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**Application Note**

# An Introduction to Vector Control of AC Motors Using the V850

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## Abstract

AC motors, whilst being very economical, rugged and reliable due to the absence of commutators and brushes, have inherently poor dynamic behaviour. However, the dynamic behaviour can be made to match that of an equivalent separately excited DC motor using Field Orientated or Vector Control.

AC motors come in various forms but the 3 phase Asynchronous Induction Motor (AIM) and the 3 phase Permanent Magnet Synchronous Motor (PMSM) tend to be the most common. The method of vector control can be applied to both these types of motor.

Vector control requires computationally intensive algorithms, this coupled with closed loop control and precise Pulse Width Modulation (PWM) requires a relatively powerful microprocessor along with the relevant peripherals to make vector control a practical proposition.

The advent of low cost, high performance microcontrollers designed specifically for motor control applications, such as NEC's 32bit RISC V850 with it's DSP capabilities, means vector control of AC motors with their inherently low cost and robust characteristics can be applied cost effectively to a wide range of applications from machine tools to washing machines.

This paper provides an overview of vector control principles for AC motors including a practical example using NEC's V850E/IA1.

# 1. Vector versus Scalar Control of AC Motors

Scalar control involves controlling only the magnitude of the control variables with no concern for the coupling effects between these variables. Conversely, vector or field orientated control involves adjusting the magnitude and phase alignment of the vector quantities of the motor. Scalar control, such as the Constant Volts/Hertz method when applied to an AC induction motor is relatively simple to implement but gives a sluggish response because of the inherent coupling effect due to torque and flux being functions of current and frequency. Vector control de-couples the vectors of field current and armature flux so that they may be controlled independently to provide fast transient response.

Accurate position control is not possible with scalar control since this requires instantaneous control of the torque. This requires either, instantaneous change to the stator currents, which is not possible due to energy storage effects, or instantaneous change to the rotor current which in the case of scalar control is controlled indirectly via the stator currents. Similarly, whilst scalar control may provide acceptable steady state speed control, precise and responsive speed control due to load changes requires accurate and responsive torque control.

The vector approach overcomes the sluggish transient response when using scalar control of AC motors. If the application requires vector control then this can be achieved cost effectively using an appropriate relatively low cost microcontroller.

## 2. The vector control concept

Initially, the emphasis of this paper will be on vector control as applied to the AC induction machine it then goes on to describe the necessary adaptations to this method for controlling a PMSM.

In a typical AC induction motor, 3 alternating currents electrically displaced by $120^0$ are applied to 3 stationary stator coils of the motor. The resulting flux from the stator induces alternating currents in the 'squirrel cage' conductors of the rotor to create its own field these fields interact to create torque.

Unlike a DC machine the rotor currents in an AC induction motor can not be controlled directly from an external source, but are derived from the interaction between the stator field and the resultant currents induced in the rotor conductors. Optimal torque production conditions are therefore not inherent in an AC Induction motor due to the physical isolation between the stator and rotor.

Vector control of an AC induction motor is analogous to the control of a separately excited DC motor. In a DC motor (see figure 1) the field flux $\Phi_f$ produced by the field current $I_a$ is perpendicular to the armature flux $\Phi_a$ produced by the armature current $I_a$ . These fields are decoupled and stationary with respect to each other. Therefore when the armature current is controlled to control torque the field flux remains unaffected enabling a fast transient response.

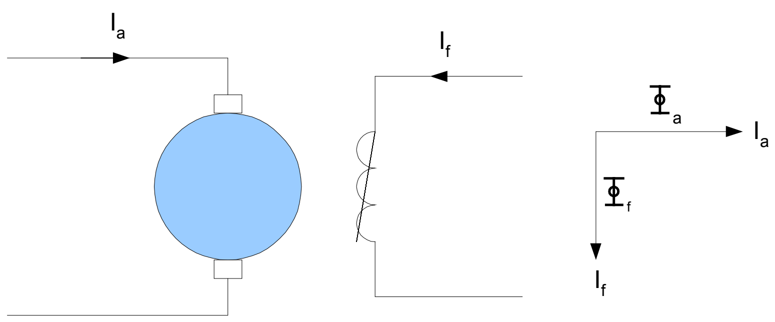



***Figure 1***

where torque $(T) \propto I_a I_f$

and where $I_a$ represents the torque component and $I_f$ the field.

Vector control seeks to recreate these orthogonal components in the AC machine in order to control the torque producing current separately from the magnetic flux producing current so as to achieve the responsiveness of a DC machine.

## 3. d-q axes

A 3 phase machine can be represented by an equivalent 2 phase machine using direct (d) and quadrature (q) axes for both stator and rotor [1].

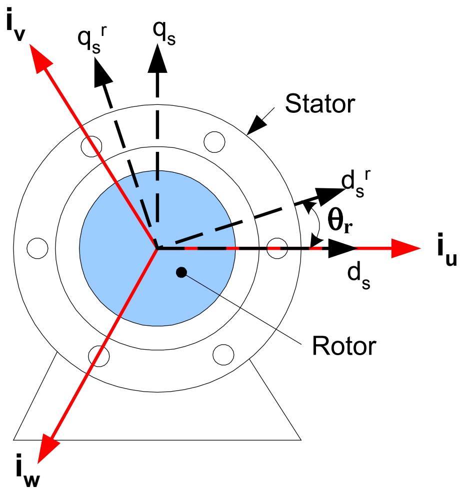



***Figure 2***

Figure 2 shows a d-q representation of an AC induction motor. $d_s$-$q_s$ represent the direct and quadrature axes of the stationary stator frame and $d_s^r$-$q_s^r$ represent those of the rotor known as the rotating reference frame.

With $i_u$ placed coincident with $\mathbf{d}_s$, it can be shown that the vector sum of the 3 stator currents $i_u$ $i_v$ and $i_w$ can be expressed in terms of the quadrature components $d_s$ and $q_s$ (some texts refer to these axes as α and β) in the stator reference frame as …

$$i_{ds} = i_u$$
$$i_{qs} = 1/\surd 3(i_v – i_w) \quad \text{eqn 1}$$

Knowing that in a 3 phase balanced system (with isolated neutral) $i_u + i_v + i_w = 0$ then equation 1 becomes …

$$i_{ds} = i_u$$
$$i_{qs} = 1/\surd 3\ (i_u) + 2/\surd 3\ (i_v) \quad \text{eqn 2}$$

Equation 2 represents the transformation of the 3 phase stator currents into a two phase orthogonal vector representation $d_s$ and $q_s$. The mathematical transformation for this process is known as a Clarke transform. In order to perform this transformation we only need to measure two of the phase currents, in this case $i_u$ and $i_v$.

A further transformation is then required in order to relate these components of the stationary stator frame to the rotating reference frame of the rotor. This is achieved using the Park transformation as follows …

$$i_{ds}^{\ r} = i_{qs}\sin\theta_r + i_{ds}\cos\theta_r$$

$$i_{qs}^{\ r} = i_{qs}\cos\theta_r - i_{ds}\sin\theta_r \qquad \text{eqn 3}$$

where $\theta_r$ represents the angular position of the rotor flux

The Park transformation provides us with the direct axis and quadrature axis components ($i_{ds}^{\ r}$ and $i_{qs}^{\ r}$) of the stator current in a synchronously rotating reference frame that rotate at an angular velocity $\omega$ and at an angle $\theta_r$ ($\theta_r = \omega t$) with respect to the $d_s$-$q_s$ axes. As a result, in the steady state, these coordinates in the rotating reference frame do not vary with time.

Referring back to the DC machine representation of figure 1, using vector control, $i_{ds(r)}$ is analogous to field current $I_f$ (the flux component) and $i_{qs(r)}$ is analogous to armature current $I_a$ (the torque component).

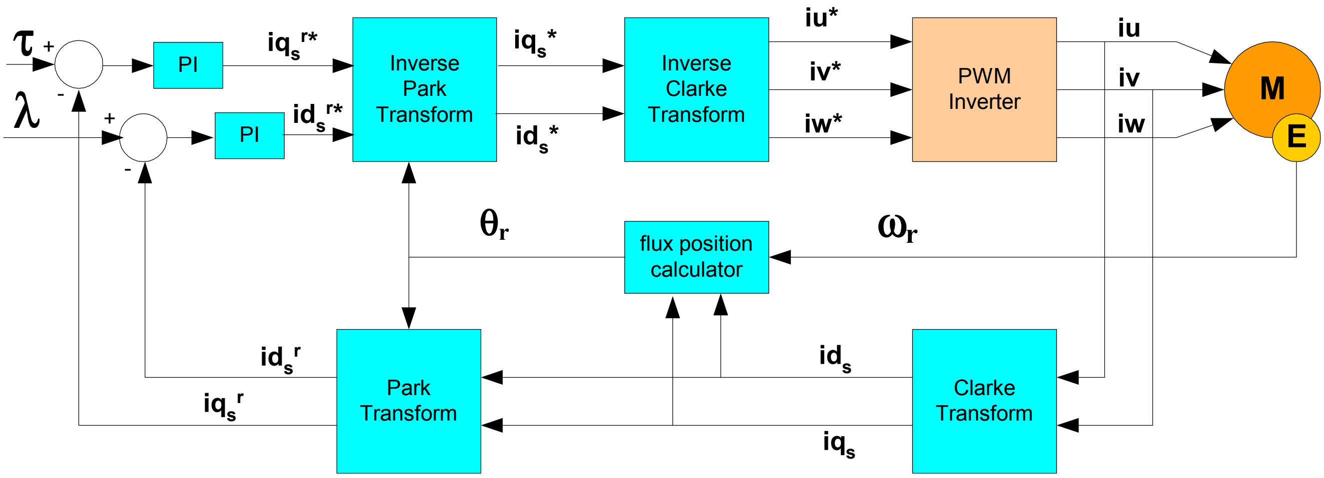
where $T \propto i_{qs}^{\ r}\, i_{ds}^{\ r}$

As long as $i_{ds}^{\ r}$ maintains alignment with the rotor's flux vector and $i_{qs}^{\ r}$ is $90^0$ in advance of $i_{ds}^{\ r}$ then flux and current can be controlled independently of each other.

## 4. Implementation of Vector Control

It has been established that $i_q$ and $i_d$ of the rotating reference frame must be controlled to provide good dynamic control of the induction motor. Using closed loop control ordered quantities of $i_q$ and $i_d$ are compared with the actual values measured from the motor.

In order to obtain the motor values we have to perform transformations on the measured 3 phase stator currents into the direct and quadrature components of the rotating reference frame. The resulting error terms are then transformed back to 3 phase quantities and applied to the motor. Figure 3 shows a representation of this process.




* represent ordered values

τ is required torque

λ is required flux

***Figure 3***

The purpose of the flux position calculator shown in figure 3 is to produce the correct field orientation by ensuring alignment of ids with the rotor flux. The angular position of the rotor flux in an AIM can either be measured directly using sensors embedded in the motor or (more commonly) indirectly. The indirect method involves calculating the angle of slip between the stator and rotor fields using known characteristics of the rotor and summing this with the physical position of the rotor. The physical position is measured (usually) using an incremental encoder fitted to the motor shaft.

The difference (errors) between the ordered and actual id and iq components are input to Proportional Integral (PI) controllers. Note that the PI controllers do not form part of vector control but are usually included in this type of system to provide optimum closed loop control of the motor. The output terms from the PI controllers that are referenced to the rotating reference frame are transformed back to the static frame using the inverse transform of equation 3 and then transformed from the static frame back into the 3 phase components using the inverse transformation of equation 2. The inverse clarke and park transforms are shown in equations 4 and 5 respectively.

$$i_u = i_{ds}$$

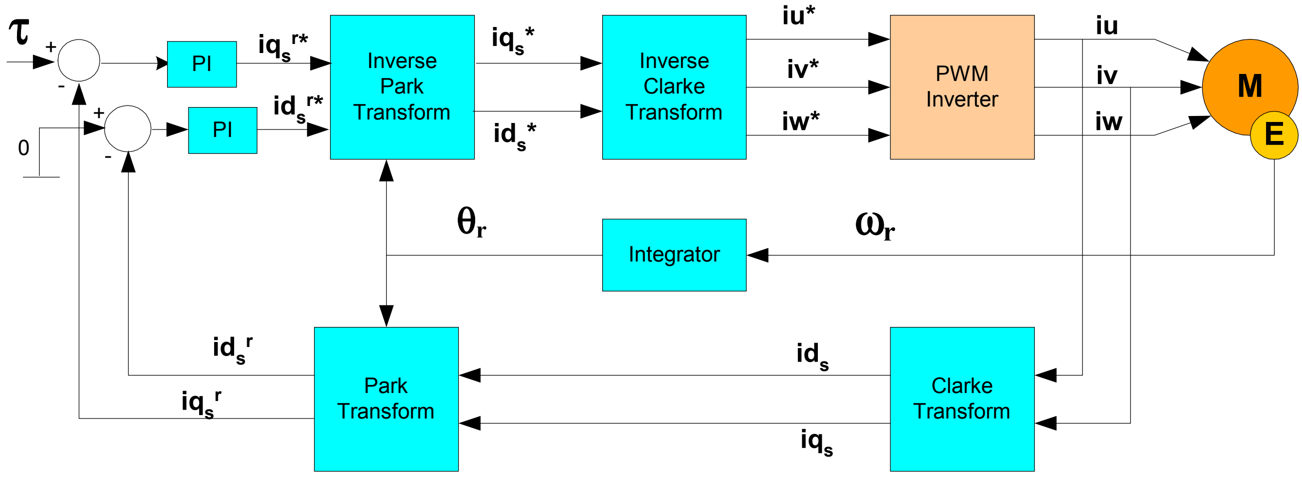
$$i_v = \sqrt{3}/2\ (i_{qs}) - (i_{ds})/2$$

$$i_w = -i_u - i_v \qquad \text{eqn 4 (inverse clarke)}$$

$$i_{ds} = i_{ds}^{\,r}\,Cos\theta_r - i_{qs}^{\,r}\,Sin\theta_r$$

$$i_{qs} = i_{ds}^{\,r}\,Sin\theta_r + i_{qs}^{\,r}\,Cos\theta_r \qquad \text{eqn 5 (inverse park)}$$

Fig 3 represents the Vector control system for an asynchronous motor however this can easily be adapted for control of a PMSM. In a PMSM the flux component is produced by the permanent magnets (the fixed field winding of figure 1 is replaced with a rotating permanent magnet). The rotor flux produced by the PM rotates at the same speed as the rotor field i.e. there is no slip. So for a PMSM the ordered $I_d$ component ($\lambda$) is set to zero and the rotor angle is obtained by integrating the rotor speed. The system configuration for vector control of a PMSM is shown in figure 4.




* represent ordered values

τ is required torque

*Figure 4*

# 5. Vector control using NEC V850

The V850 series of microcontrollers feature a 32-bit RISC CPU optimized for a wide spectrum of embedded control applications from low to high end performance this includes ASSP products designed for the specific needs of particular application fields. The CPU core performance is two to four times more powerful than in 16 bit microcontrollers having the same operating frequency and operates at frequencies up to 50 MHz.

Features of the V850 CPU are:

- 5 stage pipeline
- Harvard architecture
- 32 general purpose registers
- Simple addressing
- 16 bit instruction support
- Bit manipulation support
- DSP function
- 32-bit barrel shifter

The V850E/IA1 and V850E/IA2 (the V850E/IA2 is a subset of the IA1) are high end ASSPs designed for inverter control applications and are ideally suited for vector control of AC motors. Some of the features of the V850IAx include …

- 20nS execution time (at 50Mhz operation)
- 16 bit timers for 3 phase PWM inverter control (including dead timers)
- 16 bit up/down counter/timer for incremental encoder input
- Various 16 bit General purpose timers
- 10 bit A/D converters
- General purpose I/O
- Serial interfaces

The DSP function provides multiplication and product-sum operations that can be executed in one or two clock cycles which is ideally suited for vector control algorithms. For example, the DSP function contains a hardware multiplier that enables a 32 x 32 bit operation to be executed in 1 clock cycle (20nS at 50MHz) or 3 clock cycles if the multiplication is followed by a sum operation..

The following code sample implements part of the park transformation of equation 3 on a V850E/IA1 and illustrates the use of the multiplier.

```
dr = qs*sin(theta) + ds*COS(theta); /*equivalent C statement*/

            mov   r29,r6           theta->r6
            mov   .L12,lp          store return address
            mov   _sin,r18
            jmp   [r18]            go to sin()function, r10 will
                                   contain result of sin(theta)
_L12:
            mov   r27,r2           qs -> r2
            mul   r10,r2,zero      qs*sin(theta) (32x32)
            mov   r2,r25           result->r25
            addi  256,r29,r17      theta+90 (sin to cos)->r17
            mov   r17,r6
            mov   .L13,lp          store return address
            mov   _sin,r18
            jmp   [r18]            go to sin()function, r10 will
                                   contain result of cos(theta)

_L13:
            mov   r28,r2           ds->r2
            mul   r10,r2,zero      ds*cos(theta) (32x32)
            add   r25,r2           qs*sin(theta) + ds*cos(theta)
            st.w  r2,0[r26]        store result
```

The sin function referred to in the above example was implemented using a numerical series but could equally be implemented as a look up table.

A full implementation including this example is described in an NEC application note (available on the web) and describes vector control of a synchronous motor using a V850E/IA1.

## 6. Conclusions

This paper has shown that vector control of AC motors is a computationally intensive process that requires a high performance processor with associated peripherals. NEC has met this challenge with its range of 32 bit RISC microcontrollers in the V850 family.

NEC offers a range of micros from 8 to 32 bit that are ideally suited to all types of motor control. This coupled with a dedicated motor control sales and technical support team, numerous application notes and reference platforms offers the user a comprehensive motor control solution.

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