Robust Low-order Controller Design for Multi-modal Power Oscillation Damping using FACTS Devices

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Abstract

Damping of multi-modal oscillation through supplementary control of a single FACTS device is illustrated in this paper. This often requires multiple feedback signals in a centralised multi-input single-output (MISO) framework for which extension of the classical control design approaches is not straight forward. Past contributions have either focused on decentralised design of low order PSS in a SISO or MIMO framework; or alternatively, on robust control design techniques which of course, result in higher order controllers. This paper is an attempt to design a fixed (low) order controller which is robust and is able to damp multiple swing modes with a single FACTS device. The control design problem is formulated as a multi-objective parameter optimisation and solved using a standard evolutionary optimisation technique. Possible post-contingency operating conditions are considered explicitly during the design phase itself to reduce the conservativeness. The present exercise is a step forward towards use of Wide Area Measurement Systems (WAMS) for closed-loop supplementary control (around the primary voltage and/or power flow control loop) of the FACTS devices to improve the transfer capacity of the existing corridors.

1 Introduction

With increasing opposition to building new transmission lines, it is absolutely critical that the existing power transmission assets are fully utilised by loading them much closer to their capacity. One of the major concerns, then, is secure operation of the system primarily in the presence of low frequency electro-mechanical oscillations. These oscillations, typically in the range of 0.1-1.0 Hz, are often poorly damped especially, with increasing power transfer levels [1]. A number of incidents due to such oscillatory instability have been reported some of them eventually leading to widespread blackouts [2]. Such risks force the network operators to adopt a conservative approach and operate their system with sufficient stability margins. One way to get around this problem is to exert supplementary control over voltage and/or power flow through Flexible AC Transmission Systems (FACTS) devices already installed in key transmission corridors [3]. This could potentially improve the dynamic behaviour of

the system and thereby, allow the transmission lines to be operated much closer to their capacity, without compromising security [4].

The key challenge, however, is proper design of the damping controller for the FACTS devices. The controller must ensure that oscillations settle within a specified time for a range of operating conditions some of which could not be anticipated in advance. It should be able to do this with optimum control effort such that satisfactory performance is achieved with minimum dynamic rating of the expensive FACTS devices. In general, all the critical swing modes of the system are not adequately ‘observable’ at the FACTS location which is decided primarily based on the steady-state power flow and/or voltage control considerations [5]. Hence, the control formulation is required to be in a multi-input, single-output (MISO) framework. For ease of implementation and subsequent tuning, the controller structure should be simple comprising of a few lead-lag blocks. Ideally, the maximum order should be limited to three or four following the standard structure of PSSs [6], which the utilities are very well used to.

Researchers, over the years, have addressed one or more of these concerns. However, most of them have either focused on decentralised design of low order PSS in a SISO or MIMO framework; or alternatively, on robust control design techniques which of course, result in higher order controllers. Kamwa et. al. [7] proposed multiple fixed structure PSS design using a non-linear constrained optimisation technique. The formulation is multi-variable and includes additional robustness constraints. The design, however, is based on a single operating condition which is the worst scenario in terms of the required phase angle compensation. This approach, although reasonably robust, can be highly conservative. Do Bomfim et. al. [8] used genetic algorithm to optimise the performance of low order PSSs over a family of operating conditions. However, no additional constraint targeted towards optimisation of the control effort is used which might be justified in case of relatively inexpensive excitation systems, but not for expensive FACTS devices.

Chaudhuri et. al. applied $\mathcal{H}_\infty$ mixed-sensitivity [9] and loop-shaping [10] techniques with pole placement to ensure performance and a degree of robustness with optimum control effort. However, the design is based only on the nominal operating condition with a maximized performance radius around it, which is conservative. Vittal et. al. used structured

singular value [11] approach which includes off-nominal operating conditions as structured uncertainties resulting in a less conservative design. But the order of the controller, like the approach before, is at least as large as the open-loop system which could be prohibitively high for practical systems, even if a simplified equivalent is considered for design. Vittal et. al. applied $\mathcal{H}_\infty$ loop-shaping for structured plants [12] which involves proper selection of loop-shaping filter apart from the issues already mentioned above.

Chow et. al. proposed a model matching $\mathcal{H}_\infty$ control for robust redesign of the nominal controller [13] taking into account the off-nominal operating conditions. Ramos et. al. used dynamic output feedback for decentralised design using LMIs [14] considering multiple operating conditions. The controller order, however, is at least, as high as the open loop plant for both these approaches. The above list is, by no means, an exhaustive one but is reasonably representative of the limitations of the past research in achieving all the design specifications outlined above.

Our contribution in this paper is in formulating the control design problem to address all the following concerns comprehensively. Some of the ideas here are adopted from past contributions (mentioned above) which attempted to address one or more of these issues in isolation.

- Centralised design in MISO framework to damp multiple swing modes using a single FACTS device
- Simple low order controller for ease of implementation and subsequent tuning
- Considering probable post-contingency operating conditions at the design stage to reduce the conservativeness
- Optimising control effort to minimise the cost of additional dynamic rating of the expensive FACTS devices

A parameter optimisation framework [7, 8] is adopted to capture all these design objectives. The problem is solved using an evolutionary optimisation technique rather than the classical gradient based approaches. The classical gradient based approaches are sensitive to initial guess for starting values of parameters, which in this optimisation problem

is difficult to estimate a-priori.

The design methodology is illustrated through a case study on the reduced equivalent of the New England - New York (NETS - NYPS) test system, see Fig. 1. A supplementary damping controller for a Thyristor Controlled Series Capacitor (TCSC) is designed to damp the three critical inter-area modes using feedback signals from remote locations. Ensuring a minimum settling time over a range of operating conditions with optimum control effort is considered as the design specification. The maximum order and the structure of the controller is fixed *a priori* in accordance with one of the standard PSS structures recommended in [6]. With restrictions on the order and structure of the controller, it is, in general, impossible to adopt an analytical approach to solve such a multi-objective optimisation problem. Therefore, a parametric optimisation approach is used here and the solution is sought using Particle Swarm Optimisation (PSO) [15], a standard evolutionary optimisation technique.

The performance of the designed controller is validated through non-linear simulations for a range of contingencies including the ones which were not considered during the design. The benefits of control effort optimisation and use of multiple operating conditions to reduce the conservativeness of the design is demonstrated by comparing the present results with those obtained in the past using classical $\mathcal{H}_\infty$ approach [9].

2 Controller Design

The design methodology for a low order n -input, 1-output (MISO) controller is described in a general form in this section. It is assumed that there are n number of critical inter-area modes which are highly observable from n different locations. The controller is made up of only gain ($K_1, K_2, \dots K_n$) and a maximum of three first order lead-lag blocks in each channel, see Fig. 2, apart from the standard low pass noise filters ($T_m = 0.01$ s) and the high-pass washout blocks ($T_w = 10.0$ s). Measured signals are denoted as $P_1, P_2, \dots P_n$ and the control signal to the actuating FACTS device as u in Fig. 2. The structure and order of the compensators in each channel are chosen to resemble one of the standard PSS structures described in [6].

2.1 Objective Function

The controller is required to ensure that oscillations settle within 10.0 s for all the operating conditions considered during the design. It is therefore, necessary that modal oscillation corresponding to each of the n critical inter-area modes settle within 10.0 s. Desired closed-loop damping ratios for each mode are dictated by the minimum settling time assuming the frequency of oscillation should not change appreciably from open to closed loop. Moreover, these performance specifications have to be achieved with optimum control effort. Calculation of the gain and time constants of the controller, required to achieve the above specifications, can be formulated as a multi-objective optimisation problem which can then be solved using any standard optimisation technique.

The design specifications are as follows:

1. Modal oscillation due to all the poorly damped inter-area modes should settle within 10.0 s for all the operating conditions considered during design.
2. Frequency of oscillation of the inter-area modes should not change appreciably from their open-loop values.
3. Controller effort should be optimum.

An objective function is formulated to include these three design specifications. For individual modal oscillations, which closely exhibits a second-order system behaviour, settling time (T_s) depends on the product of the damping ratio (ζ) and the natural frequency of oscillation (ω), which in turn is decided by the real part (σ) of the poles as follows [17]:

$$T_s = \frac{4}{\zeta\omega} = \frac{4}{\sigma} \quad (1)$$

Hence, the closed-loop poles corresponding to the n critical modes should be on the left side of the constant σ ($\sigma_{ref} = 0.4$) line to ensure a maximum settling time of 10.0 s. This requirement is captured in the first objective (3).

From (1), the desired closed-loop damping ratios turn out to be higher for lower frequency modes to ensure a minimum settling time for individual modal oscillations. The second requirement is, therefore, addressed by capturing the difference between the desired

(ζ_{ref}) and actual damping ratios for each of the critical inter-area modes. Minimising this difference guarantees a specified settling time without appreciable change in frequency.

$$\zeta_{ref} = \frac{\sigma_{ref}}{\omega} = \frac{4}{T_s \omega} \quad (2)$$

The third specification is taken care of by minimising the average controller gain $mean(A)$ in each channel. The average gain is the mean of the Bode magnitudes over the frequency range of interest.

These three objectives are considered for n critical inter-area modes taking into account k probable operating conditions. The individual objectives, given by (3), (4) and (5), are combined with appropriate weights (α_j) to form the overall objective function, given by (6).

$$f_1 = \sum_{p=1}^n \sum_{q=1}^k (\sigma_{ref} - \sigma_{pq})^2 \quad (3)$$

$$f_2 = \sum_{p=1}^n \sum_{q=1}^k (\zeta_{ref} - \zeta_{pq})^2 \quad (4)$$

$$f_3 = \sum_{p=1}^n \sum_{q=1}^k mean(A_{pq})^2 \quad (5)$$

$$F = \sum_{j=1}^3 \alpha_j \times f_j \quad (6)$$

In (3) - (5), the suffixes p and q denotes the mode number and the operating condition number, respectively. The weights (α_j) are chosen such that contribution of individual objectives, (3), (4) and (5), based on the initial guess of parameters, is similar in the overall objective function (6). In other words, the weights are selected to ensure that each part is minimised with cumulative the objective function in order to improve the overall convergence.

2.2 Constraints

Following constraints are imposed on the optimisation problem:

- In order to avoid any unstable poles and zeros of the controller and also to ensure

that none of the controller mode is too fast, an upper limit of T_{max} and a lower limit of T_{min} were set for each of the unknown time constants T_j , $j = 1, 2, \dots, 6n$ (optimisation variables), see Fig. 2. The gains, K_i , $i = 1, 2, \dots, n$ are limited in the range $K_{min} \leq K_i \leq K_{max}$.

- Constraint on closed-loop stability of the system is implicitly imposed through introduction of a high penalty factor $L = 10^6$ in the objective function in case any closed-loop poles are on the right half of the s-plane.

The overall optimisation problem can be mathematically expressed as in (7).

$$\begin{aligned}
& \min_{K_i, T_j} (F + L), \quad i = 1, 2, 3, \dots, n; \quad j = 1, 2, \dots, 6n \\
& s.t. \quad T_{min} \leq T_j \leq T_{max} \quad \forall j = 1, 2, \dots, 6n; \quad -K_{min} \leq K_i \leq K_{max} \quad \forall i = 1, 2, \dots, n \\
& \quad \quad \quad L = \begin{cases} 0 & \text{if } \zeta_{pq} > 0 \\ 10^6 & \text{if } \zeta_{pq} \leq 0 \end{cases}
\end{aligned} \tag{7}$$

where, ζ_{pq} is the closed loop damping ratio with the candidate controller for the p^{th} mode under q^{th} operating condition.

2.3 Optimisation Solution

The above multi-objective constrained optimisation problem can be solved using any standard optimisation technique. However, it is not straightforward to come up with a reasonable initial guess for the parameter set. Hence, evolutionary optimisation techniques (e.g. genetic algorithm, particle swarm optimisation etc.) have been found to be more effective in terms of convergence. The results presented in this paper were obtained using a particle swarm optimisation (PSO) technique [15]. Other evolutionary optimisation techniques, e.g. genetic algorithm, simulated-annealing etc. are currently being explored to find the one best suited for this application.

2.4 PSO Technique

Particle Swarm Optimisation is a guided random search technique [15]. This is an effective optimisation tool for continuous and discrete objective functions. The solution space is

initially populated with random numbers. Each potential solution, called a particle, is given a random velocity in d -dimension where, d is the number of parameters to be optimised and is flown through the problem space. The previous best position of each particle is represented by p_{ibest} and is related only to a particular particle i . The corresponding best fitness value of i^{th} particle is denoted as $p_{best-fit}(i)$. The best position of all the particles in the swarm is represented as the G_{best} and the corresponding fitness is referred to as $G_{best-fit}$.

The basic concept of PSO technique lies in accelerating each particle towards its individual best position and the global best position at each iteration. The amount of acceleration with respect to both individual and global best position is given random weighting. The maximum search space is specified by limiting the velocities and positions of particles to certain minimum and maximum values. At each iteration, the position (p) and velocity (v) of each particle i is updated using (8) and (9).

$$v_i(k+1) = g \times v_i(k) + c_1 \times rand \times (p_{ibest} - p_i(k)) + c_2 \times rand \times (G_{best} - p_i(k)) \quad (8)$$

$$p_i(k+1) = p_i(k) + v_i(k+1) \quad (9)$$

where, v_i and p_i are the velocity and position of particle i and g , c_1 and c_2 are the inertia, cognitive and social components of acceleration, respectively. The *rand* function generates a random number at each iterations for exploring the search space. The optimal solution is obtained when the fitness of G_{best} is less than a pre-specified tolerance or the fitness does not change for a significant number of consecutive iterations. The PSO parameters g , c_1 and c_2 are selected as 0.8, 2.0 and 2.0 respectively, following [15]. The PSO technique is applied in this paper to find the parameters for the fixed low order damping controller as mentioned in the earlier sections.

3 Case Study

3.1 Test System

A reduced equivalent of the New England - New York interconnected power system from early seventies, shown in Fig. 1, is considered here for the case study. Although this test system is a simple one it is reasonably representative of a typical inter-connected system with poorly damped inter-area oscillations. Therefore, the methodologies described here can be extended, in general, for large practical systems.

There are nine equivalent generators (G1-G9) in the New England area, four (G10-G13) in New York and the remaining three (G14-G16) are dynamic equivalents of the neighbouring areas. New York and New England systems are interconnected through three major tie-lines connecting buses 60-61, 27-53 and 53-54. The power flow and dynamic data for this system is given in [16].

Small signal analysis reveals four inter-area modes [9] out of which three are critical and require additional damping. Frequency of these modes are 0.39 Hz, 0.50 Hz and 0.62 Hz under the nominal operating condition. A TCSC is assumed to be installed in one of the lines connecting New York (bus 50) and the adjacent region (bus 18) to facilitate/control the power transfer between these areas. The percentage compensation of the TCSC under nominal steady-state condition is 50% with an allowable dynamic range of variation from 10% to 80%. The objective here is to design a supplementary damping controller around the primary power flow control loop of the TCSC in order to damp the inter-area oscillations.

Lack of adequate observability of all the three critical inter-area modes at the TCSC location - which is based on steady-state power flow control consideration - necessitated adoption of remote feedback signals available through the wide-area measurement systems (WAMS) infrastructure. Power flow in lines connecting buses 51-45, 18-16 and 13-17 were chosen for the 1st, 2nd and 3rd mode, respectively, based on the modal observability analysis [16, 9]. The readers can refer to [16] for further details of this test system.

3.2 Operating Conditions

For the test system described in the previous subsection, nine operating conditions, described in Table 1, are identified as the probable ones and also in terms of their severity in exciting inter-area oscillations. In Table 1, CI represents constant impedance load, CC represents constant current load and CP represents constant power load. Linearised models corresponding to the nine operating conditions were generated for design and performance validation. There is always a possibility that scenarios other than those considered during the design might be encountered in practice. Hence, only six (Models. 1, 2, 4, 5, 8 and 9 in Table 1) randomly chosen operating conditions, including the nominal one (Model 1 in Table 1), are considered during design leaving the remaining three for robustness validation. These six operating conditions are marked in bold in Table 1.

3.3 Controller Design

The general methodology outlined in Section 2 is followed for the case study on this particular test system. The reference damping ratios for the three modes are chosen according to (2) to ensure a settling time of 10.0 s for each of them. Higher frequency modes thus require less damping and vice versa. For the frequencies, 0.4 Hz, 0.5 Hz and 0.62 Hz, the specified reference damping ratios ζ_{ref} are chosen as 0.16, 0.13 and 0.10, respectively, see (2).

The optimisation problem is solved using PSO algorithm described earlier in Section 2.4. Position of each particle is a vector consisting of the solution variables or the optimisation variables. In this exercise these are the three gains (K_1, K_2 and K_3) and the eighteen time-constants ($T_1, T_2, \dots, T_{18}$) for the lead-lag blocks, see Fig. 2. The position which gives the best value for the objective function is considered as the optimum solution and the gains and time constants are obtained from the global optimum position vector, G_{best} . Twenty-one solutions variables (18 time-constants + 3 gains) are chosen randomly for the first PSO iteration with the number of particles selected as 20. The maximum and minimum limits for velocities are chosen to be 10 and -10 and for position variables, they are chosen as 100 and 0.01. After 400 iterations the best fitness did not change significantly over the

subsequent iterations and the corresponding parameters are therefore, selected. Solution to this multi-objective constrained optimisation problem resulted in the controller parameters given in Table 2.

For certain lead-lag blocks, the time constants at the numerator and the denominator turned out to be identical (e.g. T_1 and T_2 ; T_5 and T_6 ; T_{13} and T_{14}) indicating the redundancy of these blocks. Thus, the algorithm automatically revealed the unnecessary blocks converging down to the minimum controller order required to achieve the design specifications. The resulting controller is shown in Fig. 3.

3.4 Computational effort

On an average, each optimal solution was found within 10-15 minutes on an Intel P5 3.2 GHz PC. But the computation time is not so important as the design is done offline. With increasing number of parameters, the population size would increase and so would the computational effort and time.

To find the convergence statistics, 20 trial runs were also performed with different initial random populations and the outcome is summarised in Table 3. The statistics show the consistency in convergence of the PSO for different initial populations. The consistency is not affected unless the number of parameters are too large.

3.5 Linear Analysis

The location of the open loop and closed loop poles (excluding the high frequency and the faster ones) are shown in Fig. 4 for one operating condition. The three critical poles are shifted to the left beyond the respective reference damping ratio lines with very little change in frequencies. The effect on the rest of the poles is insignificant. Also the additional poles introduced in the closed loop are all well damped.

Robustness of the designed controller is evaluated in terms of the damping ratio (ζ), frequency of oscillation (ω) and more importantly, the settling time (T_s) for individual modal oscillations under all the probable operating conditions listed in Table 1. The results, presented in the form of bar graphs in Figs. 5, 6, 7 and 8, are to be evaluated keeping the following design criteria in mind: individual modal oscillation should settle within 10.0 s

and frequency of oscillation should not change appreciably. It can be seen from Fig. 5 that in absence of any controller, the settling times for the three critical modes are higher than 10.0 s under all operating conditions.

The closed loop settling times, shown in Fig. 6, are within the specified 10.0 s target (except for a few little violations) indicated by the horizontal line indicating that the first design specification is met.

The range of variation of frequency is not appreciable; 0.05 Hz (0.38 - 0.43 Hz), 0.06 Hz (0.46 - 0.52 Hz) and 0.1 Hz (0.55 - 0.65 Hz) for modes 1, 2 and 3, respectively, as seen in Fig. 7. Although there is scope for improvement, it can be reasonably claimed that the 2nd specification is met. To achieve a minimum settling time, the damping ratios are obviously different for the three modes (different frequencies), as is expected from (2). For lower frequency modes (1st inter-area mode), the damping ratios are in general, higher and vice versa, as revealed in Fig. 8.

Above findings in frequency domain, based on the linearised models of the system around different operating conditions, demonstrate that the design specifications, stated earlier in Sections 2.1 and 3.3 have been achieved. The performance in presence of nonlinearities is presented through time domain simulation results in the next section.

3.6 Non-linear simulation

Non-linear simulations are carried out using Matlab Simulink for a range of contingencies to demonstrate the performance and robustness of the designed controller. Three-phase solid faults are simulated at different buses for 80 ms followed by outage of one of the adjacent lines. Critical tie-line outages between NYPS and NETS are considered due to their severity in terms of exciting inter-area oscillations. The simulation results are shown in Figs. 9 - 13.

For each figure, the two subplots on the top shows the angular separation between generators G1, G15 and G15, G13; the one on the bottom-left exhibits power flow in line 51-45 and the bottom-right one shows the variation in percentage compensation of the TCSC about its steady state setting of 50%. A comparison of the performance with $\mathcal{H}_\infty$ approach [10] (shown as grey line) against the proposed technique is presented for three line outage scenarios. It is seen that the proposed controller performs better compared to

$\mathcal{H}_\infty$ due to the less conservativeness of the former. Outage of lines 60-61 and 40-41 are intentionally left out during design for reasons described in Section 3.2. It is to be noted that in Fig. 11, a low-frequency mode is present in the closed loop which delays the approach to steady-state value. If the time scale is expanded this could be seen to happen at around 65 s. However, as the objective here is to illustrate settling of the oscillations over 10.0-15.0 s period, this expanded graphs are not shown.

Figs 9 - 11 show that oscillations settles within 10-12 s with the proposed controller whereas, they continue beyond 12.0 s with the $\mathcal{H}_\infty$ controller. This is due to violation of limits on compensation of TCSC, as evident from the bottom-right subplots. Conservativeness of the $\mathcal{H}_\infty$ controller, designed on the basis of a single (nominal) operating condition, demands more control effort resulting in these limit violations. Moreover, optimisation of average controller gain, through (5), enables the proposed controller to achieve the desired specification with lesser control effort.

To substantiate the claim of optimum control effort and less conservativeness, the performance of the designed controller is compared with the $\mathcal{H}_\infty$ controller with tighter limits (i.e. reduced dynamic rating) on the compensation of the TCSC, 20% - 70%. From Figs 12 and 13, it is evident that although the oscillations take slightly longer than 10-12 s to settle, the performance of the proposed controller (black line) is appreciably better than that of the $\mathcal{H}_\infty$ controller (grey line); the latter, due to reasons stated above, suffering from excessive limit violation. This confirms that the proposed control, considering multiple operating conditions, is less conservative and can potentially provide satisfactory performances with smaller dynamic ratings of FACTS devices unlike control designs based only on the nominal operating condition.

4 Conclusion

This paper demonstrates robust low order controller design for damping multi-modal oscillations using a single FACTS device. Ensuring a minimum settling time over a range of operating conditions with optimum control effort is considered as the design specification. These specifications are combined as a multi-objective parametric optimisation technique,

leading to a robust low order centralised MISO controller. A case study is carried out on the reduced equivalent of the New York-New England power system (from the seventies) to demonstrate the control design methodology and validate the performance and robustness. A comparison with the past results clearly demonstrates the less conservativeness of the proposed approach with respect to $\mathcal{H}_\infty$ control. Thus the proposed design produces the same level of performance with less dynamic range of the expensive FACTS devices.

The present exercise is a step forward towards the use of WAMS for closed-loop supplementary control (around the primary voltage and/or power flow control loop) of FACTS devices to improve the transfer capacity of the existing corridors. Further work is planned to design and simulate such controllers for large practical power systems and investigate the additional benefits over the existing controllers as benchmarks.

Acknowledgment

The authors are grateful to Dr Ganesh K Venayagamoorthy for parts of this work.

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Table 1 Probable operating conditions for the test system in Section 4.1. The ones marked in bold were considered during design leaving the rest for robustness validation.

Table 2 Gains and time-constants of the lead-lag blocks in Fig. 2 obtained from the PSO algorithm.

Table 3 Statistics of 20 PSO optimisation trials.

Figure 1 A reduced equivalent of the New England - New York interconnected power system with an installed TCSC.

Figure 2 General block diagram of n -input, 1-output controller

Figure 3 Simplified structure of the designed controller automatically achieved by the PSO algorithm. Three lead-lag blocks from Fig 2 turned out to be redundant. Parameters are listed in Table 2.

Figure 4 Location of the open loop and closed loop poles (excluding the high frequency and faster ones) under nominal operating condition. Movement of the critical poles from open loop to closed loop is marked.

Figure 5 Open loop settling time (in seconds) for the three (mode 1, mode 2 and mode 3) modal oscillations under different operating conditions. Settling times are well above the desired 10.0 s level.

Figure 6 Closed loop settling time (in seconds) for the three (mode 1, mode 2 and mode 3) modal oscillations under different operating conditions. Apart from a few close violations, settling time for most cases is below the specified limit of 10.0 s.

Figure 7 Frequency of oscillation (in Hz) for each inter-area mode (mode 1, mode 2 and mode 3) under different operating conditions. Range of variation of frequencies is 0.05 Hz, 0.06 Hz and 0.1 Hz for modes 1, 2 and 3, respectively.

Figure 8 Damping ratio for each inter-area mode (mode 1, mode 2 and mode 3) under different operating conditions. Damping ratios are in general, higher for lower frequency

modes to guarantee a minimum settling time as expected from (1).

Figure 9 Dynamic behaviour of the system following a fault at bus 60 for 80 ms and subsequent outage of line 60-61. Black line: response with proposed controller; Grey line: response with H-infinity control from [10].

Figure 10 Dynamic behaviour of the system following a fault at bus 53 for 80 ms and subsequent outage of line 53-54. Black line: response with proposed controller; Grey line: response with H-infinity control from [10].

Figure 11 Dynamic behaviour of the system following a fault at bus 40 for 80 ms and subsequent outage of line 40-41. Black line: response with proposed controller; Grey line: response with H-infinity control from [10].

Figure 12 Dynamic behaviour of the system following a fault at bus 53 for 80 ms and subsequent outage of line 53-54. *Dynamic range of the TCSC is reduced to 20% - 70%.* Black line: response with the proposed controller; Grey line: response with H-infinity control from [10].

Figure 13 Dynamic behaviour of the system following a fault at bus 60 for 80 ms and subsequent outage of line 60-61. *Dynamic range of the TCSC is reduced to 20% - 70%.* Black line: response with proposed controller; Grey line: response with H-infinity control from [10].

Table 1: Probable operating conditions for the test system in Section 3.1. The ones marked in bold were considered during design leaving the rest for robustness validation

No.	Tie-Line flow (MW)	Outage of line	Load Type
1	700	No outage	CI
2	700	53-54	CI
3	700	60-61	CI
4	700	27-53	CI
5	100	No outage	CI
6	900	No outage	CI
7	700	No outage	CI + CC
8	700	No outage	CI + CP
9	700	No outage	Dynamic

Table 2: Gains and time-constants of the lead-lag blocks in Fig. 2 obtained from the PSO algorithm

K_1	K_2	K_3	T_1	T_2	T_3	T_4
0.01	0.2781	0.2795	0.01	0.01	0.01	0.0154
T_5	T_6	T_7	T_8	T_9	T_{10}	T_{11}
0.01	0.01	0.01	0.4174	1.4325	0.3429	0.01
T_{12}	T_{13}	T_{14}	T_{15}	T_{16}	T_{17}	T_{18}
0.5799	0.01	0.01	0.01	0.4467	0.01	0.4819

Table 3: Statistics of 20 PSO optimisation trials

Best Fitness	Worst Fitness	Mean	Standard Deviation
1.1884	2.1425	1.6876	0.2677

Figure 3: Simplified structure of the designed controller automatically achieved by the PSO algorithm. Three lead-lag blocks from Fig 2 turned out to be redundant. Parameters are listed in Table 2

Figure 4: Location of the open loop and closed loop poles (excluding the high frequency and faster ones) under nominal operating condition. Movement of the critical poles from open loop to closed loop is marked

Figure 5: Open loop settling time (in seconds) for the three (mode 1, mode 2 and mode 3) modal oscillations under different operating conditions. Settling times are well above the desired 10.0 s level

Figure 6: Closed loop settling time (in seconds) for the three (mode 1, mode 2 and mode 3) modal oscillations under different operating conditions. Apart from a few close violations, settling time for most cases is below the specified limit of 10.0 s

Figure 7: Frequency of oscillation (in Hz) for each inter-area mode (mode 1, mode 2 and mode 3) under different operating conditions. Range of variation of frequencies is 0.05 Hz, 0.06 Hz and 0.1 Hz for modes 1,2 and 3, respectively

Figure 8: Damping ratio for each inter-area mode (mode 1, mode 2 and mode 3) under different operating conditions. Damping ratios are in general, higher for lower frequency modes to guarantee a minimum settling time as expected from (1)

Figure 9: Dynamic behaviour of the system following a fault at bus 60 for 80 ms and subsequent outage of line 60-61. Black line: response with proposed controller; Grey line: response with H-infinity control from [10]

Figure 10: Dynamic behaviour of the system following a fault at bus 53 for 80 ms and subsequent outage of line 53-54. Black line: response with proposed controller; Grey line: response with H-infinity control from [10]

Figure 11: Dynamic behaviour of the system following a fault at bus 40 for 80 ms and subsequent outage of line 40-41. Black line: response with proposed controller; Grey line: response with H-infinity control from [10]

Figure 12: Dynamic behaviour of the system following a fault at bus 53 for 80 ms and subsequent outage of line 53-54. *Dynamic range of the TCSC is reduced to 20% - 70%.* Black line: response with the proposed controller; Grey line: response with H-infinity control from [10]

Figure 13: Dynamic behaviour of the system following a fault at bus 60 for 80 ms and subsequent outage of line 60-61. *Dynamic range of the TCSC is reduced to 20% - 70%.* Black line: response with proposed controller; Grey line: response with H-infinity control from [10]