# The Principle of Field Orientation as Applied to the New TRANSVEKTOR Closed-Loop Control System for Rotating-Field Machines

By Felix Blaschke

*When rotating-field machines are employed as drive motors, the question of torque generation and control requires special consideration. It is, for instance, possible to use the vector of the stator voltage or the vector of the stator current as the manipulated variable for the torque, depending on whether the static converter supplying the motor provides a variable voltage or a variable current. This paper describes the principle of field orientation – a new closed-loop control method for rotating-field machines [1 to 4] – by way of reference to an induction motor. It is shown how these manipulated variables must be influenced to provide instantaneous and well-damped adjustment of the torque independently of the inherent characteristics of an induction motor.*

## Field orientation with current control

The principle of field orientation can best be explained by reference to the characteristics of a d.c. motor. Fig. 1 shows a d.c. motor of the non-salient-pole type. Arranged in the stator perpendicular to each other are two windings 1 and 2. Owing to the action of the commutator, the rotating armature winding 3 produces the effect of a stationary winding. If a current $i_1$ is passed through field winding 1, a magnetic field $\Psi$ builds up in the motor (Fig. 2, left). For the generation of a torque, a current $i_3$ must also be passed through the armature winding. The armature current and field now set up forces in the directions shown. Since the axis of the armature winding is perpendicular to the field, the forces are applied with maximum leverage to the shaft. Hence, this position of the armature winding is the most favourable one for torque generation. The armature winding also builds up a field that is superimposed on the original field and is perpendicular to it. This effect is undesirable, since it turns the field out of the optimal position. For this reason, the armature field is compensated by a compensating winding 2 arranged in the stator in the same plane as the armature winding and carrying the same current, but in the opposite direction ($i_2 = -i_3$). This stator winding and the field produce in the stator a reaction torque which acts against the armature. The currents and the field may be represented by the vector diagram* shown on the right in Fig. 2. In a d.c. machine, therefore, current $i_1$ forms the field and currents $i_2$ and $i_3$, together with the field, form the torque.

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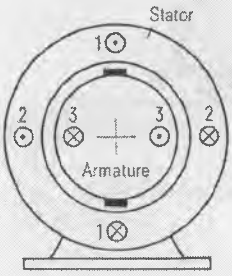
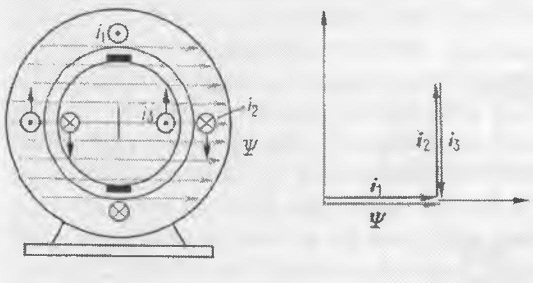
* For a definition as space vectors due to KOVACS and RACZ see [5]. Space vectors and matrices are denoted by boldface letters.

In an induction motor, the place of the commutator-fed armature winding is taken by a short-circuited winding which may, for instance, consist of conductor bars distributed uniformly round the periphery and connected by two short-circuiting rings at the ends (Fig. 3). The current required in this winding for the setting up of a torque can only be generated by induction, i.e. by field change. Again a field is set up by a current $i_1$ in winding 1. If now a current $i_2$ is suddenly



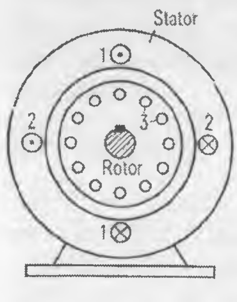

1 Field winding
2 Compensating winding
3 Armature winding

Fig. 1 Representation of a d.c. motor



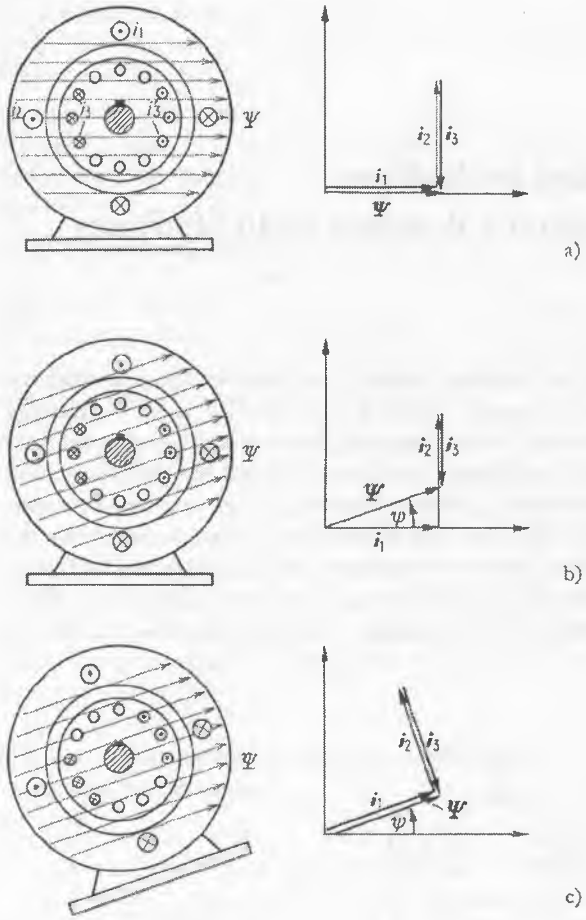

Field and currents — Vector diagram

Fig. 2 State of field and currents in a d.c. motor




1, 2 Stator windings
3 Rotor winding

Fig. 3 Representation of an induction motor




Left: Field and currents

Right: Vector diagrams

Fig. 4 States of field and currents in an induction motor

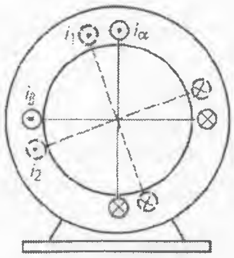


Fig. 5 Conversion of the required currents into attainable currents

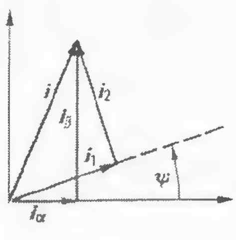


Fig. 6 Vector diagram for Fig. 5

injected into winding 2, previously acting as a compensating winding, it causes an opposing current $i_3$ to be induced in the rotor. In the first instant this is exactly equal to stator current $i_2$ but opposite. The conditions obtaining in this first instant are therefore identical to those in a d.c. machine (Fig. 4a). However, since the induced rotor current requires a field change, the vector diagram is changed after a certain time to that shown in Fig. 4b. For the sake of simplicity, the rotor is assumed to be locked, as is indicated by the unchanged position of the shaft. The field has rotated slightly and the original alignment of the current vectors $\boldsymbol{i}_1$ and $\boldsymbol{i}_2$ with respect to the field has been lost. If – fictitiously – the stator is now turned until $\boldsymbol{i}_1$ and the field are again parallel (Fig. 4c), the orientation is restored. If the field is not allowed to move from the direction of $\boldsymbol{i}_1$, but the stator is turned continually with the field rotation, rigid orientation of the currents across the field is obtained. Consequently, the conditions at any instant are the same as in a d.c. motor. Rotation of the stator is, of course, merely an aid in representation.

In reality the stator and the windings $\alpha$ and $\beta$ remain stationary (Fig. 5). In the measure shown, it is only the current vector $\boldsymbol{i}$ formed from $\boldsymbol{i}_1$ and $\boldsymbol{i}_2$ that is important (Fig. 6). Instead of producing this rotating vector from rotating windings 1 and 2 with constant currents $i_1$ and $i_2$, it is now necessary to produce it from stationary windings $\alpha$ and $\beta$ with variable currents $i_\alpha$ and $i_\beta$. Fig. 6 shows which values the currents $i_\alpha$ and $i_\beta$ must assume at any instant. $i_\alpha$ and $i_\beta$ depend not only on the freely selectable values $i_1$ and $i_2$, which may, for instance, be constant, but also on the angle of the field $\psi$ with respect to the stator axis $\alpha$:

$$i_\alpha = i_1 \cos\psi - i_2 \sin\psi,$$

$$i_\beta = i_1 \sin\psi + i_2 \cos\psi. \qquad (1)$$

This relationship can be realized by the computation circuit shown in Fig. 7 which is called a vector rotator VR, since it causes the current vector to be rotated by the angle of the field. Fig. 8 shows the application of this vector rotator for field-orientated control in an induction motor. In the vector rotator the required positioning values $i_\alpha^{(*)}$ and $i_\beta^{(*)}$ are formed from the setpoint values $i_1^*$ and $i_2^*$ and the angle functions of the field angle $\psi$. These values are fed to a variable-current static converter U as manipulated variables for the currents $i_\alpha$ and $i_\beta$ in the corresponding stator windings. The information on the field angle $\psi$ required by the vector rotator is obtained by measuring the field vector in the motor [6]. The two components of the field vector are measured by Hall generators arranged at different angles in the air gap and are converted to the required angle functions $\sin\psi$ and $\cos\psi$ by a vector analyzer [1].

This arrangement, which effects field orientation of the stator current, provides separate access to the field through $i_1$ and to the torque-producing current through $i_2$. Thus it is possible to operate an induction motor in the same manner as a d.c. motor with current control.

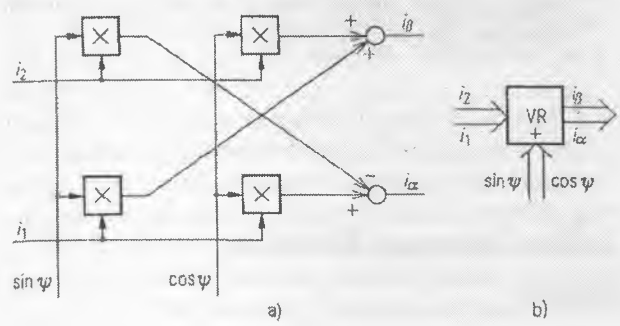
To simplify the above explanation, it has been assumed that the rotor is locked. The same result would, however, also be obtained with a rotating rotor. The only difference between rotation of the field to which orientation is being carried out and that obtaining with a locked rotor lies in the rotation of the rotor.

## Vector representation of field orientation

For the following it will be expedient to employ vectors to express the relationships established at the beginning. The relationship between $i_1$, $i_2$ and $i_\alpha$, $i_\beta$, shown in equation (1), can be looked upon as a co-ordinate transformation of current vector $\boldsymbol{i}$ from the field-oriented to the stator-oriented co-ordinate system. If the current vector in the field co-ordinate system is defined as $\boldsymbol{i}_\psi = \begin{pmatrix} i_1 \\ i_2 \end{pmatrix}$ and the current vector in the stator co-ordinate system as $\boldsymbol{i}_S = \begin{pmatrix} i_\alpha \\ i_\beta \end{pmatrix}$, this co-ordinate transformation can be expressed as follows with the aid of the rotational matrix $\boldsymbol{D}\,(+\psi) = \begin{pmatrix} \cos\psi & -\sin\psi \\ \sin\psi & \cos\psi \end{pmatrix}$:

$$\boldsymbol{i}_S = \boldsymbol{D}\,(+\psi)\,\boldsymbol{i}_\psi . \tag{2}$$

Here, the vector rotator shown in Fig. 7 contains the transformation function of the rotational matrix.




a) Computation circuit b) Symbol

Fig. 7 Vector rotator for transformation from the field co-ordinate system to the stator co-ordinate system

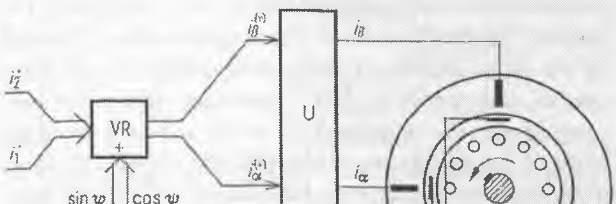
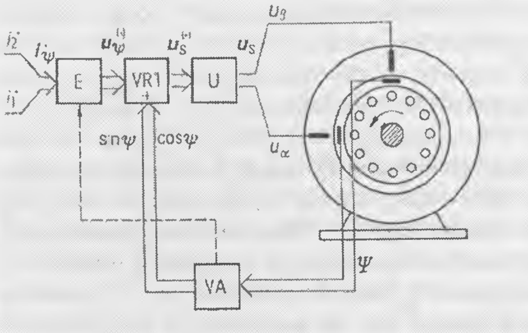
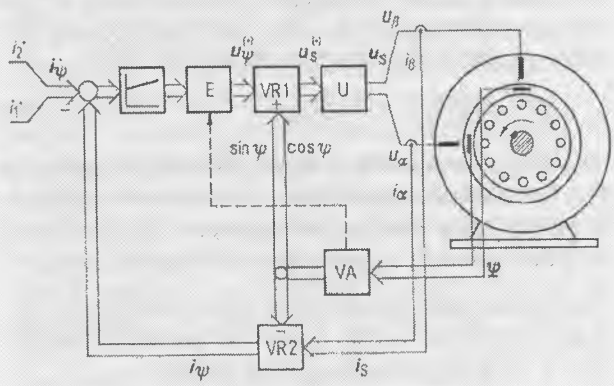



Fig. 8 Application of a vector rotator for field orientation in an induction motor




a) Open-loop control




b) Closed-loop control

Fig. 9 Field orientation in an induction motor with voltage control

## Field orientation with voltage control

In the case of a variable-voltage static converter, the voltages $u_\alpha$ and $u_\beta$ are available across the windings $\alpha$ and $\beta$ through manipulated variables $u_\alpha^{(*)}$ and $u_\beta^{(*)}$. To achieve field orientation, it is therefore necessary here, in contrast to current control, to determine the voltage positioning values $u_\alpha^{(*)}$ and $u_\beta^{(*)}$ necessary for the current setpoint values $i_1^*$ and $i_2^*$. The relationship is established in two steps. First of all, the voltage vector $\boldsymbol{u}_\psi^{(*)}$ in the field co-ordinate system is formed from the current vector $\boldsymbol{i}_\psi^*$ which is in turn formed from $i_1^*$ and $i_2^*$. This vector consists of the vectors for the resistive and inductive voltage drops of the current and the vector for the back e.m.f. in the motor. This relationship is established in a computation circuit E (Fig. 9a), which requires information from the motor and contains a simulation of the structure of the motor [1]. In a second step the result is transformed to the voltage vector in the stator co-ordinate system $\boldsymbol{u}_S^{(*)}$ by a co-ordinate transformation

$$\boldsymbol{u}_S^{(*)} = \boldsymbol{D}\,(+\psi)\,\boldsymbol{u}_\psi^{(*)},$$

which corresponds to that for current control. This transformation is carried out by the vector rotator VR 1 (Fig. 9a). The components $u_\alpha^{(*)}$ and $u_\beta^{(*)}$ of this vector are then fed to the static converter as manipulated variables.

The motor current set up by the applied voltage depends, among other things, on the resistance of the motor. This in turn depends on the operating temperature which cannot generally be taken into account in the computation circuit. Consequently, the current vector $\boldsymbol{i}_\varphi$ deviates from its setpoint value $\boldsymbol{i}_\varphi^*$ and it is necessary to superimpose closed-loop control of the current vector $\boldsymbol{i}_\varphi$ on this control (Fig. 9b). Since the components of $\boldsymbol{i}_\varphi$ remain steady under steady-state operating conditions, the deviation of $\boldsymbol{i}_\varphi$ from the required value $\boldsymbol{i}_\varphi^*$ caused by resistance change can be corrected by integral-action controllers. The actual value $\boldsymbol{i}_\varphi$ required for the control is obtained by measurement of the stator-oriented current vector $\boldsymbol{i}_\mathrm{S}$ and subsequent transformation of the field co-ordinate system. The transformation specification is obtained by inversion of equation (2):

$$\boldsymbol{i}_\varphi = \boldsymbol{D}^{-1}(+\psi)\,\boldsymbol{i}_\mathrm{S} = D(-\psi)\,\boldsymbol{i}_\mathrm{S}. \quad (3)$$

The vector rotator VR 2 required for this is shown in Fig. 9b. It has the same structure as that shown in Fig. 7, it merely being necessary to substitute $-\psi$ in place of $+\psi$; this leads to a sign change of the crossed loops.

The arrangement described thus also makes field orientation of the stator current of an induction motor possible with a static converter for voltage control.

Hence, the principle of field orientation ensures dynamically high-grade control for induction motors, independently of the type of static converter employed.

*References*

[1] Blaschke, F.: Das Prinzip der Feldorientierung, ein neues Verfahren zur Regelung der Asynchronmaschine. Siemens-Forschungs- u. Entwicklungsber. 1 (1971) No. 2

[2] Böhm, K.; Wesselak, F.: Variable-Speed A.C. Drives with Static Frequency Converter Feed. Siemens Rev. XXXIX (1972) pp. 126 to 129

[3] Flöter, W.; Ripperger, H.: Die TRANSVEKTOR-Regelung für den feldorientierten Betrieb einer Asynchronmaschine. Siemens-Z. 45 (1971) pp. 761 to 764

[4] Bayer, K.-H.; Waldmann, H.; Weibelzahl, M.: Field-Oriented Closed-Loop Control of a Synchronous Machine with the New TRANSVEKTOR Control System. Siemens Rev. XXXIX (1972) pp. 220 to 223

[5] Kovács, K.P.; Rácz, I.: Transiente Vorgänge in Wechselstrommaschinen. Budapest: Publishing House of the Hungarian Academy of Sciences 1959

[6] Langweiler, F.; Richter, M.: Flußerfassung in Asynchronmaschinen. Siemens-Z. 45 (1971) pp. 768 to 771

[7] Weh, H.: Elektrische Netzwerke und Maschinen in Matrizendarstellung. Mannheim, Zürich: Bibliogr. Inst. 1968

[8] Naunin, D.: Ein Beitrag zum dynamischen Verhalten der frequenzgesteuerten Asynchronmaschine. Berlin, Techn. Univ., Diss. 1968

[9] Hasse, K.: Zur Dynamik drehzahlgeregelter Antriebe mit stromrichtergespeisten Asynchron-Kurzschlußläufermaschinen. Darmstadt, Techn. Hochsch., Diss. 1969

[10] Blaschke, F.; Ripperger, H.; Steinkönig, H.: Regelung umrichtergespeister Asynchronmaschinen mit eingeprägtem Ständerstrom. Siemens-Z. 42 (1968) pp. 773 to 777

# Field-Oriented Closed-Loop Control of a Synchronous Machine with the New TRANSVEKTOR Control System

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*Synchronous machines are being employed on an ever increasing scale in industrial drive systems fed by static converters. The reasons for this lie in their straightforward, robust construction, the simple manner in which they can be magnetized [1] and their excellent characteristics when used in conjunction with static converters [2]. Since these drives are expected to offer the same high-grade dynamic characteristics as variable-speed d.c. drives, provision must be made to control the torque instantaneously to a linear curve relationship. The same applies to control of the magnetization. Both control operations must be decoupled, i.e. one must only influence the torque and active power, and the other only the magnetization and reactive power.* TRANSVECTOR® *control, which operates on the principle of field orientation, is eminently suitable for control functions of this type.*

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In field-oriented control the stator current is divided into two components which determine the torque and magnetization independently of each other. Together with the magnitude of the flux, the component $i_2$ (Fig. 1) perpendicular to the rotating flux vector* determines the torque. On the other hand, the magnetization produced by the stator winding is influenced directly by the flux-parallel component $i_1$. In a computing circuit, the two components are calculated for every required working point of the synchronous machine and are used to form the corresponding setpoint values for the phase currents.

The construction and mode of operation of field-oriented control for synchronous machines are described in the following by way of example of a speed control for a finish-grinding mill in a cement factory. This mill is driven by a 5 MW synchronous motor fed with a variable frequency from a cycloconverter. The mill cylinder, which is 5 m in diameter and 15 m long, serves as the

* For a definition as a space vector due to KOVACS and RACZ see [3]