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CONSIDERATIONS REGARDING OPTIMAL OPERATION REGIMES OF AN AUTO-PILOTED SYNCHRONOUS MOTOR

BY

CARMEN COJOCARU-FILIPIUC*

“Gheorghe Asachi” Technical University of Iaşi
Faculty of Electrical Engineering

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Abstract. In the paper, the auto-piloted synchronous motor (ASM) with controlled-current voltage-source inverter is considered. General criteria for its optimal operation regimes are defined having in view to identify the adequate supply current vector control strategies. The input control quantities are stated for both variants applicable to the construction of the ASM rotor excitation system: with variable inductor flux generated by d.c.-supplied field winding, or with fixed inductor flux produced by permanent magnets.

A number of four different optimal operation regimes and corresponding control methods are defined as follows: at constant excitation flux with fixed, optimal current control angle, $\varepsilon = 90^{\circ}$ or, with unity power factor value, $\cos\varphi =$ $= 1$; at constant resulting flux with unity power factor value, $\cos\varphi = 1$ or, with fixed optimal current control angle value, $\varepsilon = 90^{\circ}$. In order to appreciate the operation regime expediency the following performance indicators have been considered: the linearity of the torque-current dependency, the value of the torque-per-current ratio, the magnitude of the rated apparent power of the supplying convertor compared to that of the electromagnetic power developed by the ASM.

Conclusions are drawn regarding the control method utility, the recommended ASM construction and the control system requirements.

Key words: auto-piloted synchronous motor; optimal operation regimes; vector control strategies.

* *e-mail*: cojocaru.cg@gmail.com

1. Introduction

The optimal operation of an auto-piloted synchronous motor, ASM can be defined by establishing similarities and specific differences with respect to the operating characteristics of a classical direct current motor with mechano-galvanic commutator, DCM. The modern motion control achieved with an ASM usually consists in controlling the developed electromagnetic torque in a given speed range (Chattopadhyay,1997).

Owing to the self-piloted operation of an ASM, the supply frequency, *f*, corresponding to a given speed value, does no more represent a control quantity, in contradistinction with the case of an asynchronous or synchronous motor where frequency is an outside imposed supply quantity, representing an imposed control signal.

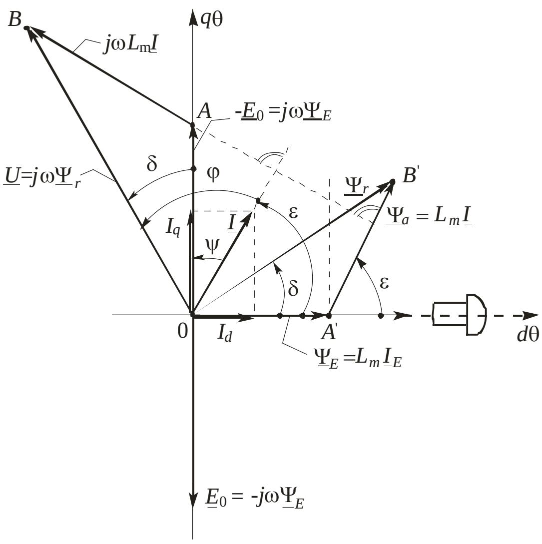

Fig. 1 – Defining the input control quantities for the optimal operation of an ASM: δ is the imposed voltage control angle; ε – the imposed current control angle.

The input control signals of an ASM ascertaining its operation regime are defined in what follows. In Fig. 1 the steady-state voltage and magnetic flux space phasor diagrams are presented for a three-phase ASM with isotropic, linear magnetic core and sinusoidal distribution of the air gap magnetic field, neglecting the stator winding ohmic resistance and leakage reactances and taking into consideration only the fundamental harmonic wave of signals.

2. Input Control Quantities of an ASM

The electromagnetic torque, M is considered to be the controlled quantity and the input signals that determine its value can be: the r.m.s. values of the phase voltage, U and current, I, the voltage control angle, δ (defined between the voltage space phasor $\underline{U}$ and the rotating quadrature axis $q\theta$), the current control angle, ε, (defined between the space voltage phasor $\underline{I}$ and the rotating longitudinal axis $d\theta$), and the excitation flux $\underline{\Psi}_E$ which is a controllable signal in case that the d.c. excitation current, I_E is variable.

During the historical evolution of the self-controlled electronically commutated motors two supply and control methods have been chronologically applied to an ASM as follows:

a) Supplying with imposed sinusoidal voltage, when the r.m.s. value U and the control angle δ of the supplying voltage are enforced as input control quantities and a PWM voltage-source inverter (CSU) is utilized. The steady-state torque expression in this case is:

$$M = mp\frac{U}{\omega L_m}\Psi_E \sin\delta, \tag{1}$$

where: m is the number of phases, p – the number of pole pairs, $\omega = 2\pi f$, L_m – the magnetizing inductivity of the stator winding. Torque in this case is not independent with respect to frequency (speed) and the torque control requires keeping constant the ratio U/ω for any speed value determined by the load torque magnitude.

b) Supplying with imposed sinusoidal current, when the r.m.s. value I and the control angle ε of the supplying current are enforced as input control quantities and a PWM voltage-source inverter associated with a current control system, or a PWM current-source inverter can be utilized in this case as the electronic commutator of the ASM. The steady-state torque expression results to be:

$$M = mp\Psi_E I \sin\varepsilon, \tag{2}$$

conveniently denoting that torque only depends directly on the supplying current amplitude and phase while it is invariant with voltage and frequency (speed) values. Operation characteristics can be obtained in this case, similar to those of a classical shunt-excited d.c. motor with mechano-galvanic commutator.

3. Criteria of Optimal Operation of an ASM Supplied with Imposed Sinusoidal Current

An ASM with imposed-current supplied stator winding is considered so that the r.m.s. value of current, I and the current control angle ε are imposed through the vector-control and self-piloting system.

The imposed-current supplying mode makes an ASM have an operation very close to that of a classical d.c. motor. Thus, imposing the current control angle ε in the operation of an ASM determines the position of the stator armature flux space phasor with respect to the rotating excitation $d\theta$ axis, while the same positioning angle is achieved in a classical DCM by shifting the supplying brushes axis on the commutator, with respect to the stator (fixed) excitation axis, *d*.

For a comparative study on different torque control strategies, we shall consider speed having a fixed, given value, ω = const. The current r.m.s. value, I is a variable quantity and the control angle ε can also vary taking values in the range $\varepsilon = [0^o\ldots180^o]$, corresponding to a phase-shift angle of current with respect to the induced e.m.f. phasor, $-\underline{E}_0$, $\psi = [-90^o\ldots0^o]\cup[0^o\ldots90^o]$. The phasor diagram in Fig. 1 also shows the following relations between angles ψ, ε, δ and the power factor angle, φ:

$$\psi = 90^o - \varepsilon; \quad \varphi = 90^o + \delta - \varepsilon. \tag{3}$$

A number of four different optimal operation regimes and corresponding control methods are defined as follows (Cojocaru-Filipiuc, 1999):

1) Operation at constant excitation flux, Ψ_E = const. (E_0 = const.) with $\varepsilon = 90^o$ ($\psi = 0$), when $\cos\varphi$ and U are quantities that vary freely as functions of the load current value, I;

2) Operation at constant excitation flux, Ψ_E = const. (E_0 = const.) with $\cos\varphi = 1$, when ε is an adjusted quantity and U is freely variable according to the load current value, I.

3) Operation at constant resulting flux, Ψ_r = const. (U = const.), with $\cos\varphi = 1$, when ε and E_0 (respectively I_E) are adjusted quantities;

4) Operation at constant resulting flux, Ψ_r = const. (U = const.), with $\varepsilon = 90^o$, when $\cos\varphi$ and E_0 (respectively I_E) are adjusted quantities.

In order to appreciate the operation regime expediency the following performance indicators have been considered: the linearity of the torque-current dependency, the value of the torque-per-current ratio, the magnitude of the rated apparent power of the supplying convertor compared to that of the electromagnetic power developed by the ASM (Muntean *et al.*, 2006; Muşuroi & Popovici, 2006).

In what follows an analyze is made for the proposed control strategies and their consequences on the operation of the assembly convertor – electrical machine. In the exemplifying phasor diagrams the same speed value, ω = const. is considered and two different values of the load current, I and $I' > I$ are taken into account.

3.1. ASM Operation at Ψ_E = const. and $\varepsilon = 90^o$ ($\psi = 0$)

In this case, the ASM operation is equivalent to the classical d.c. motor with compensation winding and brushes placed on the q axis. The phasor diagram for two distinct values of current, I and I' is presented in Fig. 2. The excitation flux, $\underline{\Psi}_E$ and the induced e.m.f., $\underline{E}_0$ are considered constant, of the unity value.

For the control angle having the value ε = 90º, the torque value is maximized for a given load so that the ratio torque per current, *M/I* is constant and takes the maximum value:

$$M/I = mp\Psi_E = \text{max.} = \text{const.} \tag{4}$$

The torque-current dependency is a linear function, (5) that enables achievement of a convenient, linear, independent control of torque through the current value and respectively of speed through the voltage value

$$M = mp\Psi_E I = k_M I. \tag{5}$$

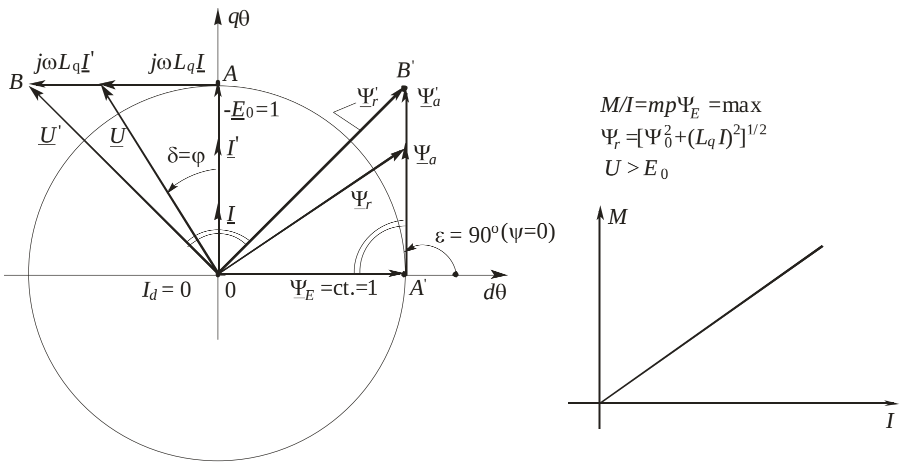

Fig. 2 – ASM operating at Ψ_E = const. and ε = 90º.

For an increased current value, $I' > I$ the phase-shift φ between voltage and current phasors increases, diminishing the power factor value. The decrease of the power factor value can be attenuated by adopting a reduced transversal reactance, X_q, which means that the salient pole rotor configuration can be a recommended constructive solution.

The resultant flux (6) increases with the current r.m.s. value, *I* and, consequently, the magnetic circuit must be design-dimensioned according to the rated load value. Magnetic saturation can occur at overloading and consequently, weak core utilization at small load values can be present,

$$\Psi_r = \left[\Psi_E^2 + \left(L_q I\right)^2\right]^{1/2}. \tag{6}$$

The voltage value at the stator winding terminals,

$$U = \omega\left[\Psi_E^2 + \left(L_q I\right)^2\right]^{1/2} = \left[E_0^2 + \left(X_q I\right)^2\right]^{1/2}, \tag{7}$$

is always higher than the e.m.f. E_0. This leads to the conclusion that the convertor apparent power, $S_{\mathrm{conv}} = UI$ is dimensionally higher than the electromagnetic power of the ASM, $P_{\mathrm{em}} = E_0 I$:

$$S_{\mathrm{conv}} = UI > P_{\mathrm{em}} = E_0 I\ . \tag{8}$$

3.2. ASM Operation at Ψ_E = const. and $\cos\varphi = 1$

If the current control angle ε is adjusted at values $\varepsilon > 90°$ the current phasor, $\underline{I}$ can be imposed to be in phase with the voltage phasor at the stator winding terminals, $\underline{U}$, permanently assuring a unity value of the power factor, $\cos\varphi = 1$.

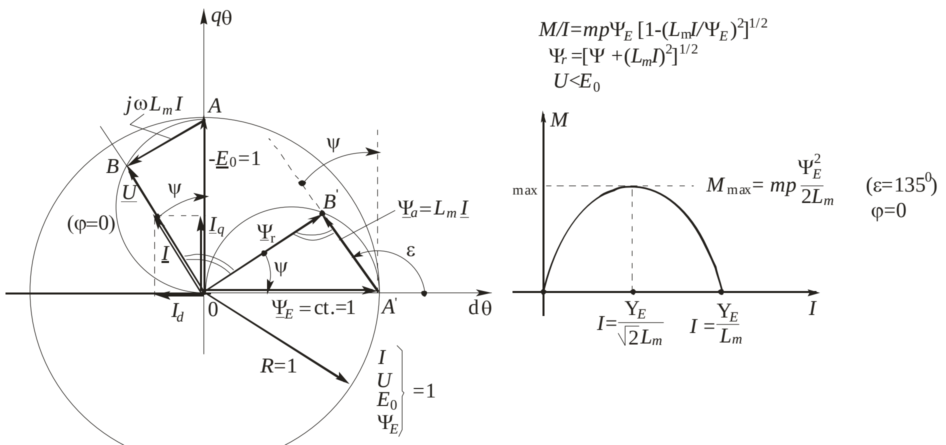

Fig. 3 – ASM operating at Ψ_E = const.; $\cos\varphi = 1$.

As the phasor diagram in Fig. 3 shows, in order to achieve the condition $\varphi = 0$ for any value of the load current, it is necessary that the adjustment of current control angle, $\varepsilon = f(I)$ follow rigorously the variation of the load current according to the relation:

$$\varepsilon = 90^{\mathrm{o}} + \arcsin(L_m I / \Psi_E). \tag{9}$$

Therefore, to operate at $\cos\varphi = 1$ for any value of the load current I, it is necessary to introduce a phase-shifting block between the rotor position detecting system and the inverter command system that has to achieve the function $\varepsilon = f(I)$, given by relation (9).

The torque expression becomes:

$$M = mp_p\Psi_E I\sin\varepsilon = mp\Psi_E I\left[1-\sin^2\psi\right]^{1/2} = mp\Psi_E I\left[1-(L_m I/\Psi_E)^2\right]^{1/2} \quad (10)$$

and shows a non-linear variation with the load current, having a maximum point characterized by the following extreme values:

$$M_{\max} = mp\frac{\Psi_E^2}{2L_m} \quad \text{and} \quad I_{(M_{\max})} = \frac{\Psi_E}{\sqrt{2}L_m}. \quad (11)$$

The torque-current ratio is dependent on the load value and it is smaller than in the previous case, §.3.1:

$$M/I = mp\Psi_E\left[1-(L_m I/\Psi_E)^2\right]^{1/2} = mp\Psi_E\sin\varepsilon\,. \quad (12)$$

The resultant flux, Ψ_r and the voltage value at the stator winding terminals, $U = \omega\Psi_r$ show a non-linear decrease with the load current, owing to the current demagnetizing effect.

The voltage value at the stator winding terminals is:

$$\Psi_r = \left[\Psi_E^2 - (L_m I)^2\right]^{1/2} \quad (13)$$

and it can be derived the expression of the voltage corresponding to the operating point with maximum value of torque, respectively at $\varepsilon = 135^{\circ}$:

$$U_{(M_{\max})} = \omega\left[\Psi_E^2 - \left(\frac{\Psi_E}{\sqrt{2}}\right)^2\right]^{1/2} = \omega\Psi_E\frac{1}{\sqrt{2}} = E_0\frac{1}{\sqrt{2}}. \quad (14)$$

The inverter apparent power results to be smaller than the electromagnetic power developed by the ASM at any load value:

$$UI < E_0 I, \quad S_{\text{conv}} < P_{em}. \quad (15)$$

3.3. ASM Operation at Ψ_r = const. and $\cos\varphi = 1$

In an ASM with electromagnetic excitation, the operation with constant resultant flux, Ψ_r = const. and with unity value power factor, $\cos\varphi = 1$ can be achieved by increasing the excitation current, I_E and simultaneously increasing the current control angle, ε correlated to the load current independent increase.

The phasor diagram in Fig. 4 shows that, in order to keep constant the resultant flux, Ψ_r = const. and to maintain the maximum value of the power factor, $\cos\varphi = 1$ while the load current increases, the excitation current I_E must be increased according to the relation:

$$I_E = (1/L_m)\left[\Psi_r^2 + (L_m I)^2\right]^{1/2} \quad (16)$$

and, in addition, the current control angle must be augmented simultaneously, at values greater than 90^o, $\varepsilon > 90^o$, as a function of the load current variation, according to the the following law:

$$\varepsilon = 90^o - \psi = 90^o + \text{arctg}\frac{L_m I}{\Psi_r}. \tag{17}$$

The most important consequence of this control strategy is the fact that the electromagnetic torque developed by the ASM has now a linear dependency with respect to the load current variation. From triangle OA′B′ in Fig. 4 the following expression is obtained:

$$M = mpI\Psi_E \cos\psi = 3z_p I\Psi_r. \tag{18}$$

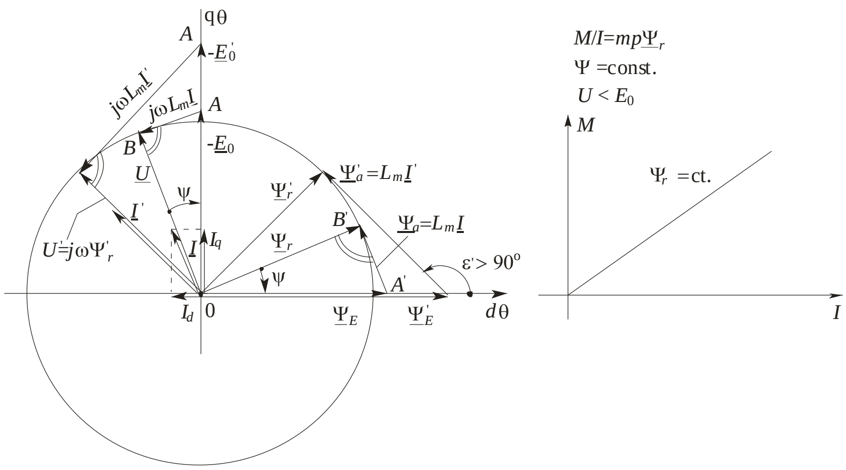

Fig. 4 – ASM operating at Ψ_r = const. and $\cos\varphi = 1$.

The stator terminal voltage is proportional to the speed value,

$$U = \omega\Psi_r = \omega \times \text{const}. \tag{19}$$

and an independent control of torque and speed is achieved like in the classical d.c. motor with compensation winding.

The load current has a demagnetizing effect, but the resultant flux is maintained constant according to the relation:

$$\Psi_r = \left[\Psi_E^2 - (L_m I)^2\right]^{1/2} = \text{const}. \tag{20}$$

since ASM operates in an over-excited regime. This makes the induced e.m.f. E_0 be higher than the terminal voltage and the electromagnetic power developed is also higher than the apparent inverter power:

$$E_0 = \omega L_m I_E = \left[U^2 + (X_s I)^2\right]^{1/2} > U . \quad (21)$$

$$S_{\text{conv}} < P_{em} . \quad (22)$$

3.4. ASM Operation at Ψ_r = const. and ε = 90º

Based on the information from the rotor positioning detection system the current control angle is fixed at ε = 90º similarly to the case described at §.3.1. For an ASM with electromagnetic excitation, the field current can be diminished, $\Psi_E < 1$, correlated with the increase of the load current value, I_E = = $f(I)$ so that the resultant flux can be maintained constant, Ψ_r = const.

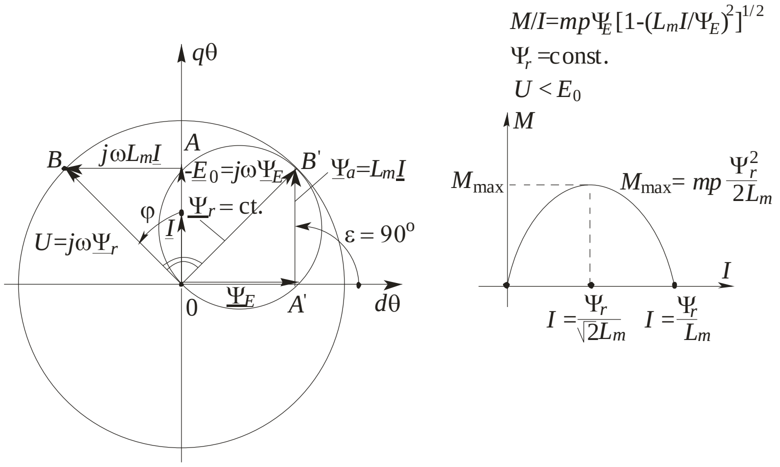

Fig. 5 – ASM operating at Ψ_r = const. and ε = 90º.

In Fig. 5, the phasor diagram OA′B′ is a right triangle with constant hypotenuses dimension for any value of the load current. The adjustment low that has to be followed by the excitation current is given by the relation:

$$I_E = (1/L_m)[\Psi_r^2 - (L_m I)^2]^{1/2} . \quad (23)$$

The electromagnetic torque shows a non-linear dependency on the load current according to the following derived expression:

$$M = mp\Psi_E I\left[1 - (L_m I/\Psi_E)^2\right]^{1/2} . \quad (24)$$

The torque – current function passes through a maximum point, when the power factor angle is φ = 45º, which is characterized by the following values:

$$M_{max} = \frac{mp\Psi_r^2}{2L_m} \text{ at } I_{(M_{\max})} = \frac{\Psi_r}{\sqrt{2}L_m} . \quad (25)$$

The torque per current ratio is also a variable quantity , dependent on the load current, always having a smaller value than in the previous case, §.3.3.

While the load current increases the regulated weakening of the field current leads to a decrease of the induced e.m.f.:

$$E_0 = \left[U^2 - (X_m I)^2\right]^{1/2}, \tag{26}$$

and the converter apparent power is smaller than the electromagnetic developed power:

$$S_{\text{conv}} < P_{em}. \tag{27}$$

Because of the non-linear torque – current dependency $M(I)$ this control strategy is not of a special practical interest.

4. Conclusions

1. An optimal operation regime is obtained for an ASM with electromagnetic excitation (ASM-ExEM) when the resultant flux is maintained constant, Ψ_r = const. and the power factor is maintained at the optimal value $\cos\varphi = 1$ for the whole rated variation range of the load current; it is achieved by simultaneous regulation of the field current, I_E according to relation (14) and regulation of the current control angle, ε according to relation (18). In this case the developed electromagnetic torque depends directly proportional on the load current value at any rotational speed value.

2. A convenient linear dependency torque-current, $M = f(I)$, is also obtained in case of an ASM with permanent magnet excitation (ASM-ExMP), with constant excitation flux , Ψ_E = const. for the current control angle fixed at the optimal value $\varepsilon = 90^{\circ}$; in this case the equipment is less complex but the power factor values decrease with the augmentation of the load current. This operation regime is similar to that of a d.c. motor without compensation of the armature reaction.

3. In both up-mentioned optimal regimes, a maximum ratio torque per current is obtained.

4. In order to achieve the current control regarding the amplitude and phase-shift angle the supplying inverter must be with bi-operational solid-state switches (transistors, GTO thyristors etc).

5. The construction of the ASM with a reduced value of the quadrature synchronous reactance is beneficial.

REFERENCES

Chattopadhyay A.K., *Advances in Vector Control of a.c. Motor Drives – a Review.* Sadhana J., Springer India, **22**, *6*, 797-820 (1997).

Cojocaru-Filipiuc C., *Contribuții la studiul teoretic şi experimental al conversiei electromecanice în maşinile cu comutație electronică autocondusă*. Ph. D. Diss., " Gh. Asachi" Technical Univ., Iaşi, 1999.

Muntean A., Radulescu M.M., Miraoui A., *Recent Developments of Electrical Drives, Wide-Speed Operation of Direct Torque-Controlled Interior Permanent-Magnet Synchronous Motors*. Springer Netherlands, 2006, 177-186.

Muşuroi S., Popovici D., *Acționări electrice cu servomotoare*. Edit. Politehnica, Timişoara, 2006.

CONSIDERAŢII PRIVIND REGIMURILE DE FUNCȚIONARE OPTIMALĂ A MOTORULUI SINCRON AUTOCONDUS

(Rezumat)

Se consideră un motor sincron autocondus, MSA de construcție sinusoidală şi alimentat de la un invertor sursă de tensiune cu curent controlat prin MLI, sinusoidal. Se definesc pentru acesta câteva criterii generale de funcționare optimală cu scopul de a identifica oportunitatea unor strategii de control vectorial adecvate. Mărimile de comandă a MSA se precizează luând in considerare ambele posibilități de realizare a excitației rotorice: cu flux inductor variabil, generat de înfăşurarea de excitație alimentată în curent continuu ajustabil şi, respectiv, cu flux inductor constant, produs de magneți permanenți.

Se definesc patru regimuri de funcționare optimală: la flux de excitație constant, cu unghi de control al curentului optimal fixat, $\varepsilon = 90^{\circ}$, sau cu valoare unitară a factorului de putere, $\cos\varphi = 1$; la flux rezultant constant şi cu valoare unitară a factorului de putere, $\cos\varphi = 1$, sau cu unghi de control al curentului fixat la valoarea optimală $\varepsilon = 90^{\circ}$. Pentru a aprecia oportunitatea impunerii regimurilor de funcționare definite s-au considerat următorii indicatori de performanţă: raportul cuplu per curent, liniaritatea dependenței cuplu-curent, valoarea puterii aparente de dimensionare a invertorului în comparație cu puterea electromagnetică dezvoltată de MSA.

Concluzii sunt formulate privind utilitatea metodelor de control propuse, construcția recomandată a MSA şi cerințele impuse sistemului de control.