the estimate of the speed. The machine torque term subtracts off the step changes in the \( Q \) value with sudden changes in the machine slip frequency. If the value of \( T_r \) is incorrect then this will result in errors in the estimate at the initial step in the torque.

The main advantages of this approach to speed estimation are that it does not rely on any special machine modifications, and it is insensitive to stator resistance at low speeds. It has been shown to perform very well in simulation at low speeds [5]. On the negative side it is clearly very dependent on machine parameter knowledge.

Figure 11 is an experimental plot of the performance of the estimator. It should be noted that the raw estimates are being passed through a speed observer [5]. One can immediately see that there is significant error at higher speeds. This behaviour was not evident in the simulation studies, and may be due to inaccurate parameter knowledge. The inaccuracy present in the estimated speed has, at this stage, prevented its use in a feedback loop.

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The conclusions that can be drawn from the material presented are:

- The PLL back-emf estimation technique works extremely well. Besides improving the performance of IPC, this filtering technique would be very useful in other drive applications.
- The IPC algorithm is very robust, compared to FOC, with respect to errors in the rotor time constant $T_r$.
- The transient performance of IPC is excellent, and is as good as an optimally tuned FOC.
- The imaginary power based speed estimation technique shows promise, but needs further work to understand and eliminate the speed estimation offsets.

V. CONCLUSIONS

This paper has presented the following:

- an outline of the IPC algorithm,
- a novel technique for accurately estimating induction machine back-emfs using phase locked loops,
- presented simulation and experimental results comparing parameter robustness of IPC and FOC,
- presented preliminary experimental results for a speed estimation technique using imaginary power.

Overall this paper demonstrates that IPC could be a genuine competitor with FOC and DTC for the control of high performance drives.

REFERENCES