

## Interaction analysis of multifunction FACTS and D-FACTS controllers by MRGA

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**Abstract:** With the growing application of flexible AC transmission systems (FACTS) and distributed FACTS (D-FACTS), the coordinating problem of FACTS and D-FACTS controllers in joint operation must be considered in modern power systems. The main purpose of this paper is to investigate the possible interaction that may occur between the distributed static series compensator (DSSC) and the static synchronous compensator (STATCOM) when they operate concurrently in the power system. The modified relative gain array (MRGA) is implemented to analyze the interactions. The application of MRGA for the effective design of multiobjective controllers of the STATCOM and DSSC is demonstrated by 2 cases of study: the first case includes the contradiction among the AC voltage control, DC link capacitor voltage control, and power oscillation damping controller of the STATCOM, and the second case is dedicated to the interaction between the different controllers of the DSSC and the STATCOM. The simulation results are carried out in PSCAD/EMTDC in order to verify the results obtained from MRGA analysis in both cases of study.

**Key words:** Flexible AC transmission systems, distributed FACTS, static synchronous compensator, distributed static series compensator

### 1. Introduction

Transient dynamic stability is of increasing importance for the safe operation of power systems in a modern integrated power network. The flexible AC transmission system (FACTS) is a newly developed technology that can greatly improve the transient stability margin via appropriate control strategy [1–3]. In practical applications, several static synchronous compensators (STATCOMs) have been installed worldwide. Compared with the traditional reactive power compensation devices, the STATCOM has better dynamic response, large compensation range, less dependence on the system voltage, and low harmonic content.

Recently, a new concept from the family of distributed FACTS (D-FACTS) has been introduced as a way to offer all of the capabilities of their FACTS counterparts, but in a most efficient way. The distributed nature of the suggested system makes it possible to achieve fine granularity in the system rating. Furthermore, it is possible to expand the system with the growing demand [4–6]. The distributed static series compensator (DSSC), as a new D-FACTS device, is composed of a low-power single-phase inverter that attaches directly to the transmission line conductor [7]. It should be emphasized that in order to preserve the transmission system symmetry, all 3 phases of the line in question are identically equipped. The distributed nature of these devices enables a fine granularity in the system rating, which, in turn, makes it possible to boost the transmission system along with the growing demand. This opportunity grants a salient benefit in the system's planning since

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the increasing requirement for power transfer capabilities would gradually be satisfied by installing new DSSC modules in the most effective line(s).

In large interconnected networks, the placement of more than one FACTS device in some regions or electrical areas will be the natural consequence of the growing use of this technology. Furthermore, with improvement of D-FACTS devices, the deployment of D-FACTS and FACTS devices concurrently will be more beneficial in the power system's transient stability. The unique feature of these new-generation FACTS devices is their multiple control function. For instance, the DSSC has the primary duty of power flow control, but it can handle secondary duties such as subsynchronous oscillation damping and low frequency oscillation damping [8–10].

Aside from these merits cited above, the implementation of more than one FACTS device or multifunction FACTS controller may lead to adverse interactions. These interactions can occur in the following combinations [11]:

- Multiple FACTS controllers of a similar kind.
- Multiple FACTS controllers of diverse kinds.
- Multiple FACTS controllers and high-voltage DC controllers.

These different control interactions have been classified into 5 frequency ranges [11]:

- 0 Hz for steady-state interactions,
- 0–3 or 5 Hz for electromechanical oscillations,
- 2–15 Hz for small-signal or control oscillations,
- 10–50/60 Hz for subsynchronous resonance interactions,
- >15 Hz for electromagnetic transients, high-frequency resonance or harmonic resonance interactions, and network-resonance interactions.

There are many papers that have attempted to analyze the adverse interactions between FACTS controllers. For instance, Wang and Zhang et al. [12,13] demonstrated the interaction assessment of FACTS control using the relative gain array (RGA) method. Moreover, analysis of the interaction between the multiple control functions of the unified power flow controller was investigated in [14].

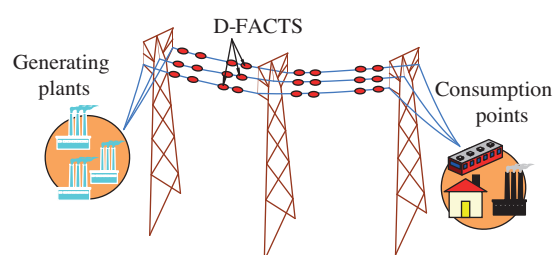
To the best of the authors' knowledge, this paper is the first attempt to study the interactions between a multiobjective static compensator (STATCOM) controller and a multiobjective DSSC controller. Furthermore, the high-frequency interactions as a result of exceeding the controller's gain are clarified in this paper, which was not addressed in other manuscripts. The modified RGA (MRGA) that was introduced in [14] is implemented to measure the interactions between the multiple control loops of the STATCOM and DSSC in order to design effective controllers. There are many other works that demonstrate the interaction of FACTS devices in power systems [15–18].

The main structure of this manuscript is as follows: Section 2 describes a brief introduction of the DSSC and its corresponding multiobjective controllers. The basic concept of the STATCOM with its normal and auxiliary controller is described in Section 3. In Section 4, the MRGA in a multiple-input, multiple-output (MIMO) system is introduced in order to measure the interaction among the different controllers of a power system. The simulation results are presented in Section 5. Finally, the conclusions are given in Section 6.

## 2. DSSC concept

The DSSC concept has been expressed based on FACTS devices, which is in fact a model of a static synchronous series compensator but in a smaller size, at a lower price, and with higher capability. For more safety and improvement in the controllability of power systems, it lies in the transfer lines in a distributed manner.

Figure 1 shows a conceptual schematic of the DSSC that is deployed in a power line so as to alter the power flow by changing the line impedance [7]. Each module is rated at about 10 KVA and is clamped on the line, floating electrically and mechanically on the line. Each module can be controlled so as to increase or decrease the impedance of the line, or to leave it unaltered. With a large number of modules operating together, it is possible to have a significant impact on the overall power flow in the line [7].



**Figure 1.** D-FACTS deployed on the power lines [7].

The low VA ratings of the modules are in line with those of mass manufactured power electronics systems in the industrial drives and uninterruptible power source markets, and this suggests that it would be possible to realize an extremely low cost. Finally, the use of a large number of modules results in high system reliability, as the system's operation is not compromised by the failure of a small number of modules [7].

A DSSC module, as shown in Figure 2, consists of a small rated (10 KVA) single-phase inverter and a single turn transformer (SST), along with the associated controls, power supply circuits, and built-in communications capability [19]. The system commands for gradual changes are received from a central control center using a wireless or power line communication technique [20]. The SST is a key component of the DSSC. It uses the transmission line conductor as a secondary winding and is designed with a high turn ratio, which reduces the current handled by the inverter and allows the use of commercial insulated-gate bipolar transistors (IGBTs) to realize a low cost [7]. The transformer core consists of 2 parts that can be physically clamped around a transmission line to form a complete magnetic circuit [21].

The module can either be suspended from the conductor or configured as a replacement for the conductor's support clamp on an insulator. Furthermore, since it does not require supporting phase-ground insulation, the module can easily be applied at any transmission voltage level. The mechanical form of the module may either clip onto the conductor or may be incorporated into the insulator suspension clamp, avoiding any concern about weight and conductor vibration damage [7].

### 2.1. DSSC normal control

The main task of the DSSC is to control the power flow in a transmission line. This objective can be achieved either by direct control, in which both the angular position and the magnitude of the output voltage are controlled, or by indirect control, in which only the angular position of the output voltage is controlled and the magnitude remains proportional to the DC terminal voltage [7].

The inverters, which are controlled in a direct mode, encounter more difficulty and require a higher cost to implement in comparison with indirectly controlled inverters. Moreover, in a direct control mode, the inverter function is usually associated with some drawbacks in terms of increased losses, greater circuit complexity, and increased harmonic content in the output; hence, the control structure used for the DSSC in this model is based on indirect control. Figure 3 shows an indirect control schematic of a DSSC module.

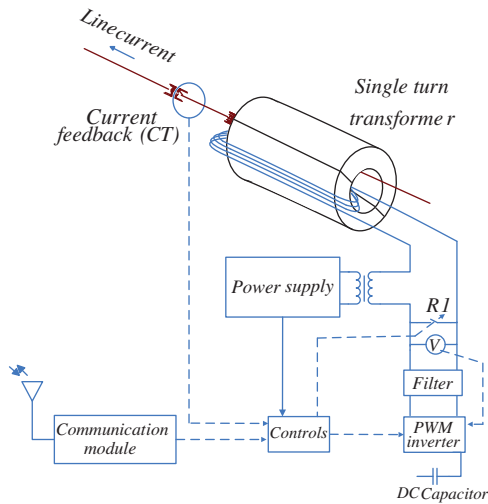


Figure 2. Circuit schematic of a DSSC module.

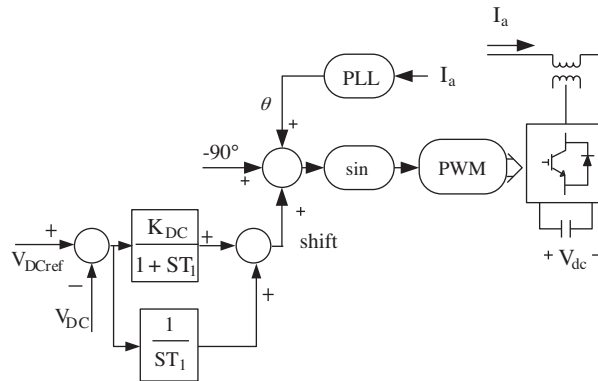


Figure 3. Indirect control of the DSSC.

Here, the controller is used to retain the charge on the DC bus capacitor and to inject a synchronous voltage that is orthogonal to the line current. In order to control the DC capacitor voltage, a small displacement ‘e’, beyond the required  $90^\circ$ , between the injected voltage and the line current, is required as a control signal. The phase-locked loop is used to provide the basic synchronization signal, ‘ $\theta$ ’, which is the phase angle of the line current. The error signal that is obtained by comparing  $V_{dc}$  with  $V_{dcref}$  is passed through a proportional-integral (PI) controller and the result will be the required phase angle displacement ‘e’. Detailed information for the DSSC power circuit is presented in Appendix A.

**2.2. DSSC enhanced with a damping controller.**

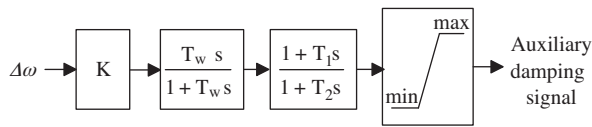
Introducing the DSSC controller at a proper location by itself does not provide the essential damping, as the primary task of the DSSC is to control the power flow in the system. In order to provide an effective damping of the low-frequency oscillations (LFOs), it is necessary to apply the coordinating tuning of the DSSC with an auxiliary LFO damping controller. Figure 4 displays the auxiliary LFO damping controller structure. It is composed of a gain block, a washout filter, and a lead-lag compensator. For the LFO auxiliary controller,  $\Delta\omega$  denotes the rotor speed deviation, which is adopted as the feedback input signal, whereas other measurable signals, such as the bus frequency and the bus voltage magnitude, have been selected in other works [3,11]. The output of the LFO damping controller is utilized to modulate the  $V_{DCref}$  to yield the proper damping of oscillations.

The damping controller is designed so as to provide an extra electrical torque in phase with the speed deviation in order to enhance the damping of oscillations. The gain setting of the damping controller is adopted so as to achieve the desired damping ratio of the electromechanical oscillations.

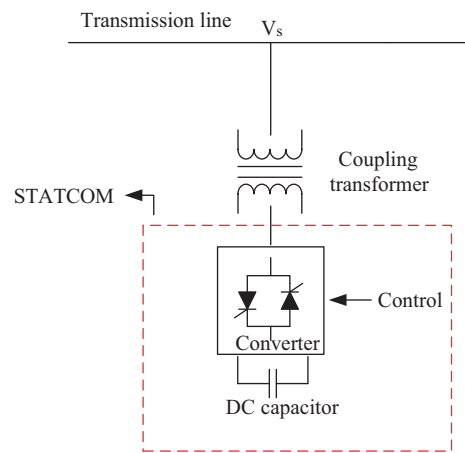
**3. Description of the STATCOM structure.**

The STATCOM is a well-known shunt-connected FACTS device based on a voltage source converter (VSC). As illustrated in Figure 5a, the typical STATCOM is realized with a 3-phase VSC, a DC link capacitor, and an interfacing transformer. Moreover, a filtering stage (not shown) is considered at the output of the VSC to alleviate the harmonic pollution in the injected voltage [11].

The STATCOM is capable of generating or absorbing the reactive power. By varying the amplitude of the produced output voltages, the reactive power exchange between the converter and the AC system can be controlled; hence, it gives the opportunity to control some specific parameters (e.g., voltage) of an electric power system. To address this in more detail, the STATCOM’s main task is to control the voltage dynamically. However, it is commonly expected to yield some ancillary duties, such as power oscillation damping, transient stability enhancement, or voltage flicker control.



**Figure 4.** Auxiliary LFO damping controller structure.



**Figure 5.** Basic diagram of the STATCOM.

**3.1. STATCOM control**

**3.1.1. Normal operation**

In normal operation, the STATCOM has 2 controllers: an AC bus controller and a DC link controller. The AC bus controller aims to control the AC bus voltage that the STATCOM is installed on. It usually consists of a PI controller that compares the measured bus voltage with the reference value in order to create an error. The error signal is then amplified in a PI controller in order to create the control signal. Figure 6 depicts the AC bus voltage controller that is granted to the STATCOM.

The DC link voltage controller has the duty of keeping the DC link voltage fixed. It usually consists of a PI controller. The measured DC link voltage is compared with its reference value to create an error. The error is then sent to a PI controller in order to create a control signal. This control schematic is demonstrated in Figure 7.

**3.1.2. STATCOM with a damping controller**

Just as with the DSSC, the STATCOM controller at a proper location by itself does not provide the essential damping, as the primary task of the STATCOM is to control the bus voltage. In order to provide an effective damping of the LFOs, it is necessary to apply the coordinating tuning of the STATCOM with an auxiliary LFO damping controller. Figure 4 displays the auxiliary LFO damping controller structure for the STATCOM, which

is formerly used for DSSC. The output of the LFO damping controller is utilized to modulate the  $\delta_{ref}$  (output of the DC controller) to yield the proper damping of oscillations. The parameters of the damping controllers for the DSSC and STATCOM are yielded through the trial and error method in order to result in the convenient damping characteristics of both the DSSC and STATCOM damping controllers. It should be mentioned that the first guess of the parameters was available for obtaining the parameters from previously published papers in the other literature [10], and with some modifications, the final parameters for this investigation were obtained. The detailed data for the LFO damping controllers for both the DSSC and the STATCOM are presented in Appendix B.

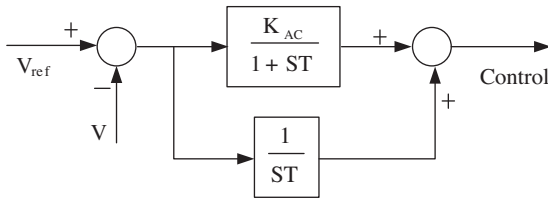


Figure 6. AC bus controller of the STATCOM.

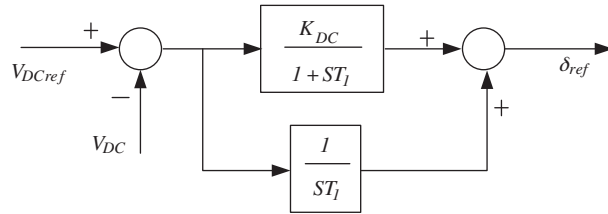


Figure 7. DC link voltage controller of the STATCOM.

4. MRGA method

The RGA that was introduced in [14] is a numerical index in order to measure the interactions between multiple control loops in MIMO systems. Figure 8 shows the basic structure of the MIMO system. The RGA allows for matching up the input-output variables that have the biggest effect on each other without having an undesirable impact on the others [14].

The relative gain  $\lambda_{ij}$  for an input  $u_j$  and output  $y_i$  is defined by the ratio of the uncontrolled gain and the controlled gain, as expressed in Eq. (1) [14]:

$$\lambda_{ij} = \frac{\frac{\partial \lambda_i}{\partial u_j} | (all\ loops\ off)}{\frac{\partial \lambda_i}{\partial u_j} | (all\ loops\ but\ y_i - u_j\ perfect)} \tag{1}$$

The uncontrolled gain is the gain between the input  $u_j$  and the output  $y_i$  in a condition in which all of the outputs have no control loop. The controlled gain is the gain between input  $u_j$  and output  $y_i$  when perfect controls are performed on the rest of the outputs, as demonstrated in Figure 9.

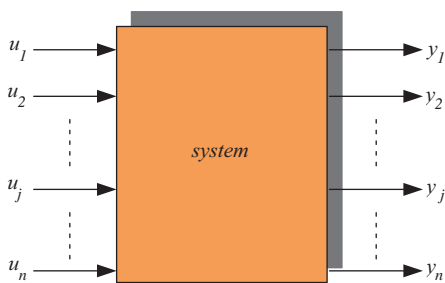


Figure 8. MIMO system.

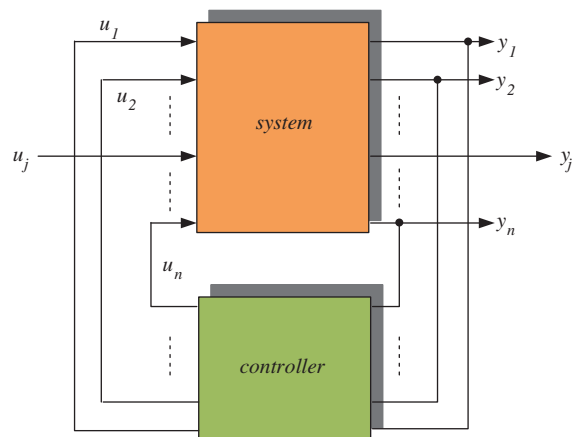


Figure 9. The RGA definition.

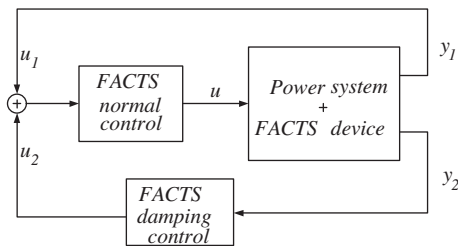
If  $\lambda_{ij} = 1$ , it means that the uncontrolled gain and controlled gain are identical. In other words, the interaction does not affect the pairing of the input  $u_j$  and the output  $y_i$ . As  $\lambda_{ij}$  is closer to unity, there are fewer interactions in the control pair:  $y_i-u_j$ . The worst case occurs when  $\lambda_{ij}$  is much greater than or much less than unity. It means that the system is faced with serious interactions.

The RGA ( $n \times n$ ) for all of the relative gains,  $\lambda_{ij}$ , which are formed from multiple control loops, can be driven by the following equation [14]:

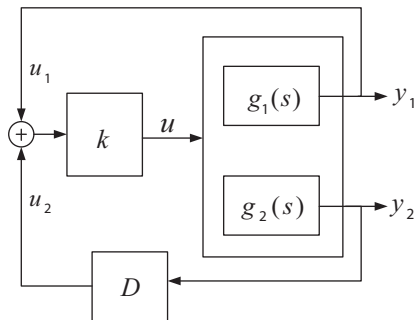
$$\square RGA = G(0) \otimes (G(0)^{-1})^T, \tag{2}$$

where  $G(s)$  is the transfer function matrix of the control system,  $\otimes$  denotes the element-by-element multiplication of the matrices, and the superscript  $T$  stands for the transpose operation of the matrix.

Figure 10 demonstrates the block diagram of the power system aggregated with a multifunction FACTS controller. The FACTS device has a normal control function considering the kind of FACTS device that will operate in order to control the power flow, voltage, etc. The FACTS controller can also be enhanced with another controller (for example, damping control) that will be superimposed onto the normal control function. Figure 11 is a summarized version of Figure 10 with some simple assumptions [14].



**Figure 10.** Power system aggregated with a multifunction FACTS controller.



**Figure 11.** Simplified block diagram of a FACTS controller with a damping controller.

According to the RGA analysis, which is driven by Eq. (1), the interaction by the FACTS normal control on its damping control is:

$$\lambda_{12} = \frac{y_2 | (all\ loops\ of\ f)}{y_2 | (loop\ y_1 - u_1\ closed)}, \tag{3}$$

where  $\lambda_{12} = 1$  is the best condition, which means that the FACTS' normal control has no effect on its damping controller. Similarly, the interaction caused by the FACTS' damping controller on its normal controller can be expressed by:

$$\lambda_{21} = \frac{y_1 | (all\ loops\ of\ f)}{y_1 | (loop\ y_2 - u_2\ closed)}. \tag{4}$$

Now, from Figure 11, in order to simplify Eqs. (3) and (4), it is observed that:

$$y_1 | (all\ loops\ of\ f) = K g_1(s) u_1, \tag{5}$$

$$y_2 | (all\ loops\ of\ f) = K g_2(s) u_2, \tag{6}$$

$$y_1 | (loops\ y_2 - u_2\ closed) = K g_1(s) (u_1 + D y_2), \tag{7}$$

$$y_2|(loops\ y_1-u_1\ closed) = Kg_2(s)(u_1+u_2), \tag{8}$$

$$y_2|(loops\ y_2-u_2\ closed) = Kg_2(s)(u_1+Dy_2) = \frac{Kg_2(s)u_1}{1-kDg_2(s)}, \tag{9}$$

$$y_1|(loops\ y_1-u_1\ closed) = Kg_1(s)(u_1+u_2) = \frac{Kg_1(s)u_2}{1-kg_1(s)}, \tag{10}$$

$$y_1|(loops\ y_2-u_2\ closed) = Kg_1(s)\left(u_1 + \frac{DKg_2(s)u_1}{1-kDg_2(s)}\right) = \frac{Kg_1(s)u_1}{1-kDg_2(s)}. \tag{11}$$

By substituting Eq. (10) into Eq. (8):

$$y_2|(loops\ y_1-u_1\ closed) = Kg_2(s)\left(\frac{Kg_1(s)u_2}{1-kg_1(s)} + u_2\right) = \frac{Kg_2(s)u_2}{1-kg_1(s)}. \tag{12}$$

Finally, from Eqs. (3), (6), and (12):

$$\lambda_{12} = 1 - kg_1(s), \tag{13}$$

and from Eqs. (4), (5), and (11):

$$\lambda_{21} = 1 - kDg_2(s). \tag{14}$$

The above definitions describe the MRGA that is given by Eqs. (13) and (14). For any power system, these equations can be comprehended in order to gain the interaction between the different controllers of the power system. This value should be taken into account when designing multifunction controllers.

#### 4.1. Implementation of the MRGA for the STATCOM case

In order to evaluate the RGA for the interaction analysis, the power system combined with a STATCOM is assumed. The investigated system is a single machine system that is connected to an infinite bus through 2 parallel transmission lines. The STATCOM is enhanced with a LFO damping controller. Figure 12 exhibits the control block diagram for the RGA analysis. The STATCOM damping controller is superimposed on the DC controller, which is the best case of damping. To achieve an effective design of the damping controller parameters, the interactions posed by alternating the gains of the DC and AC controllers can be examined by calculating the MRGA as proposed in Eqs. (13) and (14). The results of the RGA calculation are demonstrated in Table 1.

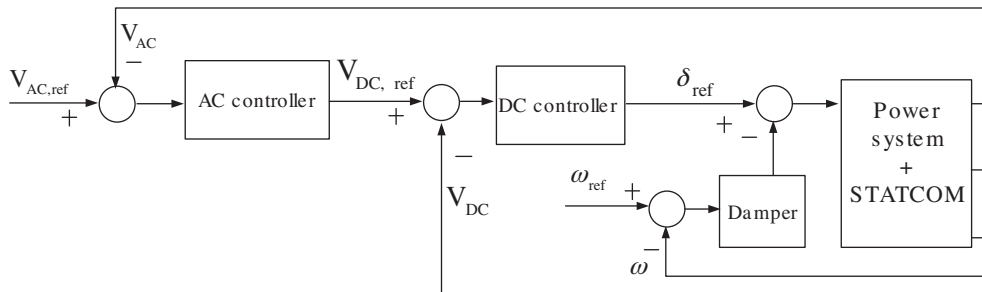


Figure 12. Implementation of the STATCOM in the RGA analysis.



The interactions between the different controllers shown in Figure 12 are measured by changing the gain values of each controller in order to achieve the best gain value, as depicted in Table 1. It should be noted that, to damp the power-system electromechanical oscillations, a damping controller is superimposed on the DC controller of the STATCOM in order to yield the best damping performance.

**Table 1.** The interaction calculated by the MRGA between the STATCOM controllers.

Gain of the DC controller in the STATCOM	Interaction caused by the DC voltage controller on the AC voltage controller
$K_{dc} = 1$	1.023
$K_{dc} = 3$	5.248
$K_{dc} = 6$	17.854
Gain of the DC controller in the STATCOM	Interaction caused by the DC voltage controller on the damping controller
$K_{dc} = 1$	1.877
$K_{dc} = 3$	8.452
$K_{dc} = 6$	21.076
Gain of the AC controller in the STATCOM	Interaction caused by the AC voltage controller on the damping controller
$K_{ac} = 1$	2.107
$K_{ac} = 2$	9.726
$K_{ac} = 4$	18.844

From Table 1, the interactions between the STATCOM DC voltage controller, AC voltage controller, and damping controller are not significant when the gain value of each controller is set to unity. In contrast, by increasing the gain settings of each controller, the interaction will be deteriorated. For example, if the gain of the DC controller of the STATCOM is set to 1, the interaction caused by the DC voltage controller of the STATCOM on its damping controller is 1.877, which is very close to unity and verifies that there is less interaction between the DC voltage controller and the damping controller of the STATCOM. Furthermore, this interaction is 21.076 if the gain of the DC controller in the STATCOM is set to 6, which is fairly large.

#### 4.2. Implementation of the MRGA for the STATCOM and DSSC case

Now, consider a condition in which both the DSSC and the STATCOM are operating in a power system. In this condition, the main duty of the DSSC is to control the power flow in the transmission line, and it can also suppress the interarea oscillation with a supplementary damping controller. In contrast, the STATCOM is operating to regulate the AC bus voltage, and it can also damp the local mode oscillations with an auxiliary damping controller. Hence, if the settings of these devices are not tuned properly, the interactions will be unavoidable. In this part, in order to evaluate the RGA for the interaction analysis, a 4-machine power system combined with the DSSC and STATCOM is assumed [22]. Both the DSSC and the STATCOM are enhanced with LFO damping controllers. Figure 13 exhibits the control block diagram of this case for the RGA analysis. The DSSC and STATCOM damping controllers are superimposed on the DC controller of each device, which is the best case of damping. To achieve an effective design of the damping controller parameters, the interactions posed by alternating the gains of the DC and AC controllers can be examined by calculating the MRGA, as proposed in Eqs. (13) and (14). The results of the RGA calculation are demonstrated in Table 2.

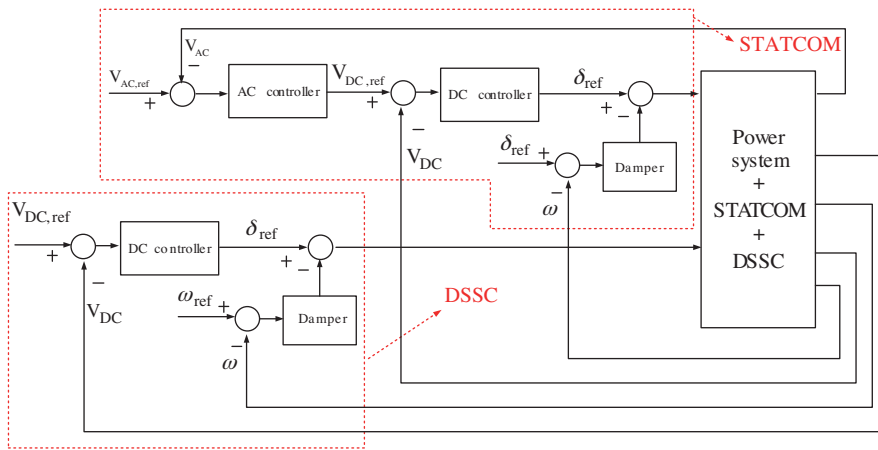


Figure 13. Implementation of the DSSC and STATCOM in the RGA analysis.

Similar to the previous part, Table 2 reveals that with an increase in the gain of each controller in the STATCOM and DSSC, the interaction between each controller of each device on the controller of another device will be deteriorated. For example, if the gain of the DC controller in the DSSC is set to 1, there is no interaction between the DSSC DC voltage controller and the STATCOM AC voltage controller, because the interaction is close to unity. In contrast, if the gain of the DC controller in the DSSC is set to 6, the interaction caused by the DC voltage controller of the DSSC on the AC voltage controller of the STATCOM is significant, because the interaction is much greater than unity.

Table 2. The interaction calculated by the MRGA between the DSSC and STATCOM controllers.

Gain of the DC controller in the DSSC	Interaction caused by the DC voltage controller of the DSSC on the AC voltage controller of the STATCOM
$K_{dc} = 1$	1.308
$K_{dc} = 6$	3.638
Gain of the DC controller in the STATCOM	Interaction caused by the DC voltage controller of the STATCOM on the damping controller of the DSSC
$K_{dc} = 1$	1.483
$K_{dc} = 6$	14.372

## 5. Simulation results

In this section, 2 cases of study are included in order to precisely investigate the interaction analysis. In the first case, the STATCOM is installed on a single machine power system and the interaction between its controllers is proposed. The second case is dedicated to the interaction analysis between the STATCOM and DSSC controllers in a 4-machine power system. As was earlier described in Section 1, interactions occur between the multiple controllers of the FACTS devices, or between the controllers of the FACTS and D-FACTS devices. These interactions are mainly related to steady-state conditions, and the dynamics of each controller has no effect on these interactions.

### 5.1. STATCOM case

Figure 14 demonstrates a power system aggregated with a STATCOM on the middle of the transmission line, L2. The STATCOM parameters are given in Appendix C. It is observed that the power system consists of 2 parallel transmission lines in order to transmit the power generated by a generator into an infinite bus.

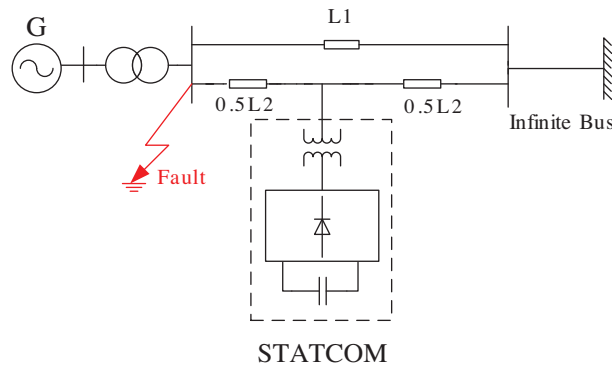


Figure 14. Power system for the STATCOM interaction analysis.

**5.1.1. Adverse interaction of the DC controller on the AC controller of the STATCOM**

In this section, in order to precisely evaluate the interaction of the DC voltage controller on the AC voltage controller, the gain of the DC controller of the STATCOM is varied from 1 to 10, and the results are shown in Figure 15. It is observed from Figure 15 that, before the STATCOM operation ( $t = 2$  s), the STATCOM’s corresponding bus voltage was 0.9825 pu, but after a while, the STATCOM began to fix the bus voltage up to 1 pu. Moreover, there is a transient state before the voltage fixing. This transient state is greatly dependent on the parameters of the STATCOM controller. By gradually increasing the  $K_{dc}$  of the STATCOM DC controller, more interaction is experienced between the DC controller and the AC controller. In a technical expression, by increasing  $K_{dc}$  from 1 to 10, the dynamic response of the AC controller deteriorates, as was earlier concluded by the RGA analysis in Table 1.

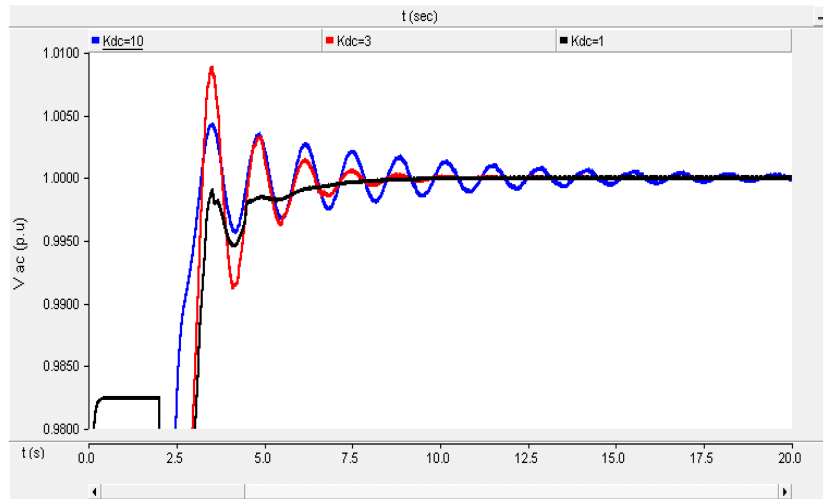


Figure 15. Interaction of the STATCOM DC controller on its AC controller.

**5.1.2. Adverse interaction of the STATCOM DC voltage controller on the LFO damping controller**

In this section, the impact of the DC controller on the LFO damping controller is investigated. It should be noted that for LFO to happen, a 3-phase-to-ground fault will occur at 20 s and it will be removed after 100 ms. The 3 cases are assumed to be the same as in the last section: the gain of the DC controller of the STATCOM is varied from 1 to 10, and the interaction caused by the DC controller of the STATCOM on the damping

controller is revealed in Figure 16. It is observed that the interactions are prone to deteriorate as the  $K_{dc}$  of the DC voltage controller increases. By selecting  $K_{dc}=10$ , the oscillations are increased and more time is needed for the system to recover to normal conditions.

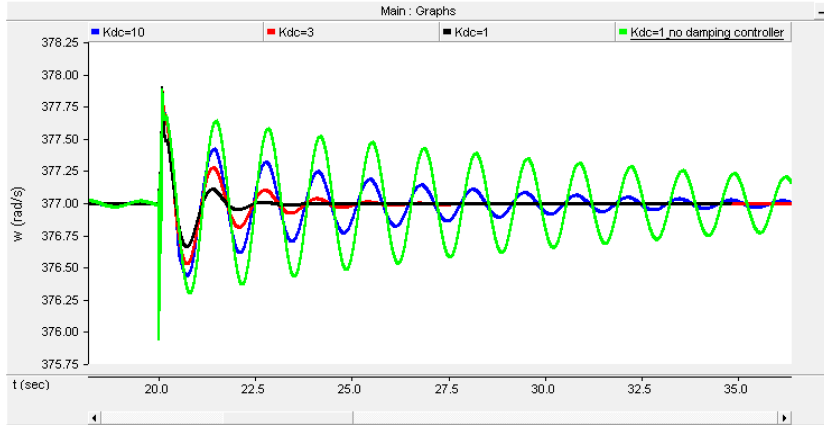


Figure 16. Interaction of the STATCOM DC controller on its damping controller.

**5.1.3. Unfavorable interaction of the AC voltage controller on the LFO damping controller**

In this section, the gain of the AC voltage controller plays an important role in the interactions between the AC voltage controller and the LFO damping controller. As  $K_{ac}$  is exceeded, large oscillations will be experienced. Figure 17 depicts this condition. As was earlier cited in Section 2, the control interaction between the individual FACTS controllers and the network or between the different FACTS controllers may lead to the onset of oscillations in the range of 2–15 Hz. These oscillations are largely dependent on the system’s strength and the choice of FACTS controllers, and they are significantly dependent on the controller gains.

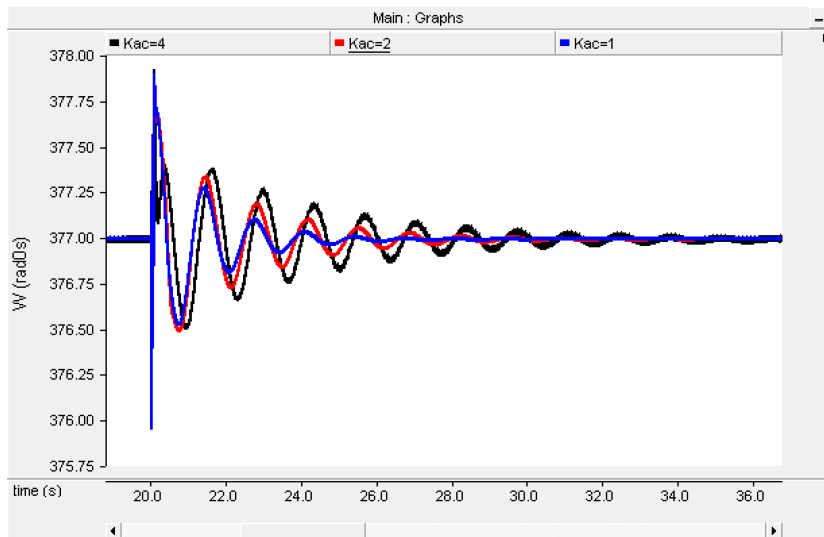


Figure 17. Interaction of the STATCOM AC controller on its damping controller.

Figure 17 reveals that with  $K_{ac} = 4$ , the power system will face large oscillations. Now assume that  $K_{ac}= 6$  to evaluate the small signal interaction, as depicted in Figure 18. It is observed that amplifying

$K_{ac}$  up to 6 leads to small signal interactions with a high frequency of 20 Hz. These interactions occur abruptly when the STATCOM operates.

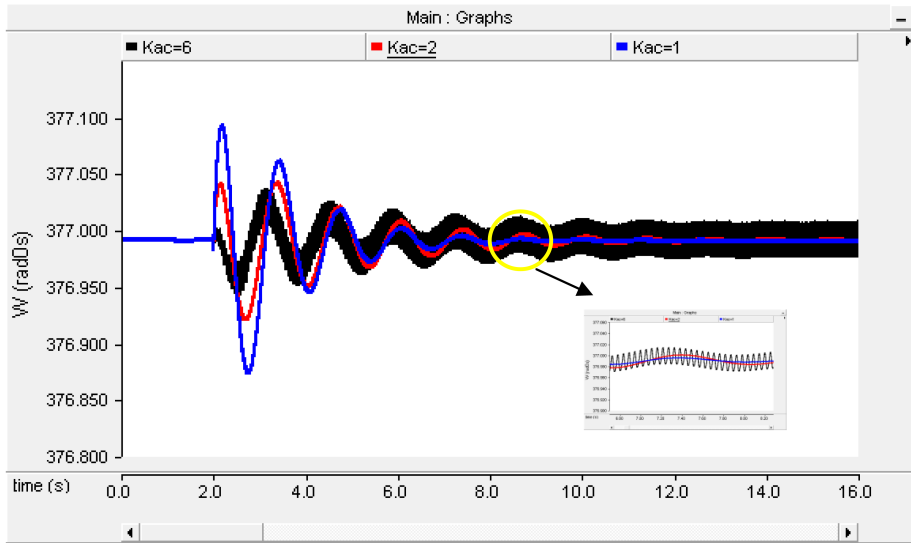


Figure 18. Interaction of the STATCOM AC controller on its damping controller.

### 5.2. DSSC case

In this part, in order to investigate the interaction between the DSSC and the STATCOM, a 4-machine power system is considered. In the following, a STATCOM as a member of the FACTS family and a DSSC as a member of the D-FACTS family are added to the system. Figure 19 shows this 4-machine power system [22] aggregated with the DSSC and STATCOM. As it is revealed, the system has 11 buses, which are separated into 2 areas. These 2 areas are linked together with 2 parallel transmission lines. The STATCOM is connected in the middle of the 2 areas in bus 8, and the DSSCs are distributed equally in the 2 parallel transmission lines. For the LFO analysis, a 3-phase-to-ground fault occurs at 55 s and is removed after 100 ms.

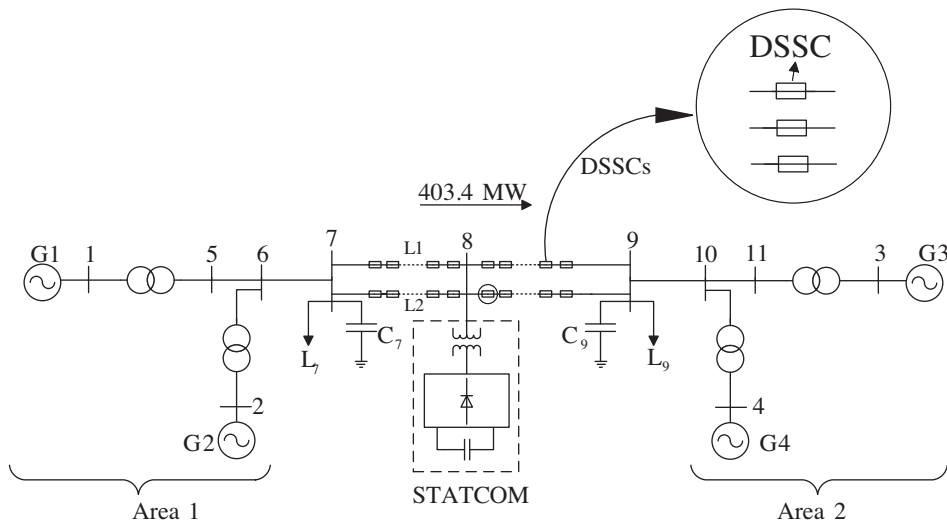
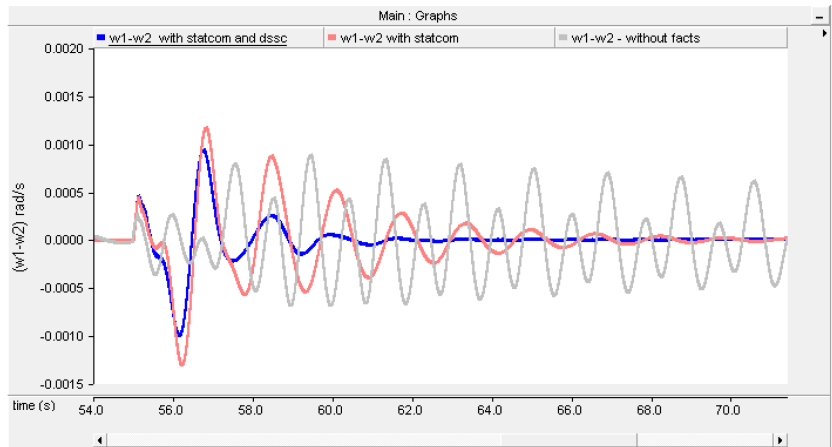


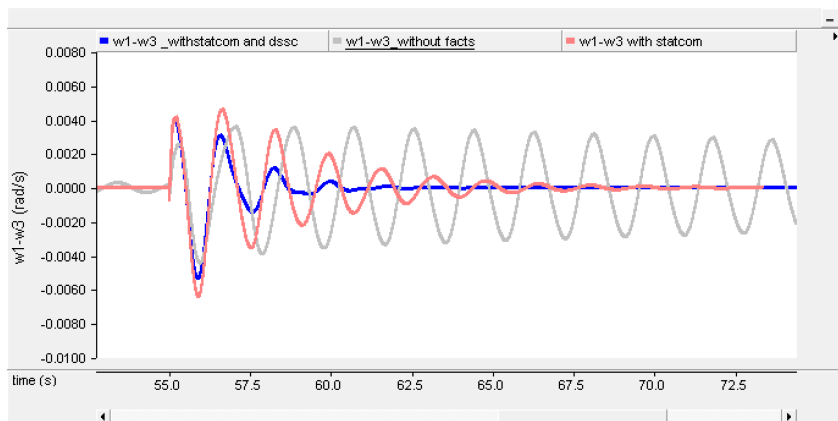
Figure 19. The power system investigated for the interaction of the DSSC and the STATCOM.

In this power system, the main duty of the STATCOM is to control the AC bus voltage (bus 8) and to damp the local mode oscillations with an auxiliary supplementary damping controller. In addition, the main duty of the DSSCs is to control the power flow in the 2 parallel transmission lines and to control the interarea mode oscillations with an auxiliary supplementary damping controller. In this section, the ability of both the DSSC and STATCOM to mitigate local and interarea mode oscillations is examined when they are operating concurrently in a power system. Hence, both the DSSC and STATCOM have separate supplementary controllers, the input signal for the DSSC damping controller is  $(\omega_1 - \omega_3)$ , which is referred to as the interarea mode oscillation, and the input signal for the STATCOM damping controller is  $(\omega_1 - \omega_2)$ , which is referred to as the local mode oscillation. The impact of operation of both the DSSC and STATCOM concurrently, are revealed in the simulation results below.



**Figure 20.** The local mode oscillations when both the DSSC and STATCOM operate.

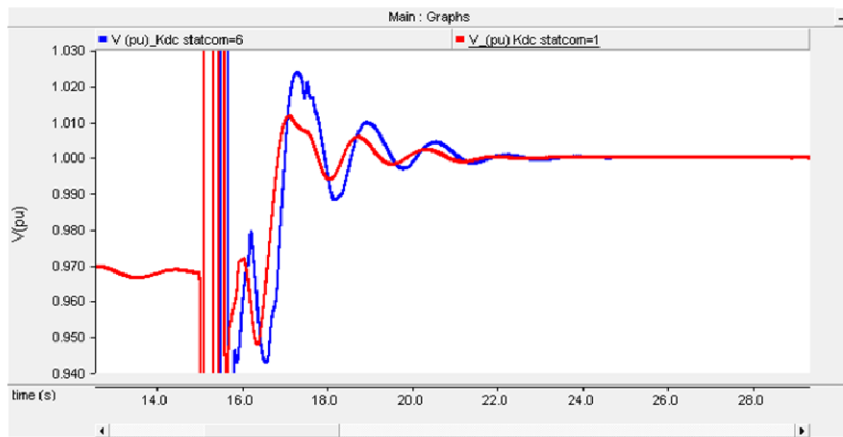
Figure 20 illustrates the local mode oscillations  $(\omega_1 - \omega_2)$  in the 3 cases of the study. In the first case, there is no DSSC or STATCOM in the power system; the second case is dedicated to enhancing the STATCOM with a supplementary controller; and in the third case, both the STATCOM and DSSC are enhanced with supplementary controllers. As depicted in Figure 20, when there is no supplementary controller, the local mode experiences large oscillations, but when the STATCOM is enhanced with a damping controller, the oscillations



**Figure 21.** The interarea mode oscillations when both the DSSC and the STATCOM operate.

decrease after a short interval of time. The superior performance for the local mode damping is achieved when both the DSSC and STATCOM are supplemented with auxiliary controllers. This verifies that operation of both the STATCOM and DSSC in the power system provides many advantages in the dynamic stability of the system.

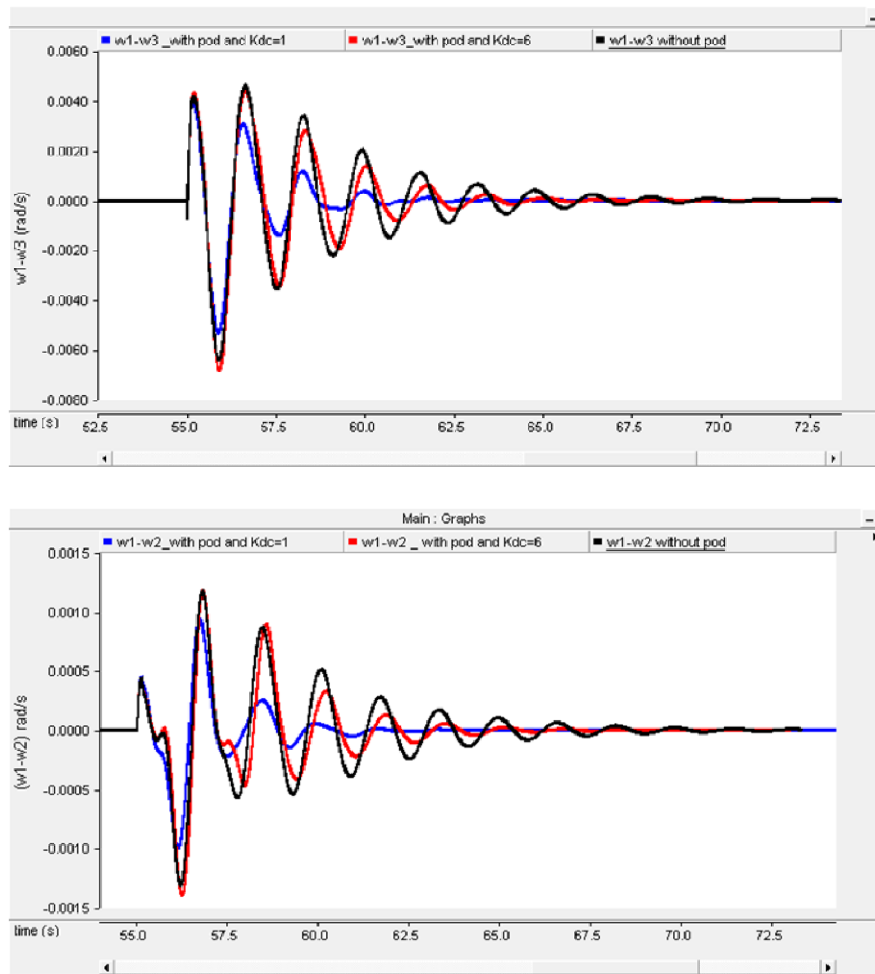
Similar simulations are carried out for interarea mode oscillations in 3 cases in Figure 21. In the first case, the system is simulated without a DSSC or STATCOM; in the second case, the DSSCs are enhanced with a supplementary controller; and the third case is dedicated to the operation of the DSSCs and STATCOM with supplementary damping controllers. It is revealed that the worst case is when there is no DSSC or STATCOM. In this case, large oscillations will be experienced for the interarea mode. Moreover, when the DSSCs are enhanced with a damping controller, the oscillations will be suppressed after a few seconds. Furthermore, the oscillations are damped greatly when both the DSSC and STATCOM are enhanced with damping controllers.



**Figure 22.** Impact of the STATCOM DC controller on the STATCOM AC controller.

In this part, the adverse interaction between the different controllers of the DSSC and STATCOM is investigated. To achieve this goal, first, the impact of the gain of the STATCOM DC controller on the AC voltage controller of the STATCOM is clarified. The gain value of the DC controller in the STATCOM has changed from 1 to 6, as depicted in Figure 22. Before the STATCOM's operation, the AC bus voltage was 0.97 pu, but after the operation of the STATCOM, it is fixed at 1 pu, and it has a transient state before fixing its voltage. It is revealed from Figure 22 that, with the increasing of the gain of the DC controller in the STATCOM, the AC controller of the STATCOM gradually becomes unstable, and it experiences more oscillations before fixing the AC bus voltage.

Figure 23a shows the impact of the gain of the STATCOM DC controller on the DSSC damping controller in the interarea damping mode, and Figure 23b shows the impact of the gain of the STATCOM DC controller on the DSSC damping controller in the local oscillation damping mode. It is revealed that, for both the interarea and local mode oscillations, when the gain of the STATCOM DC controller is varied from 1 to 6, the operation of the DSSC damping controller is deteriorated, and there is more time needed for damping the oscillations.



**Figure 23.** a) The impact of the gain of the STATCOM DC controller on the interarea mode oscillations; b) the impact of the gain of the STATCOM DC controller on the local mode oscillations.

## 6. Conclusion

In this paper, the adverse interaction between the STATCOM as a member of the FACTS family and the DSSC as a member of the D-FACTS device is investigated. The MRGA is used to analyze the interaction between the multiple controllers of the STATCOM and DSSC. The analysis is separated into 2 different parts. First of all, the interaction among the different controllers of the STATCOM, including the AC controller, DC controller, and auxiliary damping controller, is investigated. From the MRGA analysis and simulation results, it is revealed that with the increasing of the gains of the different controllers, the interactions will be deteriorated. In the second part, both the DSSC and the STATCOM are linked to the power system and they are enhanced with 2 auxiliary damping controllers. The DSSCs are used to damp the interarea mode and the STATCOM is utilized to mitigate the local mode oscillations. The results reveal that the operation of both the DSSC and the STATCOM concurrently will improve the damping of the local and area mode in the system. Furthermore, it should be noted that increasing the gains of the STATCOM AC or damping controllers will deteriorate the operation of the DSSC controllers. The same results will be obtained if the gain settings of the DSSC controllers increase, where the operation of the STATCOM controllers will deteriorate.



**Appendix A.** Specification of the DSSC.

Transformer	1/75
Inverters (single phase PWM inverter)	Power rating: 10 KVA Power devices: IGBT PWM carrier frequency: 12 kHz
Capacity of the DC side	2.1 mF
Filter	
Cut-off frequency	375 Hz
L	1.8 mH
C	200 $\mu$ F

**Appendix B.** Parameters.

LFO damping controller parameters for the DSSC:  $G = 0.04$ ,  $T_w = 10$ ,  $T_1 = 0.001$ ,  $T_2 = 0.01$ .

Max limit = 10, Min limit = -10.

LFO damping controller parameters for the STATCOM:  $G = 0.04$ ,  $T_w = 10$ ,  $T_1 = 0.04$ ,  $T_2 = 0.14$ .

Max Limit = 10, Min Limit = -10.

**Appendix C.** STATCOM data.

Rated power = 100 MVA, rated voltage = 26 KV,

frequency = 60 Hz,  $X_T(\text{sh}) = 0.1$  pu, and switching frequency = 15 KHz.

**References**

- [1] R.K. Varma, S. Auddy, Y. Semsedini, "Mitigation of sub-synchronous resonance in a series compensated wind farm using FACTS controllers", *IEEE Transactions on Power Delivery*, Vol. 23, pp. 1645–1654, 2008.
- [2] F.D. de Jesus, E.H. Watanabe, L.F.W. de Souza, J.E.R. Alves, "SSR and power oscillation damping using gate-controlled series capacitors (GCSC)", *IEEE Transactions on Power Delivery*, Vol. 22, pp. 1806–1812, 2007.
- [3] N.G. Hingorani, L. Gyugyi, *Understanding FACTS: Concepts and Technology of Flexible AC Transmission System*, New York, IEEE Press, 2000.
- [4] D. Divan, W. Brumsickle, R. Schneider, B. Kranz, R. Gascoigne, D. Bradshaw, M. Ingram, I. Grant, "A distributed static series compensator system for realizing active power flow control on existing power lines", *IEEE Transactions on Power Delivery*, Vol. 22, pp. 642–649, 2006.
- [5] D. Divan, "Improving power line utilization and performance with D-FACTS devices", *IEEE Power Engineering Society General Meeting*, Vol. 3, pp. 2419–2422, 2005.
- [6] H. Johal, D. Divan, "Design considerations for series-connected distributed FACTS converters", *IEEE Transactions on Industry Applications*, Vol. 43, pp. 1609–1618, 2007.
- [7] P. Fajri, D. Nazarpour, S. Afsharnia, "A PSCAD/EMTDC Model for distributed static series compensator (DSSC)", *International Conference on Electrical Engineering*, pp. 1–6, 2008.
- [8] M. Khalilian, M. Mokhtari, D. Nazarpour, B. Tousi, "Transient stability enhancement by DSSC with a fuzzy supplementary controller", *Journal of Electrical Engineering & Technology*, Vol. 5, pp. 415–422, 2010.

- [9] M. Mokhtari, M. Khalilian, D. Nazarpour, "Damping of low frequency oscillations in power system with distributed static series compensator (DSSC)", *International Review on Modeling and Simulation*, Vol. 2, pp. 507–512, 2009.
- [10] M. Khalilian, M. Mokhtari, S. Golshannavaz, D. Nazarpour, "Distributed static series compensator (DSSC) for sub-synchronous resonance alleviation and power oscillation damping", *European Transactions on Electrical Power*, Vol. 22, pp. 589–600, 2011.
- [11] R.M. Mathur, R.K. Varma, *Thyristor-Based FACTS Controllers for Electrical Transmission Systems*, New York, IEEE Press and Wiley Interscience, 2002.
- [12] H.F. Wang, "Interactions and co-ordination of multiple-function FACTS controllers", *European Transactions on Electrical Power*, Vol. 11, pp. 1–15, 2001.
- [13] L. Zhang, P.X. Zhang, H.F. Wang, Z. Chen, W. Du, Y.J. Cao, S.J. Chen, "Interaction assessment of FACTS control by RGA for the effective design of FACTS damping controllers", *IET Generation, Transmission & Distribution*, Vol. 153, pp. 610–615, 2006.
- [14] H.F. Wang, M. Jazaeri, Y.J. Cao, "Analysis of control conflict between UPFC multiple control functions and their interaction indicator", *International Journal of Control Automation and Systems*, Vol. 3, pp. 315–321, 2005.
- [15] S. Ammari, Y. Besanger, N. Hadjsaid, D. Georges, "Robust solutions for the interaction phenomena between dynamic loads and FACTS controllers", *IEEE Power Engineering Society Summer Meeting*, Vol. 1, pp. 401–406, 2000.
- [16] L. Xianzhang, N. Edwin, Lerch, D. Povh, "Optimization and coordination of damping controls for improving system dynamic performance", *IEEE Transactions on Power Systems*, Vol. 16, pp. 473–480, 2001.
- [17] L. Jun, T. Guangfu, L. Xingyuan, "Interaction analysis and coordination control between SSSC and SVC", *International Conference on Power System Technology*, pp. 1–9, 2006.
- [18] T. Nguyen, R. Gianto, "Optimal design for control coordination of power system stabilizers and flexible alternating current transmission system devices with controller saturation limits", *IET Generation, Transmission & Distribution*, Vol. 4, pp. 1028–1043, 2010.
- [19] D. Divan, "Distributed intelligent power networks - a new concept for improving T&D system utilization and performance", *IEEE Transmission and Distribution Conference*, pp. 1–6, 2004.
- [20] D.J. Marihart, "Communications technology guidelines for EMS/SCADA systems", *IEEE Transactions on Power Delivery*, Vol. 16, pp. 181–188, 2001.
- [21] M. Rauls, "Analysis and design of high frequency co-axial winding transformers", MSc, University of Wisconsin - Madison, USA, 1992.
- [22] P. Kundur, *Power System Stability and Control*, New York, McGraw-Hill, 1994.