Generalized Predictive Control (GPC) – Ready for Use in Drive Applications?

Kennel R., Senior Member, IEEE, Linder A., Linke M.

University of Wuppertal, 42097 Wuppertal-Germany
Tel.:+49 (202) 439-3950, Fax +49 (202) 439-2924
www.ema.uni-wuppertal.de

Abstract — A usual argument against GPC is its demand for processing power. In industry, however, this is not a serious argument if better control performance can be reached. As the development of new processors with increased performance takes place rather rapidly, the lag of processing power never was a long-term issue to prevent new algorithms from being introduced.

This paper presents a practical realization of Generalized Predictive Control (GPC) for field oriented control of induction machines. The results are compared with conventional PI-control.

Considering the strong real time conditions of drive applications, implementation aspects according to the great calculation effort in case of GPC are discussed to contribute to closing the gap between theory and practice.

Index terms — field-oriented control, predictive control, Generalized predictive control (GPC), model based predictive control (MBPC), observer, induction machine

I. INTRODUCTION

During the last decades several proposals have been made to use predictive control algorithms for high performance systems. Few of the presented schemes, however, have been realized in industrial applications so far [1]. Nevertheless, after some further progress, it can be expected that the advantages of predictive algorithms would lead to an increased number of industrial implementations in the future.

An interesting approach to unify different ideas of predictive control is Generalized Predictive Control (GPC) according to [2-4]. It generates a sequence of (future) control signals within each sampling interval to optimize the control effort of the controlled system. This is done by minimizing a rather complex cost function. Due to the high calculation power required for GPC, real applications in drive systems are very rare. Therefore most papers just present simulation results.

This paper presents an implementation of GPC as both the current and the speed control of an induction machine drive.

II. PREDICTIVE CONTROL SCHEMES

A. Basic structure of GPC

The concept behind several model based predictive algorithms, especially GPC, is shown in fig. 1. The drive inverter (process G(z)) includes the well-established space vector modulation technique to control the switching states of the inverter.

![Fig.1 Basic structure of GPC](image)

GPC belongs to the group of “long-range predictive controllers” and generates a set of future control signals in each sampling interval, but only the first element of the control sequence is applied to the system input.

The prediction of the system output $y$ is based on two different components:

- The “free response” represents the predicted behaviour of the output $y(t+j|i)$ (in the range from $t+1$ to $t+N$), based on old outputs $y(t-i|i)$ and inputs $u(t-i|i)$, assuming a future control action of zero.
- The “forced response” represents the additional component of the output $y$ resulting from the optimization criterion.
The total prediction is the sum of both components (for linear systems). Together with the known reference values the future errors can be calculated by

\[ e(t+j|t) = w(t+j|t) - y(t+j|t) \]

with \( j \) counting from 1 to \( N \). Caused by these “future errors”, future control signals are calculated to force the output to the desired reference values.

In addition to its well-known good control performance the robustness properties makes GPC interesting and realizable for practical control applications. For this purposes GPC offers a compact control strategy in terms of model mismatches, variable dead time and disturbances [2].

### B. Model based predictive control

The classical predictive control approach in drive applications includes several different control strategies. As presented in [1] the different 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 controls. In difference to that GPC belongs to the model based predictive control (MBPC) strategies, which are founded on totally different ideas.

The idea of MBPC has been developed to calculate a control function for the future time in order to force the controlled system response reaching 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 to be calculable by an appropriate model.

The control sequence is generated by an optimizing procedure, often resulting in a quadratic cost function. Fig.2 explains the basic idea of model based predictive control.

### C. The GPC process model

A properly designed process model is the basis of all predictive control algorithms, because it is the fundament for prediction. GPC uses the CARIMA model [2,14] which offers inherent disturbance handling.

![Disturbance step response and command step response](image.png)

At least when considering small signal behavior, even a non-linear plant can usually be described by a locally-linearized parametric model like fig.3, where the capital letters indicate the z-transformed quantities of the input \( u(t) \), the output \( y(t) \) and the disturbance \( \xi(t) \).

\[ Y(z) = G(z)U(z) + G_d(z)\Xi(z) \quad (2.1) \]

It is generally impossible to predict the system behavior by neglecting the disturbance term \( \xi(t) \) and considering the step response only. The predicted output is improved significantly by considering the disturbance \( \xi(t) \) term. Therefore several strategies to develop a suitable disturbance model are discussed in the literature [14].

GPC uses a model description

\[ Ay(t) = Bu(t-1) + \frac{C\xi(t)}{\Delta} \quad (2.2) \]

where the backward shift operator in the polynomials \( A \), \( B \) and \( C \) is neglected for simplicity and \( \Delta \) is the differencing operator. Note that \( t \) can be replaced by a discrete time.

The noise component \( C\xi(t) \) is hardly to be identified exactly in industrial processes, but it can be used to assimilate a priori knowledge according to the noise. To obtain good disturbance rejection and robustness to parameter changes, this component can be seen as a design polynomial.
Consequently it is derived from equation (2.2)

\[ y'(t) = \frac{\Delta}{T} y(t) \]  
(2.3)

\[ u'(t) = \frac{\Delta}{T} u(t) \]  
(2.4)

These equations describe the filtered band-passed output and input signals by replacing \( C \) through a suitable design polynomial \( T \). Even though a complete theoretical justification for this derivation is missing in literature, the inherent disturbance model of GPC offers observer characteristics like a stationary Kalman-filter [9].

III. Drive Applications

A GPC control scheme was implemented as both speed and current controller of a voltage source inverter fed squirrel cage induction machine.

A. Machine dynamics

The complex space vector theory is a powerful tool in dynamic machine analysis [5]. The machine equations in complex space vector quantities are

\[ u_s = r_s i_s + \frac{d\psi_s}{dt} + j/\omega_s \psi_s \]  
(3.1a)

\[ 0 = r_l i_l + \frac{d\psi_r}{dt} + j(\omega_r - \omega) \psi_r \]  
(3.1b)

while \( \omega \) is the angular velocity of a general reference frame, \( \omega_s \) is the rotor velocity and \( \psi_s, \psi_r \) represent the complex notation of the stator and rotor flux linkages. Therefore the flux linkage equations can be derived as

\[ \psi_s = l_s i_s + l_h i_r \]  
(3.2a)

\[ \psi_r = l_h i_s + l_i i_r \]  
(3.2b)

The electromagnetic torque can be described by the external product of the flux and current considering the load and normalized time constant.

\[ \tau_m \frac{d\omega}{d\tau} = \left[ \psi_s \times i_s \right]_z - T_L \]  
(3.3)

where the time is normalized as \( \tau = \tau_R \) \( \omega_R \) is the rated speed of the rotor.

After some basic transformations the currents in equation (3.1a,b) can be replaced considering equation (3.2a,b) by the equivalent flux linkages leading to a signal flow graph according to fig. 5.
The signal flow graph represents three physically separated structures of an induction machine. The right hand side of fig. 5 represents the rotor winding, the left hand side represents the stator winding both as first order systems. The lower part of fig. 5 shows the mechanical system while $T_L$ and $\omega_k$ representing the load torque and the speed of the k-reference system. (For a more detailed theoretical derivation see [5]).

B. Analysis for current control

Replacing the stator flux linkage by the stator current (see fig. 5) and substituting the influence from the rotor to the stator by an induction voltage $u_r$ leads to

$$\tau_s \frac{d i_s}{dt} + i_s = -j\omega_k \tau_s l_s + \frac{1}{r_s} (u_s - u_r)$$  \hspace{1cm} (3.4)

The stator voltage $u_s$ is used as a force function for the stator currents. Neglecting the induction voltage from the rotor due to its slower dynamic and replacing the k-reference system by the field reference system-s the stator transfer function can be derived from equation (3.4).

$$G_s(s) = \frac{1}{r_s \tau_s} \frac{1}{s + j\omega_k \tau_s}$$  \hspace{1cm} (3.5)

Fig. 6 represents simulation results of an induction machine according to fig. 5 fed by an inverter with 3 kHz switching frequency, with and without consideration of the cross coupling. Of course, a linear approach cannot consider sufficiently the non-linear cross couplings between the stator currents $i_{sq}$, $i_{sd}$. To avoid the influence of cross coupling a complex current controller is necessary.

C. Analysis of the speed control

The standard cascade control structure has been used to implement the speed controller on the basis of GPC, but considering a future state control as well.

To optimize the speed control loop the current control loop is replaced by an approximation, as it is dominated by the inverter time constant. The field oriented control ensures decoupling between the $dq$-components. Therefore equation (3.3) gets modified to

$$\tau_m \frac{d \omega}{dt} = \psi_{sd} i_{sq} - T_L$$  \hspace{1cm} (3.6)

Considering equation (3.6) the dynamic behavior of the speed control loop is described completely.

IV. EXPERIMENTAL RESULTS

GPC control scheme was applied to a field oriented controlled induction machine and compared with conventional PI control. The PI-controllers have been optimized using standard optimization criteria (e.g. symmetrical optimum). GPC has been separately implemented in the current and speed control loop according to [4]. To avoid the danger of insufficient processing power, GPC was implemented in a real laboratory setup on an Intel 233-MHz Pentium processor to handle even sophisticated mathematical matrix functions within the time limit. Besides the GPC controllers an additional conventional PI-controller was used to ensure the magnetizing flux at a constant value (see fig.7).
The cross couplings of the currents were neglected in controller design due to its great demand for calculation power. The experimental results of the current control loop are shown in Fig. 8.

Both controllers make use of the maximum inverter voltage for a short time, but GPC provides both, a shorter rise time as well as a shorter settling time.

The real advantage of GPC becomes visible in more noisy applications due to its inherent filter characteristics. The speed control suffers under noisy signals as it must be optimized for lower dynamics to avoid severe disturbances. With GPC it is possible to ensure very fast step response without additional filtering.

The observer characteristics expected by theoretical derivations in chapter II.C have been confirmed by experiment. The respectable different results in fig. 9 between the two control strategies are obtained by less filtering in the case of GPC. The conventional PI-control strategy is strongly influenced by the dominating filter time constant.
The results are obtained using a linear model approach for speed- and current-control to reduce the demand for process power. Even though time-saving precalculation has been implemented in GPC it needs twice the calculation time of the conventional control algorithm (see fig. 10).

![Graph](image)

Fig. 10 Cycle time of the different control strategy

V. CONCLUSION

A realization of the control algorithm GPC is described. GPC is proved to be robust against model–mismatching and unexpected dynamics and superior to PID-control due to the precalculation of the system behaviour. It is a really competitive control algorithm through its inherent noise rejection without additional filters. The GPC algorithm offers interesting features not obtainable with conventional algorithms.

On the other hand the higher demand on calculation time is not negligible. Therefore several proposals are made not to calculate the complete GPC algorithm on time, but to use precomputing as far as possible [13]. These methods allow to combine the advantages of GPC with less demanding calculations.

REFERENCES


