Robust Nonlinear Predictive Control Applied to Induction Motors

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ABSTRACT

In this paper, a nonlinear predictive controller is proposed for a variable-speed induction motor. The research work is directed towards improving the trajectory tracking capability, stability guarantee, robustness to parameter variations, and disturbance rejection. The Generalized Predictive Control (GPC) without constraint and output-constrained controller to induction motor drive is illustrated. The variables to be controlled are rotor speed and flux trajectory. The load torque is considered an unknown disturbance. Finally, the tuning parameter of GPC is automatically determined. The simulation results show a good performance for the nonlinear dynamic system.

Keywords-robust; induction motor; polynomial approach; output contraint; predictive control

I. INTRODUCTION

Generalized Predictive Control (GPC) is among the most popular control techniques, having many ideas in common with Dynamic Matrix Control (DMC) [1] and Model Algorithm Control (MAC) [2]. The control algorithms differ mainly in the plant (and/or noise) models used and the cost function chosen. The GPC exhibits very good performance and robustness provided that the tuning parameters are property selected. However, the selection of these parameters is not an easy task. First there are no precise guidelines for the selection of these parameters in order to ensure closed loop stability [2, 3], although recent works have proposed modifications of the prototypical structure in order to guarantee stability. GPC algorithms have been proposed under various names by several authors [4-7] and constitute a class of powerful control algorithms that have been widely applied on industrial processes. GPC is a technique with success in industrial applications. Besides its quality, GPC provides unconstrained case linear laws easy to implement in polynomial formulations [3, 4] and can further be reinforced by adding equation constraints for stability. The application to fast processes with constraints has been delayed and the optimal control action is generally provided by an on-line optimization procedure, generally a time-consuming process.

The classical predictive control approach to drive applications includes several different control strategies. The various control schemes can be divided in a few main groups. The most published schemes so far belong to the families of hysteresis-based or trajectory-based predictive control. On the contrary, GPC belongs to the Model-Based Predictive Control (MBPC) group, which is founded on totally different ideas. The idea of MBPC is to calculate a control function for the future time in order to force the controlled system's response to reach the reference value. Therefore, the future reference values have to be known (which is the case in many industrial applications) and the system behavior must be calculable by an appropriate model. All the GPC algorithms are very similar because they have the same general idea in common. Authors in [7, 8] present an approach to the design of an RST cascade predictive structure to control rotor position, speed, and the rotor flux amplitude of an induction machine. The proposed cascaded version introduces a formulation of the reference signals in the structure of the inner and external loop which enables tracking flux and position. The purpose is to propose a new methodology to current-fed induction motor. This approach results from a combination of the differential flatness properties and the monovariable GPC with the Multiple Reference Model (GPC/MRM) algorithm. The chosen outputs are the rotor speed and the square of the rotor flux [8]. Different techniques have been proposed from the active–set methods to LMI [11]. Lately, the idea of moving a part of the computational effort offline emerged and alternative techniques [9, 10] emerged based on look–up tables of linear affine controllers for regions of the sate–space. The continuous robust GPC of a permanent synchronous motor drive is explored in [14]. This work combines GPC controller with linear predictive control technology for Permanent Magnet Synchronous Model (PMSM). A Continuous Linear Model (CTLM) is used to develop the GPC controller and determine the degree of the relative disturbance in [12-14, 18]. The SVPWM (Space Vector Pulse Width Modulation) GPC of linear induction motor drives was studied in [14, 15]. The authors used space vector pulse with modulation. Authors in [19, 20] used the FOD (Field Oriented Control) for the robustification of explicit predictive control law [20]. The work in [21] is based on parametric programming and concentrates on control robustification. GPC strategy is introduced for the prediction of the Controlled Autoregressive Integrated Moving Average (CARIMA) plant model in [10, 21].

In this paper, an algorithm based on RST is presented. Our method uses the synchronous motor as a highly nonlinear multivariable system. It deals with the development of a high performance nonlinear predictive control induction motor drive. The research work is directed towards improving the trajectory tracking capability, stability guarantee, robustness to parameter variations, and disturbance rejection. Simulation results and the concluding remarks on the advantages and perspectives are also presented.

II. GENERALIZED PREDICTIVE CONTROL

A predictive strategy first requires the definition of a numerical prediction model. A commonly used form in GPC is the CARIMA model [6]:

$$A(q^{-1})y(t) = B(q^{-1})u(t-1) + C(q^{-1})\frac{\xi(t)}{\Delta} \quad (1)$$

where $u(t)$, $y(t)$ are the process input and output, A and B are polynomials in the backward shift operator, $\xi(t)$ is an uncorrelated random sequence and the operator $\Delta(q^{-1}) = 1 - q^{-1}$ ensures an integral control law.

$$A(q^{-1}) = 1 + a_1q^{-1} + \cdots a_{na}q^{-na}$$

$$B(q^{-1}) = 1 + b_1q^{-1} + \cdots b_{nb}q^{-nb}$$

$$C(q^{-1}) = 1$$

n_a and n_b are degrees of polynomials A and B respectively.

A. Definition of the Quadratic Cost Funtion

The performance index is a weighted sum of predicted output tracking errors and future control errors, so the cost function to be minimized is [10, 19, 20].

$$i = \sum_{j=N_1}^{N_2} \varepsilon_y^2(t+j) + \lambda \sum_{j=1}^{N_u} \varepsilon_u^2(t+j-1) \quad (2)$$

Assuming $\varepsilon_u(t+j) = 0$ for $j \geq N_u$:

$$\varepsilon(t+j) = y(t+j) - y_{ref}(t+j)$$

with:

$$\varepsilon_u(t+j) = \Delta\mathrm{u(t+j)} - \Delta u_{ref}(t+j) \quad (3)$$

where N_1 and N_2 are the minimum and maximum costing horizons, N_u is the control horizon, and λ is the control weighting factor. The GPC version with reference models imposes that the predicted output tracks a reference trajectory y_{ref} coupled to a reference control signal u_{ref}. The originality of our approach is the formulation of the reference models for the y_{ref} for the rotor speed and the planified trajectories which satisfy the motor's constraints. The reference control signal u_{ref} will be expressed in terms of the chosen outputs [9-11, 20]. The linear structure RST law can be used in order to obtain access to a larger class of table controllers, by means of the Youla –Kucera parameterization.

III. DESIGN OF THE RST POLYNOMIAL CONTROLLER

To solve the minimization problem [10], an optimal *j*-step ahead predictor based on the output error must be computed:

$$\Delta(q^{-1})A(q^{-1})J(q^{-1}) + q^{-1}F_j(q^{-1}) = 1$$

$$G_j(q^{-1}) + q^{-1}H_j(q^{-1}) = B(q^{-1})J_j(q^{-1})$$

where F_j, G_j, H_j, and J_j are solutions of the Diophantine equations.

The optimal control law which minimizes the cost function is first deduced in a matrix form:

$$\varepsilon_{u\,opt} = -M[if\varepsilon_v(t) + ih\epsilon_u(t-1)] \quad (4)$$

with:

$$M = [G^TG + \lambda I_{Nu}]^{-1}G^T = \begin{bmatrix} M_1^T \\ \vdots \\ M_{Nu}^T \end{bmatrix} \quad (5)$$

where:

$$G = \begin{bmatrix} g_{N_1}^{N_1} & g_{N_1-1}^{N_1} & \cdots & \cdots \\ g_{N_1+1}^{N_1+1} & g_{N_1}^{N_1+1} & \cdots & \cdots \\ \cdots & \cdots & \cdots & \cdots \\ g_{N_2}^{N_2} & g_{N_2-1}^{N_2} & \cdots & g_{N_2-N_u+1}^{N_2} \end{bmatrix}$$

The coefficients of the matrix G correspond to the step response:

$$if = [F_{N_1}(q^{-1}) \cdots F_{N_2}(q^{-1})]^T$$

$$ih = [H_{N_1}(q^{-1}) \cdots H_{N_2}(q^{-1})]^T$$

$$\varepsilon_{uopt} = [\varepsilon_{uopt}(t) \cdots \varepsilon_{uopt}(t+N_u-1)]^T$$

$$S(q^{-1})\Delta u(t) = -R(q^{-1})(t) + T(q^{-1})w(t) \quad (6)$$

with:

$$[S(q^{-1})] = degree[B(q^{-1})]$$

$$R(q^{-1}) = M_1^T if;\mathrm{degree}[R(q^{-1})] = degree[A(q^{-1})];$$

$$T(q^{-1})w(t) = \Delta(q^{-1})S(q^{-1})u_{ref}(t) + R(q^{-1})y_{ref}(t) \quad (7)$$

where $R(q^{-1})$, $S(q^{-1})$, and $T(q^{-1})$ compose the equivalent controller of the GPC algorithm [2, 7]. The minimization of (7) provides the determination of the polynomials' structure of the GPC controller as shown in Figure 1.

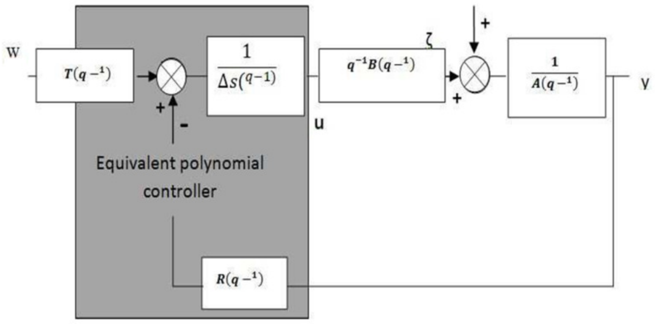

Fig. 1. Equivalent polynomial controller.

IV. MATHEMATICAL MODEL OF INDUCTION MOTOR FRAME ABC

The induction motor is generally used in industrial applications because it is reliable, robust, and has a low cost. A well-founded induction motor gives good results under various operating states. To achieve this, the values of the motor are kept in mind. Dynamic simulation plays a significant part in evaluating a model's design process in order to eliminate design errors. The induction motor is modeled in a synchronously revolving rotor flux-oriented frame, which is used as a reference. For sensorless vector control and induction motor control methods, accurate knowledge of a few induction motor parameters is necessary. The presentation of the drive will degrade if the original data in the motor do not match the values utilized in the controller. Various mechanisms have been developed to calculate the online and offline parameters of the induction machine for its application in high-performance drives. The aim of this paper is to present dynamic modeling and other considerable approaches used for estimating the induction motor parameters. Also, some simulation examples related to dynamic modeling and parameter estimation techniques, which may be useful for specialists in the field of electric drive control systems, are considered. Electrical drives based on induction motors are commonly used in industrial applications due to their simplicity and low maintenance cost. We are interested in the induction motor ABC frame model. Park transformation is not needed to realize the system. However, even if traditional control techniques of induction machines are adopted, e.g. scalar control, FOC, Direct Torque Control (DTC), predictive control, etc., improvements can be achieved in order to extend the operating range, improve behavior during saturations in order to reduce electrical influence and mechanical parameter variations, and improve transient performance. The reader is referred to [12-16] for the general theory of electric machine and induction motors for related control.

$$V = RI + \frac{d\varphi}{dt} \quad (7)$$

$$\begin{bmatrix} v_{sa} \\ v_{sb} \\ v_{sc} \end{bmatrix} = \begin{bmatrix} R_s & 0 & 0 \\ 0 & R_s & 0 \\ 0 & 0 & R_s \end{bmatrix} \begin{bmatrix} I_{sa} \\ I_{sb} \\ I_{sc} \end{bmatrix} + \frac{d}{dt} \begin{bmatrix} \varphi_{sa} \\ \varphi_{sb} \\ \varphi_{sc} \end{bmatrix} \quad (8)$$

The rotor voltage is described by the matrix form:

$$\begin{bmatrix} v_{ra} \\ v_{rb} \\ v_{rc} \end{bmatrix} = \begin{bmatrix} R_r & 0 & 0 \\ 0 & R_r & 0 \\ 0 & 0 & R_r \end{bmatrix} \begin{bmatrix} I_{ra} \\ I_{rb} \\ I_{rc} \end{bmatrix} + \frac{d}{dt} \begin{bmatrix} \varphi_{ra} \\ \varphi_{rb} \\ \varphi_{rc} \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix} \quad (9)$$

With the previous hypotheses, all the relations of induction motor are presented. The matrix of the real flux is:

$$\begin{bmatrix} \varphi_{sabc} \\ \varphi_{rabc} \end{bmatrix} = \begin{bmatrix} L_s & M_{sr} \\ M_{sr} & L_r \end{bmatrix} \quad (10)$$

with:

$$[L_s] = \begin{bmatrix} L_s & M_s & M_s \\ M_s & L_s & M_s \\ M_s & M_s & L_s \end{bmatrix} \quad (11)$$

$$[L_r] = \begin{bmatrix} L_r & M_r & M_r \\ M_r & L_r & M_r \\ M_r & M_r & L_r \end{bmatrix} \quad (12)$$

$$[M_{sr}] = \begin{bmatrix} \cos(\alpha) & \cos(\alpha + 2\pi/3) & \cos(\alpha - 2\pi/3) \\ \cos(\alpha - 2\pi/3) & \cos(\alpha) & \cos(\alpha + 2\pi/3) \\ \cos(\alpha + 2\pi/3) & \cos(\alpha - 2\pi/3 & \cos(\alpha) \end{bmatrix} \quad (13)$$

The dynamic equation of the system is described by:

$$J\frac{d\Omega}{dt} = T_E - T_L \quad (14)$$

where J is the inertia of the machine, R_s and R_r are the stator and rotor resistances, L_s and L_r are the stator and rotor inductances, Ω is the rotor speed, α is the rotor position, M_{sr} is the mutual inductance, p is the number of pole pairs, f is the friction coefficient, T_L is the load torque, and T_r is the time rotor constant.

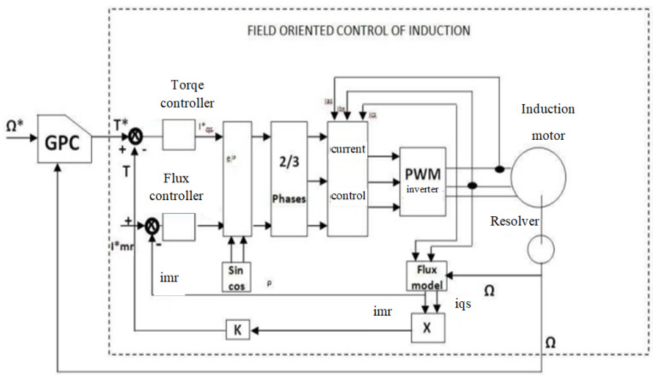

Fig. 2. Field oriented control of 1C by GPC.

V. FIELD ORIENTATION CONTROL

The considered plan is an experimental setup of a squirrel cage induction motor. Benchmark systems for the positioning control laws of asynchronous machine details regarding the general theory of electric machines and induction motors can be found in [16, 17, 21]. The machine considered is a three (squirrel) cage asynchronous motor with two pairs of poles in star power connection. The model takes into account the matrix transformations of the one phase system to a two phase representation, and the field oriented control including a torque and flux loop. The aim of the inner torque and flux control is to obtain a particular situation corresponding to the control of a DC motor. The model summarized in Figure 2 will be used to test the polynomial law in speed and position. For robust control of the motor velocity (good stability margins, small overshoot of the step response according to the guaranteed stability recommendation [22]), the auto calibration procedure by a controller is designed. The compliant link where the torque is often saturated during rapid slewing is controlled. The tuning parameters have their optimal values [21, 22].

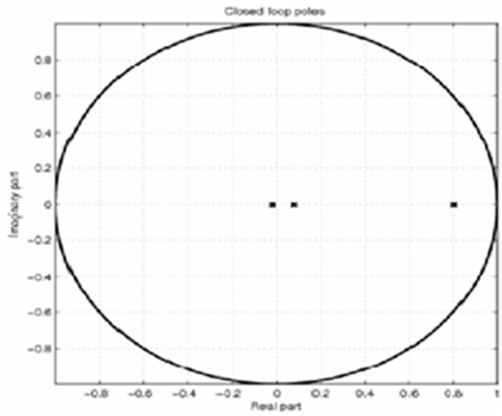

Fig. 3. Closed loop of poles.

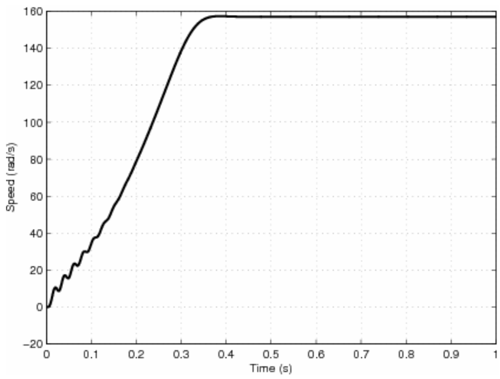

Fig. 4. Velocity of the induction motor.

VI. STUDY AND TEST OF STABILITY

The stability of the scheme can be tested by looking in the Bode or Black diagram (Figures 6-7).

$$H(q^{-1}) = \frac{q^{-1}B(q^{-1})R(q^{-1})}{S(q^{-1})\Delta(q^{-1})A(q^{-1})} \quad (15)$$

The results are shown to exhibit the stability of the external loop, considering the open loop is defined as in [10]. This is a test for both the induction machine and the polynomial algorithm. The frequency does not enter 3db, guaranteeing an overshoot less than 5. For a robust control of the motor velocity (good stability margin, small overshot of the step response) according to the guaranteed stability recommendations and the auto calibration procedure, the above described controller is designed.

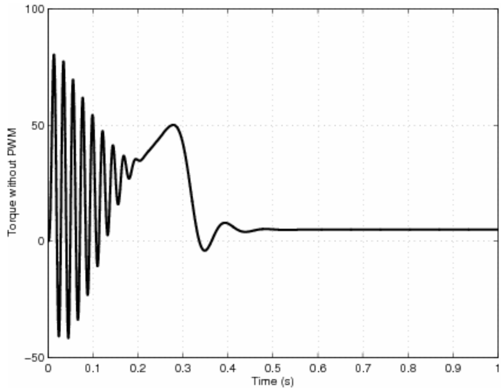

Fig. 5. Torque with PWM.

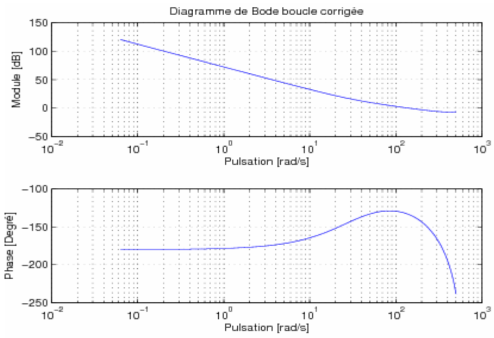

Fig. 6. Bode plot.

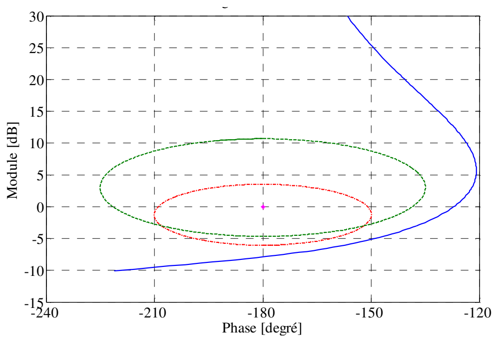

Fig. 7. Black plot.

VII. SIMULATION RESULTS

To test the performance of the nonlinear predictive controller, simulations were performed on an IM with nominal parameter values given in the Appendix and the load torque shown in Figure 8. The digital model of the motor is run with a sample time of 1μs. The space vector PWM inverter feeding the induction motor has a PWM period of 100μs. The full state vector is well known, where the stator voltage, stator current and speed are taken from the IM model and the rotor is estimated by (9). At first, the machine controlled by the cascade control law is run with the nominal values of the machines parameters. The tracking performance for rotor speed with measure is shown in Figure 9, with disturbance at 0.5s in Figure 10, and without disturbance in Figure 11.

$$\frac{\Omega(t)}{\Gamma(t)} = \frac{1.344q^{-1}+3.024q^{-2}+1}{1-0.92q^{-1}-0.02q^{-2}} \tag{16}$$

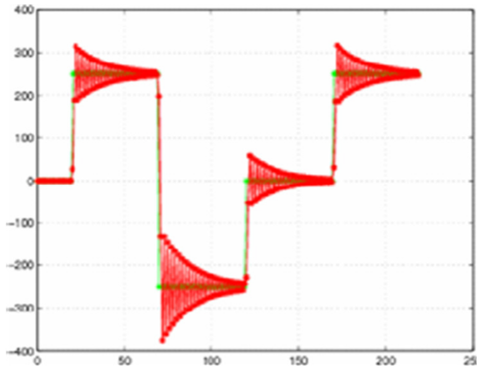

Fig. 8. Torque with constraints.

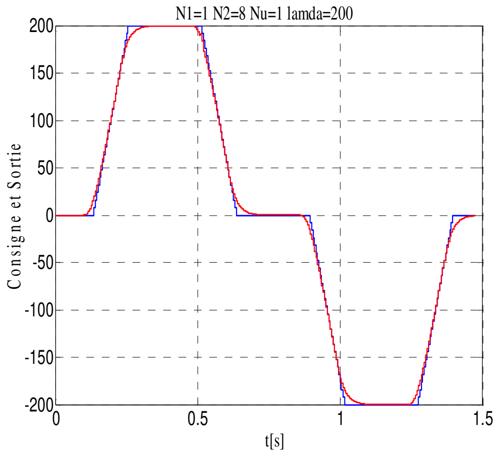

Fig. 9. Output reference speed.

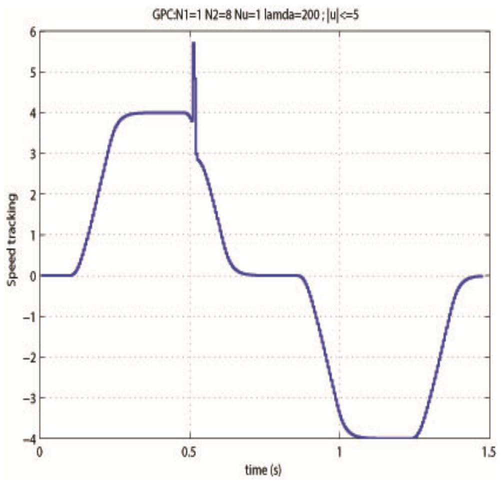

Fig. 10. Output speed with disturbance.

The simulations were performed with a sampling period of T_s=0.05s. We chose the GPC parameters N_1, N_2, N_u, λ, GM, QM, and BM. $w(t+j)$ is the future set point and N_1, N_2, N_u, and λ, are parameters that must be elaborated. $G = [1.34,5.68,0.96,14.24,18.53,22.81,24.09,31,,96,1]^T$ is a column vector and GG^T=2919.09 is the scalar sum of the squares of the first eight step responses.

$$R(q^{-1}) = 0.284 - 0.237q^{-1} - 0.0048q^{-2}$$

$$S(q^{-1}) = 1 + 0.734q^{-1}1$$

$$T(q^{-1}) = 0.0043q + 0.000182q^1 + 0.00319q^2 + 0.00319q^3 + 0.0045q^4 + 0.00594\, q^5 + 0.0731q^6 + 0.1006q^6$$

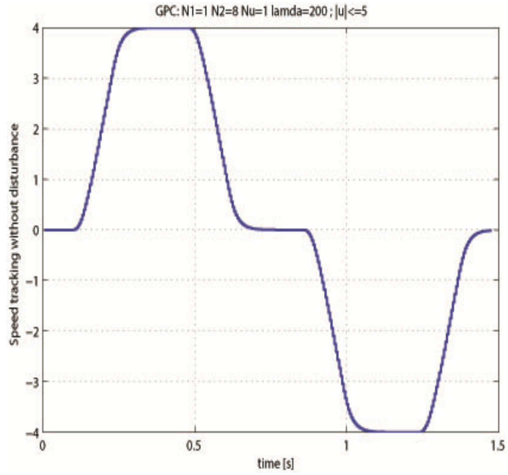

Fig. 11. Output speed without disturbance

VIII. CONCLUSION

In this paper, nonlinear predictive control is developed for speed and flux tracking of an induction motor drive. It was shown that this kind of control is effective for solving the control problem of induction machines. The computation of the predictive control law is easy and does not need online optimization.

The performance of nonlinear predictive control to the induction machine drive is exhibited and the rejection of the unknown load torque is enhanced. This work presented the simulated induction motor with an ABC frame, and generalized predictive control without and with constrains. RST synthesis was used for the rotor speed controller of the induction motor. Simulation results were given in the case of nominal and mismatched parameters of the complete nonlinear model. This is particularly beneficial in the case of motor driven speed, as seen in the example of a computer-controlled compliant link where the torque is often saturated during rapid slewing, forming an interesting limiting case and making the performance and robustness evaluation of the designed controller a challenging engineering problem. The choice of the tuning parameters is not yet optimized, essentially dealing with the choice of the control weighting factor and the output prediction horizons. However, the resulting performances are satisfactory, and the appropriate choice of the GPC tuning knobs may improve the robustness of this controller.

APPENDIX

The control law was implemented on a small 1.5KW induction motor, which corresponds to the Benchmark AC machine of the LAN (Laboratoired'Automatique de Nantes), with the following features:

$R_r = 2.61\Omega$, $J = 0.0256\text{Kgm}^2$
$R_s = 4.287\Omega$, $f = 0.0029$
$L_r = 0.368\text{H}$, $p = 2$
$L_s = 0.404\text{H}$, $w_{\text{nom}} = 150\text{rad/s}$
$M = 0.368\text{H}$, $T_{\text{em}} = 10\text{Nm}, \Phi_{r\alpha\beta} = 0.725\text{Wb}$

The GPC chosen design parameters of the robust controller as shown in Figure 1 (gain margin(dB), ΦM: phase margin (degree), BW : bandwidth(rad/s)) are:

$N_1 = 1$: is the minimum cost

$N_2 = 8$: is the maximum cost.

$N_u = 1$: is the control horizon.

$\lambda = 200$: is the control weighting.

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