

Model of Voltage Source Inverter for Estimation Methods with Observers

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Abstract— The pulse-width modulation voltage source inverters are most commonly applied in frequency converters that are used for supplying AC motors. At present, the importance of the so-called sensorless control of AC drives is growing. More common sensorless methods are methods working with the mathematical models of machines. The mathematical models of the AC motor that are used in sensorless control methods with different types of observers and estimators require knowledge of stator currents and voltages. The paper describes a model of the voltage source inverter with the possibilities of the compensation non-linear effects such as dead-time and the voltage drop on a power switching device.

1. INTRODUCTION

AC motors are often preferred choice in variable-speed drive applications. For high performance, it is possible to use a vector control or direct torque control of the AC motor. The modern control methods, for example the sensorless control, soft computing methods, use different mathematical models of the AC motors. The essence of the model based methods is the use of a particular algorithm for calculation of the speed and rotor position from known or measured variables such as stator currents and voltages. The values of stator currents and voltages can be obtained by direct measurement using current and voltage sensors at the terminals of the AC motor [1, 2].

2. VOLTAGE SOURCE INVERTER

For a supplying induction motor, there is suitable an indirect frequency converter with a voltage DC link (see Fig. 1). Power semiconductor switches S1 to S6 are realized by modern power semiconductor devices, for example IGBTs, MOSFETs, IGCTs [3, 4].

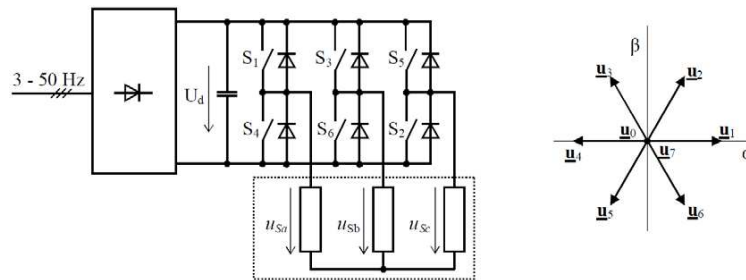


Figure 1: Block scheme of the indirect frequency converter with the voltage DC link.

In Table 1, there are described all switching combinations and stator voltage values that can occur at different phases of the AC motor (see Fig. 1).

Table 1: Stator voltages and switching combination of the voltage source inverter.

Voltage vector	$\underline{u}_0$	$\underline{u}_1$	$\underline{u}_2$	$\underline{u}_3$	$\underline{u}_4$	$\underline{u}_5$	$\underline{u}_6$	$\underline{u}_7$
Switches	S_4, S_6, S_2	S_1, S_6, S_2	S_1, S_3, S_2	S_4, S_3, S_2	S_4, S_3, S_5	S_4, S_6, S_5	S_1, S_6, S_5	S_1, S_3, S_5
[Combination]	[000]	[100]	[110]	[010]	[011]	[001]	[101]	[111]
u_{Sa}	0	$2/3 U_d$	$1/3 U_d$	$-1/3 U_d$	$-2/3 U_d$	$-1/3 U_d$	$1/3 U_d$	0
u_{Sb}	0	$-1/3 U_d$	$1/3 U_d$	$2/3 U_d$	$1/3 U_d$	$-1/3 U_d$	$-2/3 U_d$	0
u_{Sc}	0	$-1/3 U_d$	$-2/3 U_d$	$-1/3 U_d$	$1/3 U_d$	$2/3 U_d$	$1/3 U_d$	0
$u_{S\alpha}$	0	$2/3 U_d$	$1/3 U_d$	$-1/3 U_d$	$-2/3 U_d$	$-1/3 U_d$	$1/3 U_d$	0
$u_{S\beta}$	0	0	$1/\sqrt{3} U_d$	$1/\sqrt{3} U_d$	0	$-1/\sqrt{3} U_d$	$-1/\sqrt{3} U_d$	0

The table shows that the voltage source inverter is able to provide eight correct switching combinations, which eight voltage vectors $\underline{u}_0$ to $\underline{u}_7$ based on the theory of complex vectors correspond (see Fig. 1).

3. VSI MODEL RESPECTING VOLTAGE DROPS ON SWITCHING ELEMENTS AND DEAD TIMES

The VSI model requires knowledge of stator currents and voltages, whose values can be obtained by direct measurement using sensors currents and voltages at the terminals of the AC motor (see Fig. 2).

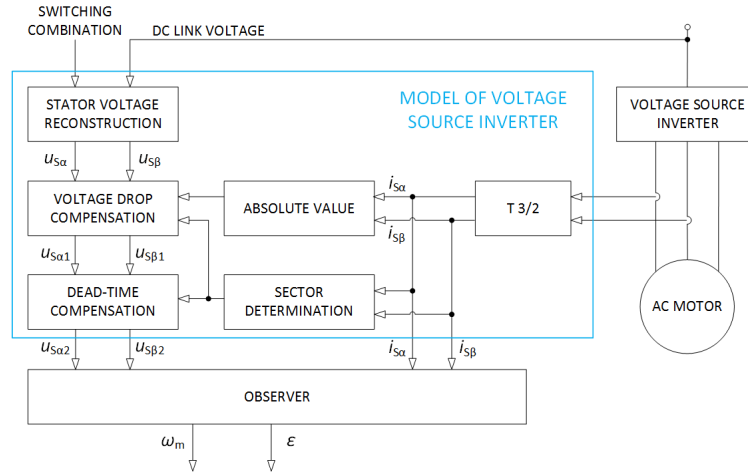


Figure 2: Block diagram of the processing and compensation measured values for the observer.

For the measurement of the phase stator currents, the situation is simpler because we can measure directly the value that we need. The stator voltage generated by the PWM voltage inverter causes a ripple of the phase currents. For the control, there is not necessary to know the current waveform during switching period. It is necessary to determine the mean value of the stator currents per PWM period, not per period of the stator current. The mean value can be easily obtained using the PWM module synchronization with the AD converter. The stator currents should be scanned at the same time. From the viewpoint of the current control, there is appropriate to measure stator currents just before entry into the current control loop algorithm. Then actual data are at disposal.

The stator voltages can be estimated direct or indirect. The direct measurement requires high quality voltage sensors. At indirect method, there is used simpler voltage sensor that is connected to DC link. This voltage sensor measures DC voltage with a low frequency voltage ripple. The stator voltages are calculated using the DC link voltage and actual switching combination of the voltage source inverter.

It is known that the voltage source inverter represents generally non-linear system. The non-linearities are caused mainly by the dead-time and real properties of the power switching devices, for example a voltage drop on the power switching device. By neglecting these non-linearities, it is obvious that the calculated stator voltages are not correct at indirect method. However, the observers need correct terminal voltage of the AC motor.

3.1. Voltage Drop Compensation of the Power Semiconductor Device

IGBT transistors are used as switching elements in VSI. Their VA characteristic is shown in Fig. 3.

The collector current I_C is depending on the saturation voltage U_{CES} and temperature T . The characteristic corresponding with the known temperature is chosen for the linearization. This characteristic is replaced by linear relationship related with a threshold voltage U_{TH} and a differential resistance R_D , which corresponds with the relationship $U_{CES} = U_{TH} + R_D I_C$. The block scheme for the voltage drop compensation is shown in Fig. 4.

This is a simple vector summation of the measured voltage vector with the other two vectors. The first one is a constant for each sextant and corresponding with the threshold voltage U_{TH} . A double threshold voltage is resulting because the current flows through two power switches. The

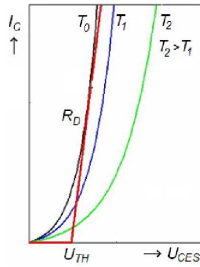


Figure 3: VA characteristics of the power switching device and their linearization.

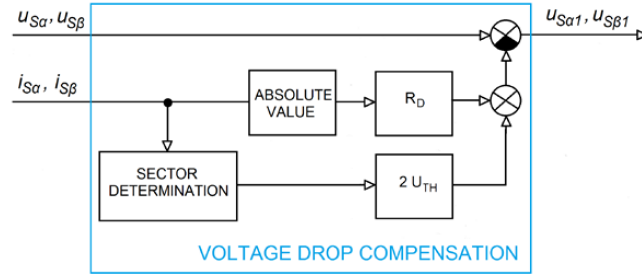


Figure 4: Principle of the switch voltage drop compensation.

second vector has an identical direction with the measured current and the size of this vector is proportional to the current. The proportionality constant is the differential resistance R_D .

The described nonlinearity appears as a superimposed sixth harmonic. This effect is applied more on machines supplied by the low voltage, because the threshold voltage can be considered constant. Fig. 5 shows experimental results before and after the voltage drop compensation during a reverse action. The simulated effect is applied when the voltage is less than approximately 4 V. It is evident that compensation is not totally perfect (indication of a hexagon). The ideal curve has a spiral shape after the compensation.

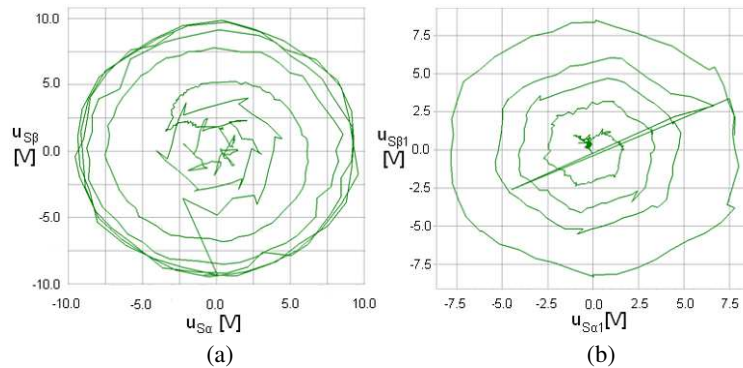


Figure 5: Voltage drop compensation ((a) before compensation, right, (b) after compensation (experimental results)).

3.2. Dead Time Compensation

The dead time is the protective time interval used during switching of transistors in a branch. Nowadays, the dead time is automatically generated by the PWM modulator between switching of power devices. The implementation of the dead time decreases the mean value of the stator voltage, because the actual pulse is shorter than required. This effect is significant for narrow pulses, when the mean value is low and around the borders of sextants. The calculation of the stator voltage using the switching combination and the DC link voltage brings a voltage distortion at the closed current loop. The stator voltage vector in α, β coordinate system generates the hexagon instead of the circle. For the low magnitude of the stator voltage vector is this effect more noticeable. Fig. 5 shows this effect, respectively it is the combination of the dead time and voltage drops of the power switching devices.

There are many ways how to eliminate the distortion caused by the dead time. One of them is the alternative to override the dead time directly in the control system. Another possibility is a correction table with the dead time values [5, 6]. Knowledge based on the sensorless control with different types of observers, e.g., Luenberger observer, offers another solution. It is very simple, undemanding in terms of an algorithm and provides interesting results. The principle is based on replacing the part of the voltage waveform where the dead time effect is reflected. This part is replaced by another curve, e.g., slope of the curve at this point. Data from the real AC drive can be seen in Fig. 6. From the voltage components $u_{S\alpha1}, u_{S\beta1}$, there are calculated the normalized voltage components $u_{S\alpha1.n}, u_{S\beta1.n}$. The time courses are replaced by tangent calculated from the

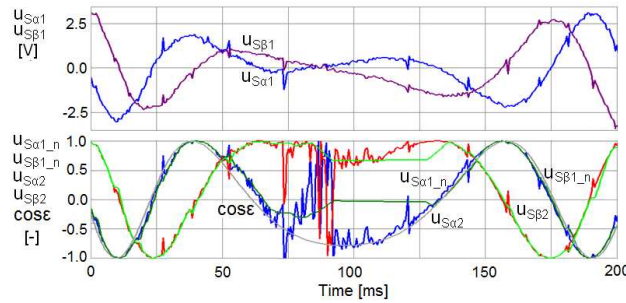


Figure 6: Experimental results of dead time compensation.

time course of the perpendicular component at short time intervals. Glitches during the dead time are effectively suppressed (see components u_{Sa2} , $u_{Sβ2}$). For comparison, the lower figure contains the cosine of the measured position angle (see $\cos \varepsilon$) [7].

4. CONCLUSIONS

The PWM voltage source inverters based upon modern switching devices has obtained a dominant position in the AC drives market. The mathematical models of the AC machine supplied by VSI and the entire control structure of the AC drive neglect non-linearities, or replace these non-linearities by linearized dynamic members. When the distorted stator voltage at the input of the linear observer is used, it is not possible to obtain on its outputs correct estimated values of quantities. After closing feedback control loops, behaviour of the AC drive can be very unstable. The easiest way is the non-linear effects to compensate. Therefore, the waveforms of the stator voltage vector components have to be corrected. Then they are much more usable and stable in the particular speed range around zero, though it still does not follow the measured quantity. It has been achieved stable operation of the sensorless control method with the Luenberger observer by applying the described voltage correction. Problems especially during speed reversing have been resolved.

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