IOSR Journal of Applied Physics (IOSR-JAP)
e-ISSN: 2278-4861.Volume 12, Issue 1 Ser. I (Jan. – Feb. 2020), PP 01-06
www.iosrjournals.org

Full Phase Control of Rectified Reactive Electromotor

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Abstract: *In this paper, we show the control means of rectified reactive electromotor, that ensure full phase functioning regime. Into details, we study a control algorithm with direct magnetization current.*
Keywords: *Full phase control; Rectified reactive electromotor*

Date of Submission: 20-12-2019 Date of Acceptance: 03-01-2020

I. Introduction

In recent years, the variable speed operation of the induction motor is achieved by modern inverters. Fast switching frequency inverters are now available at relatively low cost, at the same time the modern induction machines are now replacing DC motors in industrial applications. Where a fast speed and torque responses in four quadrants is required. One of the best suitable and more reliable techniques to effectively control the speed of induction motor is the Direct Torque Control (DTC) technique proposed by Takahashi and M. Depenbrock [1]. In last two decades the use of AC drives with DTC technique have gradually increased due to its advantages over the Field Oriented Control (FOC) techniques, good dynamic performance, precise and quick response of stator flux and electromagnetic torque, robust against machine parameter variations, no current control loop and simplicity of the algorithm [3, 4].A classical or conventional DTC drive system, which is based on a fixed hysteresis bands for both torque and flux controllers, suffers from a varying switching frequency, which is a function of the motor speed; stator fluxes and stator voltage; it is also not constant in steady state. Variable switching frequency is undesirable at low speed operation; an appreciable level of noise is present which is mainly due to the low inverter switching frequency. The high frequency is limited by the switching characteristics of the power semiconductor devices. Therefore, there will be large torque ripples and distorted wave forms in currents and fluxes. Several solutions have been proposed to keep constant switching frequency like in [2-8].

The control techniques of asynchronous machine drive including Scalar control, Vector or Field Oriented Control (FOC), Direct Torque and Flux Control (DTC (or) DTFC) or Direct Self Control (DSC) and Adaptive control. Scalar control is based on the steady state motor model while Vector control is based on dynamic model of motor. Scalar control, as the name indicates is due to magnitude variation of the control variables only, and disregards the coupling effect in the machine. For example, the voltage of a machine can be controlled to control the flux, and frequency or slip can be controlled to control the torque. Scalar controls are easy to implement and have been widely used in industry. Scalar control techniques with voltage fed and current – fed inverters etc. In the mid 1980s, an advanced Scalar Control technique, known as Direct Torque and Flux Control (DTFC or DTC) or Direct Self-control (DSC) was introduced for voltage-fed PWM inverter drives. The DTC proposed by Takashi and M. Depenbrock for variable load and speed asynchronous motor drives. It was a good alternative to the other type of vector control which known as FOC [5] due to some well known advantages, such as simple control structure, robust and fast torque response without co-ordinate transformation PWM pulse generation and current regulators moreover, DTC minimizes the use of motor parameters. Besides these advantages, DTC scheme [6] still had some disadvantages like high torque and current ripples, possible problems during starting and low speed operation, variable switching frequency.

II. The Characteristics Of Control Means For Rectified Reactive Electromotor With Full Phase Functioning Regime

We assume that the supply of reactive electromotor windings is done with symmetrical m-phase sinusoidal voltages system, that form a rectified commutator-inverter (Figure 1)

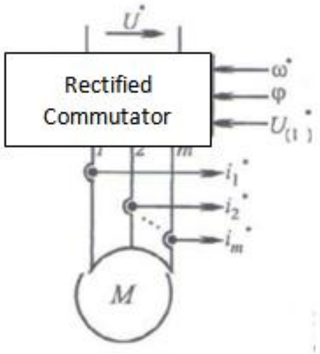

Figure 1: Supply circuit of reactive electromotor from invertor rectified commutator

$$U_S = \begin{bmatrix} u_1 \\ u_2 \\ . \\ . \\ . \\ u_m \end{bmatrix} U_{(1)} = \begin{bmatrix} \cos(\omega.t+\varphi) \\ \cos(\omega.t+\varphi-\rho) \\ . \\ . \\ . \\ \cos(\omega t+\varphi-\rho.(m-1)) \end{bmatrix}$$

With φ – initial phase that characterizes voltage position relatively to longitudinal axis of rotor magnetic symmetry d; $\rho = 2\pi/3$; $U_{(1)}$– the amplitude of voltage; ω – angular frequency

After transformation in d,q coordinates system,

$$U = \frac{2}{m}.\nabla(\gamma)^T.D_S = U_{(1)}.\begin{bmatrix} cos\varphi \\ sin\varphi \end{bmatrix} = \begin{bmatrix} U_{(1)d} \\ U_{(1)q} \end{bmatrix}$$

The symmetrical system of m-phase sinusoidal voltages is linked with voltages system in d,q axes as follows:

$$U_S = D_S^T.\nabla(\gamma).U$$

In stationary regime, the electromagnetic processes are characterized by the currents:

$$I_{(1)d} = \frac{R_1.U_{(1)d} + \omega.L_q.U_{(1)q}}{R_1^2 + \omega^2.L_d.L_q} = \frac{U_{(1)}.(R, cos\varphi + \omega.L_q.sin\varphi)}{R_1^2 + \omega^2.L_d.L_q}$$

$$I_{(1)q} = \frac{R_1.U_{(1)q} - \omega.L_d.U_{(1)d}}{R_1^2 + \omega^2.L_d.L_q} = \frac{U_{(1)}.(R, sin\varphi - \omega.L_q.cos\varphi)}{R_1^2 + \omega^2.L_d.L_q}$$

With $U_{(1)d} = U_{(1)}.cos\varphi$; $U_{(1)q} = U_{(1)}.sin\varphi$

The electromagnetic torque in rotor pair of poles and stator phases in stationary regime is defined after replacement of currents:

$$M = 2.L_m.\frac{\left(R_1U_{(1)d} + \omega.L_q.U_{(1)q}\right).(R_1.U_{(1)q} - \omega.L_d.U_{(1)d})}{(R_1^2 + \omega^2.L_d.L_q)^2}$$

The control of electromagnetic torque is possible by acting on voltage parameters $U_{(1)}, \omega, \varphi$.

Let us assume given $U_{(1)}$ and ω. The initial phase φ in that case is determined by the load on electromotor shaft. The maximal energetic efficiency corresponds with the equality of currents $I_{(1)d}$ and $I_{(1)q}$.

Thus $\varphi = \varphi_0 = arctang(\frac{R_1+\omega.L_d}{R_1-\omega.L_q})$

If we maintain the load angle $\varphi = \varphi_0$, then the control of electromagnetic torque and consequently the rotor rotation speed is possible by acting on voltage amplitude $U_{(1)}$. The expression of electromagnetic torque is:

$$M = U_{(1)}^2.\frac{L_d - L_q}{(R_1 - \omega_1 L_q)^2 + (R_1 + \omega.L_d)^2}$$

It corresponds to reactive electromotor mechanical characteristics control with maximal energetic efficiency factor shown in figure 2.

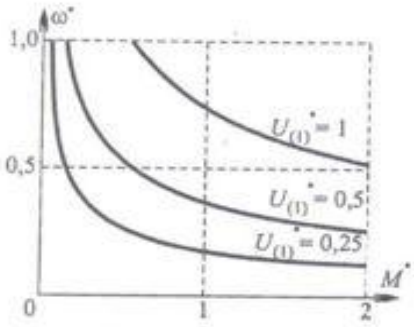

Figure 2: Mechanical characteristics with maximal value of energetic efficiency factor

The formation of electromagnetic torque is convenient for direct current magnetization.
For direct current magnetization $I_{(1)d}$, the electromagnetic torque is proportional to current $I_{(1)q}$, called load current.
The necessary stabilization level of magnetization current I_0 is determined for single march regime ($I_{(1)q} = 0$) with nominal voltage $U_{(1)} = U_B$ and basic speed value $\omega = \omega_B$. In that regime, the resistance R_1 brings very little influence and the magnetization current $I_0 \approx \sqrt{2}.U_B/\omega_B.L_d$.
For direct magnetic current $I_{(1)d} = I_0$, the electromagnetic torque

$$M = \left(L_d - L_q\right).U_{(1)}.I_0 \frac{R_1 sin\varphi - \omega.L_d.cos\varphi}{R_1^2 + \omega^2.L_d.L_q},$$

With $\varphi = arc\ cos\left[\frac{I_0.(R_1^2+\omega^2.L_d^2)}{U_{(1)}.\sqrt{R_1^2+\omega^2.L_d.L_q}}\right] + arc\ tang\ \left(\frac{\omega.L_d}{R_1}\right)$

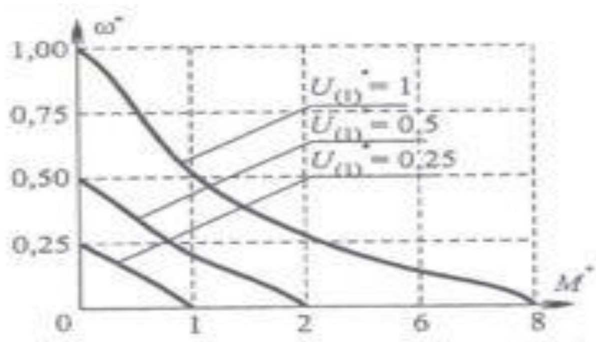

Figure 3: Mechanical characteristics with constant magnetization current

The expression will determine the reactive electromotor mechanical characteristics for direct magnetization current, that are represented in figure 3.

For control that ensures maximal energetic efficiency, it is necessary to vary both the longitudinal and transversal current loops and maintaining their equality.
In that case, the fastaction of control for electromagnetic torque is determined by the longitudinal loop time constant $T_d = L_d/R$, that is considerably higher than the transversal loop time constant $T_q = L_q/R$.

III. Design Of Magnetisation Current Control Loop

We assume that current vector I_S elements are observable, and i_d and i_q can be calculated. We study the stabilization current i_d algorithm.
Considering the equation

$$u_d + \omega . L_q . i_q = R_1 . (1 + T_d . P) . i_d$$

With $T_d = L_d / R_d$; ω – rotor rotation angular spped.
We represent that equation that characterizes the control object as a structural circuit in figure 4. We also include the control installation in the circuit in figure 4.

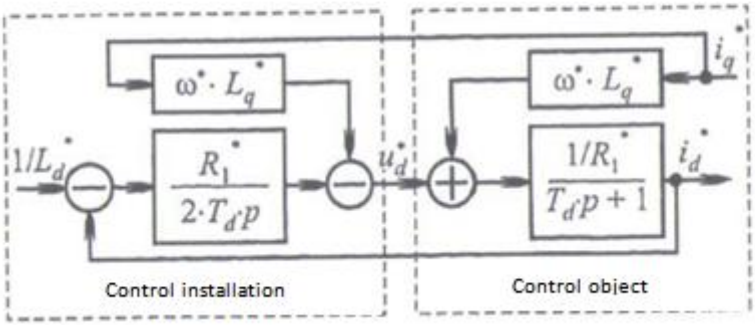

Figure 4: The stabilization system of magnetization current

We also include the control installation in the circuit.
The control system has a control loop on perturbation signal i_q^* and a control loop on magnetization current i_d^* with integral regulator.
The transfer function of magnetization current i_d^* control system is:

$$W_d = \frac{1}{2.T_d^2.P^2 + 2T_d.P + 1} \approx \frac{1}{2T_d P + 1}$$

On input of magnetization current control loop, we have a constant signal $1/L_d^*$, that permits to stabilize the magnetization current at the level of single march current.

IV. Design Of Electromagnetic Torque Control Loop

If we maintain the magnetization current constant $i_d^* = 1/L_d^*$, then the electromagnetic torque can be proportional to load current:

$$M^* = L_d^* . i_d^* . i_q = i_q^*$$

Thus, the torque control will depend only on current i_q regulation.
Let us find the current i_q stabilization algorithm assuming that current i_d is constant.
For the design of load current i_q regulator, we can neglect the speed ω, because the fast action of current i_q loop is greater than the fastaction of mechanical processes and magnetization current loop.
The equation that characterizes the control object is $u_q = \omega . L_d . i_d = R_1 . \left(1 + T_q . p\right) . i_q)$
With $T_q = L_q / R_1$.
We represent that equation in the form of structural circuit in figure 5. We also include the control installation.

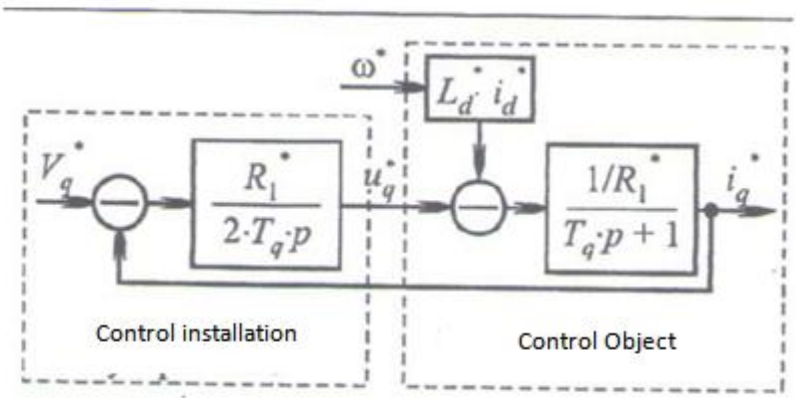

Figure 5: Control loop of electromagnetic torque

The control system is a closed loop on load current with integral regulator.
The transfer function of load current control loop is:

$$W_q = 1/(2.T_q^2.P^2 + 2T_q + 1) \approx 1/(2T_qP + 1).$$

At the input of current loop we include an element for limitation of electromagnetic torque value that is the limitation element of output signal.

V. Design Of Rotor Rotation Speed Control Loop

We study speed stabilization algorithm with direct magnetization current. The control of speed is linked with the control of electromagnetic torque. This arises from movement equation:

$$JP\omega = M - M_r$$

Or in per-units $T_{Mech}.P.\omega^* = M^* - M_r^* = i_q^* - i_r^*$,
With $T_{Mech} = J.\omega_B/M_B$ – Mechanical time constant;

$$M^* = i_q^*;\ M_r^* = i_r^*$$

The load current i_q^* is constructed by the structural circuit figure 5. The control of electromotor rotor rotation speed is achieved by the load current loop input signal V_q^*. From its variation will change the value of M^* and consequently the speed of ω^*.
The construction of given rotor rotation speed dynamic characteristics is done through in series correction. The structural circuit is shown in figure 6.

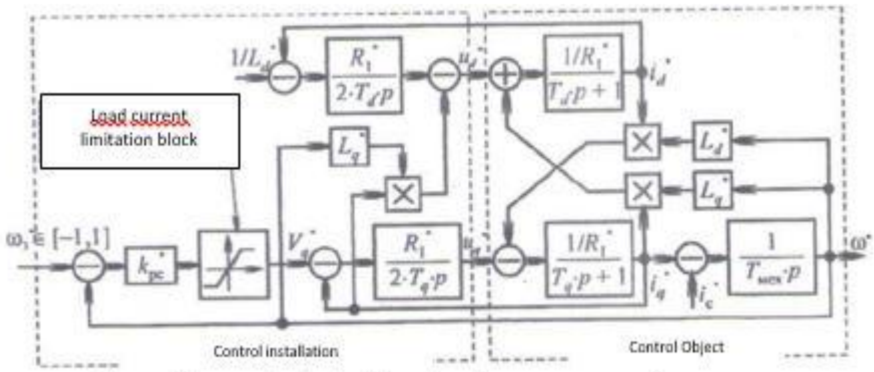

Figure 6: Structural circuit of reactive electromotor control system

The speed loop regulator object is the mechanical part of the electromotor and the current loop with transfer function:

$$W_0(P) = \frac{1}{(2.T_q.P + 1).T_{Mech}.P}$$

The speed regulator transfer function is chosen so as to ensure standard speed loop transfer function:

$$W_{sr} = \frac{(2.T_qP + 1).T_{Mech}.P}{2.T_\mu.P.(T_\mu P + 1)}$$

We assume $T_\mu = 2.T_q$; thus

$$W_{sr} = \frac{T_{Mech}}{4.T_q} = K_{sr}^*$$

VI. Algorithm Of Information Formation For The Construction Of Control Signals

The initial data for rectified reactive motor are the informations on phase stator currents I_S and rotor position. We use as position captor the sinus-cosinus selsyn.
The information is presented in the form of vectors:

$$v_d = V_m \cos(\gamma)\,, v_q = v_m\, sin(\gamma)$$

The rotor rotation speed:

$$\omega = P\gamma = (v_d.Pv_q + v_q.Pv_d)/(v_d^2 + v_q^2),$$

From the signals captor we construct the rotation matrix

$$\nabla(\gamma) = \frac{1}{\sqrt{v_d^2 + v_q^2}} \cdot \begin{bmatrix} v_d - v_q \\ \\ \\ v_q \, v_d \end{bmatrix}$$

Thus we have the currents values in d,q coordinates:

$$I^{*T} = (2/m).I_S^{*T}.D_S^T.\nabla(\gamma) = [i_d^* i_q^*]$$

From the values and according to the figure 6, we calculate u_d^* and u_q^* and next $U^{*T} = [u_d^* u_q^*]$

$$U_S^* = \nabla(\gamma).D_S^T.U^*$$

We construct the functioning control algorithm of the rectified commutator.

VII. Conclusions

Full phase functioning regime of rectified reactive electromotor is feasible by introducing in symmetrical system of windings sinusoidal voltages. The control of reactive electromotor in that case is done by acting on voltage parameters: amplitude, frequency and movement angle of initial voltage phase relatively to longitudinal axe of magnetic symmetry.

If given the voltage amplitude and frequency, then the reactive machine will have a synchronous torque linked with the movement angle of initial voltage phase.

If we have a captor of position control for rotor magnetic axis position, then we can define the voltages in d,q coordinates system, and construct electromagnetic torque so as to ensure maximal energetic efficiency or constant magnetic current.

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IOSR Journal of Applied Physics (IOSR-JAP) is UGC approved Journal with Sl. No. 5010, Journal no. 49054.

Biya Motto Frederic. "Full Phase Control of Rectified Reactive Electromotor." *IOSR Journal of Applied Physics (IOSR-JAP)*, 12(1), 2020, pp. 01-06.