Fuzzy Logic Control Contribution to the Direct Torque Control for Three Level Inverter Fed Induction Machine

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***Abstract*– This paper presents a control strategy of an induction machine supplied by three level inverters (NPC). The induction machine with the control strategy should provide, at the constraining requests, a response with high performances in electromagnetic torque and flux. This paper aims to demonstrate the contribution of fuzzy logic in the direct torque control (FDTC). This method based on a new fuzzy logic controller to select the output voltage vector by replacing the hysteresis comparators and look-up table in the conventional DTC scheme. By using FDTC not only the torque and flux ripples reduce significantly but also the THD of the phase current decreases since a more sinusoidal current waveform is achieved.**

Simulation results have verified the feasibility of the proposed control algorithm using Matlab / Simulink.

***Index Term*-- Three level inverters (NPC), induction motor, FDTC, Fuzzy controller.**

I. INTRODUCTION

Induction machines have been widely used in industrial field as actuators, since they are more rugged, reliable, compact, efficient and cheaper then Direct Current (DC) machines. However, difficulties in high performance induction machine drive arise, as the machine's model is complicated, highly coupled, nonlinear, multivariable and uncertain [1].

The recent advances of both high power switching devices and fast microprocessors have allowed the implementation of sophistically command algorithms. One of the common used control strategies is the direct torque control (DTC).

Direct torque control (DTC) method has emerged as an alternative to Field Oriented Control (FOC) method for high performance ac drives since [2] [3]. The merits of DTC are fast torque response, simple structure (no need of complicated coordinate transformation, current regulation or modulation block), and robustness against motor parameter variation [4] [5].

Nevertheless, DTC presents some disadvantages such as high current, flux and torque ripple, difficulties in torque and flux control at very low speed, slow transient response to the step change in torque during start up [6], [7] [2]. It is well established that these disadvantages are mainly due to the use of hysteresis torque and flux controllers [8].

For this reason, several variation methods were proposed to minimize the problems, these includes the use of dithering signals [9], replacing the hysteresis with the non hysteresis based controllers [10], application of space vector modulation (SVM) [11] [12] and recently the optimisation of switching vector selection by means of multilevel inverter [13].

In the recent years, the Fuzzy Direct Torque Control (FDTC) have been successfully applied to many control problems, as they need no accurate mathematical models of the uncertain nonlinear systems under control [14][15].

On the other hand, multi-level inverters have become a very attractive solution for high power application areas [16][17]. The three-level neutral point clamped (NPC) inverter is one of the most commonly used multi-level inverter topologies in high power ac drives. By comparing to the standard two-level inverter, the three-level inverter presents its superiority in terms of lower stress across the semiconductors, lower voltage distortion, less harmonic content and lower switching frequency [18].

In this case, this work consists to present a direct torque control applied for induction motor using three level voltage inverters. In addition to overcome the problems cited above, we try to combine the advantages of both FDTC in the induction machine drive. Thus, the hysteresis comparator and the switching table in the DTC conventional are replaced by a fuzzy logic switcher.

II. PRINCIPE OF DTC AND THREE LEVEL INVERTERS

The direct torque and flux control has been introduced by I. TAKAHASHI in 1985 from the flux-oriented method and the principle of the DC motor [19]. Fig. 1 shows the block diagram of a direct torque control of induction machine supplied by three level inverters. A switching table is used to determinate the control sequence that should be applied to the voltage inverter switches, such as the torque and flux errors are kept within the specified bands.

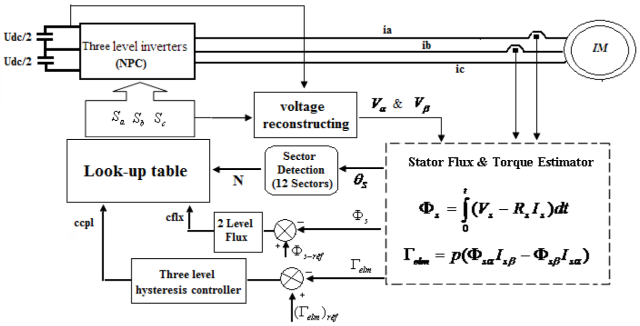


Fig. 1. Direct torque control of induction machine supplied by three level inverters

A. DTC strategy

Based on the state equations of the induction motor written in stator reference frame, (α, β) coordinate:

The stator flux is estimated from the measure of the sizes of current and voltage and their transformation by equations (1), (2):

$$\Phi_{s\alpha} = \int_0^t (V_{s\alpha} - R_s I_{s\alpha})dt \tag{1}$$

$$\Phi_{s\beta} = \int_0^t (V_{s\beta} - R_s I_{s\beta})dt \tag{2}$$

The stator flux linkage is given by equation (3):

$$\Phi s = \sqrt{\Phi_{s\alpha}^2 + \Phi_{s\beta}^2} \tag{3}$$

.

And the stator flux angle, is calculated by,

$$\theta_s = \tan^{-1}(\Phi_{s\beta} / \Phi_{s\alpha}) \tag{4}$$

The expression of the electromagnetic torque is obtained from the statorique flux $\Phi_{s\alpha}$, $\Phi_{s\beta}$ and currents $I_{s\alpha}$, $I_{s\beta}$ by equation (5):

$$\Gamma_{elm} = p(\Phi_{s\alpha} I_{s\beta} - \Phi_{s\beta} I_{s\alpha}) \tag{5}$$

B. Three level inverters and DTC

B.1 Three level inverters (NPC)

The three-level inverters (NPC) presented in Fig.2 has several advantages over the standard two-level inverter, such as a greater number of levels in the waveforms, lower dV/dt, less harmonic distortion and lower frequencies [20].

The output voltages of the inverter relatively to the middle point O with using the connection functions of the half-arm $\left(S_{i1}^b, S_{i0}^b\right)$ are defined as follows:

$$\begin{bmatrix} Va \\ Vb \\ Vc \end{bmatrix} = \frac{E}{6} \begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix} \times \left\{ \begin{bmatrix} S_{11}^b \\ S_{21}^b \\ S_{31}^b \end{bmatrix} - \begin{bmatrix} S_{10}^b \\ S_{20}^b \\ S_{30}^b \end{bmatrix} \right\}$$

With $S_{i1}^b = S_{i1} \times S_{i2}$, $S_{i0}^b = S_{i3} \times S_{i4}$.

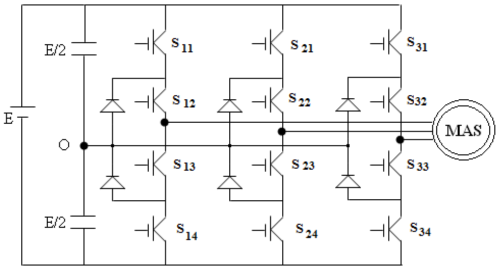


Fig. 2. Three level inverters voltage feeding an induction motor

To analyze the potential generated by this inverter 3 states, every arm is schematized by three switches allow to connect independently the borders of the stator to three potential of the source (E/2, 0 and –E/2).

In general, the switching condition, for each vector that generates three level output, can be defined as given in table (1).

Table I
Switching combination of switches for each phase leg on NPC

S_{i1}	S_{i2}	S_{i3}	S_{i4}	V_i	Switching state
ON	ON	OF	OF	$E/2$	2
OF	ON	ON	OF	0	1
OF	OF	ON	ON	$-E/2$	0

B.2 Vectors tensions and phase level sequences of a three level inverters

By making a transformation in the plane (α, β), we define a vector voltage resulting partner in the spatial position of the stator flux, and it follows itself that shade of states different from this vector is 19.

The Fig.3 shows the various discreet positions, in the plane α β, of the vector tension generated by the three level inverters.

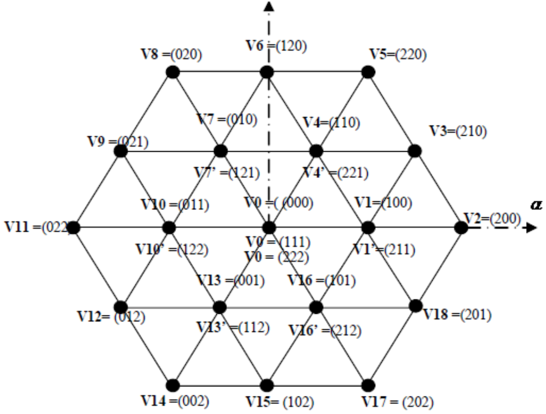


Fig. 3. Vectors tensions generated by the 3 level inverters

B.3 Sectors definition

The complex plane in Fig.4 is divided into 12 sectors i, with i= [1, 12] of 30° each, starting with the first sector situated between -30° and 0°.

When the stator flux vector is in a sector **i**, the control of the flux and the torque can be assured by selecting one of 27 voltages vectors possible.

Depending on the stator flux position (sector) and the values of the outputs of torque and flux controller, $\varepsilon_{\Phi s}$ and $\varepsilon_{\Gamma elm}$ respectively, the optimal vector is selected, from all vectors available in Fig.4, the notation (2, 1, 0) means phases a, b, c of the inverter output are connected respectively to the positive, neutral and negative bus bars of the DC-link.

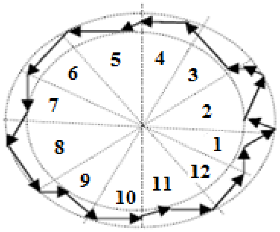


Fig.4: Selection of vectors tensions Vs corresponding to the control of the flux Φ_s for a 3 - level inverter

B.4 Torque and Flux hysteresis controllers

The selection of voltage vector is based in the operating conditions whether it is in low, medium or high speed (or torque). 3 level torque hysteresis and 2 level flux hysteresis comparator inherently produce the appropriate status according the motor operating conditions.

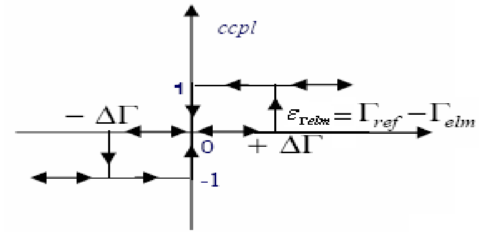


Fig. 5. Three level hysteresis comparator of torque

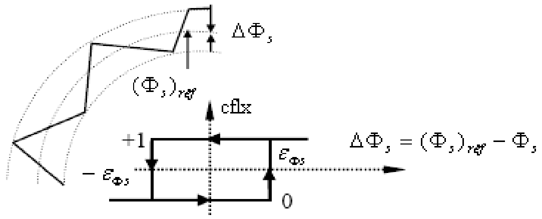


Fig. 6. two level hysteresis comparator of flux

B.5 The Switching Table of the conventional DTC

The elaboration of the command structure of the three level inverters NPC feeding an induction motor is based on the hysteresis controller output relating to the variable flux (cflx) and the variable torque (ccpl) and the sector N corresponding to the stator flux vector position. The truth table is given by the Table III.

Table III
The switching table for 3-level inverters

N	**cflx = 1**			**cflx = 0**		
	ccpl=1	**ccpl=0**	**ccpl=-1**	**ccpl=1**	**ccpl=0**	**ccpl=-1**
1	V3	V19	V15	V6	V20	V12
2	V6	V20	V18	V9	V19	V15
3	V6	V19	V18	V9	V19	V15
4	V9	V19	V3	V12	V20	V18
5	V9	V20	V3	V12	V19	V18
6	V12	V19	V6	V15	V20	V3
7	V12	V20	V6	V15	V19	V3
8	V15	V19	V9	V18	V20	V6
9	V15	V20	V9	V18	V19	V6
10	V18	V19	V12	V3	V20	V9
11	V18	V20	V12	V3	V19	V9
12	V3	V19	V15	V6	V19	V12

C. The proposed fuzzy direct torque control (FDTC)

By analyzing the structure of the switching table, we note that it can be printed as fuzzy rules. Therefore, a first fuzzy logic-switcher can replace the switching table and the hysteresis controllers, whose inputs are the errors on the flux and torque denoted respectively dF & dT, and the argument θ of the stator flux (should remain between ± π) denoted Teta. The following fig.7 shows the block diagram of the FDTC.

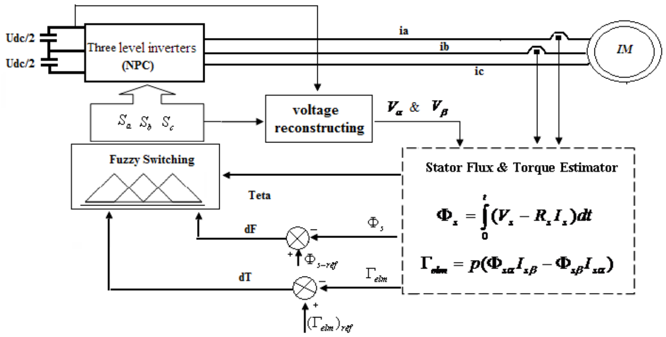


Fig. 7. Proposed fuzzy direct torque control FDTC

Figure 8 shows the design of fuzzy logic system in Matlab/simulink and also the configuration of its inputs and outputs as membership functions.

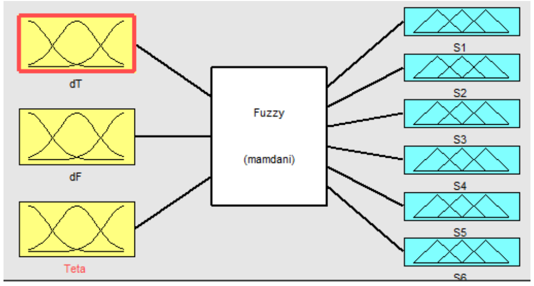


Fig. 8. Matlab/Simulink design of the fuzzy logic switching table used in FDTC

The fuzzy rules base with 168 rules can be obtained from the following table IV.

Table IV
Fuzzy logic Switcher rules

θ 1

dT/dF	P	N
PL	V3	V5
PM	V2	V4
PS	V14	V15
Z	V20	V19
NS	V18	V17
NM	V10	V8
NL	V11	V9

θ 2

dT/dF	P	N
PL	V3	V5
PM	V4	V6
PS	V14	V15
Z	V19	V20
NS	V18	V17
NM	V12	V10
NL	V11	V9

θ 3

dT/dF	P	N
PL	V5	V7
PM	V4	V6
PS	V15	V16
Z	V20	V19
NS	V13	V18
NM	V12	V10
NL	V1	V11

θ 4

dT/dF	P	N
PL	V5	V7
PM	V6	V8
PS	V15	V16
Z	V19	V20
NS	V13	V18
NM	V2	V12
NL	V1	V11

θ 5

dT/dF	P	N
PL	V7	V9
PM	V6	V8
PS	V16	V17
Z	V20	V19
NS	V14	V13
NM	V2	V12
NL	V3	V1

θ 6

dT/dF	P	N
PL	V7	V9
PM	V8	V10
PS	V16	V17
Z	V19	V20
NS	V14	V13
NM	V4	V2
NL	V3	V1

θ 7

dT/dF	P	N
PL	V9	V11
PM	V8	V10
PS	V17	V18
Z	V20	V19
NS	V15	V14
NM	V4	V2
NL	V5	V3

θ 8

dT/dF	P	N
PL	V9	V11
PM	V10	V12
PS	V17	V18
Z	V19	V20
NS	V15	V14
NM	V6	V4
NL	V5	V3

θ 9

dT/dF	P	N
PL	V11	V1
PM	V10	V12
PS	V18	V13
Z	V20	V19
NS	V16	V15
NM	V6	V4
NL	V7	V5

θ 10

dT/dF	P	N
PL	V11	V1
PM	V12	V2
PS	V18	V13
Z	V19	V20
NS	V16	V15
NM	V8	V6
NL	V7	V5

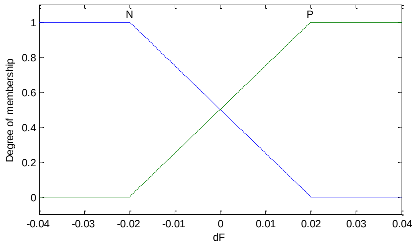
θ 11

dT/dF	P	N
PL	V1	V3
PM	V12	V2
PS	V13	V14
Z	V20	V19
NS	V17	V16
NM	V8	V6
NL	V9	V7

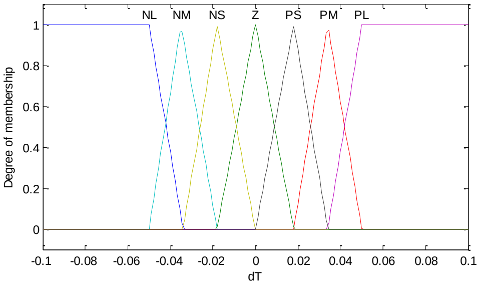
θ 12

dT/dF	P	N
PL	V1	V3
PM	V2	V4
PS	V13	V14
Z	V19	V20
NS	V17	V16
NM	V10	V8
NL	V9	V7

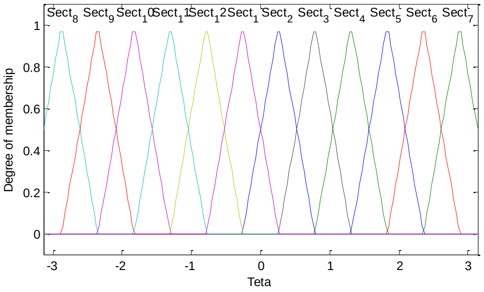
The membership functions of the FL-switcher are given by Fig. 9. The linguistic used for stator flux error are N (negative error), and P (positive error). For the torque error, the terms used are NL (negative large error), NM (negative medium error), NS (negative small error), Z (zero error), PS (positive small error), PM (positive medium error) and PL (positive large error). It can be seen that the linguistic terms of torque are more than that of the flux.



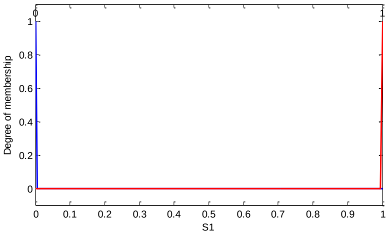
(a) The membership functions for stator flux error



(b) The membership functions for electromagnetic torque error



(c) The membership functions for stator flux position



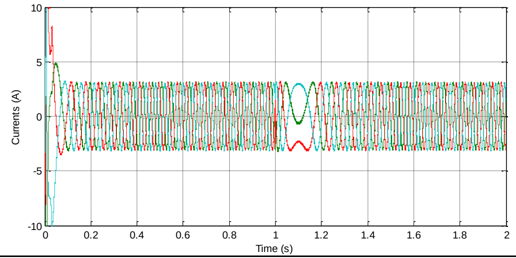
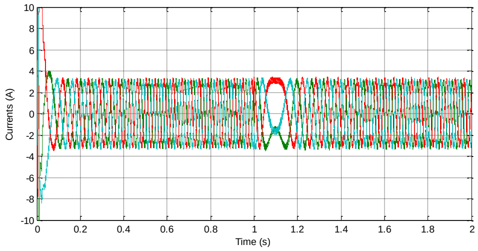
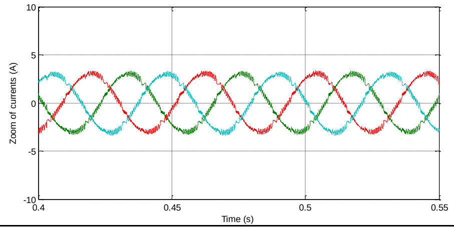
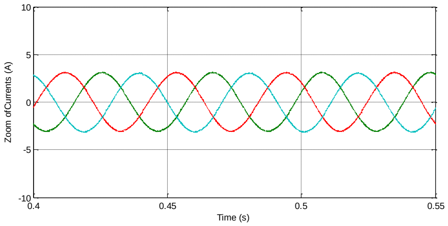
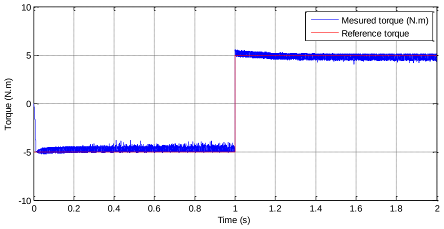
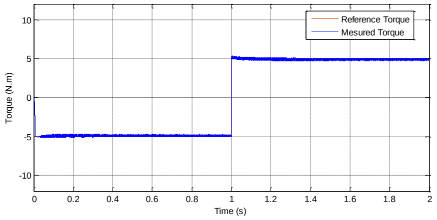
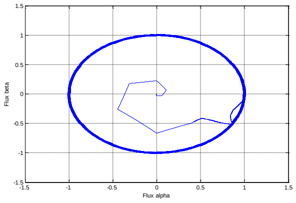
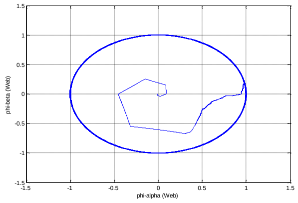
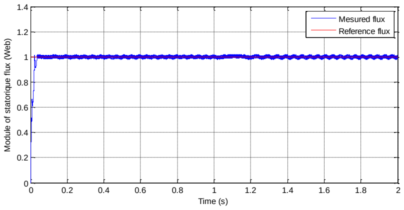
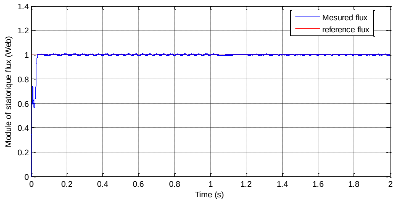
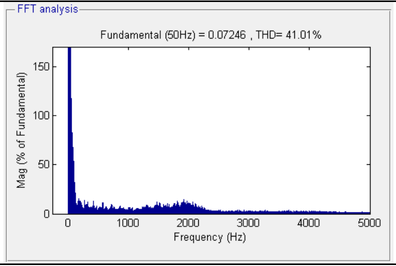
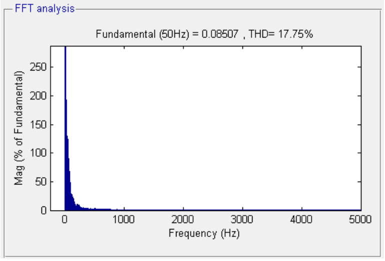
(c) The membership functions for state switches as singletons

Fig. 9. The distributions of membership functions for all fuzzy variables.

IV. SIMULATION RESULTS

Simulations results were carried out to verify the effectiveness of using FDTC strategy.

In order to valid the quality of the drives, a simulation test on 1.5 kW induction machine has been performed. The test was carried out during 2 seconds. A step change of reference torque was applied from -5N.m to +5 N.m at t=1s.

	(a)	
	(b)	
	(c)	
	(d)	
	(e)	
	(f)	
Fig. 11. Simulation results of conventional DTC: (a) stator current time evolution, (b) zoom of stator current time evolution, (c) Time evolution of Torque, (d) Stator flux in the $\alpha\beta$, (e) Time evolution of flux, (f) spectrum of current.		Fig. 12. Simulation results of FDTC: (a) stator current time evolution, (b) zoom of stator current time evolution, (c) Time evolution of Torque, (d) Stator flux in the $\alpha\beta$, (e) Time evolution of flux, (f) spectrum of current.

The obtained simulation results show that:

- The simulation results in Fig.12 (a, b) show that the current's stator ripples with FDTC is significantly reduced compared to DTC conventional Fig.11 (a, b).
- The ripple of Torque with FDTC strategy is significantly reduced Fig.12 (c) compared to Fig.11 (c).
- The ripple of stator flux trajectory with FDTC is significantly reduced Fig.12 (d) compared to Fig.11 (d).
- It's seen that the statorique currents in FDTC presented a good THD 17,75% Fig.12 (f) and 41,01% in DTC conventional Fig.11 (f).

The Fuzzy direct torque control (FDTC) of an induction machine supplied by three level inverters reduces advantage the harmonics of currents and the ripple of torque and flux.

V. CONCLUSION

In this paper, we have presented the direct torque control of an induction machine, supplied by three level inverters (NPC), with both its classical version and integration of fuzzy logic. This contribution of fuzzy logic has improved clearly dynamic and static (disturbance rejection) performances, with very good robustness against change in mechanical parameters. In order to decrease torque ripple, the membership functions, used in torque fuzzification, are increased (seven membership functions of torque). On line adaptation of the stator resistance, which can vary with temperature and operating point, and the real implementation of the presented techniques in a DSP board are the prospects of our next work.

Table IV
Induction Machine parameters

Rated Power P	$1.5\ kW$
Voltage V	$220/380\ V$
Number of Pair Poles n_p	2
Stator Resistance R_s	$5.63\ \Omega$
Rotor Resistance R_r	$2.62\ \Omega$
Stator Self-Inductance L_s	$0.018\ H$
Rotor Self-Inductance L_r	$0.018\ H$
Mutual Inductance M	$0{,}20\ H$
Total inertia J	$0{,}02\ kg.m^2$
Friction coefficient f	$0{,}0057\ N.m.s$

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