Advanced FACTS control

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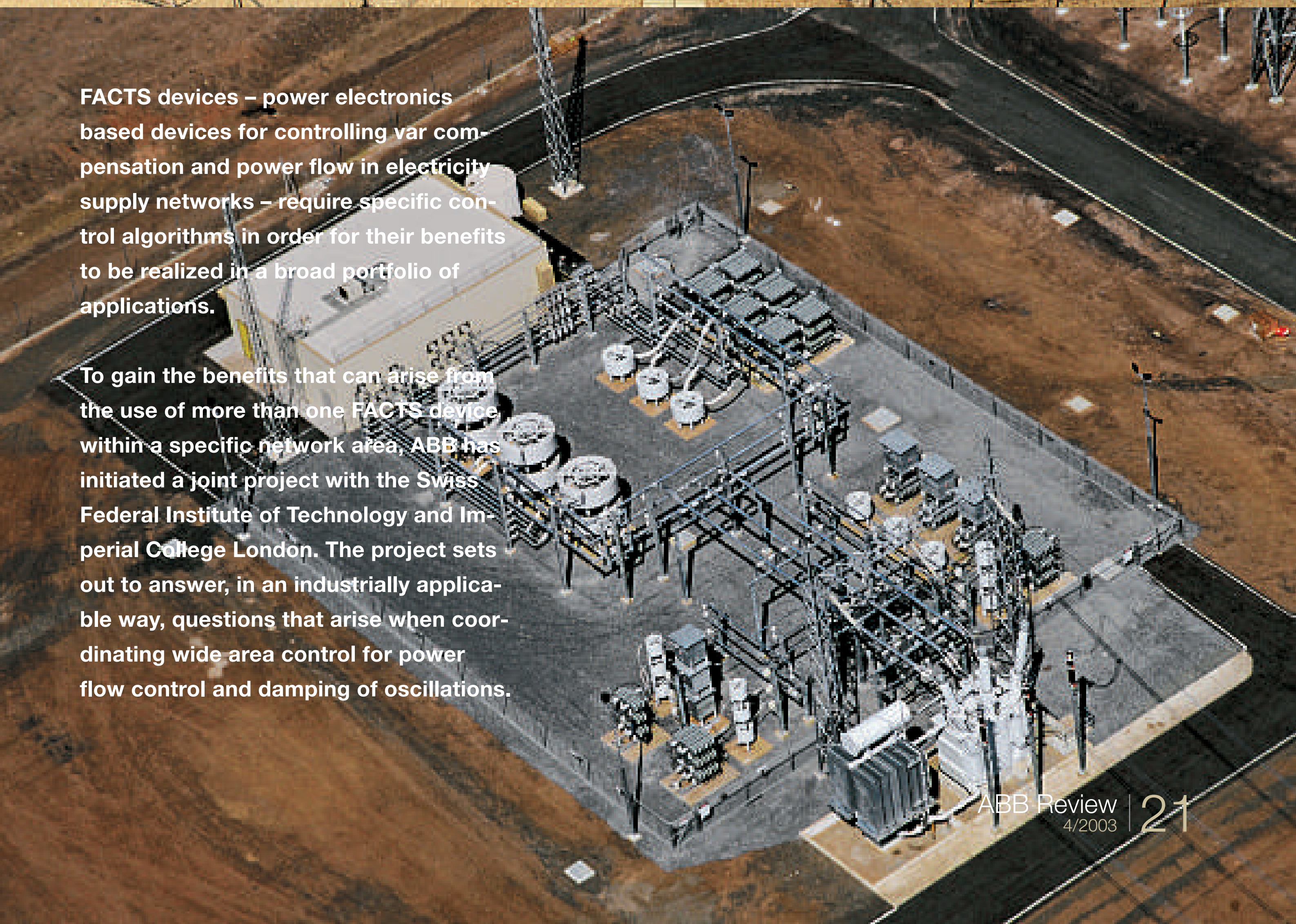


FACTS devices – power electronics based devices for controlling var compensation and power flow in electricity supply networks – require specific control algorithms in order for their benefits to be realized in a broad portfolio of applications.

To gain the benefits that can arise from the use of more than one FACTS device within a specific network area, ABB has initiated a joint project with the Swiss Federal Institute of Technology and Imperial College London. The project sets out to answer, in an industrially applicable way, questions that arise when coordinating wide area control for power flow control and damping of oscillations.

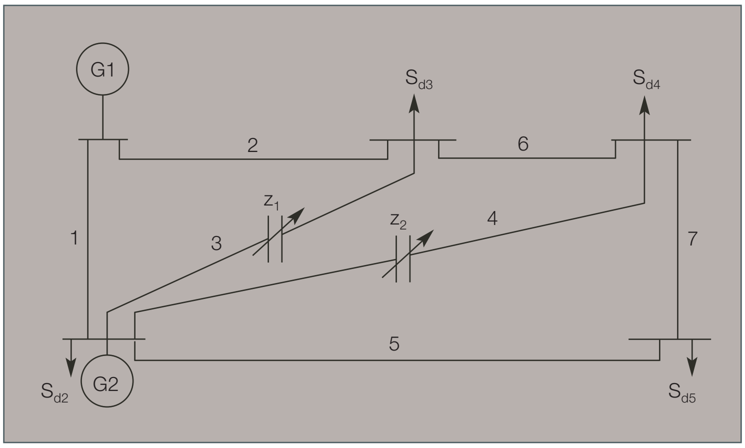
Power networks continue to expand and adapt as demand for electricity grows, new technology emerges and market conditions change. However, the addition of controllability in order to fully utilize existing transmission capacity, or of new controllable lines, can bring new problems with it. Often, the controllability of the system as a whole then has to be upgraded.

Controllable power electronics devices are available today that not only offer utilities a whole host of new options but also are leading to a new class of system: Flexible AC Transmission Systems, or FACTS. FACTS devices are integrated in a system for a variety of reasons, such as power flow control, reactive power (var) compensation, or ancillary functions like damping of oscillations.

Controlled transmission paths are increasingly necessary in order to enhance transmission logistics and allow more competitive power system operation. However, the number of paths that can be controlled is limited by the control systems' present-day inability to cope with an inherent tendency to interact adversely. Moreover, badly damped oscillatory modes can limit transmission capability and hinder the efficient use of remotely generated energy, such as hydropower. Market activities can be limited, too. Given all this complexity, coordinating damping controllers can be a difficult task.

To solve the related problems ABB Corporate Research and ABB Power Systems initiated a cooperative project with the Swiss Federal Institute of Technology and Imperial College London. Both of these institutes have extensive experience in power system control and their work has significantly influenced the industry's embrace of FACTS.

1 5-bus test system. Controllable series compensators (denoted by impedances Z_1, Z_2) are located in lines 3 and 4. S_d is the load power at buses 2–5.



Project goals are defined

The key problem is that the design of the controller for a new controllable device affects the entire power system. This is because any one device works in an environment in which there are several other controllers, and these may interact with one another. Also, all the other controllers in a power system contribute to the design problem. It follows then that a key requirement of any new controller is that it shall neither negatively affect the overall system nor necessitate a redesign of controllers already implemented, such as generator controls or power system stabilizers.

FACTS devices are integrated in a system for a variety of reasons, such as power flow control, reactive power (var) compensation, or ancillary functions like damping of oscillations.

The main goal of the initiated project is therefore to work out the requirements and constraints for such a controller and propose an appropriate design. This design should be easily scalable to different control ranges and be compatible with ancillary functions. These requirements led to the following specifications being defined:

- The controller design shall not require a redesign of network controllers already implemented.
- The various network controllers should work together and use the same control approach.
- The design should exhibit a robustness that is in keeping with the changing requirements of modern power system operation.
- Modularity is required for all control tasks to allow FACTS devices to be adapted for every kind of application.
- Scalability of the design to different control ranges must be possible.
- Undesirable behavior or malfunctions in contingency situations (faults, line tripping, etc) must be avoided.

Coordinated FACTS control

With the development of FACTS devices, utilities are today able to considerably enhance power flow controllability. This is important in the context of growing energy demand and the emergence of energy trading markets. Another problem is that, for environmental reasons, restrictions are often placed on the installation of urgently needed power transmission lines. Maintaining a reliable supply of electricity on defined line corridors without affecting other paths or the consumers in the system will therefore be crucial in the future.

Series flow control devices introduce new control variables into the power flow calculations. One important component is the controllable series compensator (CSC), which, by allowing fast, continuous changes in the transmission line impedance, provides an effective means of power flow control. Using a CSC, active power flows along the compensated transmission line can be maintained at a specified value under various operating conditions.

A more exact method of computing sensitivities – one that also takes the actual power system condition into consideration – would obviously be useful for analyzing power flow control with controllable devices. Linearization of the load flow equations around the nominal operating point yields such sensitivities, thereby defining a sensitivity matrix. The sensitivities can be used to calculate a system's total active power loss or to estimate the effect on the transfer capability of variations in certain parameters, eg those describing other transfers, operating conditions or assumed data.

> How many transmission paths can be controlled is limited by the control systems' inability to cope with an inherent tendency to interact adversely.

An important question that has to be answered concerns the line flow regions that are obtainable for a set of controllable components with a given control range. The concept of load flow feasibility boundaries presented in [1] addresses this. The same concept can also be used to calculate the increases in load and generation that are possible without violating given line flow constraints.

Power flow control

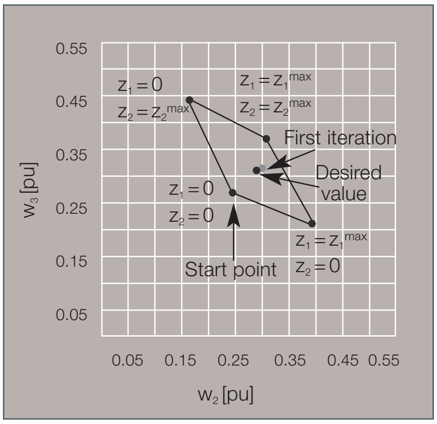
Power flow control aims at controlling active and sometimes reactive power flow through certain lines at specified levels. Control here is based on the implementation of power flow sensitivities. The controlled devices are CSCs.

The power flow through a transmission line varies approximately as a quadratic function of the degree of series capacitor compensation between 0 and 100%. This can best be explained by referring to the simple 5-bus test system in 1.

Quadratic models can be used to represent the line flow feasibility boundaries for different levels of compensation. The boundaries are not perfectly straight lines, but they could, with very high accuracy, be approximated by straight lines 2. Thus, it suffices to calculate the line flows in the corners.

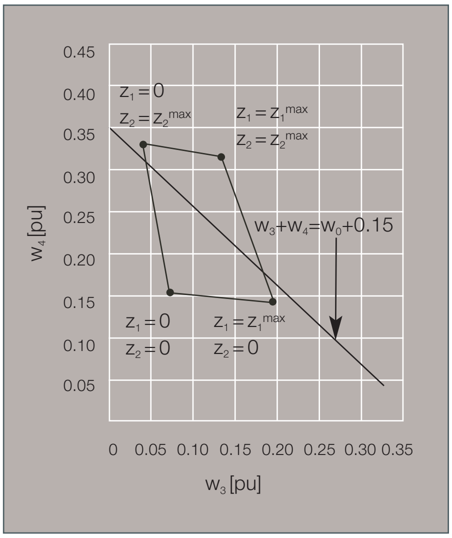
It is now supposed that the power flows in lines 3 and 4 (1) are to be controlled according to some specified power flow

2 Line flow feasibility boundaries



w_2, w_3 Variables for active power flow over lines 2 and 3 in Fig. 1

3 Load flow feasibility boundaries for scenario I

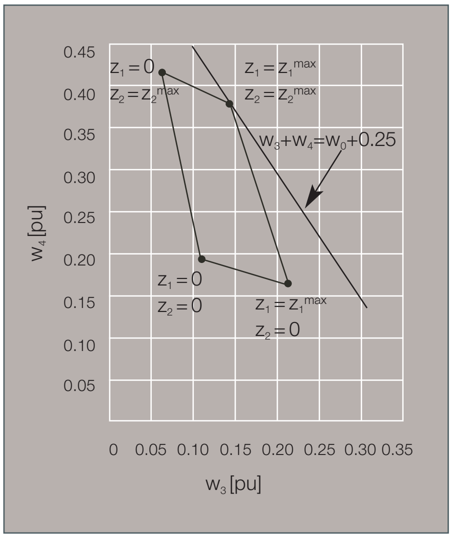


w_3, w_4 Variables for active flow over lines 3 and 4 in Fig. 1

Scenario I	
P_{L3}	Base case + 15%
P_{L4}	Base case + 20%
G_2	Base case + 35%
$w_3 + w_4$	Base case + 29%

Scenario II	
P_{L3}	Base case + 44%
P_{L4}	Base case + 38%
G_2	Base case + 82%
$w_3 + w_4$	Base case + 69%

4 Load flow feasibility boundaries for scenario II



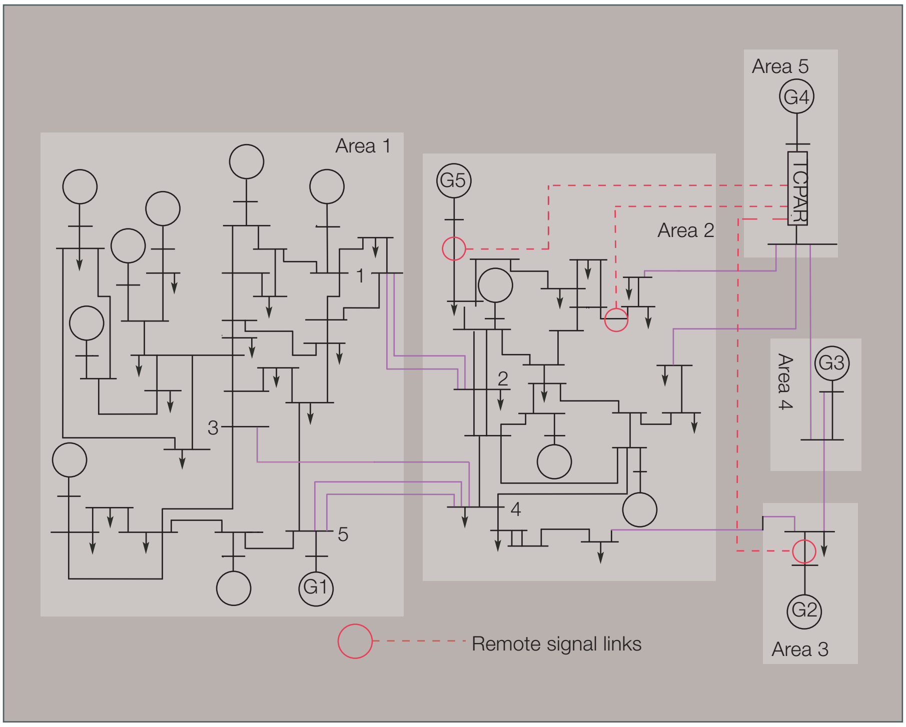
control data. To achieve the specified power the control variables can be calculated using the sensitivity matrix. Taking the starting point in 2 as the base case, then using the sensitivity relations and substituting numerical values, a solution is obtained after three iterations. A solution very close to the desired value is obtained after the first iteration. The second and third iterations yield only very minor improvements.

It will now be assumed that, from the base case, the loads on buses 3 and 4 increase, and that this increase is met by generator G2. It is further assumed that the additional power flows on lines 3 and 4, where the CSCs are located. It is now relevant to ask how long, and how much, load can be added before power flow controllability is lost on lines 3 and 4. 3 and 4 show, for two different scenarios, the different line flow regions in which there is still control. But whereas in 3 the controllability is still flexible, in 4 the active power flow through lines 3 and 4 cannot be increased to the specified amount. Another possibility is, of course, to keep the power flow on lines 3 and 4 at the point (z_1^{max}, z_2^{max}), with the remaining power flowing through other lines.

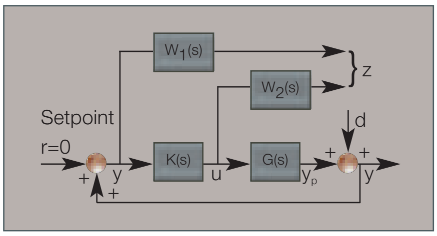
Damping control

Low-frequency oscillations (0.2–1.0 Hz) involving large subsystems of an interconnected system are an inherent feature of power system operation [3].

5 System model used for study
TCPAR Thyristor-controlled phase angle regulator



6 Mixed sensitivity formulation



K(s)	Controller being designed
G(s)	Linearized model of power system
$w_1(s)$, $w_2(s)$	Mixed sensitivity weights
d	Disturbance

These oscillations comprise many electromechanical modes, often larger in number than the controllable devices installed in the system. In recent years, much research work has been focused on designing new control structures that seek to improve the damping of these multiple oscillatory modes. The primary idea behind the control design is to employ a combination of remote stabilizing signals and diverse modal content. The remote stabilizing signals are often referred to as 'global signals' to illustrate that they contain information about the overall network dynamics, as opposed to local control signals lacking adequate observability of the relevant system dynamics [4]. It may be more cost-effective to implement centralized controllers using global signals than to install new control devices [5]. Here, the goal of the project team is to demonstrate and test a multivariable control design methodology for robust damping of inter-area oscillations employing remote stabilizing signals for a TCPAR (Thyristor Controlled Phase Angle Regulator) installed in the study system model shown in 5. This one FACTS device will be required to damp several modes and be designed to operate in harmony with the existing generator excitation controllers (which were included in the model) without requiring redesign of that control.

> The study shows that when an LMI framework is used, a controller can be designed which is unaffected by plant variation and tolerates non-linearities.

Damping control design: a multi-objective optimization problem

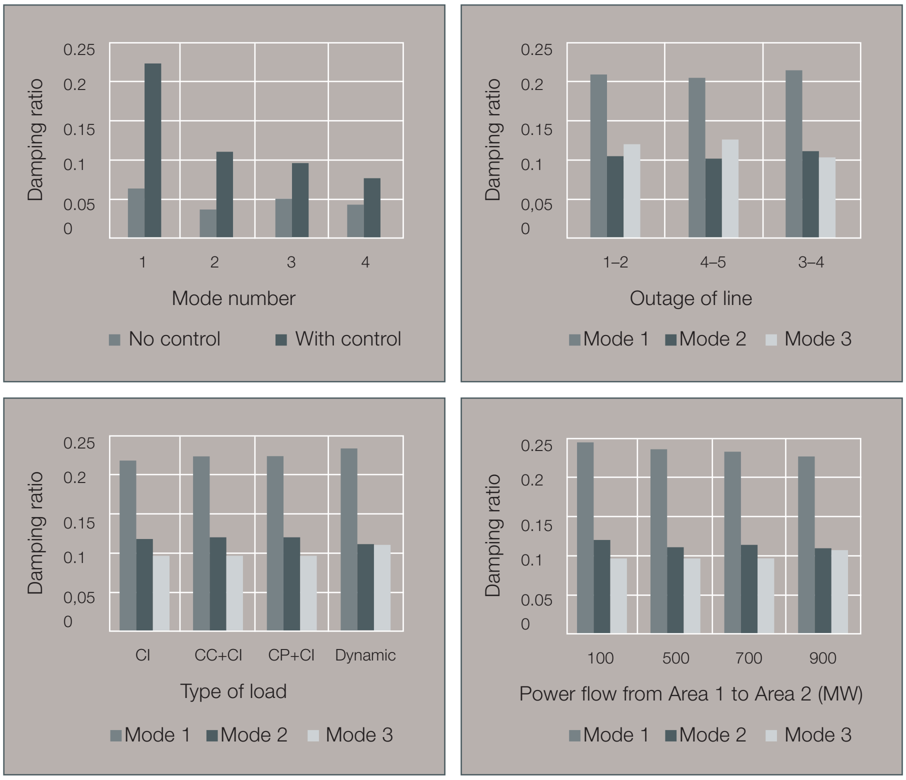
Oscillations in power systems are triggered by events such as sudden variations in load demand or voltage regulator action in response to faults. The primary function of the damping controllers is to minimize the impact these disturbances have on system operation.

> The research has demonstrated that effective damping of multiple swing modes can be achieved through appropriate design of a single TCPAR.

The design objective is essentially to minimize a weighted mixed objective function. This is shown in 6 as a disturbance rejection problem with a constraint on control effort.

The controller is obtained through numerical optimization once the problem has been formulated in the Linear Matrix Inequality (LMI) framework. For the system shown (as an example) in 5, a 3-input, 1-output controller was designed for the TCPAR using three stabilizing signals from three different remote locations. The output of the LMI solver produced a high-order controller that would be difficult to implement. The controller was subsequently simplified by means of model order reduction to a 6th-order controller. To ensure that it retains all of the desired properties and is robust enough to handle plant variation, the reduced-order controller was tested on the original system model for many different operating conditions. The tests provide an eigen-analysis of the system. 7 shows that the damping ratios of at least 4 modes are significantly improved by the controller. Further, the damping remains good for a variety of load types, tie-line powers and line outages.

7 Robustness validation under different operating conditions

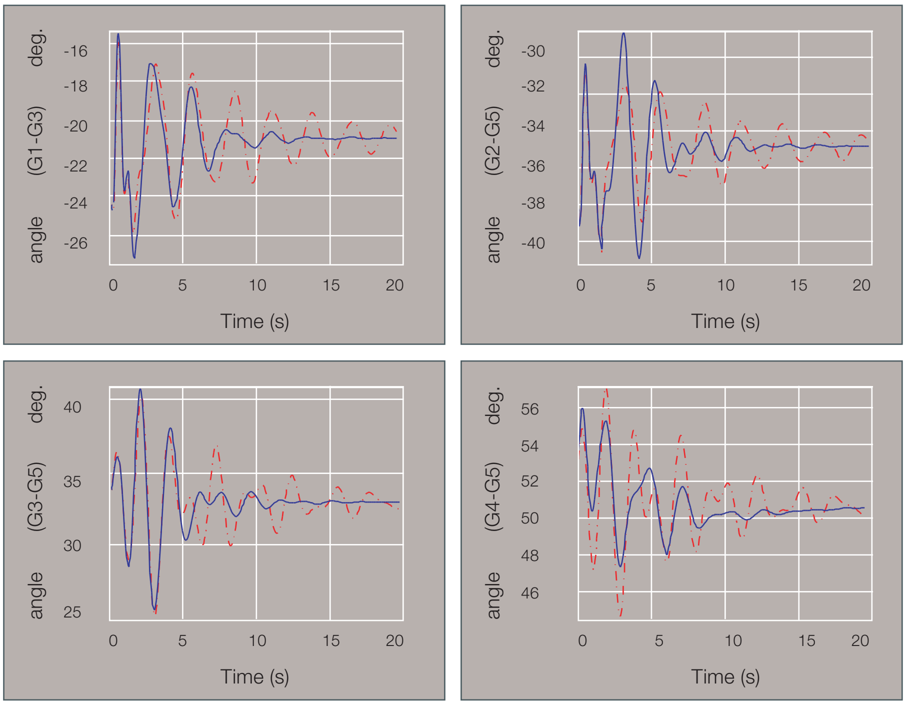


CI Constant impedance load model
CC Constant current load model
CP Constant power load model

To assess the LMI-based controller's performance when the system experiences non-linearities, such as saturation, a time-step simulation was performed.

A three-phase bolted fault was initiated near bus 4 on one of the tie-lines connecting buses 4 and 5 for 80 ms (approximately 4 cycles) followed by opening of the faulted line. The graphs in 8 show the relative angular separation of machines G1, G2, G3 and G4 from that of machine G5, illustrating that the inter-area oscillations are damped out in 10–5 seconds, considerably faster than

8 Dynamic response of the studied system



Dashed line: without control Solid line: with control

nous phasors and control signals [6]. Without such measurement each FACTS device can only damp modes observed in local signals, which is a more restrictive situation considering that the FACTS devices are likely to be sited, for reasons of steady-state power control, in a small number of power corridors. The study has demonstrated that when an LMI framework is used, a controller can be designed which is robust enough to be unaffected by plant variation, tolerant of non-linearities and capable of operating without adversely affecting existing generator controllers.

without the new controller with remote signaling in place. Observation of the dynamic response of the various existing control loops showed no indication of adverse interaction of the TCPAR damping action.

The research has demonstrated that effective damping of multiple swing modes can be achieved through appropriate design of a single TCPAR. It requires the use of remote or global signals (from which to observe the modes), but this is a realistic option given the rapid advances being made in the field of phasor measurement and wide-area monitoring, using GPS that can provide real-time synchro-

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