torque changes. Still according to [8], two approaches are mainly used: the method based on the loss model and that based on the measurement of power. In this paper we use the first approach and show that non-deterministic optimization algorithms (GA, PSO and SA) can be used to calculate the optimal flux which minimizes the loss of the IM for a given speed and load torque.

2.1 Loss model of induction motor

The synchronous reference frame model of a three-phase IM is used [8]. The block diagram of the control system under study is shown in Fig. 1. For an angular velocity and torque points, the control module uses an optimization algorithm that calculates the optimum flux i_u to minimize the IM losses equation.

The losses in the IM are mainly composed of rotor copper losses (P_{jr}), copper losses in the stator (P_{js}), iron losses (P_{fe}) and mechanical losses (P_m). The losses of IM are calculated as follows:

$$P_{loss} = P_{js} + P_{jr} + P_{fe} + P_m \tag{1}$$

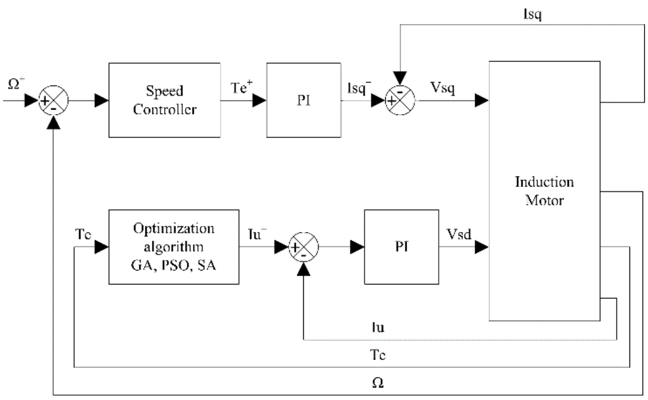

Fig. 1. Block diagram of the three-phase IM control system

Since the mechanical losses are not related to magnetic flux, they are omitted in calculation the optimal flux. This same equation is presented in [9] as follows where each term is defined in Table 1:

$$P_{loss}(i_d, i_q, \omega_e) = \left(R_s + \frac{\omega_e^2 L_m^2}{R_m}\right) * i_d^2 + \left(R_s + \frac{R_r L_m^2}{L_r^2} + \frac{\omega_e^2 L_m^2 L_{lr}^2}{R_m L_r^2}\right) * i_q^2 \tag{2}$$

It is important to note that the synchronous angular velocity ω_e can be approximated by the angular velocity of the motor ω_r when the slip is negligible (light load conditions). Still according to [9], the magnetic flux i_u and electromagnetic torque T_e are defined as follows:

$$i_u = \sqrt{i_d^2 + i_q^2} \tag{3}$$

$$T_e = \frac{3}{2} p \frac{L_m^2}{L_r} * i_d i_q \tag{4}$$

The optimization problem of the magnetic flux as a function of torque and speed is to find values for i_d and i_q that minimize equation (2) while generating an electromagnetic torque T_e greater or equal to the required torque T_r. In addition, i_d and i_q must meet two requirements: that of the maximum current and maximum voltage.

$$i_d^2 + i_q^2 \le I_{max}^2 \tag{5}$$

$$(\omega_e L_s i_d)^2 + (\omega_e \sigma L_s i_q)^2 \le V_{max}^2 \tag{6}$$

where
$$\sigma = 1 - \frac{{L_m}^2}{L_s L_r} \tag{7}$$

I_{max} is the maximum current possible and V_{max} is the maximum voltage possible. It is then possible to represent the loss of IM, the electromagnetic torque and the two constraints as a cost function that we minimize using optimization algorithms described the next section. In this cost function, i_d and i_q are the variables to be optimized for given angular speed ω_e and electromagnetic torque T_{req} given:

$$F_{cost}(i_d, i_q) = P_{loss}(i_d, i_q, \omega_e) + Penalty_{Treq} + Penalty_{Imax} + Penalty_{Vmax} \tag{8}$$

where

$$Penalty_{T_{req}} = \begin{cases} \frac{T_{req}}{T_e} * 10^9, & if \quad T_e < T_{req} \\ 0, & if \quad T_e \ge T_{req} \end{cases} \tag{9}$$

$$Penalty_{I_{max}} = \begin{cases} 0, & if \quad i_d^2 + i_q^2 \le I_{max}^2 \\ \frac{i_d^2 + i_q^2}{I_{max}^2} * 10^9, & if \quad i_d^2 + i_q^2 > I_{max}^2 \end{cases} \tag{10}$$

$$Penalty_{V_{max}} = \begin{cases} 0, & if \quad V^2 \le V_{max}^2 \\ \frac{(\omega_r L_s i_d)^2 + (\omega_r \sigma L_s i_q)^2}{V_{max}^2} * 10^9, & if \quad V^2 > V_{max}^2 \end{cases} \tag{11}$$

where

$$V^2 = (\omega_e L_s i_d)^2 + (\omega_e \sigma L_s i_q)^2 \tag{12}$$

We use a very large constant (here $1 * 10^9$) in equations(9), (10) and (11) to separate the valid