# STARTING CHARACTERISTICS OF INDUCTION MOTORS FED FROM A CURRENT SOURCE INVERTER UNDER FIELD ORIENTATION CONTROL

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## ABSTRACT

The field orientation control method of induction motors has been applied in order to give the induction motor a d.c. motor - like characteristics . This paper is directed to study the starting characteristics of such a system in order to determine starting time , maximum peak current passing in the windings and maximum peak torque produced during the staring period .
The starting characteristics of an induction motor fed from a current source inverter under field orientation control are developed. The starting current and torque with this mode of control were compared with those which will be developed when the motor is fed from a sinusoidal 3-phase voltage source.The superiority of the starting characteristics of a 7.5 kW motor with field orientation control was observed if compared with the characteristics of the motor when fed from a sinusoidal supply. The field orientation control can be applied in industrial plants as well as the utilization in service centers of aircraft engines and their appliances. The mentioned control technique can help too much in the development of aircraft electrical equipment , as well as for different aircraft actuators and their hydraulic equipment.

## 1.INTRODUCTION

The field orientation control method of induction motors has been applied in several industrial applications. Both VSI and CSI have been used to control the speed of induction motors with field orientation control[3],[4]. However , no much attention has been given for the investigation of the transient starting performance with this type of control. It is the purpose of this paper, therefore, to develop the transient current and torque

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characteristics of an induction motor fed from a CSI under field orientation control. To this end a relatively simple approach was developed . In order to assess the starting transient performance of the motor under field orientation control, the transient characteristics of a 7.5 kW motor were compared with the transient performance when the motor was fed from a conventional sinusoidal supply.

## 2. STARTING CHARACTERISTICS WITH SINUSOIDAL VOLTAGE SOURCE

Assuming that the induction motor is an ideal cylindrical rotor machine, the instantaneous positive-sequence component equations of the motor are given by

$$\begin{bmatrix} \bar{v}_s \\ \bar{v}_r e^{j\theta} \end{bmatrix} = \begin{bmatrix} R_s + L_s p & M p \\ M(p - jw_r) & R_r + L_r(p - jw_r) \end{bmatrix} \begin{bmatrix} \bar{i}_s \\ \bar{i}_r e^{j\theta} \end{bmatrix} \qquad (1)$$

where $\theta$ is the rotor angular position, $R_s$ the stator phase resistance, $R_r$ the rotor phase resistance, $L_s$ and $L_r$ are the stator and rotor self inductances, M is the mutual inductance and p is the operator d/dt

The rate-of-change of currents are derived from eqn.(1) as

$$\begin{bmatrix} p\, \bar{I}_s \\ p\, (\bar{i}_r e^{j\theta}) \end{bmatrix} = \frac{1}{L_s L_r - M^2} \begin{bmatrix} \bar{v}_s L_r \\ -\bar{v}_s M \end{bmatrix} - \begin{bmatrix} R_s L_r & -M R_r \\ -R_s M & R_r L_s \end{bmatrix} \begin{bmatrix} \bar{I}_s \\ \bar{i}_r e^{j\theta} \end{bmatrix}$$

$$-j\, w_r \begin{bmatrix} M^2 & M L_r \\ -M L_s & -L_s L_r \end{bmatrix} \begin{bmatrix} \bar{i}_s \\ \bar{i}_r e^{j\theta} \end{bmatrix} \qquad (2)$$

The differential equations of the motor referred to stationary d-q axes can be derived from eqn.(2) by separating the real and imaginary parts of the currents and voltages to obtain[5]

$$\begin{bmatrix} p\, i_{sd} \\ p\, i_{sq} \\ p\, i_{rd} \\ p\, i_{rq} \end{bmatrix} = \frac{1}{L_s L_r - M^2} \left[ \begin{bmatrix} v_{sd} L_r \\ v_{sq} L_r \\ -v_{sd} M \\ -v_{sq} M \end{bmatrix} + \begin{bmatrix} -R_s L_r & 0 & M R_r & 0 \\ 0 & -R_s L_r & 0 & M R_r \\ M R_s & 0 & -R_r L_s & 0 \\ 0 & M R_s & 0 & -R_r L_s \end{bmatrix} \begin{bmatrix} i_{sd} \\ i_{sq} \\ i_{rd} \\ i_{rq} \end{bmatrix} \right.$$

$$\left. + w_r \begin{bmatrix} 0 & M^2 & 0 & M L_r \\ -M^2 & 0 & -M L_r & 0 \\ 0 & -M L_s & 0 & -L_r L_s \\ M L_s & 0 & L_r L_s & 0 \end{bmatrix} \begin{bmatrix} i_{sd} \\ i_{sq} \\ i_{rd} \\ i_{rq} \end{bmatrix} \right] \qquad (3)$$

The electromagnetic torque developed is obtained from

$$T_e = P\, M\, (\, i_{rd}\, i_{sq} - i_{sd}\, i_{rq}\, ) \qquad (4)$$

where P is the number of pole-pairs.

The rate-of-change of speed is expressed by

$$p\, w_r = ( T_e - T_f ) / J \tag{5}$$

where $T_f$ is the opposing torque as a function of $w_r$ ,and J is the moment of inertia of the motor and the load.

From eqns.(3),(4) and (5), the starting characteristics of a 7.5 kW I.M. , loaded with a 7.5 kW d.c. generator was computed by a digital computer using 4th-order Runge-Kutta method of numerical integration.

## 3. STARTING CHARACTERISTICS WITH CSI AND FIELD ORIENTATION CONTROL

The d-q equation for a squirrel-cage induction motor, with d-q axes fixed on the stator, can be expressed in an alternative form than this given in eqn.(3) , by

$$\begin{bmatrix} v_{sq} \\ v_{sd} \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} R_s + p\, L_s & 0 & p\, M & 0 \\ 0 & R_s + p\, L_s & 0 & p\, M \\ p\, M & -w_r M & R_r + p\, L_r & -w_r L_r \\ w_r M & p\, M & w_r L_r & R_r + p\, L_r \end{bmatrix} \begin{bmatrix} i_{sq} \\ i_{sd} \\ i_{rq} \\ i_{rd} \end{bmatrix} \tag{6}$$

Using a reference frame rotating synchronously with the magnetic field ,the rotor equation of a squirrel cage I.M. is obtained as

$$0 = R_r \bar{i}_r + d\bar{\psi}_r /dt + j\, w_r \bar{\psi}_r \tag{7}$$

where

$$\bar{\psi}_r = M\, \bar{i}_s + L_r \bar{i}_r \tag{8}$$

Changing the d-q coordinates to two coordinates in the direction and perpendicular to the rotor flux, field coordinates, the following relationship can be derived

$$di_\mu /dt = - R_r/L_r (i_\mu - i_1 ) \tag{9}$$

From which ,

$$i_\mu = I_1 ( 1 - e^{-t/\tau_r} ) \tag{10}$$

where $I_1$ is the steady state value of $i_1$ and $\tau_r$ is the rotor time constant.

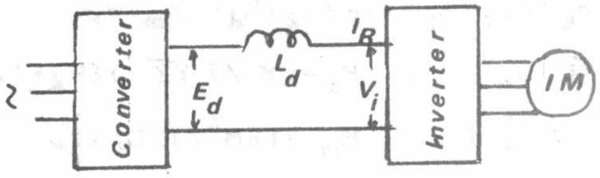


Fig.(1) Schematic diagram of CSI drive I.M.

The torque equation is obtained from

$T_e = - \bar{\psi}_r \times \bar{i}_r$
as

$$T_e = P\ ( M^2 i_\mu / L_r)\ i_2 \tag{11}$$

From Fig.(1) , the equation of the d.c. link current will be

$$L_d p\ I_R + R_d I_R = E_d - V_i \tag{12}$$

where $V_i$ is the average input voltage of the inverter.

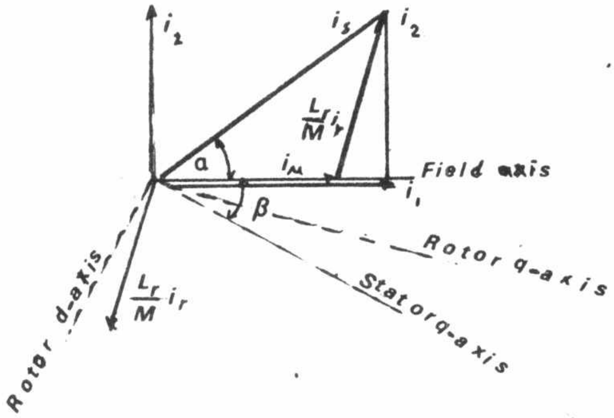


Fig.(2) Phasor diagram in field coordinates

From eqn.(6) and Fig.(2), which shows the phasor diagram of the motor in field coordinates,the average inverter input voltage $V_i$ can be deduced as

$$V_i = (2\sqrt{3}/\pi)R_s\ i_s + (6M^2/\pi\ L_r)(i_\mu\ w_r + R_r i_2/L_r)\ \sin\alpha \tag{13}$$

Neglecting phase current harmonics , then

$$i_s = (2\sqrt{3}/\pi)I_R \tag{14}$$

Substituting from eqn.(13) and (14) in (12) we get

$$L_e p i_2 + R_e i_\mu^2 / i_2 + (R_e + R_{re})i_2 = (i_s / i_2)E_d - K_m\ w_r \tag{15}$$

where $L_e = (\pi / 2\sqrt{3})L_d$ , $R_e = (\pi / 2\sqrt{3})(R_d + 12R_s/\pi^2)$ ,

$R_{re} = (6M^2/\pi\ L_r^2)R_r$ , $K_m = (6M^2/\pi\ L_r)i_\mu$

Eqn.(15) describes the electrical performance of the motor under field orientation control.
In order to obtain the transient performance of the motor , the

mechanical equation is also needed. Thus in addition to eqn.(15), eqn.(5) is also used. Thus eqn.(5),(11) are used to obtain the transient current and torque characteristics following starting the induction motor, when it is initially electrically and mechanically inert, with field orientation control. To imply the field orientation control method during starting ,the system shown in Fig.(3) was used. Numerical integration of eqns.(15) and (5) was performed using 4th-order Runge-Kutta method.

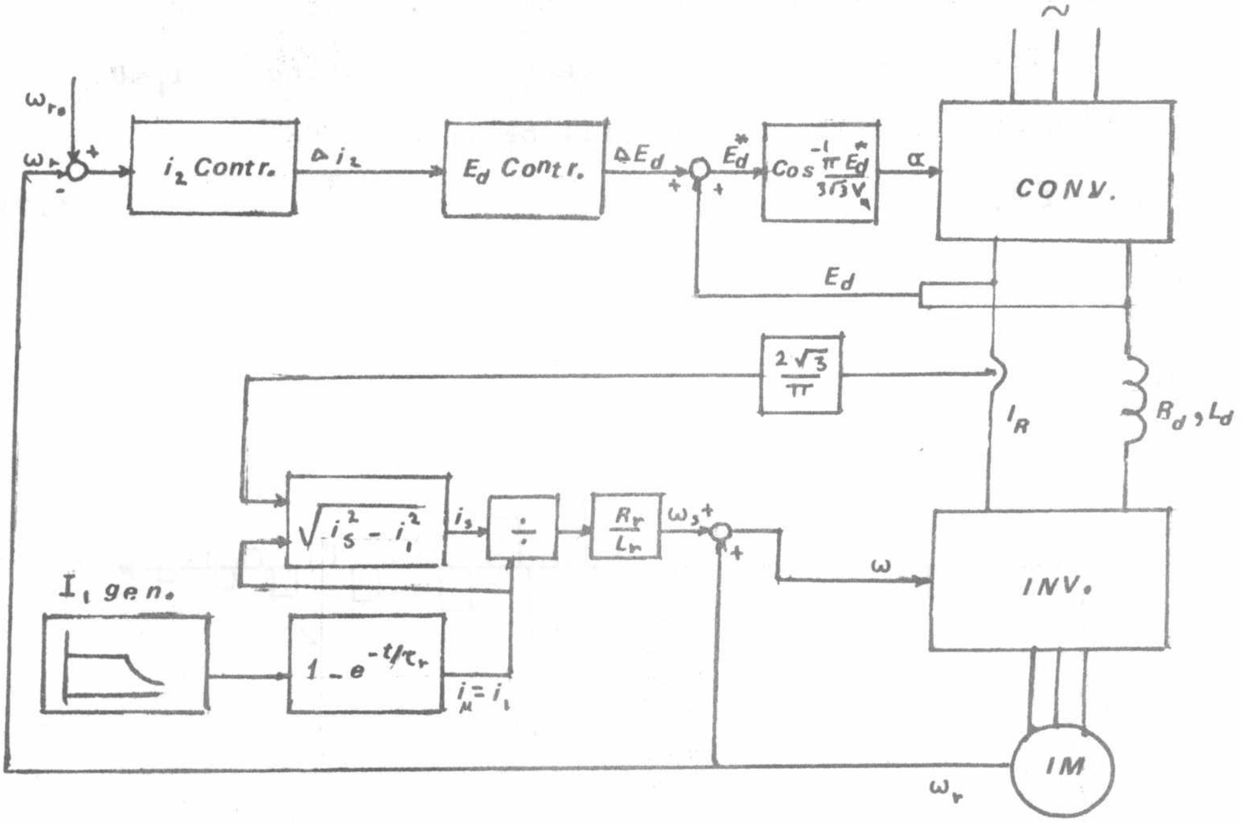


Fig.(3) Scheme of field orientation control

### 3.1 Determination Of The Initial Conditions

To solve eqns.(5) and (15) by Runge-Kutta method , the initial values of the variable quantities $i_1$, $i_2$, $i_\mu$ and $w_r$ should be determined.
At the beginning of starting, $i_\mu$ , $i_2$ and $w_r$ are all zero

Rewriting eqn.(9) in the form

$$i_1 (R_r/L_r) = di_\mu /dt + (R_r/L_r) i_\mu$$

and multiply both sides by M we get

$$i_1 M(R_r/L_r) = d\psi_r/dt + (R_r/L_r) M i_\mu \qquad (16)$$

Assuming that $\phi_r$ is constant during the small step of Runge-Kutta method of solution , therefore eqn.(16) reduces to

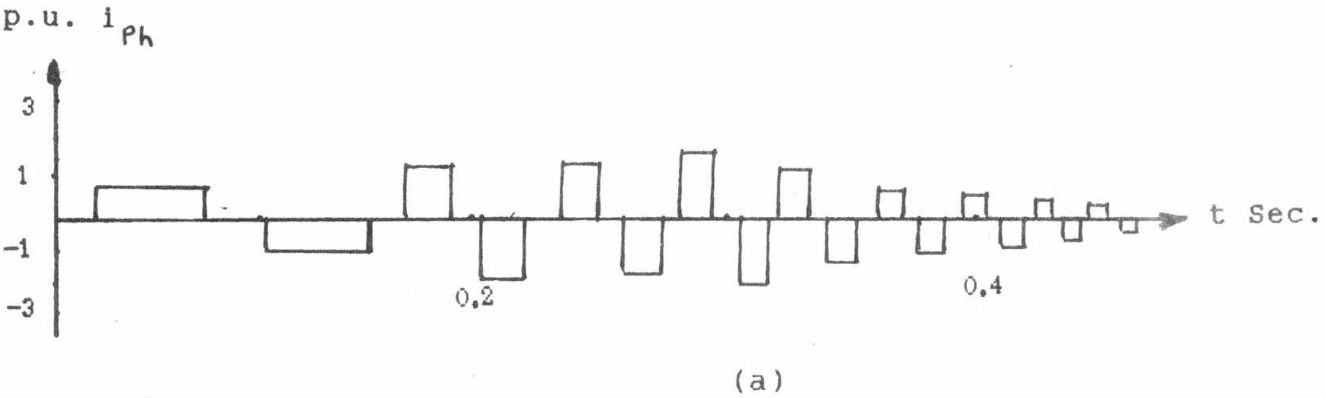
$i_1 = i_\mu$

Thus at $t=0$ , $i_1 = i_\mu = 0$

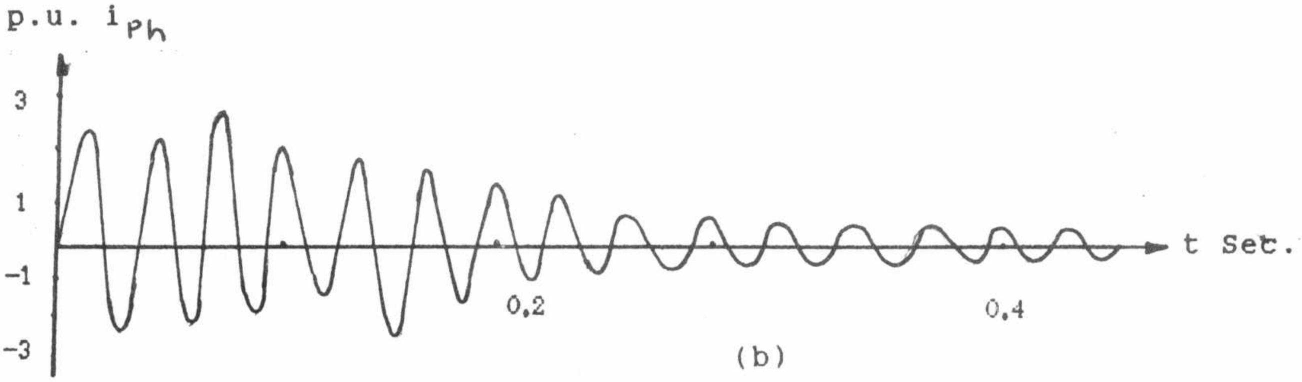
Eqn.(15) can be simplified to avoid the overflow which will otherwise appear when substituting $i_2 = 0$ at $t = 0$ , by assuming first that $i_2 = i_1$ then substituting $i_1 = 0$

Therefore eqn.(15) at $t = 0$ will be reduced to

$$L_e \, p i_2 = \sqrt{2} \, E_d \tag{17}$$



(a)



(b)

Fig.(4) Starting phase current
(a) with field orientation control
(b) with 3-phase sinusoidal supply

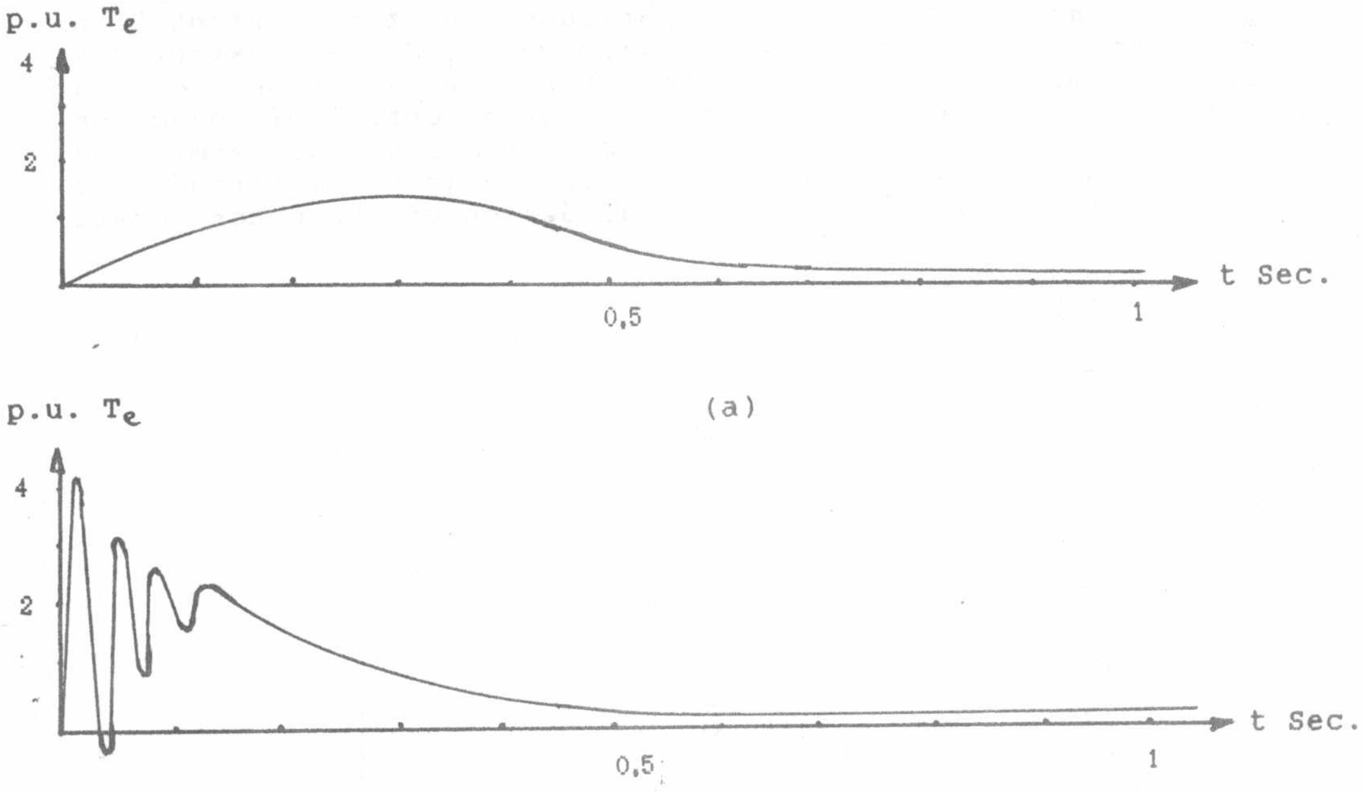


Fig.(5) Starting developed torque
(a) with field orientation control
(b) with 3-phase sinusoidal supply

## 4. RESULTS

Fig.(4) and Fig.(5) show the starting current and torque characteristics of a 7.5 kW 3-phase induction motor whose data is given in Table(1).[6] The motor was loaded with a 7.5 kW d.c. generator whose data is also given in Table(1). Fig.(4)a is the starting transient current when the motor is fed from a CSI under field orientation control. Fig.(4)b is the starting transient current when it is fed from a 3-phase conventional sinusoidal voltage source. Figs.(5)a and (5)b are for the transient torque in both cases. It is observed from these figures that the maximum peak current under field orientation control was about 1/4 of that with 3-phase sinusoidal voltage supply. Also ,the maximum peak torque under field orientation control was about 1/3 of that with a 3-phase sinusoidal voltage supply.

## CONCLUSION

A method from which the transient performance of the CSI fed induction motor, with field orientation control, can be obtained is shown. Comparisons with the performance for a normal 3-phase supply were made. From these comparisons ,the field orientation control method of induction motor improves to a great extent the starting characteristics of the motor ;in addition to its advantages as a decoupling method of speed control of induction motors. The reduction of the peak current and torque permits a choice of a small rating thyristors in the inverter circuit and allows modification in the mechanical design of the motor shaft for less transient peak torque.

Table 1

| | | |
|---|---|---|
| Nameplate Motor Data | | |
| Output | 7.5 | kW |
| Voltage | 220 | V |
| Primary current | 27.35 | A |
| Frequency | 50 | HZ |
| No. of poles | 6 | |
| J - total | 0.511 | Kg.m |
| Motor Parameters | | |
| $R_s$ | 0.1695 | Ω |
| $R_r$ | 0.2445 | Ω |
| $L_s$ | 32.50 | mH |
| $L_r$ | 32.96 | mH |
| M | 31.59 | mH |
| Filter Parameters | | |
| $R_d$ | 0.335 | Ω |
| $L_d$ | 324 | mH |
| Nameplate of d.c. generator | | |
| Output | 7.5 | kW |
| Voltage | 220 | V |
| Speed | 1200 | r.p.m. |
| $R_a$ | 0.58 | Ω |
| Field | shunt | |

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## NOMENCLATURE

| | | |
|---|---|---|
| VSI | voltage source inverter | |
| CSI | current source inverter | |
| $E_d$ | d.c.output voltage of controlled rectifier bridge, | V |
| $I_R$ | d.c. link current , | A |
| $T_e$ | developed torque, | N.m |
| $T_f$ | opposing torque, | N.m |
| J | moment of inertia of motor and load | Kg.m |
| P | number of pole-pairs | |
| i | instantaneous current, | A |
| v | instantaneous voltage, | V |
| $w_r$ | rotor speed, | elec.rad./s. |
| $\theta$ | rotor angular position, | elec.rad. |
| p | operator d/dt | |
| $\psi_r$ | flux linkage of the rotor, | Wb |
| R | phase resistance, | Ω |
| L | phase self inductance, | H |
| M | mutual inductance, | H |

subscripts s and r denote stator and rotor respectively , subscripts d and q denote stationary direct and quadrature components respectively, subscript $\mu$ denotes magnetizing current, subscripts 1,2 denote direct and quadrature field coordinates components respectively.