NEC V850 family a challenge for 3 phase inverters control

CONSTANTIN PATRASCU, DAN POPESCU
Computer Science Department, Automation Department
University of Craiova
ROMANIA

Abstract: - 3 phase inverters are used in industry, in a wide range of applications, like AC and BLDC motor control, or active power filters control. The economic constraints and new standards legislated by governments place increasingly stringent requirements on electrical systems. The new generations of equipment must have higher performance parameters such as better efficiency and reduced electromagnetic interference. To fulfill these requirements the control units of the inverters must have powerful processors which can perform enhanced algorithms to reduce torque ripples and harmonics, and to improve dynamic behavior.
This paper provides, in the first part, an overview of the main control methods of inverters in an AC motor control application and in an active power filter application. The second part provides an overview of NEC V850 capabilities for inverter control including some examples.

Key-words: - 3 phase inverters, AC motors, Active power filters, NEC microcontrollers

1 Control methods

1.1 AC motor control

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.

The Field Oriented Control is the "de facto" method used for motor control [1]. It consists in controlling the components of the motor stator currents, represented by a vector, in a rotating reference frame *d,q* aligned with the rotor flux.

The vector control system requires the dynamic model equations of the induction motor and returns to the instantaneous currents and voltages in order to calculate and control the variables.

The electric torque of an AC induction motor can be described by the interaction between the rotor currents and the flux wave resulting from the stator currents induction.

$$m_M = 2/3\ \ L_0 \Im m\, [i_s\, (imre^{j\varphi}]$$

Since the rotor currents cannot be measured with cage motors, this current is replaced by an equivalent quantity described in a rotating system coordinates called *d,q* and following the rotor flux.

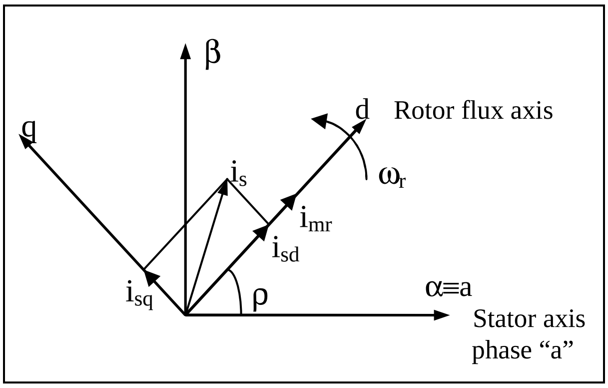

Fig.1 *Stator Current and Flux Space Vectors in the d,q Rotating Reference Frame and its Relationship with the Stationary Reference Frame.*

The instantaneous flux angle ρ is calculated by the motor flux model. *isd* and *isq*, the stator current components in the *d,q* frame, are obtained directly from *ia*, *ib* and *ic*, the fixed coordinate stator phase currents, with the Park transformation:

$$\begin{vmatrix} i_{sd} \\ i_{sq} \end{vmatrix} = \begin{vmatrix} \cos\rho & \cos(\rho-2\pi/3) & \cos(\rho+2\pi/3) \\ -\sin\rho & -\sin(\rho-2\pi/3) & -\sin(\rho+2\pi/3) \end{vmatrix} * \begin{vmatrix} i_a \\ i_b \\ i_c \end{vmatrix}$$

Then the torque can be expressed as follow:

$$m_M = k\, i_{mv}\, i_{sq} \quad \text{with} \begin{cases} k = 2/3\,(1-\sigma)\, L_S \\ i_{mr} = 1/L_m\, \Psi_R \end{cases}$$

In steady-state conditions the stator current i_s defined in the above mentioned rotating system is considered constant as well as the magnetizing current i_{mr} representing the rotor flux and i_{sq} being equivalent to the motor torque. δ is the load angle that equals to zero when no load, i_{sd} is linked to i_{mr} with the following equation:

$$i_{sd} = i_{mr} + T_R\, di_{mr} / dt$$

T_R is the rotor time constant.

This system together with the angle transformations change the induction motor into a machine very similar to a DC motor where i_{mr} corresponds to the DC motor main flux and i_{sq} to the armature current.

The field orientated control method achieves the best dynamic behaviour, whereby the lead and disturbance behaviour can be improved with shorter control cycle times. The field orientated control method is a de facto standard to control an induction motor in adjustable speed drive applications with quickly changing load as well as reference speeds. Its advantage is that by transforming measurable stator variables into a system based on field coordinates the complexity of the system can be enormously reduced. As a result a relatively simple control method very similar to a separated exited DC motor can be applied.

The role of the processor in such a system is to translate the stator variables (currents and angle) into a flux model as well as compare the values with the reference values and update the PI controllers. After the back transformation from field to stator coordinates the output voltage will be impressed to the machine with a symmetric, an asymmetric PWM whereby the pulse pattern is on-line computed by the processor or a hardware generated space vector method. In some systems the position is measured by an encoder, this extra cost can be avoided implementing an observer model or in particular cases, a Kalman filter.

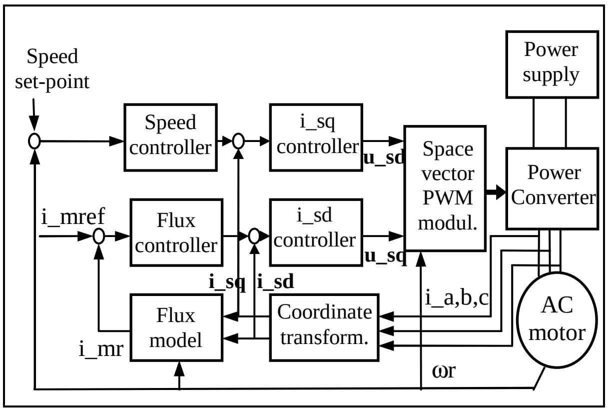

Fig.2 *Block Diagram of a Three Phases Asynchronous Motor Driver Using a FOC Structure*

1.2 Control Algorithm of a parallel active power filter

Shunt active power filters allow the compensation of current harmonics and unbalance, together with power factor correction, and can be a much better solution than conventional approach (capacitors and passive filters).

In active power filter's design and control, instantaneous reactive power theory was often served as the basis for the calculation of compensation current [2]. In this theory, the mains voltage was assumed to be an ideal source in the calculation process. The *pq* theory, since its proposal, has been applied in the control of three-phase active power filters.

The digital signal processor is synchronized with the mains voltage U_1 (see Fig. 3) and the algorithm is performed N-times per the mains period. The sampling period can be calculated with the formula:

$$T_P = \frac{T_S}{N} \tag{1}$$

where: T_S – period of the mains voltage,
$f_S = T_S^{-1}$ – frequency of the mains voltage,
N – total number of samples per mains period.

Three-phase current signals can be transformed into the equivalent two-phase representation. The transformation (1-2-3 → α-β-0) from the three-phase current signals i_{L1}, i_{L2}, i_{L3}, to the two-phase $i_{L\alpha}$, $i_{L\beta}$ with an additional neutral signal i_{L0} can be written in a matrix form as:

$$\begin{bmatrix} i_{L\alpha} \\ i_{L\beta} \\ i_{L0} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \\ 1/\sqrt{6} & 1/\sqrt{6} & 1/\sqrt{6} \end{bmatrix} \begin{bmatrix} i_{L1} \\ i_{L2} \\ i_{L3} \end{bmatrix} \tag{2}$$

In the next step, the two-phase signals are transformed from the rotating, to the stationary reference frame. This transformation is commonly called the reverse Park transformation and can be digitally calculated by equations:

$$\begin{cases} p_{+} = i_{L\alpha} \sin\left(\frac{2\pi n}{N}\right) - i_{L\beta} \cos\left(\frac{2\pi n}{N}\right) \\ q_{+} = i_{L\alpha} \cos\left(\frac{2\pi n}{N}\right) + i_{L\beta} \sin\left(\frac{2\pi n}{N}\right) \end{cases} \tag{3}$$

where the digital sinusoidal reference signal is given by formula:

$$\sin\left(\frac{2\pi n}{N}\right) = \sin\left(\frac{2\pi f s n T_S}{N}\right) \tag{4}$$

where: n – index of the current sample.

Signal p_+ represents instantaneous active power and signal q_+ instantaneous reactive power. The DC components of signals p_+ and q_+ are removed by a high-pass digital IIR filter.

For stabilizing the DC voltage a proportional controller is used, response of it is calculated by equation [2]:

$$\Delta U_{C12} = k_P \left(U_R - (U_{C1} + U_{C2})\right) \tag{5}$$

where:
U_{C1}, U_{C2} – voltage on capacitor C_1 and C_2, respectively,
k_P – gain of voltage controller,
U_R – DC reference voltage.

Signal ΔU_{C12} is subtracted from the component p_+

$$p_{C+} = p_+ - \Delta U_{C12} \,. \tag{6}$$

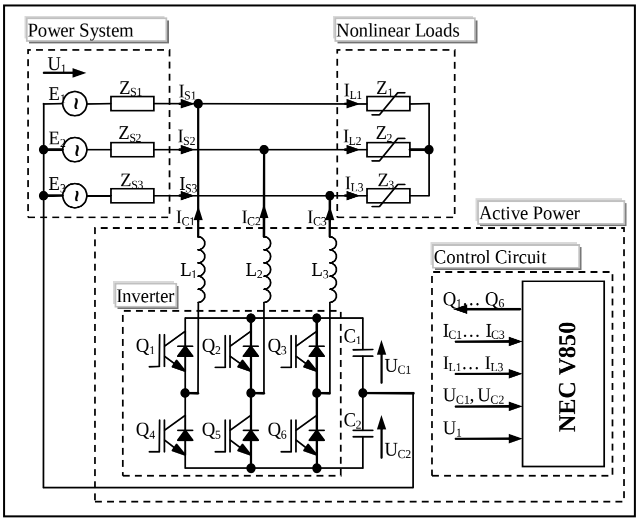

Fig.3 *Block diagram of the active power filter*

In the next step components p_{C+} and q_+ are transformed by Park transformation to the two-phase representation:

$$\begin{cases} i_{CR\alpha} = p_{C+} \sin\left(\frac{2\pi n}{N}\right) + q_{+} \cos\left(\frac{2\pi n}{N}\right) \\ i_{CR\beta} = -p_{C+} \cos\left(\frac{2\pi n}{N}\right) + q_{+} \sin\left(\frac{2\pi n}{N}\right) \end{cases} \tag{7}$$

and then transformed back to the three-phase signals

$$\begin{bmatrix} i_{CR1} \\ i_{CR2} \\ i_{CR3} \end{bmatrix} = \sqrt{\frac{3}{2}} \begin{bmatrix} 2/3 & 0 & \sqrt{6}/3 \\ -1/3 & \sqrt{3}/3 & \sqrt{6}/3 \\ -1/3 & -\sqrt{3}/3 & \sqrt{6}/3 \end{bmatrix} \begin{bmatrix} i_{CR\alpha} \\ i_{CR\beta} \\ i_{L0} \end{bmatrix} \tag{8}$$

2 NEC V850ES microcontrollers features

The algorithms presented in the subsections 1.1 and 1.2 are complex and therefore require a fast processor, able to perform the above controls with short cycle times.

The low cost, high performance families of microcontrollers designed specifically for motor control applications, such as NEC's 32bit RISC V850 with it's DSP capabilities, can be applied cost effectively to a wide range of applications, like AC and BLDC motor control, or active power filters control.

The V850ES are 32-bit single-chip microcontrollers that realize high-precision inverter control due to high-speed operation.

They have on-chip ROM, RAM, a bus interface, DMA controller, a variety of timers including a 3-phase sine-wave PWM timer for motors, serial interfaces, and peripheral functions such as A/D converters. SRAM or ROM can be connected as external memory [3]. The V850ES has an FCAN (Full Controller Area Network) controller peripheral function.

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. 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 provides multiplication and product-sum operations that can be executed in one or two clock cycles which is ideally suited for vector control algorithms
- 32-bit barrel shifter
- Memory program space: up to 512 MB linear. Data space: 4 GB linear
- Multiply instructions (On-chip hardware multiplier executing multiplication in 1 or 4 clocks)
  16 bits × 16 bits → 32 bits
  32 bits × 32 bits → 32 bits or 64 bits

Also, V850ES include features designed for inverter control applications:

- 16 bit timers for 3 phase PWM inverter control (including dead-band 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 used in both control algorithms presented above and illustrates the use of the multiplier [4].

```
dr = qs*sin(theta) + ds*cos(theta); /*equivalent C
statement*/
    mov r29,r6          theta->r6
    mov .L12,lp         store return addr.
    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 addr.
    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.

In the applications, processing of timer interrupts are used to calculate control along the d-q axis and final output of the u, v, and w phase voltage values is performed by the PWM timer function (timer AB) of V850ES.

Functional Overview of the timers

Timer ABn (TABn) and the TABn option (TABOPn) can be used as an inverter function that controls a motor. It performs a tuning operation with Timer AAx (TAAx) and A/D conversion can be started when the value of TABn matches the value of TAAx.

The following operations can be performed as inverter control functions:

- 6-phase PWM output function with 16-bit accuracy (with dead-timer, for upper and lower arms)
- Timer tuning operation function (tunable with TAAx)
- Period setting function (period can be changed during operation of crest or valley interrupt)
- Compare register rewriting: Anytime rewrite, batch write, or intermittent rewrite (selectable during TABn operation)
- Interrupt and transfer culling functions
- Dead-time setting function
- A/D trigger timing function of A/D Converters 0 and 1 (four types of timing can be generated)
- 0% output and 100% output available
- 0% output and 100% output selectable by crest interrupt and valley interrupt
- Forced output stop function
- At valid edge detection by external pin input (INTP1/INTP3)

Configuration of the timer

The inverter control function consists of the following hardware:

- the 6-phase PWM output can be produced with dead time by using the output of TABn (TOABn1, TOABn2, TOABn3)
- The output level of the 6-phase PWM output can be set individually.
- The 16-bit timer/counter of TABn counts up/down triangular waves. When the

timer/counter underflows and when a period match occurs, an interrupt is generated. Interrupt generation, however, can be suppressed up to 31 times.

- TAAx can execute counting at the same time as TABn (timer tuning operation function). TAAx can be set in four ways as it can generate two types of A/D trigger sources (INTTAAxCC0 and INTTAAxCC1), and two types of interrupts: on underflow interrupt (INTTABnOV) and period match interrupt (INTTABnCC0).

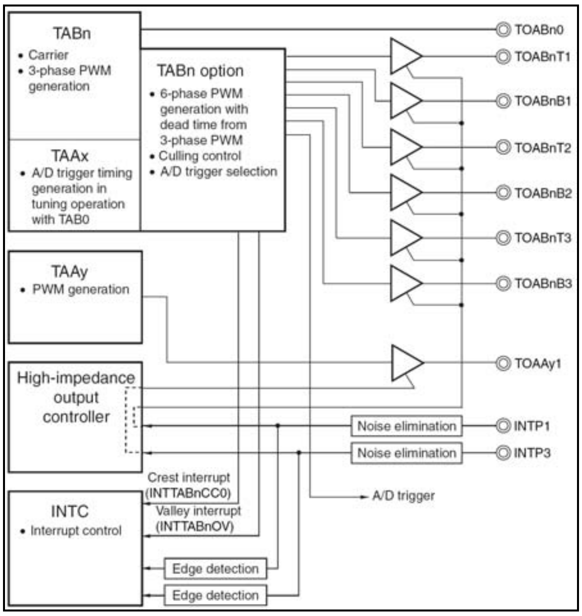

Fig.4 *Block diagram of inverter control*

3. Program structure for motor control

3.1 Speed control

The target current value is calculated based on the differential between the target speed (previously set or calculated) and the current speed. In the application circuit example, PI control is used in the speed control block. The equations used for speed control are shown below [5].

$o\_speed = kp \times (o\_position - now\_position)$

Remark o_speed: Target speed
kp: Position-proportional gain
o_position: Target position
now_position: Current position

In the application circuit example, PI (Proportion, Integral) control is used in the speed control block. The equations used for speed control are shown below.

$d\_speed = o\_speed - now\_speed$
$o\_iqp = ksp \times d\_speed$
$o\_iqi (n) = o\_iqi (n - 1) + (ksi \times d\_speed (n - 1))$
$o\_iq = o\_iqp + o\_iqi (n)$

Remark d_speed: Differential between target speed and current speed
o_speed: Target speed
now_speed: Current speed
o_iqp: Speed-proportional component current value
ksp: Speed-proportional gain
o_iqi: Speed-integral component current value
ksi: Speed-integral gain
o_iq: Target current value
n: Current component
n−1: Previous component

3.2 Current control

The target voltage for the d-q axis is calculated based on the current return value converted for the d-q axis and the target current value.

For current control, the d-axis current (id) and q-axis current (iq) are converted via the following equations to obtain a target voltage for each axis.

$o\_vd = ki \times (-id)$
$o\_vq = ki \times (o\_iq - iq)$

Remark o_vd: Target d-axis voltage
ki: Current-proportional gain
id: d-axis current value
o_vq: Target q-axis voltage
o_iq: Target q-axis current value
iq: q-axis current value

id and iq are obtained by converting current values for the u and v phases to d-q axis coordinates. The equations are shown below.

$id = iv \times \cos\theta r - iu \times \cos (\theta r - 2\pi/3)$
$iq = iv \times \sin\theta r - iu \times \sin (\theta r - 2\pi/3)$

Remark id: d-axis current value
iq: q-axis current value
iu: u-phase current value
iv: v-phase current value
θr: Angle of rotation

3.3 Three-Phase Voltage Conversion

The equations used to convert voltage values (vd and vq) calculated for the d-q axis to 3-phase coordinates are shown below.

$o\_vu = o\_vd \times \cos\theta r - o\_vq \times \sin \theta r$
$o\_vv = o\_vd \times \cos (\theta r - 2\pi/3) - o\_vq \times \pi \sin (\theta r - 2\pi/3)$
$o\_vw = -o\_vu - o\_vv$

Remark o_vu: Target u-phase voltage
o_vv: Target v-phase voltage
o_vw: Target w-phase voltage
o_vd: Target d-axis voltage
o_vq: Target q-axis voltage
θr: Angle of rotation

3.4 PWM conversion

The on-chip PWM function of the V850ES is used to perform PWM output of the calculated 3- phase AC voltage.

The calculated target voltage is output by a 16-bit timer (TM00) that is used for the 3-phase sine-wave PWM inverter of the V850ES.

The TM00 register operates as a up/down timer or up timer. The cycle is controlled by compare register. TM00 register start/stop and timer prescaler division are controlled by the control register 00 (TMC00).

The timer TM00 features three waveform modes as comparative waveforms for PWM generation: Symmetrical triangular waves, Asymmetrical triangular waves, Saw-tooth waves.

3.5 Read of A/D values

The NEC V850ES microcontrollers have an Analog to Digital Converter with 10 to 24 inputs channels (depends of the version).

The A/D Converter has the following features.

- 10-bit resolution
- Successive approximation method
- The following functions are provided as operation modes.
  - Continuous select mode
  - Continuous scan mode
  - One-shot select mode
  - One-shot scan mode
- The following functions are provided as trigger modes.
  - Software trigger mode
  - Timer trigger mode
  - Hardware trigger mode
- Power-fail monitor function (conversion result compare function)
- Self diagnostic function
- Discharge function

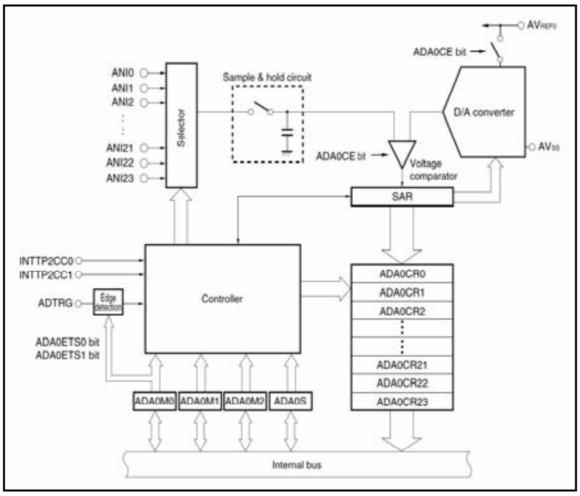

Fig.5 *Block diagram of A/D converter*

A/D conversion of the phase currents and voltages value begins at the start of interval interrupt servicing and the converted values are inputs and used in feedback processing.

4. Conclusions

This paper has shown that vector control of AC motors and active filters control are computationally intensive processes 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 also a range of micros from 8 to 32 bit that is ideally suited to all types of inverter control. This coupled with a dedicated technical support team, numerous application notes and reference platforms offers the user a comprehensive control solution.

Being a product line family of singlechip microcontrollers designed for automotive, they can be use in applications like high speed BLDC motors control, necessary in the next generations of cars with fuel cells and electric motors.

Such an application is already started by the authors and will be presented in a following paper.

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