# A. C. INVERTER DRIVE WITH FIELD ORIENTED CONTROL AND OPTIMUM PWM STRATEGY

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## Abstract

The PWM procedures which are minimizing the losses origining from the upper harmonic currents can be applied at field oriented controls as well. Though at the execution of the field oriented control there is no possibility for the sudden change of phase angle position of the voltage vector the time duration of the transient process and the quality characteristics of it equal practically at the accurate execution of field oriented control strategy.

## Introduction

PWM controls which are minimizing the losses origining from the upper harmonic currents of the induction motor start to appear in a considerable number in the implemented drives. Drives optimized from this point of view produce a minimum warming up of the motors at basic harmonic voltage (flux), insignificant low order torque components and smaller current peaks too as other control strategies. The optimum control has been applied up to now only in such drives, in which the dynamic properties didn't play an important role. It is expedient to enjoy the recounted advantages of the optimum control at such drives too which require fast dynamics, but if doing so the drives have to be supplied not only with numerous control circuits but even optimum PWM strategy has to be adopted to the new requirements.

## Realization of the Optimum PWM Procedures

The basic idea of the optimum control is illustrated by Fig. 1. There in a stationary $XY$ coordinate system the $\bar{\psi}$ motor stator flux and its $\bar{\psi}_1$ basic harmonic vector pathes are drawn for a symmetry angle of 60°. It can be seen,

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that out of the possible seven voltage vectors (which correspond the various possible connections of the motor phases to the d. c. bars) in the selected 30° the application of the $\bar{U}_I = U$, $\bar{U}_{II} = Ue^{j\pi/3}$ and $\bar{U}_{VII} = 0$ voltage vectors is only expedient. If we take the commutation frequency permissible for the inverter and required basic harmonic voltage, then with this conditions by appropriate control the $\bar{\psi}$ vector path has to be brought as close as possible to the $\bar{\psi}_1$ basic harmonics value, because the difference of the two fluxes is determining the upper harmonic currents.

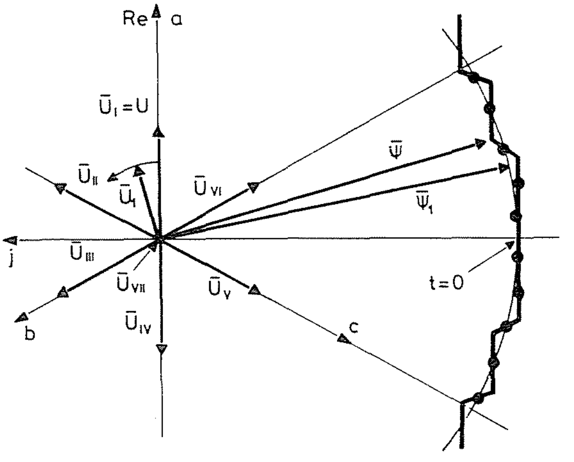


*Fig. 1.* Voltage vectors and stator flux vector path

We can basically speak about two optimum procedures. In the first one the commutation angles belonging to the optimum *PWM* and the layout of the phases of the motor for the bars are precalculated and then being built in into the memory [1—3]. In the second one the commutation angles and the motor circuits are realised and calculated by a $\mu$P system with on-line calculation [4—6]. The upper harmonic losses belonging to various commutation numbers are indicated in Fig. 2. as a function of the basic harmonic voltage. In Figure 2. $\gamma$ is the number of commutations belonging to 1/6 period of the basic harmonic.

Fig. 3. displays the sequence of motor voltage vectors giving optimum control. In general as the function of the basic harmonic voltage—for a given commutation number—with three various switching sequences the needed frequency range can be comprehended. These were marked in Fig. 2. and Fig. 3. by identifying numbers.

The control built up in such way can change the motor voltage in general in steps of 1%, having larger memory capacity even 0,5% can be reached, which satisfies amply the general plant drives. The commutation numbers are

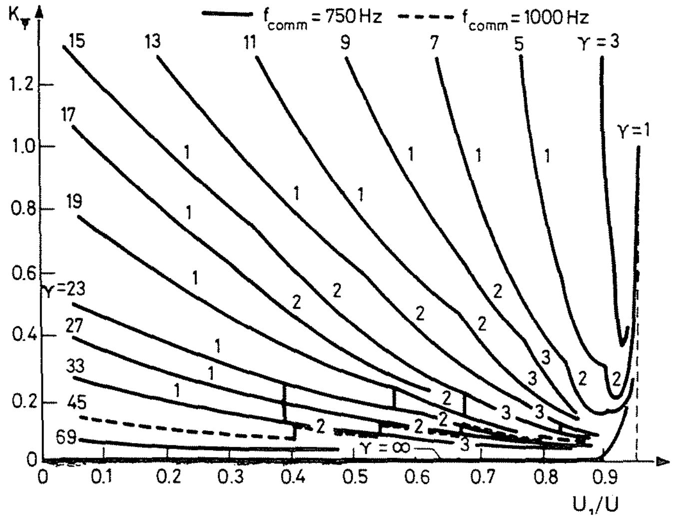


*Fig. 2.* Motor harmonic losses versus fundamental voltage component

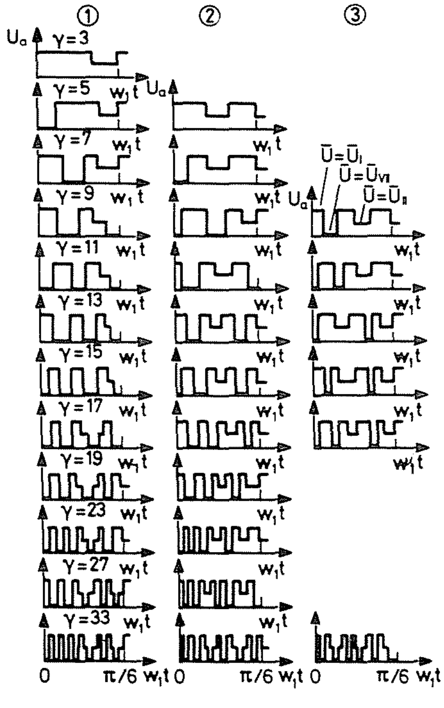


*Fig. 3.* Motor phase voltage-time function for different number of commutations

changed stepvise based on the given maximum commutation frequency, as it is given as an example in Fig. 2. presuming for one element 1000 Hz maximum commutation frequency (for the whole inverter in such case the maximum commutation frequency will be $6 \times 1000 = 6$ kHz).

The memory needed for the control depends upon the applied commutation numbers (i. e. from the permissible commutation frequency). If the maximum commutation number is $\gamma = 45$ and 1% voltage steps are satisfactory then the memory capacity needed for the control will be about 12 kby.

The optimum control programmed in anticipation can be realized in such a way too, that the commutation angles are fixed in the memory in greater voltage steps and the intermediate ones are determined by interpolation. But in practice this control did not come into general use.
The on-line execution of the optimum control needs more complicated calculations [4, 5, 6] and is in general never as accurate as the one programmed in anticipation. One possible solution of it can be the following.
Let the required basic harmonic voltage be (Fig. 1.)

$$\bar{U}_1 = U_1 e^{jw_1 t} \tag{1}$$

where $w_1$ is the required angular frequency. This voltage has to be produced in the time interval shown in Fig. 1. with voltage vectors $\bar{U}_I$, $\bar{U}_{II}$ and $\bar{U}_{VII} = 0$. In a very short $\Delta t$ time the process can be taken into consideration as such as well, that the mentioned vectors are switched on the motors one by one for $\alpha_1$, $\alpha_2$ and $\alpha_3$ part time, therefore

$$U_1 e^{jw_1 t} = \alpha_1 \bar{U}_I + \alpha_2 \bar{U}_{II} + \alpha_3 \bar{U}_{VII} = \alpha_1 U + \alpha_2 U e^{j\frac{\pi}{3}} \tag{2}$$

or in the components of a stationary coordinate system

$$\begin{aligned} U_1 \cos w_1 t &= \alpha_1 U + \frac{\alpha_2}{2} U = \left(\alpha_1 + \frac{\alpha_2}{2}\right) U , \\ U_1 \sin w_1 t &= \frac{\sqrt{3}}{2} \alpha_2 U . \end{aligned} \tag{3}$$

From this

$$\begin{aligned} \alpha_2 &= \frac{U_1}{U} \sin w_1 t , \\ \alpha_1 &= \frac{U_1}{U} \cos w_1 t - \frac{\alpha_2}{2} . \end{aligned} \tag{4}$$

The equations above give the values of $\alpha_1$ and $\alpha_2$ i. e. that in $\Delta t$ time intercal for $\alpha_1 \Delta t$ time $\bar{U}_I$, for $\alpha_2 \Delta t$ time $\bar{U}_{II}$, and for $\alpha_3 \Delta t$ time $\bar{U}_{VII}$ vector has to be switched to the motor. Obviously at that time many problems have to be solved:

a) In the vicinity of $t=0$ in Fig. 1. the value of $\alpha_2 \Delta t$ shows itself frequently smaller, than the permissible computation time, therefore in this step $\alpha_2=0$ has to be applied in Equation (4). In such case the received $\alpha_2$ values have to be accumulated as long such a value is received which can be executed. But from Fig. 1. it can be seen this as well that for $t<0$ times such situations have to be seen in advance, thus for the first calculation where in time interval $-\frac{\pi}{6}<t<0$ the received value of $\alpha_2$ does not offer the possibility of execution, there this value has to be increased in such a way that the $\alpha_2$ values of the time steps lasting $t=0$ have to be added to it.

b) The time duration of one time step is determined by the switching frequency of the elements, though the too big commutation frequency—at least from the point of view of the steady state operation—doesn't make sense. It is worth to change the time of step in such a way, that the 60° symmetry of the vector parths could be held, thus if the time duration of the step is then

$$\frac{60^\circ}{w_1 \tau}=\mathrm{INT} \tag{5}$$

i. e. it should be a full number.

In this arrangement the time step $\tau$ can be changed as a function of the $w_1$ fundamental angular frequency. But the bigger trouble is, that the time step of the impulses is given at a given $w_1$, thus the impulses follow each other with equal time step (obviously with changing $\alpha_1$ and $\alpha_2$ values). In Fig. 4. there is a comparison of the upper harmonic losses calculated for the on-line and the accurately optimized processes. It can be seen, that in the case of

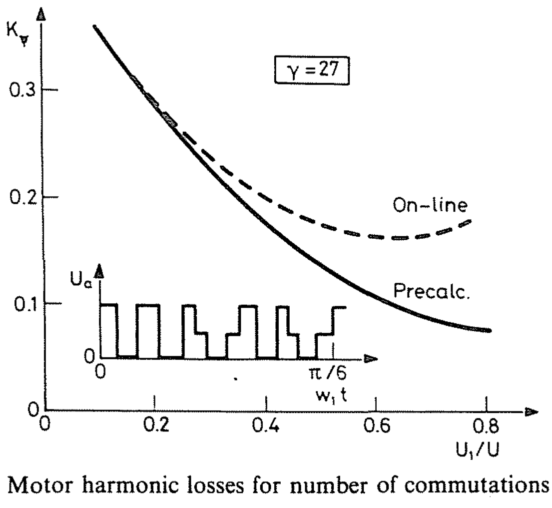


*Fig. 4.* Motor harmonic losses for number of commutations $\gamma=27$

bigger basic harmonic voltages (from 80% of the maximum output voltage) the two procedures give a significant difference, while the results for the smaller fundamental harmonics are near to each other. Thus in the range of the greater voltages it is expedient to change the time of steps too (longer step in the vicinity of $t=0$ and a shorter one of $t=\pm\pi/6$).

## Requirements of the Field Oriented Control

It is well known, that at the field oriented control of induction motors the Park vector components of the motor voltage—in a coordinate system which is fixed to the rotor flux—can be determined by the following equations:

$$\begin{aligned} U_x &= i_x R - i_y W_1 L' + \frac{d\psi_r}{dt} + L' \frac{di_x}{dt}, \\ U_y &= i_y R + i_x W_1 L' + W_1 \psi_r + L' \frac{di_y}{dt}. \end{aligned} \tag{6}$$

At variation of torque the $\mathbf{U}_y$ voltage component (Fig. 5. a, b), at the variation of the $\psi_r$ rotor flüx the $\mathbf{U}_x$ voltage are changed. For the intensive dynamic the variations must be very fast. E. g. at the control of the torque the variation of $i_y$ current is defined by $T' = L'/R_r$ time constant, the value of which is 20—40 ms-s.

If the process has to be speeded up then the transfer function of the subordinate current control loop has to chosen in such a way, that the time constant of the current change should be 1—5 ms-s. This can be achieved by intensive temporary increas of $\mathbf{U}_y$ voltage. Correspondingly voltage $\mathbf{U}_y$ may change in a sudden and therefore the phase position of the resultant voltage will change too. Similar process is caused by the change of the rotor flux, but in such case $\mathbf{U}_x$ changes faster and $\mathbf{U}_y$ slower (Fig. 5. c, d). It can be seen from the investigations carried out above, that at field oriented control the absolute value of the motor terminal voltage and its phase angle should be fast changeable. At the application of optimum *PWM* the variation of the absolute value does not cause particular difficulties. For the control programmed in advance the angles programmed for one commutation number have to be programmed for a larger voltage range, as for one given speed a larger voltage range has to be comprehended. Applying on-line optimum *PWM*, the fast variation of the voltage amplitude can be solved without any difficulty. But the fast variation of the voltage phase position causes difficulties. It is a lucky situation, that the fast variation of the phase angle is only at the beginning of the transient necessary and with the application of base signal integrators the sudden change of phase angle is avoidable. This influences

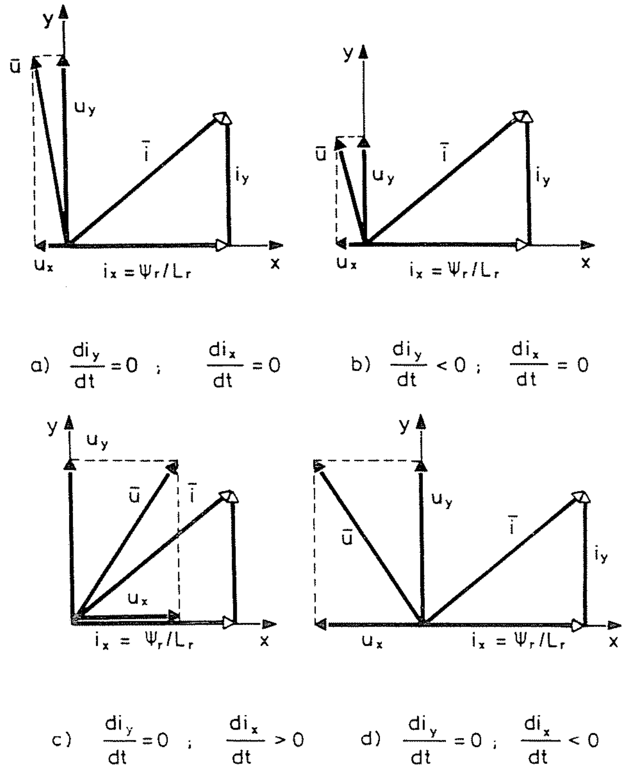


*Fig. 5.* Voltage-vector before and at the beginning of the transient process

only to a small extent the formation of the transient process. Fig. 6. shows the results of the computer aided investigation. In Figure "*a*" curves valid for the accurate field oriented control, in Figure "*b*" curves valid for the

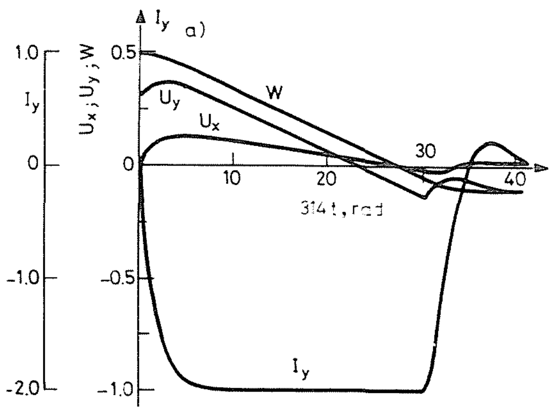


*Fig. 6/a*

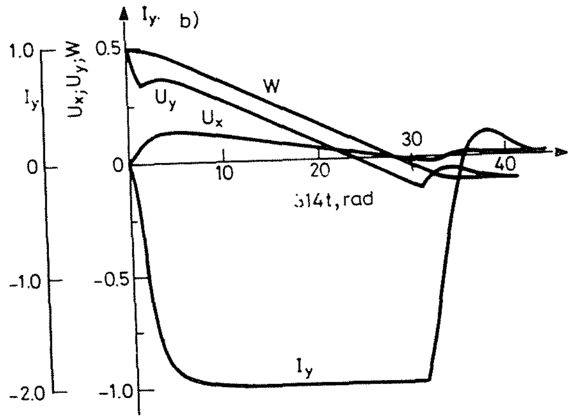


*Fig. 6/b* Field oriented control. At the reversal of rotation from $W=0,5$ to $W=-0,1$; *a*) Accurate control; *b*) With base signal integrator; Motor parameters are (p. u.) $R=R_r=0,02$; $L'=0,16$; $L=2,0$; $T_{start}=0,3$ sec

optimalised *PWM* control are represented. At the latter it was presumed the control is processed by the voltage amplitude as well as the $w_1$ angular frequency which is positioned into a steady state coordinate system. At the same time a base signal integrator is applied as well.

It can be seen, that the difference is negligible. Though it has to be noted, that within the angular frequency of the voltage vector the phase angle variation of the voltage vector in the coordinate system rotating with $\psi_r$ has to be taken into consideration:

$$w_1 = W + \frac{I_y R_r}{\psi_r} + \frac{d\alpha}{dt}. \tag{7}$$

Working out of the real system is under process based on the computer aided investigation.

## *List of symbols*

$L'$ – stator transient inductance
$L$ – stator inductance
$R$ – stator resistance
$R_r$ – rotor resistance

$W_1$—angular velocity of the coordinate system fixed to the rotor flux vector
$w_1$— angular velocity of voltage vector in steady state coordinate system
$W$— rotor angular velocity
$K_\psi$—motor harmonic losses in p. u. ($K_\psi = 1$ for the simple inverter)
$U = \frac{2}{3} U_{dc}$ ($U_{dc}$ — d. c. supply voltage).

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