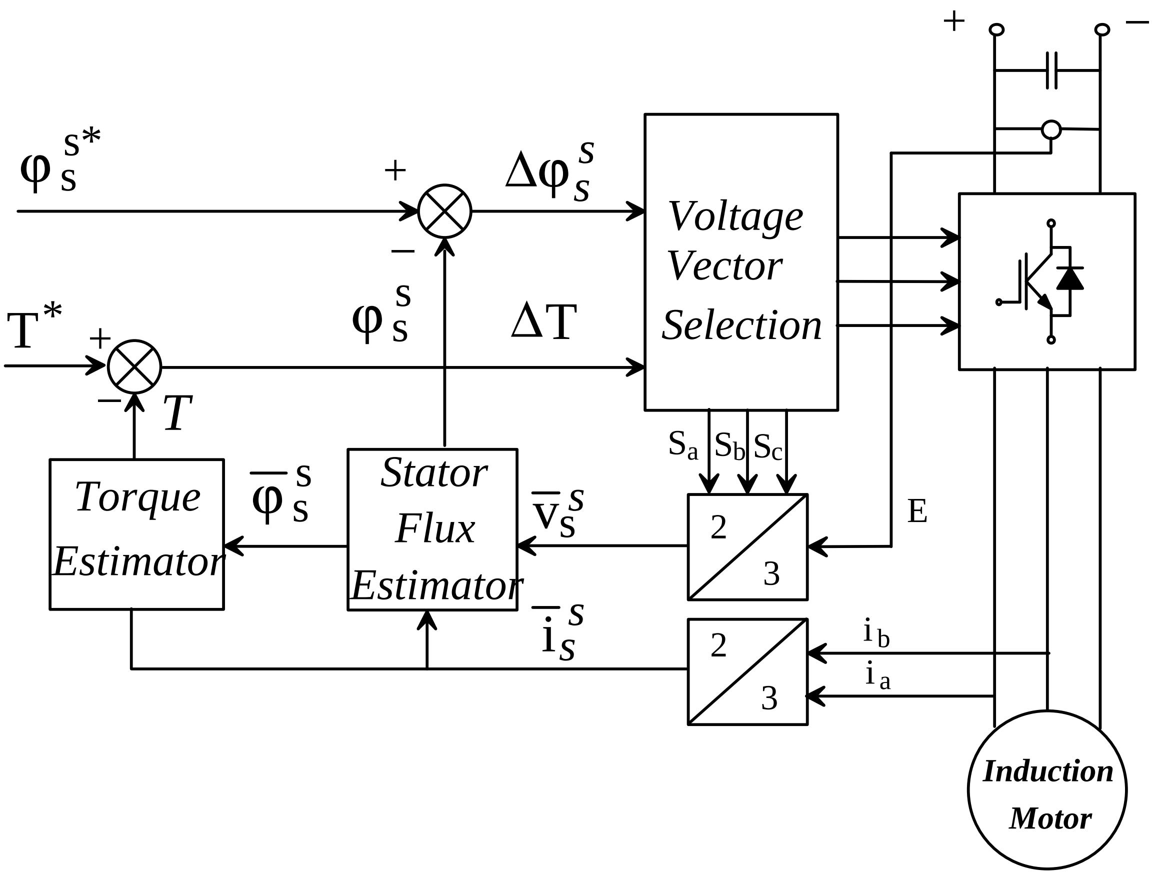
DIRECT TORQUE CONTROL FOR INDUCTION MOTOR DRIVES

MAIN FEATURES OF DTC

- Decoupled control of torque and flux
- Absence of mechanical transducers
- Current regulator, PWM pulse generation, PI control of flux and torque and co-ordinate transformation are not required
- Very simple control scheme and low computational time
- Reduced parameter sensitivity

BLOCK DIAGRAM OF DTC SCHEME

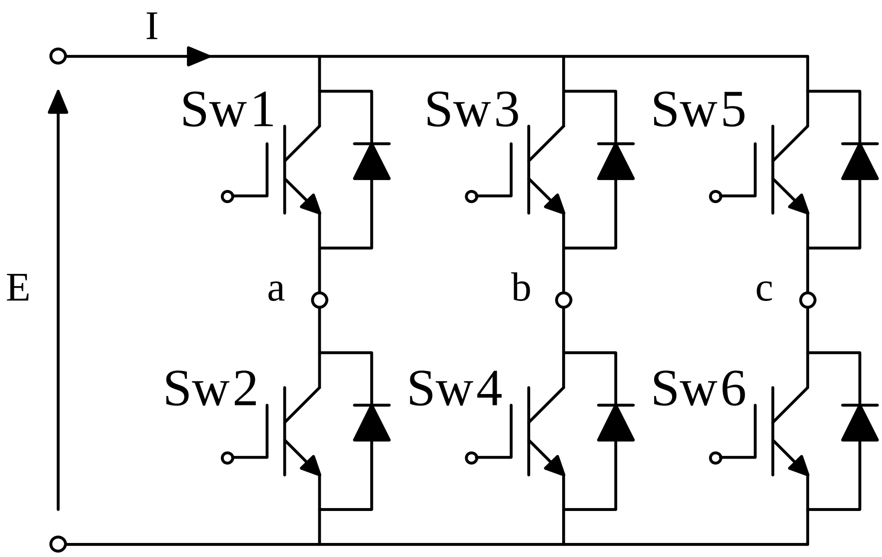


In principle the <u>DTC method</u> selects one of the six nonzero and two zero voltage vectors of the inverter on the basis of the instantaneous errors in torque and stator flux magnitude.

MAIN TOPICS

- ⇒ Space vector representation
- ⇒ Fundamental concept of DTC
- ⇒ Rotor flux reference
- ⇒ Voltage vector selection criteria
- ⇒ Amplitude of flux and torque hysteresis band
- ⇒ Direct self control (DSC)
- ⇒ SVM applied to DTC
- ⇒ Flux estimation at low speed
- ⇒ Sensitivity to parameter variations and current sensor offsets
- ⇒ Conclusions

INVERTER OUTPUT VOLTAGE VECTORS



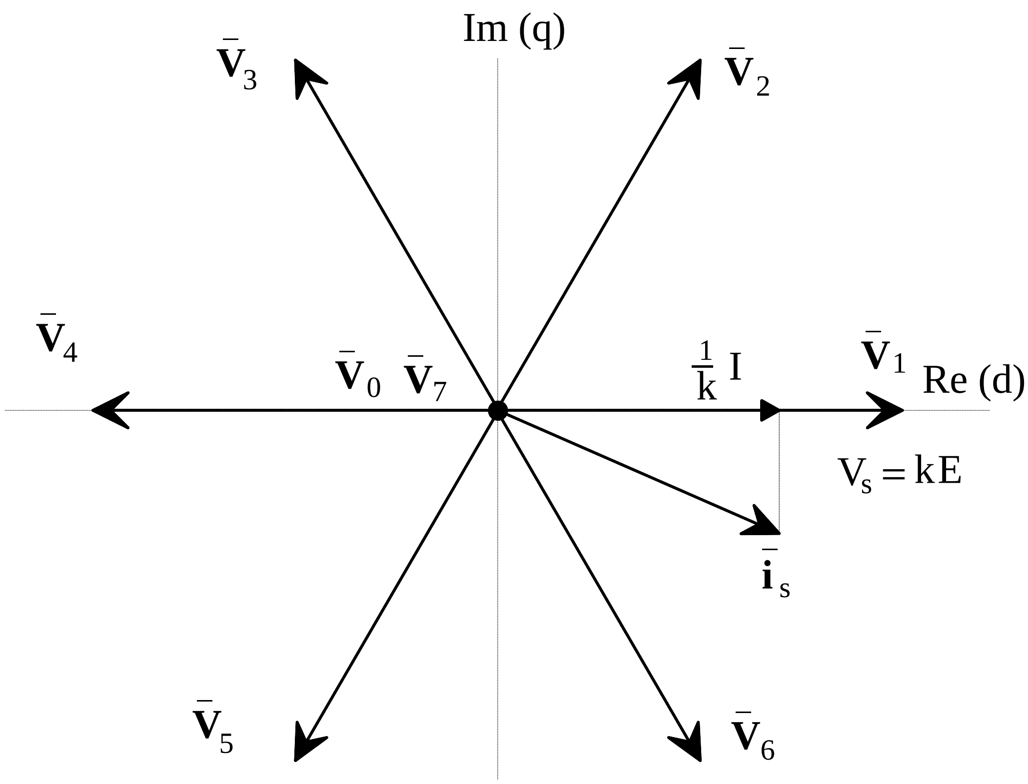
Voltage-source inverter (VSI)

For each possible switching configuration, the output voltages can be represented in terms of space vectors, according to the following equation

$$\bar{v}_s^s = \frac{2}{3}\left(v_a + v_b e^{j\frac{2\pi}{3}} + v_c e^{j\frac{4\pi}{3}} \right)$$

where v_a, v_b and v_c are phase voltages.

Sw1	**Sw2**	**Sw3**	**Sw4**	**Sw5**	**Sw6**	**$S_a(t)$**	**$S_b(t)$**	**$S_c(t)$**	$\overline{v}_k$
OFF	**ON**	**OFF**	**ON**	**OFF**	**ON**	**0**	**0**	**0**	$\overline{v}_0$
ON	**OFF**	**OFF**	**ON**	**OFF**	**ON**	**1**	**0**	**0**	$\overline{v}_1$
ON	**OFF**	**ON**	**OFF**	**OFF**	**ON**	**1**	**1**	**0**	$\overline{v}_2$
OFF	**ON**	**ON**	**OFF**	**OFF**	**ON**	**0**	**1**	**0**	$\overline{v}_3$
OFF	**ON**	**ON**	**OFF**	**ON**	**OFF**	**0**	**1**	**1**	$\overline{v}_4$
OFF	**ON**	**OFF**	**ON**	**ON**	**OFF**	**0**	**0**	**1**	$\overline{v}_5$
ON	**OFF**	**OFF**	**ON**	**ON**	**OFF**	**1**	**0**	**1**	$\overline{v}_6$
ON	**OFF**	**ON**	**OFF**	**ON**	**OFF**	**1**	**1**	**1**	$\overline{v}_7$



Inverter output voltage vectors

GENERAL REPRESENTATION OF THE INVERTER OUTPUT VOLTAGE VECTORS

The inverter switching configuration defines the line-to-line voltages by

$$v_{ab} = E\left[S_a(t) - S_b(t)\right]$$

$$v_{bc} = E\left[S_b(t) - S_c(t)\right]$$

$$v_{ca} = E\left[S_c(t) - S_a(t)\right]$$

In the absence of omopolar generators and assuming a symmetrical machine yields

$$v_a + v_b + v_c = 0$$

and the line-to-neutral voltages can be expressed as a function of two line-to-line voltages

$$v_a = \frac{2v_{ab} + v_{bc}}{3}$$

$$v_b = \frac{v_{bc} - v_{ab}}{3}$$

$$v_c = \frac{-v_{ab} - 2v_{bc}}{3}$$

Then, by substitution we obtain

$$v_a = E\,\frac{2S_a(t)-S_b(t)-S_c(t)}{3}$$

$$v_b = E\,\frac{2S_b(t)-S_a(t)-S_c(t)}{3}$$

$$v_c = E\,\frac{2S_c(t)-S_a(t)-S_b(t)}{3}$$

Using these equations the space vector of the phase voltages becomes

$$\bar{v}_s^s = \frac{2}{3}\,E\left[S_a(t)+S_b(t)e^{j\frac{2\pi}{3}}+S_c(t)e^{j\frac{4\pi}{3}}\right]$$

The power balance equation, neglecting the inverter losses, leads to

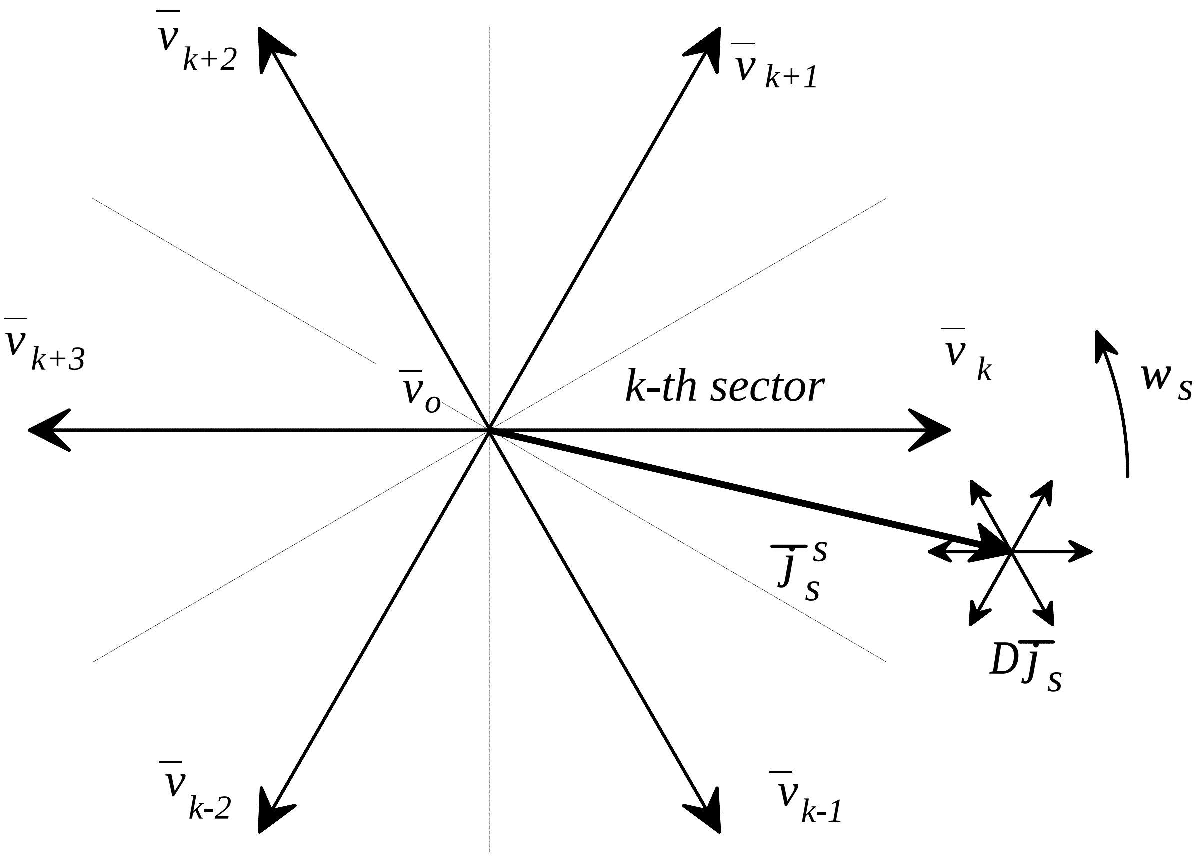
$$I = \frac{2}{3}\left[S_a(t)+S_b(t)e^{j\frac{2\pi}{3}}+S_c(t)e^{j\frac{4\pi}{3}}\right]\bullet\ \bar{i}_s^s$$

FUNDAMENTAL CONCEPT OF DTC

STATOR FLUX VECTOR VARIATION

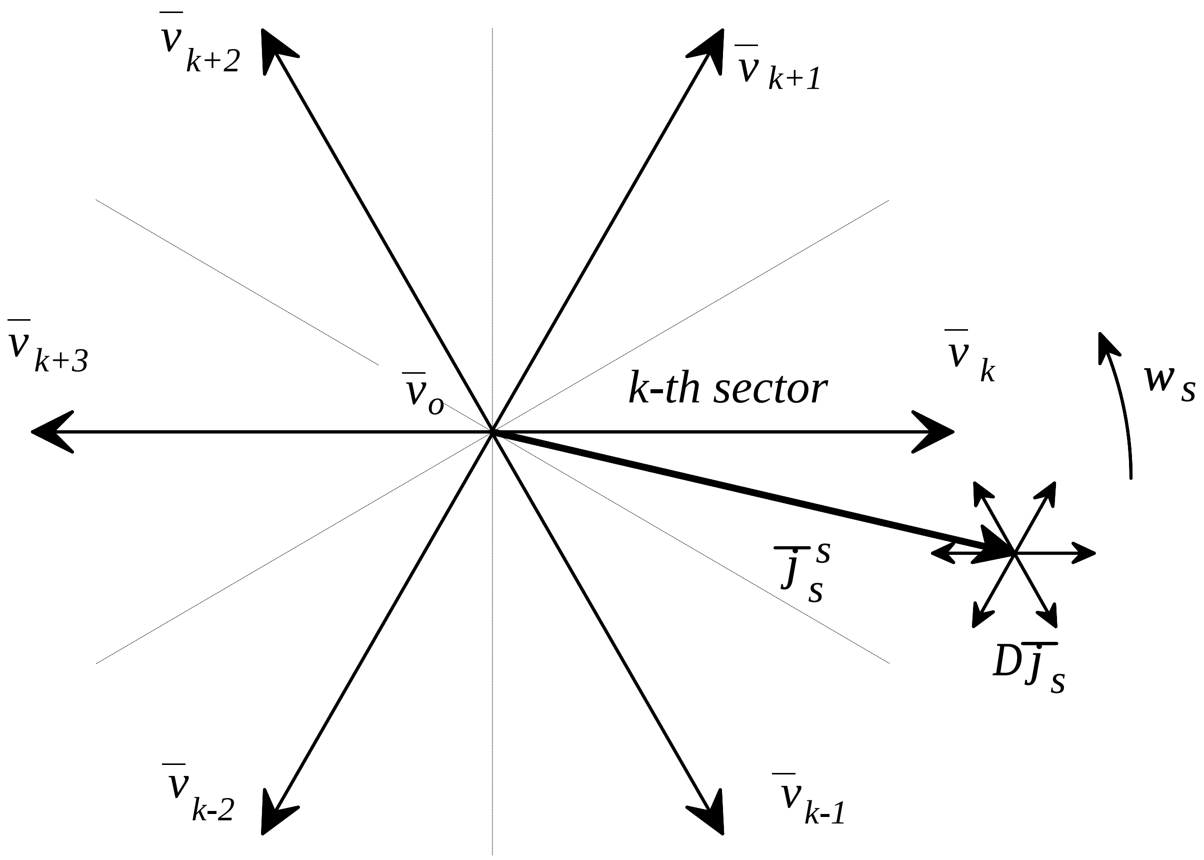
Assuming the voltage drop $R_s \bar{i}_s^s$ small, the stator flux is driven in the direction of the stator voltage $\bar{v}_s^s$

$\Delta\bar{\varphi}_s^s \cong \bar{v}_s^s \, \Delta T$, where ΔT is the sampling period



The flux variation is proportional to E, ΔT and has the same direction of the voltage vector applied.

VOLTAGE SPACE VECTOR NAMES



v_k	Þ	*radial positive voltage vector*	
v_{k+1}	Þ	*forward positive*	“
v_{k+2}	Þ	*forward negative*	“
v_{k+3}	Þ	*radial negative*	“
v_{k-1}	Þ	*backward positive*	“
v_{k-2}	Þ	*backward negative*	“
v_0 *e* v_7	Þ	*zero*	“

ROTOR FLUX AND TORQUE VARIATION

From the general equations written in the rotor reference frame, we can derive

$$\overline{\varphi}_r^r = \frac{L_m}{L_s} \frac{1}{1+s\sigma\tau_r} \overline{\varphi}_s^r \qquad \text{with} \qquad s = 1 - \frac{L_m^{\ 2}}{L_s L_r}$$

This equation shows the nature of rotor flux dynamic response for changes in stator flux

$$T = \frac{3}{2} p \frac{L_m}{\sigma L_s L_r} \overline{\varphi}_s^r \bullet j\, \overline{\varphi}_r^r = \frac{3}{2} p \frac{L_m}{\sigma L_s L_r} \varphi_s\, \varphi_r \sin \vartheta_{sr}$$

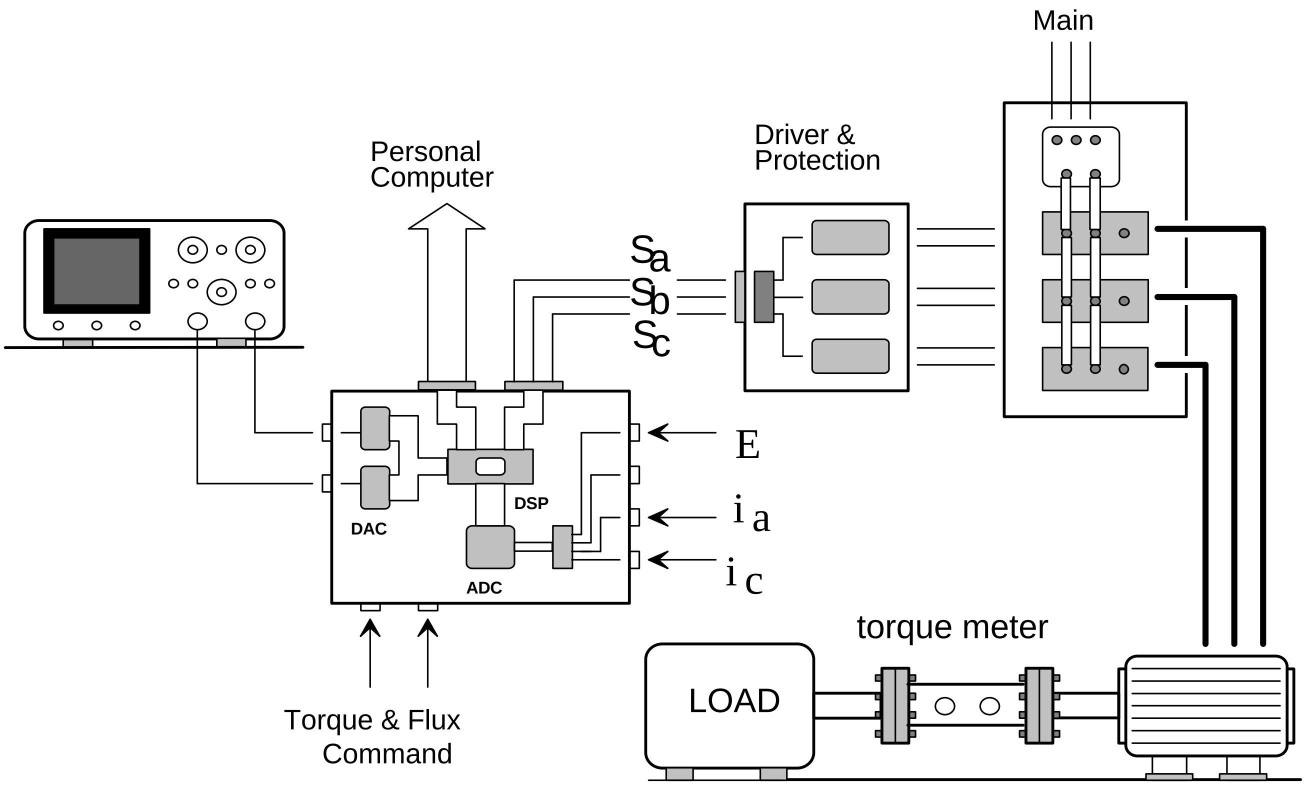
Any stator flux vector variation determines a torque variation on the basis of two contributions

I) The variation of the stator flux magnitude

II) The variation of the stator flux phase angle with respect to rotor flux

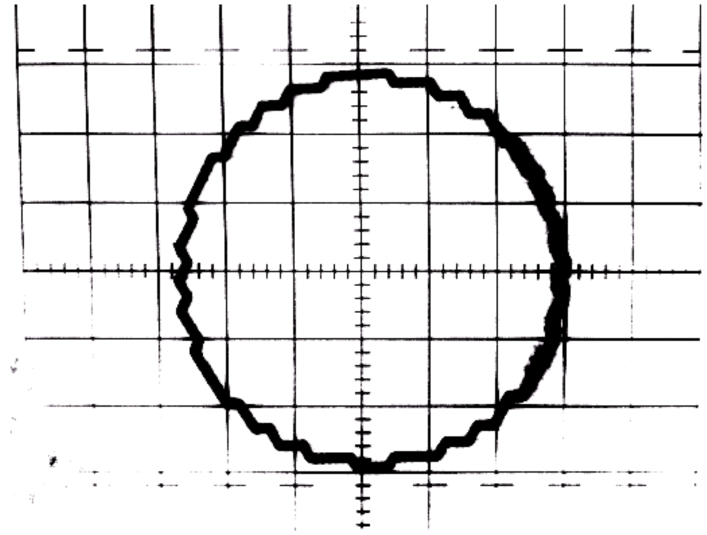
Any command which causes the flux angle ϑ_{sr} to change will determine a quick torque variation.

EXPERIMENTAL SET-UP

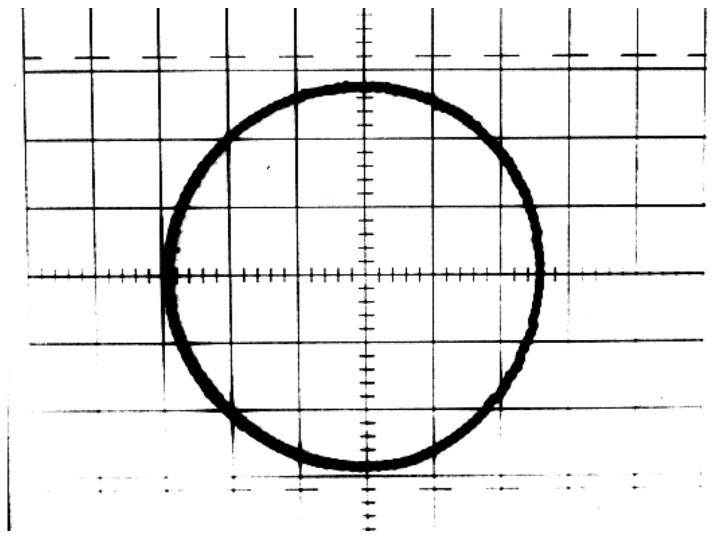


- IGBT inverter, 1000 V, 50 A
- DSP TMS320E15, 20 MHz.
- 1 MHz, 8-channel, 12-bit A/D converter
- 2-channel, 16-bit D/A converter

EXPERIMENTAL RESULTS



Stator flux locus, steady state, w_m = 100 rad/s



Rotor flux locus, steady state, w_m = 100 rad/s

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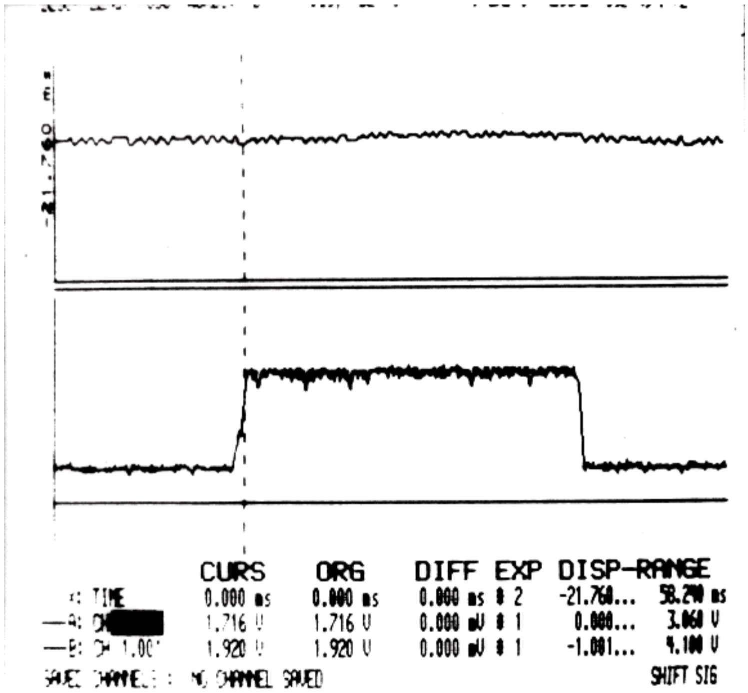

Estimated d and q components of stator flux during the response to a torque command alternating between 50% and 200% of the rated torque

<u>These results show that the decoupling between the stator flux components can be achieved controlling directly the magnitude of the stator flux</u>