Predictive control of synchronous generator: a multiciterial optimization approach

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Abstract
The paper deals with the predictive control design for nonlinear systems. The resulting control system performances depend on the choice of the control design parameters, namely the prediction horizon, the control horizon and the control input penalization. For an optimal choice these parameters a genetic algorithm has been applied. The theory of multicriterial optimization has been used to combine several control objectives in one objective function. The proposed approach has been evaluated using an example of the 259MVA synchronous generator of the nuclear power plant Mochovce (EMO).

Keywords: predictive control, synchronous generator, nonlinear model, genetic algorithm, multicriterial optimization

Introduction

The synchronous generator is an integral part of power systems so there is an interest to design the controller with the best possible control performances. A number of synchronous generator control algorithms were proposed in the past, but only few of them have been implemented in industry. From the control theory point of view the synchronous generator is a nonlinear system with variable properties that can be linearized in an operating point, so the control algorithms based on the linear control theory can be used. The synchronous generator control objectives can be characterized as follows:

- - To ensure a minimal voltage steady state offset.
- - To obtain an acceptable voltage settling time.
- - To obtain the desired active power oscillation damping.

The first two requirements can be satisfied using the PI controller. However, this controller can not ensure the desired damping of transient processes. For this reason the special circuits called the power system stabilizer are added to the synchronous generator control systems.

It is advantageous to satisfy all of above requirements using one control algorithm. One of the possibilities is to use the predictive control algorithms.

The predictive control has become popular over the past twenty years as a powerful tool in the feedback control for solving many problems for which other control approaches were proved to be ineffective (Clarke *et. Al.*, 1989).

One of these methods is described in this paper. The common feature of these methods is, that from data measured in past time $Y(k)=\{y(1),...,y(k)\}$ and $U(k)=\{u(1),...,u(k-1)\}$ one or several values of plant output is predicted. Values predicted in this way are also function of future manipulated variables $u(k)$, $u(k+1)$, ... Control strategy is then defined by minimization of functional with the loss function defined as a sum of differences between values of reference signal and a values of predictive output (prediction of control error) and the penalization of manipulated variable.

There are many approaches of predictive control, which vary from each other by the number of predicted values, used functional and also by limiting conditions for control strategy. Generalized predictive control will be introduced in the next section.

The paper is organized as follows. Firstly, design of the predictive control, genetic algorithm and multicriterial optimization are briefly introduced in the section 2. The case study is then discussed in Section 3. Section 4 includes experimental results. A summary and conclusions are given in Section 5.

1. Generalized predictive control

1.1 Plant model

Prediction itself can be realized only on the base of known model of plant. This model should accurately enough describe dynamics of a real plant. Consider that the control system is described by ARMAX model

$$A(z^{-1})y(k)=B(z^{-1})u(k)+\frac{C(z^{-1})}{\Delta}\varepsilon(k) \qquad (1)$$

where $u(k)$ is control input and $y(k)$ is output value. This model allows to incorporate the internal model of state disturbances so that the control design can ensure the offset-free performance.

1.2 Basic principle of predictive control

The predictive control algorithm uses a moving horizon, as shown in Figure 1.

Based on the plant model, the size of the future output values depending on the changes of control input is to be predicted. The control input is generated so that the desired output characteristics are achieved. The plant behavior for ph steps ahead is predicted in the time k. The least-squares method is usually used to achieve the optimal output value behavior. In this method the constraints of the control input, the control input increment and also of the process output are usually considered.

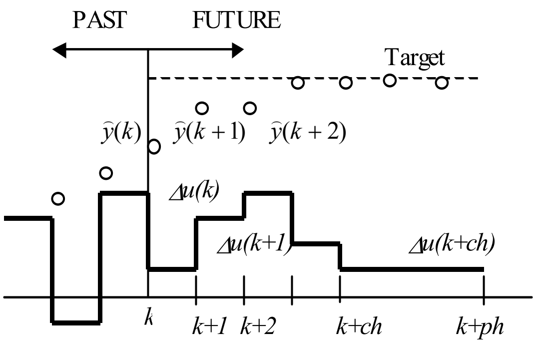

Fig.1 Basic principle of predictive algorithm

1.3 GPC design

The control objective is to minimize in a receding horizon sense the following cost function

$$J_{pc} = \sum_{j=sh}^{ph}\left[\tilde{y}(k+j)-r(k+j)\right]^2 + \sum_{j=sh}^{ph+sh-1}\rho\left[\Delta u(k+j-sh)\right]^2 \qquad (2)$$

with

$sh \geq 1$: begin of the predictive horizon
$ph \geq sh$: end of the predictive horizon
ch : control horizon
$\rho \geq 0$: penalization of control input.

It is supposed, that future values of reference signal are known $r(k+j)$, for $j = 1,2,\ldots$

The GPC control design then consists in performing the following three steps:

1. Prediction of output $\tilde{y}(k+j)$ for $j = 1,2,\ldots$, which is function of future controlled inputs $u(k+j)$ for $j = 1,2,\ldots$, is calculated a few steps ahead.
2. Optimal sequence of future control inputs according to quadratic criteria J_{pc} with a function of loss is calculated.
3. Only the first component $u(k)$ out of this sequence of control inputs will be used for control, and the whole process will be repeated in the next sampling period.

Parameters of quadratic criteria (2) and additional constraint parameters can be chosen as follows:

sh: $sh = d+1$ if plant delay time is known, otherwise $sh = 1$.

ph: is selected so as the essential part of time response of the controlled system is included in ph steps.

ch: $ch = 1$ is selected for stable and damped systems, otherwise ch will be equal to a number of unstable poles, or poles close to the stability boundary.

ρ: $\rho = 0$ is chosen in most cases. Less dynamic control is obtained by increasing ρ, but at the interest of regulation process of lower quality.

The right choice of these predictive control parameters is not simple, requires practice with the controlled plant and depends on expectations from the control.

The GPC control can be implemented using the general linear control law

$$S(z^{-1})D(z^{-1})u(k)+R(z^{-1})y(k)=T(z^{-1})r(k+1) \qquad (3)$$

i.e. the control input in the step k is obtained as follows

$$u(k)=\frac{T(z^{-1})}{S(z^{-1})D(z^{-1})}r(k+1)-\frac{R(z^{-1})}{S(z^{-1})D(z^{-1})}y(k) \qquad (4)$$

where

$$R(z^{-1})=\sum_{j=sh}^{ph} g_j.F_j(z^{-1}) \qquad (5)$$

$$S(z^{-1})=C(z^{-1})+\sum_{j=sh}^{ph} g_j.z^{-1}.H_j(z^{-1}) \qquad (6)$$

$$T(z^{-1})=C(z^{-1})\sum_{j=sh}^{ph} g_j.z^{-ph+j} \qquad (7)$$

gr_j : terms of the first line of matrix $\left[\overline{G}^T\overline{G}+\rho I_{ch}\right]^{-1}\overline{G}^T$

$\overline{G}$: matrix of dimension $[ph-sh+1; ch]$.

Polynomials $F(z^{-1})$, $H(z^{-1})$ and $G(z^{-1})$ are solutions of the following polynomial equations

$$1=E_j(z^{-1})A(z^{-1})\Delta+z^{-j}F_j(z^{-1}) \qquad (8)$$

$$E_j(z^{-1})B(z^{-1})=C(z^{-1})G_j(z^{-1})+z^{-j}H_j(z^{-1}) \qquad (9)$$

This approach has been used in our implementation.

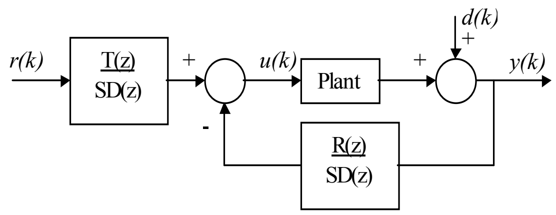

Fig.2 Simulation scheme of predictive control

2. Genetic optimization

A choice of predictive control parameters is not definite, therefore genetic algorithm is chosen.

In this case cost function is minimized

$$f_i(x)=|r-y| \Rightarrow \min \qquad (10)$$

The aim is to minimize the cost function by signal reference tracking f_1 and also by disrturbance regulation f_2.

3. Multicriterial optimization

There are often many different aspects which should be considered when optimizing problems are solved. It is obvious, that several aspects (partial objective functions) have to be considered by optimization method. It is so called "multicriterial optimization". To connect partial objective functions into one objective function, considering that partial objective functions have different weights, can be an option how to deal with several criteria.

$$F(x)=\sum_{i-1}^{N} w_i f_i(x)\,,\quad x=\{x_1,x_2,...,x_n\} \tag{11}$$

The only remaining problem is an appropriate choice of weights, which defines significance of partial objective functions $f_i(x)$. In the case that their values are incomparable they have to be synchronized. Each person can have different requests on the quality of system and therefore the values of weight coeficients are also different. Implementation of a "dominant principle" has been a significant contribution in solving multicriterial problems. It is associated with a term "Pareto optimality" set. In the case of solving problem of multicriterial optimization it holds that solution x dominate over solution y (or solution y is dominated of solution x), if

$$\forall i=1,2,...,n\,,\ f_i(x)\le f_i(y)$$

together $\exists j=1,2,...,n$, where

$$f_j(x)<f_j(y)$$

Not dominated components create pareto optimal set of solutions. It is not possible to make a decision which component from this set is the best. Each person can choose from the set a solution which is the best according own priority. It is not a target to find only one solution using present approach of solving multicriterial problem, but find all or majority of not dominated solution. Flowline of all not dominated solutions is calling „Paret's front".

The idea of Pareto optimality was used by several authors (Goldberg, 1989), (Louis and Rawlins, 1993).

4. Synchronous generator model

The synchronous generator model has been derived and described in many papers. In our paper the synchronous generator model of 5th order will be considered (MACHOWSKI, 1997).

The machine motion equation:

$$\begin{aligned}\Delta\dot{\omega}&=\frac{1}{M}(p_m-p_e-D\Delta\omega)\\ \dot{\delta}&=\omega-\omega_s=\Delta\omega\end{aligned} \tag{12}$$

Equation describing the electromagnetic processes:

$$\begin{aligned}T''_{d0}\dot{e}''_q&=e'_q-e''_q+i_d(x'_d-x''_d)\\ T''_{q0}\dot{e}''_d&=e'_d-e''_d+i_q(x'_q-x''_q)\\ T'_{d0}\dot{e}'_q&=e_b-e'_q+i_d(x_d-x'_d)\end{aligned} \tag{13}$$

Meaning of symbols is presented in Appendix 1.

In this model the screening effect of the rotor body eddy-currents in the q-axis is neglected, so that $x'_q=x_q$ and $e'_d=0$. This model reverts to the classical five winding model with armature transformer emfs neglected.

$$\begin{bmatrix}v_d\\ v_q\end{bmatrix}=\begin{bmatrix}e''_d\\ e''_q\end{bmatrix}-\begin{bmatrix}R & x''_q\\ -x''_q & R\end{bmatrix}\begin{bmatrix}i_d\\ i_q\end{bmatrix} \tag{14}$$

The synchronous generator active power can be described as follows:

$$p_e=(v_d i_d+v_q i_q)+(i_d^2+i_q^2)R \tag{15}$$

and after substitution of (14) we obtain:

$$p_e=(e''_d i_d+e''_q i_q)+(x''_d-x''_q)\, i_d i_q \tag{16}$$

During the operation of large power systems it is necessary to ensure an effective oscillation damping process.

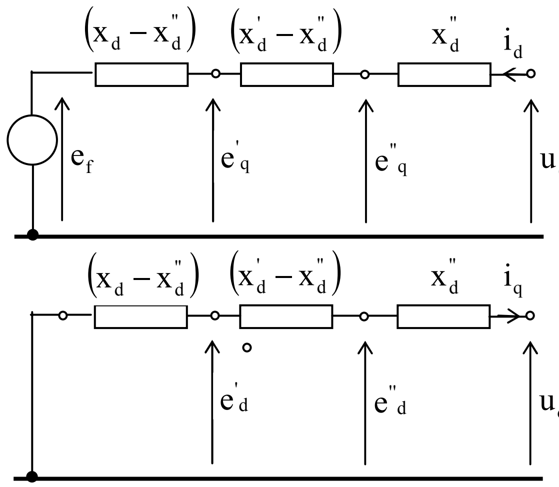

Fig.3 Generator equivalent circuits

5. Experimental results

The proposed algorithm of the synchronous generator control has been verified using an example of the 259MVA synchronous generator of the nuclear power plant Mochovce (EMO) in Slovakia (Murgaš, 2004). In our paper the synchronous generator has been described by the nonlinear model of 5th order (12) - (13). Because the GPC synthesis is based on the plant model transfer function, it is necessary to identify the ARX model of this nonlinear system at the operating point using the least-squares method. The system input is the field voltage v_f and the system output is the terminal voltage v_t. The operating point corresponds to v_t = 1p.u. The periodic square signal with amplitude 0,05p.u. and frequency 0,01Hz has been used as the input signal. The identified model transfer function is as follows:

$$\begin{aligned}T_f(z^{-1})&=\frac{0{,}00348z^{-2}-0{,}00247z^{-3}}{1-1{,}535z^{-1}+0{,}2595z^{-2}+0{,}2696z^{-3}}\,,\\ T_{VZ}&=0{,}25s\end{aligned} \tag{17}$$

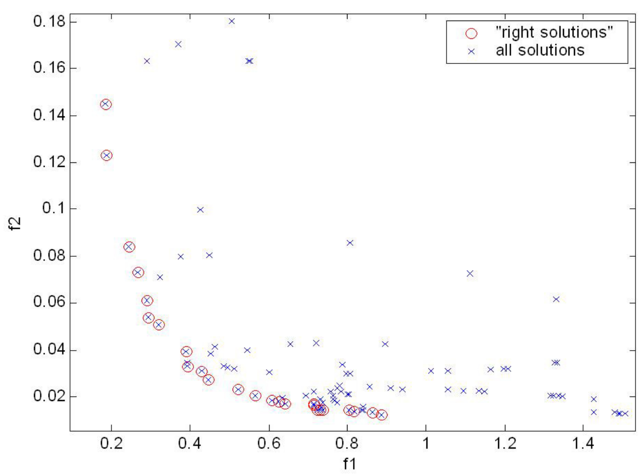

Fig.4 Solutions

Each point in this figure represents dependency of fitness function f_2 on fitness function f_1.

First solution (where $ph = 10$, $ch = 2$, $\rho = 0{,}01$) is selected from the set of "right solutions", where the value of the fitness function f_1 is the smallest, which means this solution is the best one for the reference signal tracking. We choose also the last solution (where $ph = 117$, $ch = 4$, $\rho = 1$), in which fitness function f_2 is the smallest and this solution is the best one for active power oscillation damping. The resulting control system performances of these two solutions are shown in Fig. 5 and Fig. 6. Pel_1 denotes the first solution controlled variable and Pel_2 denotes the last solution controlled variable.

Table 1 "Right solutions" set

ph	ch	ρ	f_1	f_2
10	2	0,01	0,1844	0,1447
12	3	0,01	0,1881	0,1229
19	4	0,01	0,2442	0,084
17	1	0,1	0,2666	0,0732
20	3	0,1	0,2921	0,061
23	3	0,1	0,2924	0,0539
25	4	0,1	0,3208	0,0508
36	4	0,1	0,3899	0,0393
40	1	1	0,3932	0,0331
43	2	1	0,4284	0,0311
50	2	1	0,4469	0,0272
60	3	1	0,521	0,0233
69	3	1	0,5659	0,0206
77	3	1	0,6085	0,0185
80	3	1	0,6248	0,0179
83	3	1	0,6413	0,0172
92	1	10	0,713	0,0168
93	1	10	0,7156	0,0166
98	3	1	0,7253	0,0146
99	3	1	0,731	0,0145
100	3	1	0,7366	0,0143
111	2	10	0,804	0,0142
114	2	10	0,8155	0,0138
119	3	10	0,8639	0,0135
117	4	1	0,8847	0,0121

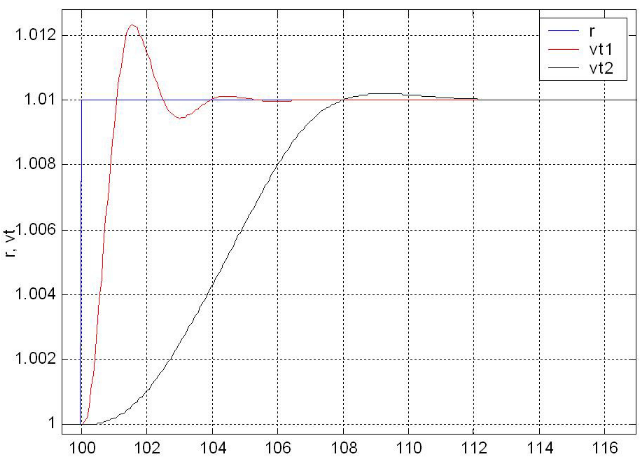

Fig.5 Time responses of the terminal voltage v_t and its desired value r

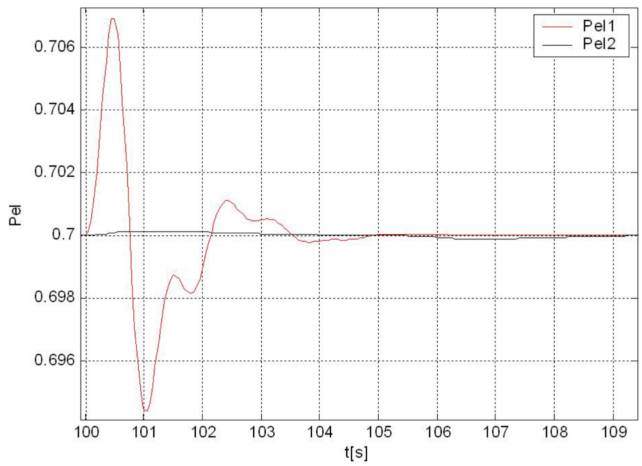

Fig.6 Time responses of the active power P_{el}

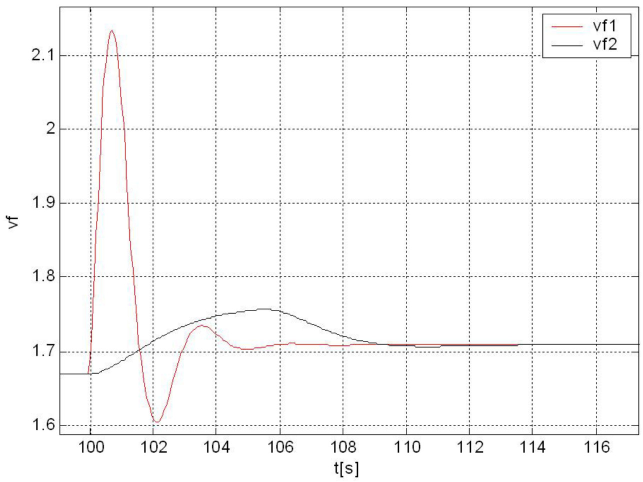

Fig.7 Time responses of the field voltage v_f

It is obvious from time responses, that Pel_1 is better in a signal reference tracking than Pel_2, which is on the other side better in active power oscillation damping. Results of reference signal tracking as well as of active power oscillation damping depend on chosen criteria.

Conclusion

In conclusion, the plant control is mostly affected by the change of the predictive horizon ph. The faster reference signal tracking is in most cases achieved by reducing ph, which means that values of fitness function f_1 are the lowest, however values of fitness function f_2 are the highest. It shows that these two criteria perform against each other. Therefore the multicriterial optimization with a dominant principle has been applied. It is up to designer to choose a solution out of right solution set (Fig. 4.), which is the most suitable for him. This is an universal approach, suitable for any plant. It is also necessary to choose a solution with respect to quality of the reference signal tracking and the active power oscillation damping.

Acknowledgement

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Appendix 1 - Symbols

ω - angular velocity of the generator (in electrical radians)

ω_s - synchronous angular velocity in electrical radians

$\Delta\omega$ rotor speed deviation

M - inertia coefficient

p_m mechanical power supplied by a prime mover to a generator

p_e - electromagnetic air-gap power

D - damping coefficient

T'_{d0}, T''_{d0} - open-circuit d-axis transient and subtransient time constants

T'_{q0}, T''_{q0} - open-circuit q-axis transient and subtransient time constants

i_d, i_q - currents flowing in the fictitious d- and q-axis armature coils

e_q - steady-state emf induced in the fictitious q-axis armature coil proportional to the field winding self-flux linkages

e'_d - transient emf induced in the fictitious d-axis armature coil proportional to the flux linkages of the q-axis coil representing the solid steel rotor body

e'_q - transient emf induced in the fictitious q- axis armature coil proportional to the field winding flux linkages

e''_d - subtransient emf induced in the fictitious d-axis armature coil proportional to the total q-axis rotor flux linkages

e''_q - subtransient emf induced in the fictitious q-axis armature coil proportional to the total d-axis rotor flux linkages

x_d, x'_d, x''_d - total d-axis synchronous, transient and subtransient reactance between (and including) the generator and the infinite busbar

x_q, x'_q, x''_q - total q-axis synchronous, transient and subtransient reactance between (and including) the generator and the infinite busbar

Appendix 2 – Parameters of the synchronous generator

$T_{d0} = 7{,}7$	$x_d = 1{,}99$	$x_q = 1{,}82$
$T_{d2} = 0{,}04$	$x^{I}_d = 0{,}267$	$x^{II}_q = 0{,}204$
$T_{q2} = 0{,}23$	$x^{II}_d = 0{,}13$	$x_t = 0{,}14$
$T_j = 0{,}0315$		$x_l = 0{,}14$

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