STABILIZING CONTROLS FOR A SYNCHRONOUS-INDUCTION GENERATOR

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Abstract - A few stabilizing controls for a synchronous induction generator is examined through the quadratic bilinear and linear regulator theory. It has been found that the unstable bilinear system can be stabilized quite easily without resorting to complicated computations. A feedback control derived from minimum time formulation is found to be very effective in stabilization.

Introduction

An induction motor when run at supersynchronous speed will deliver power as a generator. A wound rotor motor if supplied with polyphase excitation at both stator and rotor terminals will run at double normal synchronous speed. The phase sequence of the rotor voltage has to be opposite to that of the stator. The doubly fed machine will either motor or generate depending on the angle between the stator and rotor phase magnetic axes.

Though the principle of operation of the doubly fed synchronous-induction machine has been known for long time, it has not found application primarily because of lack of effective solution to the starting problem and also for the problem associated with the inherent instability of the machine [1]. Though an induction motor run at double synchronous speed can deliver power much more than rated, generation through this mode did not draw much attention. Stabilization of the synchronous-induction machine in the doubly fed motor mode has been studied by the author [2]. This article reports various stabilizing control strategies for the synchronous-induction generator through the modification of the slip ring voltage.

The Mathematical Model of the Doubly Fed Machine

The equations of a synchronous-induction generator in state notation can be written as $\[2\]$

$$\dot{y} = f[y, V] \tag{1}$$

where y is a 6 \times 1 state vector comprising of the stator and rotor currents along direct and quadrature axes of the machine, the speed variation and the angular position between the stator and rotor magnetic axes. V is a vector of rotor input voltage along the direct and quadrature axes given as

$$v = [v_{dr} \ v_{qr}]^T \tag{2}$$

The subscripts d and q refer to the direct and quadrature axes while r represents the rotor quantities, respectively. The components of the rotor voltage may be expressed as

$$V_{dr} = V_r \cos \delta \tag{3}$$

$$V_{cr} = -V_r \sin \delta \tag{4}$$

The angle δ (which is a component of the state vector y) is related to the machine speed (ω_m) as follows

$$\delta = -\omega_{e}t - \Delta\omega_{m}t - \delta_{o}$$
 (5)

where $\boldsymbol{\omega}_{\underline{\boldsymbol{\alpha}}}$ is the frequency of the excitation voltage.

Substituting (3), (4) and (5) in (1), the small perturbation model of (1) can be expressed by the following bilinear relationship

$$\dot{x} = Ax + (b_1 + b_2 x_6) u$$
 (6)

where $x_6 = \Delta \delta$ and $u = \Delta V_r$

Quadratic Feedback Controls

The matrix A in (6) has a pair of complex eigenvalues in the right half plane. Gutman [3] demonstrated that if there exists a P = $P^T > 0$ such that

$$\left(b_{1} + b_{2}\right)^{\mathsf{T}} \mathsf{P} \times \neq 0 \tag{7}$$

in the set
$$\{x \mid x \neq 0, x^{T}(PA + A^{T} P) x > 0\}$$
 (8)

Then there exists an $\alpha > 0$ such that control

$$u = -\alpha (b_1 + b_2 \times_6)^T P x$$
 (9)

will stabilize (6).

The crucial point here is the determination of the P matrix satisfying its positive definiteness criterion and relation (8) simultaneously. The computational methods suggested are quite complicated, and for higher order systems as the present one, the amount of computation may be too much. From implementation viewpoint, the matter is worse because for each possible point of operation of the generator, the P matrix has to be recomputed. The following extensions of Gutman's theorem simplifies calculation of P matrix to a great extent[2].

1. The matrix P satisfying the matrix equation

$$PA + A^{T} P - b_{1}^{T} P b_{1} + Q = 0$$
 (10)

is positive definite and symmetric, and the control strategy which will stabilize (6) is given as

$$u = -\alpha (b_1 + b_2 x_6)^T P x \text{ for the set } \{x \mid x \neq 0, \Psi > 0\}$$
 (11a)

$$u = 0$$
 for the set { x | x \neq 0, \psi < 0} (11b)

where
$$\Psi \triangle x^{\mathsf{T}} (PA + A^{\mathsf{T}} P) x$$
 (12)

Both P and Q are positive definite matrices. Selecting the weighting matrix Q appropriately, relation (11a) can be made to satisfy almost for all $x \in R^n$. Note P is the solution of the steady state matrix Riccati equation

2. The diagonal matrix P', constructed by setting all the off-diagonal elements of the Riccati matrix to zero, satisfies all the requirements and hence is also a candidate in (9).

3. The linear state regulator type control

$$u = -b_1^T P X$$
 (13)

is a candidate for stabilization of the synchronousinduction generator when the trajectory is sufficiently near the equilibrium point. Hence for relatively smaller disturbances control (13) is satisfactory.

A Quasi-Optimal Feedback Control

A feedback control strategy derived on the basis of transient control in minimum time as used for synchronous generators [4] involves differentiation of of the electromechanical torque equation and substitution of the other current derivative relations to yield a second order time varying equation of the form

$$\frac{d^2 \Delta \omega_m}{dt^2} = L(x) + b(x) u(t)$$
 (14)

The minimum time feedback control is obtained by quasilinearization of the terms L(x) and b(x). The control action instead of being bang bang is made proportional through selection of a suitable constant K and is given as

$$u(t) = -K[\Delta \omega_{m} - \frac{(\Delta \dot{\omega}_{m})^{2}}{2[L(X) - b(X) \operatorname{Sgn}\{\Delta \omega_{m}\}]}]$$

$$b(x) > 0$$
(15)

 $\Delta \dot{\tilde{\omega}}_m$ is the acceleration of the machine.

Numerical Example and Results

Figure 1 gives a plot of the angle dependent electrical torque Te for a doubly fed machine as δ is varied from -135° to 135°. It can be seen that the 10 hp motor when excited by nominal voltage on the rotor terminals can deliver about 30 hp (3 p.u.) as motor and 45 hp as generator at a slip of -1. An

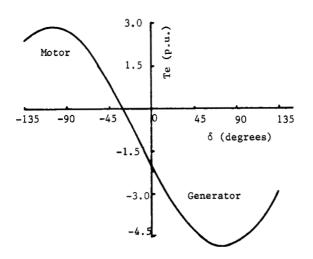


Figure 1. Variation of angle dependent torque showing the generator and motoring regions of the doubly fed machine at double synchronous speed.

operating point in the generator mode corresponding to δ = -25° is selected for this example. The corresponding A matrix is

Vectors b₁ and b₂ respectively are

$$b_1 = [-1293.448 -603.144 1344.381 626.894 0.0 0.0]^T$$
 $b_2 = [-603.144 -1293.448 626.894 -1344.381 0.0 0.0]^T$

The eigenvalues of the A matrix are

$$065.03 + j373.12, -35.55 + j372.88, .0515 + j9.78$$

The first two pairs correspond to the power frequency stator and rotor transients while the dominant pole pair with positive real parts are responsible for the growing response.

Figures 2, 3 and 4 show the response of the system for a 30% input step with various stabilizing signals. Curve a in Figs. 2 and 4 show angle and speed variation in the absence of any stabilizing control. Curve b in both figures are with stabilizing control

$$u = -\alpha (b_1 + b_2 x_6)^T P x$$

where Riccati matrix P is

0.364	0.056	0.357	0.05	-0.132	-0.08
0.056	0.442	0.056	0.431	-0.092	-0.103
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0.357	0.056	0.35	0.05	-0.137	-0.077
0.05	0.431	0.05	0.421	-0.074	-0.108
-0.132	-0.092	-0.137	-0.074	0.335	-0.003
-0.08	-0.103	-0.077	-0.108	-0.003	43.89

The elements of diagonal matrix Q are

The value of α used for the response shown is 1. It is noted that the system is stabilized with a value of α as low as 0.1. Curve c in figures 3 and 4 are with the control

$$u = -b_1^T P x$$

while curve d shows response recorded with proportional control derived from the minimum time strategy (15).

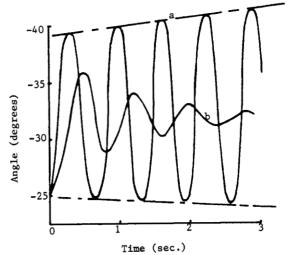


Figure 2. Torque angle variations for a 30% torque step, (a) the uncontrolled machine (b) with stabilizing control from the bilinear formulation.

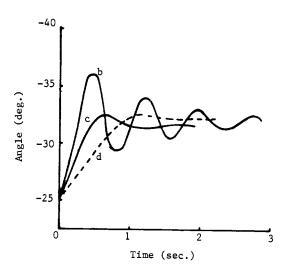


Figure 3. Continuation of figure 2, (c) response with optimal linear regulator control (d) with proportional control from frequency variation and acceleration only.

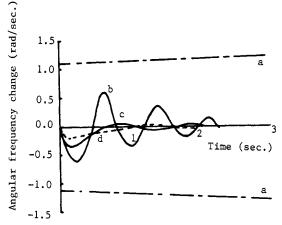


Figure 4. Angular frequency variation of the doubly fed machine in generator mode corresponding to Fig. 2, (a) envelope for the uncontrolled case (b) control from bilinear formulation (c) optimal control from linear formulation (d) proportional control from frequency variation and acceleration.

A comparison of the responses recorded show that while the bilinear system can be stabilized with a control

strategy derived from bilinear regulator problem, the control derived from linear part is more effective in stabilization. This is because the disturbance considered is relatively small and so the swing of the machine is also less. For larger disturbances the linear regulator control is ineffective. The proportional control from minimum time formulation appears to be most effective. Also this strategy may be applied to the original nonlinear set of equations (1).

Conclusions

Stabilization of a doubly fed synchronous-induction machine in the generator mode has been investigated. It has been demonstrated that the bilinear system can be stabilized quite easily, without resorting to complicated computation techniques, from linear regulator theory. A proportional control derived from minimum time formulation seems to provide the best response. This control is also easily realizable and has the potential of application to the nonlinear model as well. Large perturbation studies are in progress and will be reported later.

Acknowledgement

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