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A heuristic approach to robust control design for power systems with several FACTS devices

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Abstract

This paper presents an approach to control power systems with several flexible AC transmission system (FACTS) devices. This approach relies on 'robust control' design techniques, but uses some heuristic rules for defining the controller design procedure instead of being based on a precise definition of model uncertainties. Design algorithms of $\mathscr{H}_\infty$ and $\mathscr{H}_2$ robust controllers are cast in a 'black-box' framework, leaving some free design parameters to be tuned by the user. The resulting controllers have decentralized structure, using only local information. The strong interconnection between two FACTS devices in a power system is shown to represent a difficult situation for conventional PID controllers. This situation is directly solved by the proposed methodology. © 2002 Elsevier Science Ltd. All rights reserved.

Keywords: Power systems; Flexible AC transmission system; Robust control; Heuristic control design

1. Introduction

Large interconnected electric power systems constitute complex dynamic systems that need to be controlled in order to keep a suitable behavior. Although, up to now, this system has motivated a lot of research in control theory [1,2], most of the controller implementations that are actually in operation in real systems still employ the most conventional control design techniques. In fact, the simple PID controller is employed in most of the control loops, in a 'local control' fashion that implements distributed control architectures that rely on the controller action in order to reject coupling effects. When this coupling is proportionally small, this is a reasonable methodology. This is the case of the conventionally structured power systems, that are built in order to allow, up to the physical constraints, such a 'decoupling treatment'. The concepts of 'active power-angle' and 'reactive power-voltage' control loops, for instance, reflect this attempt to get orthogonal control inputs for independently controlling the system variables.

The hypothesis of control loop decoupling, however, is becoming no longer valid with the recent introduction of new possibilities for power system control structures based on flexible AC transmission system (FACTS) [3,4]. Basically, the FACTS technologies involve fast control of the electrical interrelated parameters of the power system (voltage, impedance, phase angle, current, reactive and active power) using high-speed power electronic devices [5]. As the use of FACTS devices has increased in electrical power systems, the coordination of several control structures has been of interest [3,4]. Challenging problems of controller design can emerge from such system, which can cause difficulties for conventional controller design techniques. It is shown in Ref. [6] that, in some circumstances, the usage of single-input single-output control design methods can lead to unstable closed-loop systems, due to inter-loop interaction.

In order to study such a situation, an electric system of minimal complexity (a single generator, a transmission line and a resistive load) is investigated here, under the action of two FACTS devices: a thyristor capacitor series compensator (TCSC) and an static VAR compensator (SVC). Due to the system low complexity, the FACTS devices become highly coupled. This coupling causes the failure of the attempts for the system stabilization with a conventional PID control structure in both devices. Note that such coupling could occur in larger systems, but its effect of debasement in controller performance would become less

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evident due to the problem complexity. This is the advantage of studying this problem in a 'minimal scale system'.

There are several control design techniques available nowadays that could be used in order to account for the multivariable nature of the problem. However, the application of such techniques is not straightforward in most of cases, making necessary some specialized knowledge for the controller design [7].

In this paper, the following question is investigated:

- Is it possible to employ a reliable and standard 'black-box' algorithm for finding a suitable controller for that power system?

This algorithm should have the following features:

- There should be few design parameters to be specified by the designer;
- There should be a straightforward design procedure that directly leads to an acceptable controller;
- The controller structure should allow the decentralized control architecture (this means that the TCSC controller should not depend on the SVC controller and vice versa);
- The controller should be 'robust', at least as the old PID controller was, in the sense that even with some modeling error, the closed-loop system should be likely to present an acceptable behavior.

The natural choices for control design black-box algorithms are the 'robust control' ones, due to the last above consideration. In this paper, the usage of some standard $\mathcal{H}_2$ and $\mathcal{H}_\infty$ robust control design algorithms is evaluated. In order to keep the control structure as simple as possible, and satisfying the third above consideration, the robust controller is used in the control of only one of the devices, with the other one controlled with the PID control.

The evaluation of the proposed design methodology is performed on the basis of simulation studies in the 'minimal complexity' electric system. Both conventional PID design and the proposed black-box robust design have been evaluated. The conventional PID controller only has not led to stable closed-loops, while the proposed black-box robust design has led to stable behaviors with good transient performance. Two dynamic situations have been simulated: system energization and power variation. Even in the cases in which the PID control stabilized the system, the black-box robust control design has shown to be much easier to implement once is not necessary the 'trial and error' approach of classical controllers.

2. Robust control

Consider the linear dynamic system equations:

$$\hat{\Sigma} : \begin{cases} \dot{x} = Ax + Bu + Ew \\ y = Cx + Du + Fw \end{cases} \tag{1}$$

$\hat{\Sigma}$ represents the model of a real system Σ that is to be controlled. The controller equations are:

$$\Sigma_k : \begin{cases} \dot{z} = A_k x_k + B_k y \\ u = C_k x_k + D_k y \end{cases} \tag{2}$$

The robust control design problem [8] arises when $\hat{\Sigma}$ behaves significantly different from Σ.

The closed-loop performance under uncertainty condition can be still guaranteed if some structure and some bounds are assumed on the difference of the design model to the actual physical system. The control design methodologies that explicitly take into account this uncertainty are called the robust control ones. The formalization of such methodologies has occurred nearly 20 years ago, and has given rise to several design procedures, like $\mathcal{H}_\infty$ control, μ-synthesis control, sliding mode control, Kharitonov-based control, etc. Each such design methodology is concerned with a specific uncertainty structure assumption. In this paper, two kinds of uncertainty are being considered:

- Norm-bounded uncertainties: the 'difference' system, $\Sigma - \hat{\Sigma}$, has an $\mathcal{H}_\infty$ norm less than a prescribed bound γ [9].
- Polytope-bounded uncertainties: the difference system, $\Sigma - \hat{\Sigma}$, is assumed to belong to a known polytope inside the parameter space [10,11].

The norm-bounded uncertainties can be taken into account by $\mathcal{H}_\infty$ controllers in any formulation [9], while the polytope-bounded uncertainties can be taken into account by both $\mathcal{H}_\infty$ and $\mathcal{H}_2$ controllers, in some LMI[1]-based designs [12,13].

The main design parameter to be provided by the user to a robust control design algorithm is the characterization of the system uncertainty. The usage of such algorithm as a black-box one, in a way that is similar to the usage of PID controllers, or classical frequency compensators, involves the definition of few parameters that will implicitly define the system uncertainty, without actually being based on any explicit derivation of this uncertainty structure. These parameters should have yet some intuitive appeal, in order to allow the designer to develop her/his own trial and error 'expert' methodology.

In order to provide an example of such control design method, consider an $\mathcal{H}_\infty$ control method of 'loop shaping' type. See, for instance, Ref. [14] for an extensive discussion on this kind of control design.

The *augmented plant* diagram, shown in Fig. 1 is considered. In this diagram, some 'fictitious' blocks, W_1, W_2 and W_3, are connected to the system. These blocks are high-pass, low-pass or band-pass filters, that will 'weight' the system signals in frequency.

Considering the input w and the vector of fictitious outputs $z = \{z_2, z_3\}$, the controller design can be performed

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[1] Linear matrix inequalities.

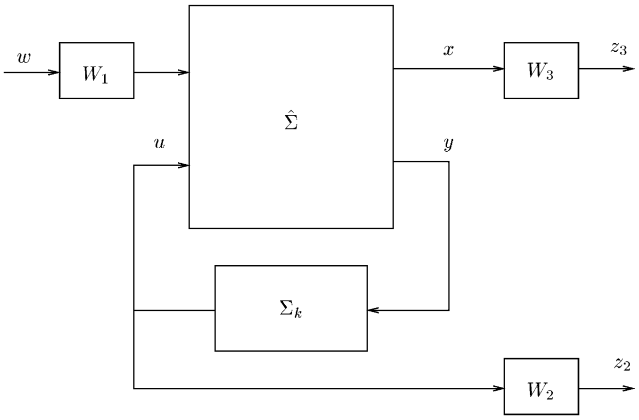

Fig. 1. Augmented system diagram, for the loop shapping $\mathscr{H}_\infty$ design.

with any standard $\mathscr{H}_\infty$ procedure for keeping the $\mathscr{H}_\infty$ norm from w to z less than a pre-specified real value γ. There are several classical references, like Refs. [9,15], explaining the structure of such algorithm.

The controller design parameters that are chosen by the user, in this case, are the cutting frequencies of the filters. The interpretation of these parameters is: the resulting controller ‘manages’ in order to attenuate the frequencies that ‘pass’ through the filters, since the control objective is to avoid the ‘interference’ of signal w in signal z. Therefore, the controller can be adjusted by changing the filters, that define the frequencies it will deal with. There are algorithms, both commercial and public-domain, that perform this design upon the specification of the system model and the weighting filters.

As a last remark, it should be noted that the ‘classical’ controller design techniques were not concerned with these robustness issues, and they did worked out for many years.

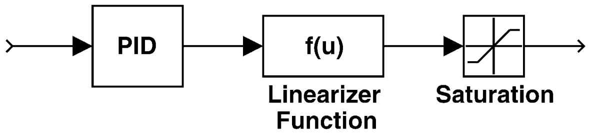

Fig. 3. Regulator circuit using a PID control.

The advantage of the employment of robust methodologies, in a black-box feature, as proposed here, is the reduction in the trial and error space, by eliminating the unstable and almost-unstable designs. The designer will search for the solutions in a set of solutions that are ‘optimal’ in a mathematical sense and that, as a consequence, do not present extremely ‘bad’ behaviors.

3. System and devices models

The TCSC and the SVC have been modeled using the MATLAB power system blockset. Fig. 2 shows the TCSC representation [16]. The device itself consists of a fixed series capacitor in parallel with a thyristor controlled reactor (TCR). A 212 μF capacitor and a 15 mH inductor have been used here.

The control structure of the device is comprised of a regulator circuit and a gate pulse generator circuit (GPG). The regulator circuit, as shown in Fig. 3, receives the comparison between the reference power and the RMS detector and goes into a PID device and the resulting output is then transformed in angle values and limited by a saturation block in the range of 95–175°. When a $\mathscr{H}_2$ or $\mathscr{H}_\infty$ controller is used the PID block is replaced by $\mathscr{H}_2$ or $\mathscr{H}_\infty$ block, respectively.

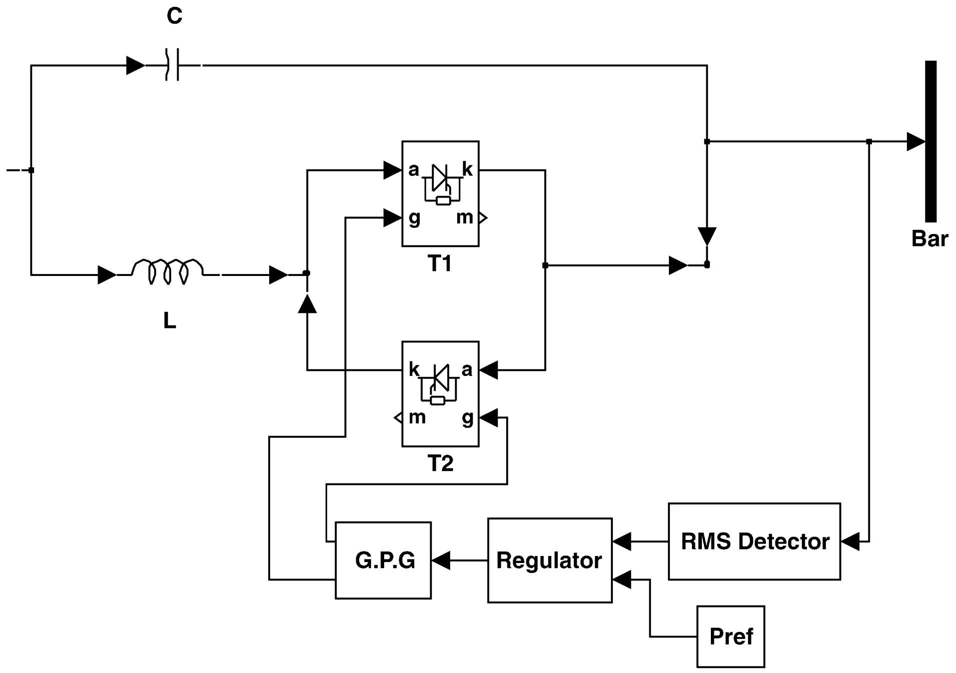

Fig. 2. Thyristor controlled series capacitor model.

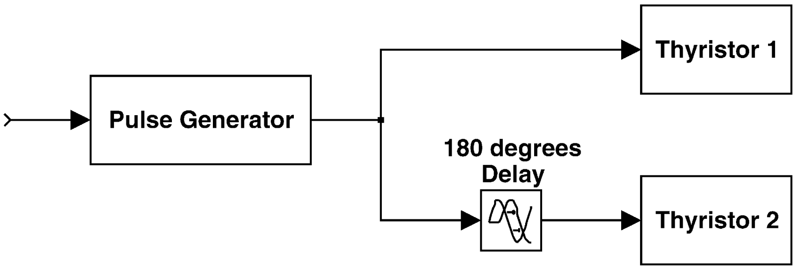

Fig. 4. Gate pulse generator.

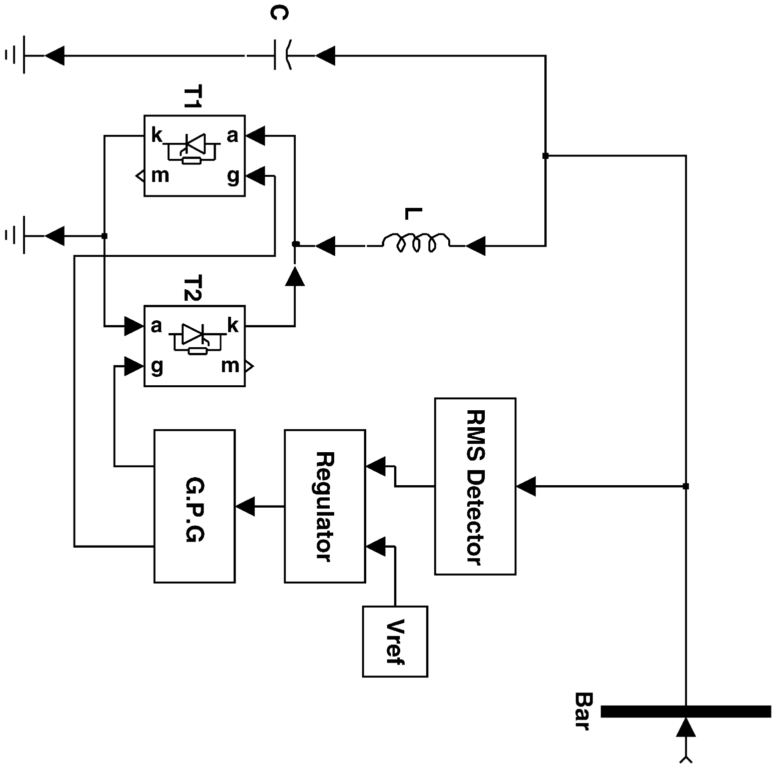

Fig. 5. Static VAR compensator model.

Fig. 4 shows the GPG circuit. The GPG provides firing pulses to thyristors converting the angle signal that comes from the regulator circuit. The thyristor 2 receives the pulse delayed of 180°.

Fig. 5 shows the SVC representation [17]. It consists of a TCR in parallel with a capacitor. The control structure of the SVC is also composed of a GPG circuit and a regulator circuit. A RMS voltage measured at the transmission line is

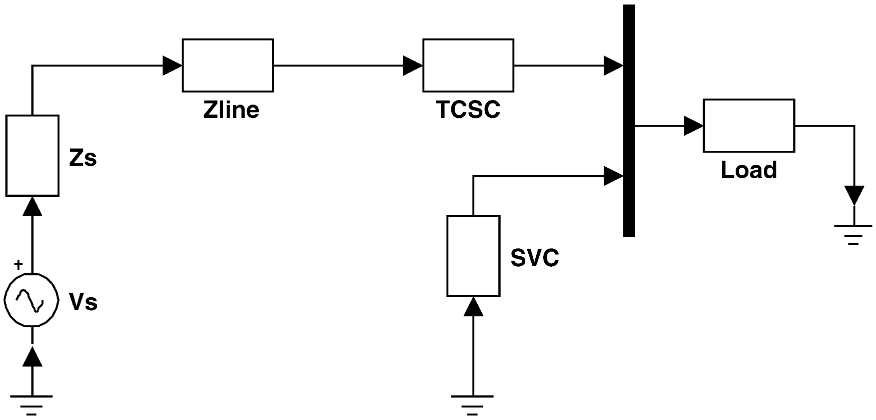

Fig. 6. Test system with two FACTS devices.

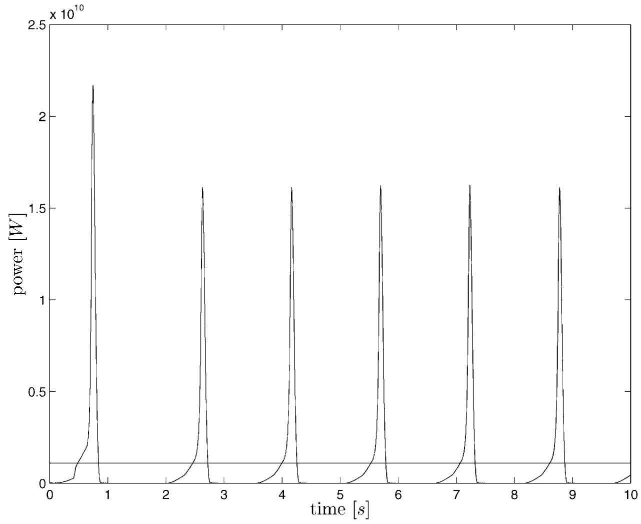

Fig. 7. Power flow during a system energization with PID control.

compared with a reference voltage and the difference between them is used as the input of the controller.

Fig. 6 shows the test system used here. A TCSC controls the power flow in the transmission line and a SVC controls the voltage at the load bus. A simple generator model comprised by a voltage source behind a transient reactance has been used. The RMS value of the generator voltage is 735 kV, 60 Hz, and the transient inductance is 132 mH. A constant impedance of 100 Ω represents the load system and the transmission line inductance is 270 mH. The resistive load causes a strong coupling between the TCSC and SVC, once power and voltage variables are algebraically related. Therefore, a steady error is present when the control references are independently set.

Firstly, a PID control structure is used in both FACTS devices (TCSC and SVC). Afterwards, the PID control structure of the SVC is changed to a robust control structure ($\mathscr{H}_2$ or $\mathscr{H}_\infty$). The dynamic situations simulated were system energization and a voltage variation at the load bus.

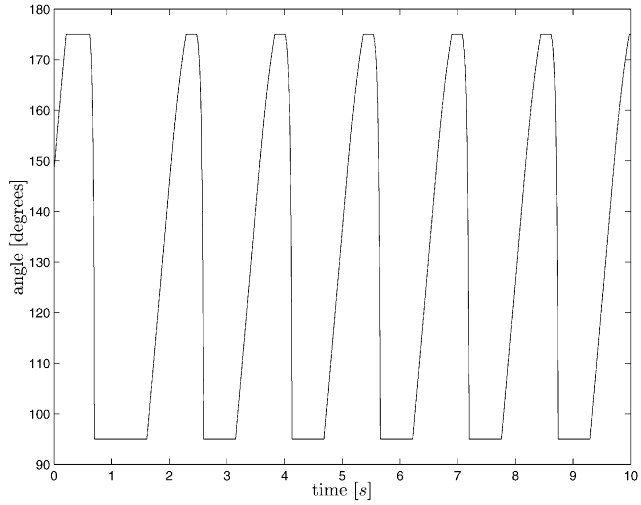

Fig. 8. Thyristor firing angle during a system energization with PID control.

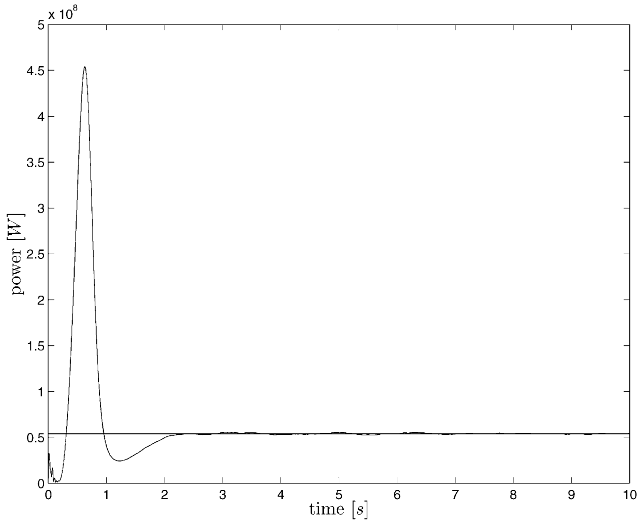

Fig. 9. Power flow during a system energization. The SVC with $\mathscr{H}_2$ control.

4. Results

In all experiments that are reported in this section, the following weighting filters were employed:

$$W_1 = \frac{0.001111(s+0.1)}{0.006667(s+1)} \tag{3}$$

$$W_2 = \frac{0.01(s+1)}{(s+0.1)}$$

$$W_3 = \frac{0.1(s+500)}{0.010053(s+200)}$$

The weighting filter W_3 was linked to the output signal y. The resulting controller was of order 12.

Figs. 7 and 8 show the power flow in the transmission line and the SVC thyristors firing angles, respectively, when the system is energized and both FACTS devices are using PID control structures. The reference voltage used for the

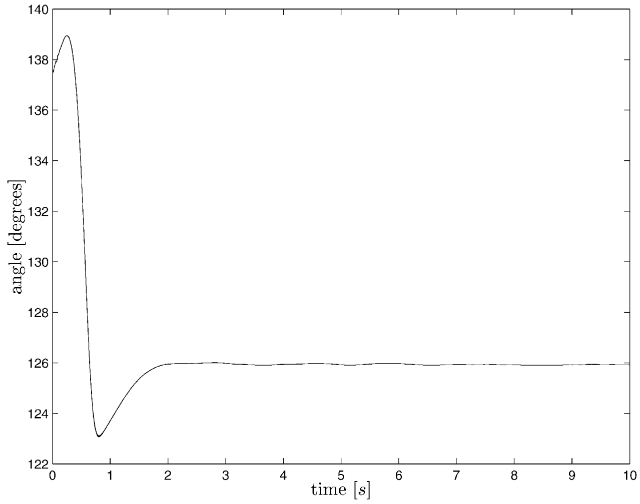

Fig. 10. Thyristor firing angle during a system energization. The SVC with $\mathscr{H}_2$ control.

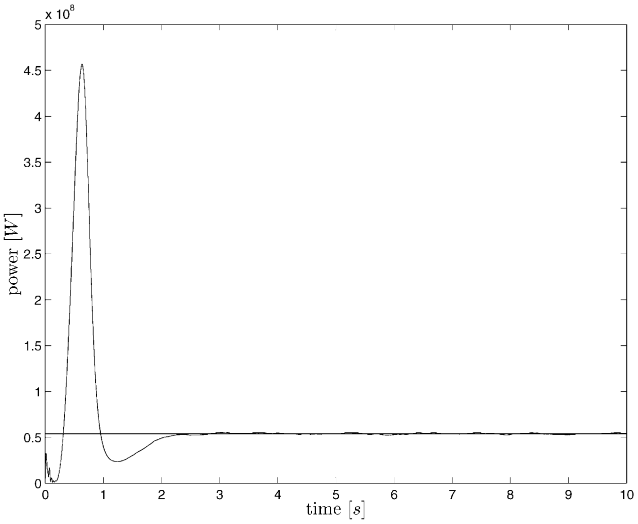

Fig. 11. Power flow during a system energization. The SVC with an $\mathscr{H}_\infty$ control.

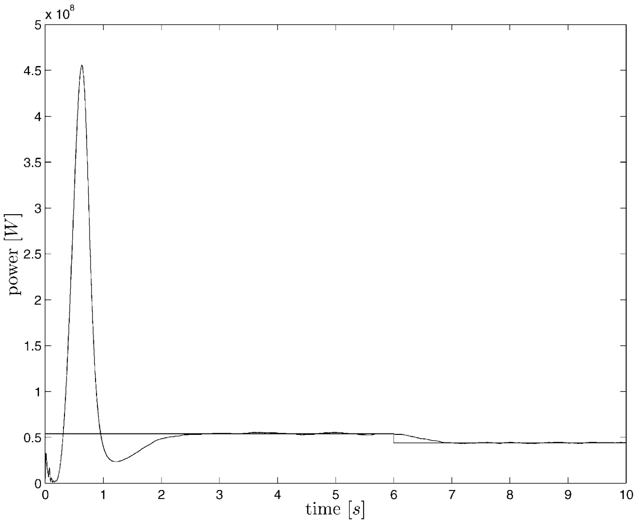

Fig. 13. Power flow during a voltage reference variation. The SVC with an $\mathscr{H}_\infty$ control.

SVC has been 73.5 kV and the reference power used for TCSC has been 110 MW. It can be seen that the system could not reach stability. Several gain adjustments have been tried for the PID controllers. In fact, the coupling between control loops has shown to be an adverse condition for this kind of control structure, as expected.

Figs. 9 and 10 show the power flow in the transmission line and the SVC thyristors firing angles, respectively, when the system is energized and the PID control structure of the SVC is replaced by an $\mathscr{H}_2$ robust controller. The reference voltage and power have been kept as the same when PID control was used. It can be seen now that the system reaches stability easily.

An $\mathscr{H}_\infty$ robust control has also been used in the SVC control structure. The results are shown in Figs. 11 and 12 for a system energization. Reference voltages are kept the same as in the previous cases. System stability is also reached easily here.

Figs. 13 and 14 show the power flow in the transmission line and the SVC thyristors firing angles, respectively, when the reference power has decreased in around 5%. The same $\mathscr{H}_\infty$ control is used here in the SVC. System stability is also reached for this dynamic situation.

Figs. 15 and 16 show the power flow in the transmission line and the SVC thyristors firing angles, respectively, after the occurrence of a fault, followed by its elimination. The same $\mathscr{H}_\infty$ control is used once more in the SVC. System stability is still reached for this dynamic situation.

Two points should be noted from these experiments:

- The more complex controller structure employed in this case (dynamic output feedback) has been able to deal

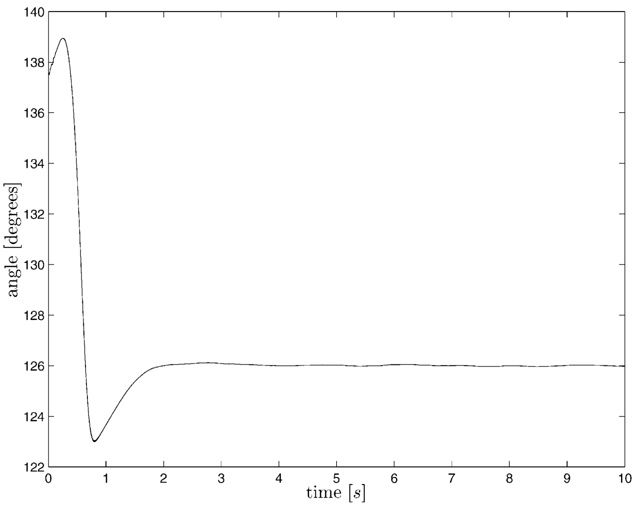

Fig. 12. Thyristor firing angle during a system energization. The SVC with an $\mathscr{H}_\infty$ control.

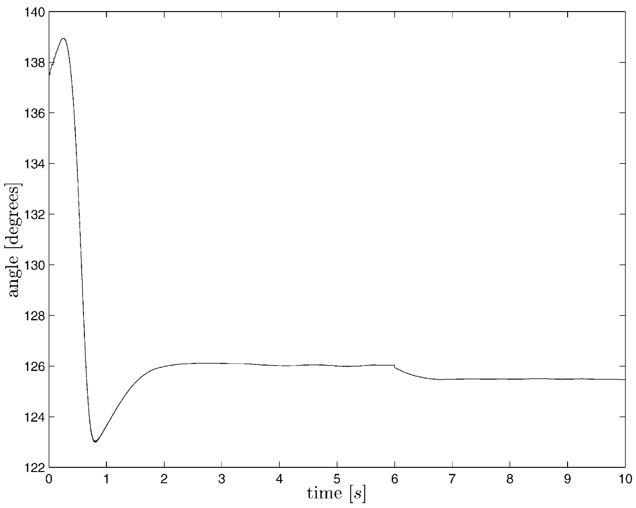

Fig. 14. Thyristor firing angle during a voltage reference variation. The SVC with an $\mathscr{H}_\infty$ control.

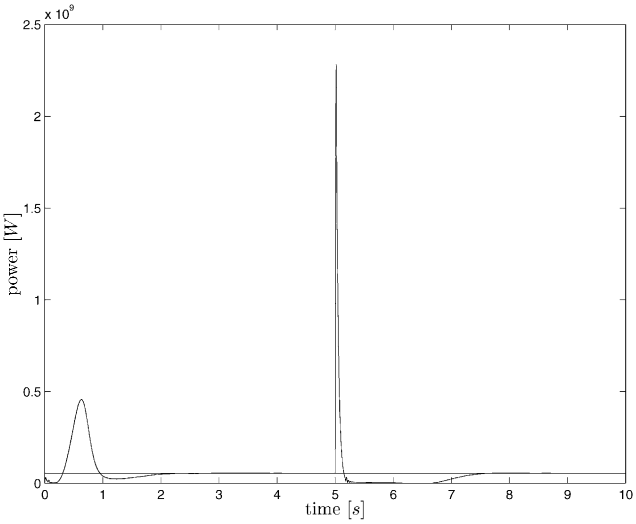

Fig. 15. Power flow after a fault. The SVC with an $\mathscr{H}_\infty$ control.

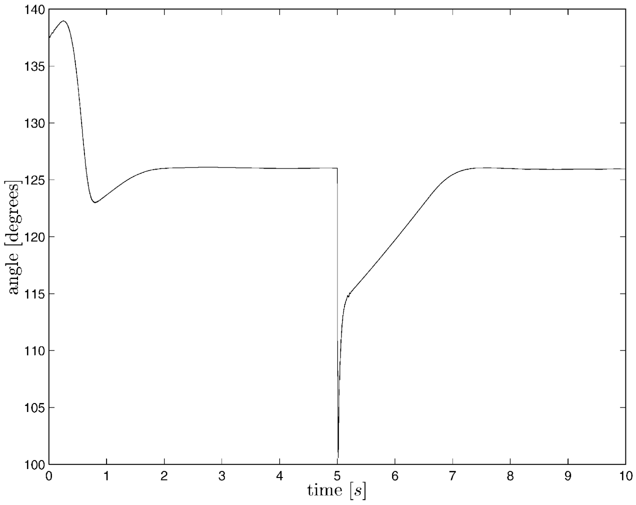

Fig. 16. Thyristor firing angle after a fault. The SVC with an $\mathscr{H}_\infty$ control.

with the issue of loop coupling, restoring the closed-loop stability.

- The tuning procedure proposed here for this controller, the black-box robust control, is as simple as a standard tuning procedure employed for conventional PID structures.

5. Conclusion

The proposed black-box robust control approach has shown to be effective for the design of controllers for FACTS devices when those devices are coupled in the same system. $\mathscr{H}_2$ and $\mathscr{H}_\infty$ criteria have been employed inside the black-box approach. Other criteria could be also used, instead of these ones.

When just classical controllers have been used for the same dynamic situations where robust controllers have operated satisfactorily, the system could not reach stability after a disturbance. This behavior is due to the situation of hard coupling between control loops that has been created in a very simple system model. This situation is an extremal case of a phenomenon that can occur in any larger system and, therefore, constitutes a preliminary test that should be applied in any power system control design procedure.

Furthermore, the design of a robust control for the studied situations have shown to be easier, once it is not necessary an exhaustive trial and error approach. Adjustments in a few design parameters of the robust controller lead directly to closed loop systems that present acceptable stability and performance.

The methodology proposed here is expected to work well in other situations of highly coupled, large and complex dynamic systems in which the development of exact or even realistic dynamic models for control design purposes is infeasible. In such cases, the usage of simplified dynamic models should be employed in combination with heuristic controller design procedures, like the black-box robust control design proposed here.

Acknowledgments

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