The International Journal of Energy & Engineering Sciences, 2020, 5 (2) 62-79
ISSN: 2602-294X - Gaziantep University


# COMPARISON OF DYNAMIC PERFORMANCES OF STATCOM, SSSC, IPFC AND UPFC ON INTER-AREA OSCILLATION DAMPING

**Saif Taher FADHIL[1], Mohammed Sameer HAMAD[2], Ali Osman Arslan[3], Ahmet Mete VURAL[3,*]**

[1] ALMustansiviyah University, Baghdad, Iraq.
[2] Salahaddin, Beige, Iraq.
[3] Electrical and Electronics Engineering Department, Engineering Faculty, Gaziantep University, Gaziantep, Turkey.

[*]Corresponding author e-mail: mvural@gantep.edu.tr

## ABSTRACT

Maintaining the stability of the power systems and ensuring the sustainability with sufficient reliability are two important challenges. Inter-area oscillations are one form of low frequency oscillations generally range between 0.1-0.8 Hz. These oscillations may occur between one group of generators in one area and another group of generators in another area that are separated by a long distance. Even a small change in the operating point in the interconnected system may trigger this phenomenon. Therefore, once detected, it is necessary to damp out these oscillations efficiently which may lead to total blackout the system in the worst case. Since Flexible Alternating Current Transmission Systems (FACTS) devices can control multi-power system parameters simultaneously and independently, FACTS devices have a high application potential and can be considered as one of the most viable solutions to damp out inter-area oscillations in an effective manner. This paper aims to show that major types of voltage source converter based FACTS devices are able to damp out inter-area oscillations successfully. The studied FACTS devices in this paper are Static Synchronous Compensator (STATCOM), Static Synchronous Series Compensator (SSSC), Interline Power Flow Controller (IPFC), and Unified Power Flow Controller (UPFC). Furthermore, the dynamic performances of these FACTS devices are also compared based on the simulated case studies on Kundur 2-Area system. Of these FACTS devices, it is shown that UPFC is the most effective FACTS solution to mitigate inter-area oscillations.

**Keywords**: Static Synchronous Compensator, Static Synchronous Series Compensator, Interline Power Flow Controller, Unified Power Flow Controller, Inter-Area Oscillation.

# 1. INTRODUCTION

As a consequence of poor damping, low frequency inter-area oscillations can be observed in a large power system with many groups of generators which are connected by relatively weak and long transmission corridors [1]. These oscillations are usually resulted from minor disturbances, even from a change in system operating point. In the inter-area oscillation mode, one generator angle in one area can swing against the generator angle in another area which is located distantly. It can also be observed as real/reactive power flows oscillation on the weak or heavily loaded transmission line that connects two remote areas. Inter-area oscillations usually occur between 0.1-0.8 Hz which can be detected by geographically spanned phasor measurement units [2]. The effective damping of inter-area oscillations are of vital concern since these oscillations limit the loading of the transmission paths, hamper optimal power flow, and reduce stability limit, which cause inefficient and unreliable grid operation. At the worst case, inter-area oscillations can even cause blackouts if not damped effectively [3]. It is well known that power system stabilizers (PSS) available on the generators are common for the alleviation of local power system oscillations however they do not effectively damp out inter-area oscillations [4]. The damping function of PSS only lessens the effects of these oscillations, but not fully eliminates. The reason is that PSS operates only with local measured data. There are different solution strategies to overcome inter-area oscillations [1].

Real power can be injected into the power system at chosen points by means of energy storage or high voltage direct current transmission. Alternatively, real power flow can be controlled at strategic branches in the grid by means of FACTS devices. The last option is the control of reactive power injection into the grid at strategic buses by means of power electronic converters of renewable energy systems such as solar and wind. Consequently, FACTS devices are expected to be a dominant option in the near future for the control of power systems due to steady rise of the voltage/current ratings of the power semiconductor switches. FACTS is referred to the acronym of "Flexible Alternating Current Transmission System", proposed by Narain G. Hingorani in EPRI in late 1980s [5]. Depending on the switching properties of the power semiconductors, FACTS devices can be classified into two groups [6]. First generation uses line commutated power semiconductor element such as thyristor. While, the second generation employs forced commutated power semiconductor element such as IGBT or IGCT. Second generation FACTS devices usually employ one or more voltage source converters (VSC) with a better response time and more controllability when compared to first generation. In this study, four types of second generation FACTS devices employing one/two VSCs are proposed to damp out inter-area oscillations of a test system. Furthermore, their dynamic performances are also compared in terms of oscillation frequency and damping ratio. A single compensator is usually studied in the literature to cope with inter-area oscillations.

For example in [7], the authors designed a power oscillation damping controller connected to the AC voltage controller of a static synchronous compensator

(STATCOM) to reduce inter-area oscillations in a two-area system with wind farm. The impact of PSS and static series synchronous compensator (SSSC) on the stability of the IEEE 14-bus test system with intermittent wind power generation was analyzed in [8]. A new current injection model of interline power flow controller (IPFC) was suggested in [9] to enhance the dynamic stability of a multi-machine power system. In [9], the most stabilizing control signal for the IPFC was identified and the damping controller parameters were optimized. The authors of [10] carried out a comprehensive analysis for power transfer control and hindering of inter-area oscillations in a two-area system with unified power flow controller (UPFC) and PSS based dynamic control scheme. Another group of studies deal with the inter-area oscillation damping problem with multi compensators.

For example, in [11], a convertible static compensator having functionalities of STATCOM, SSSC, IPFC, and UPFC was proposed. The authors investigated the performance of each FACTS device, individual or in combination, on New York State transmission system by simulation studies. It was shown that FACTS devices generally improved the voltage stability margin of the system as well as inter-area oscillations were damped effectively. In [12], three FACTS devices, namely, UPFC, IPFC, and STATCOM were compared for inter-area oscillation damping feature in Kundur 2-area system. However, SSSC was excluded and a solid result was not provided clearly about which FACTS device's performance is superior. In a PhD thesis, the small signal dynamic performance of IPFC and UPFC on inter-area oscillations were investigated. The small signal models of the example system embedded with FACTS devices were developed and the results obtained from small signal analysis were validated with PSCAD software [13]. In [14], [15], the current status of different FACTS devices on power system stability enhancement and their ability on this subject were discussed and reviewed. However a concrete result was not provided about comparison of dynamic performances of FACTS devices on inter-area oscillation damping. The dynamic performances of thyristor controlled series compensator (TCSC), STATCOM, and SSSC on the mitigation of inter-area oscillations were inspected in Kundur 2-Area system in [16].

It was demonstrated that SSSC best avoids the oscillation and has the best damping ratio. On the other hand, the local and inter-area oscillation damping characteristics of IPFC, UPFC and back to back high voltage direct current transmission were examined on Kundur 2-Area system in [17]. It was shown that direct current transmission option has generally better damping characteristics than the aforementioned FACTS devices. This paper aims to research on which VSC based FACTS device is the best effective for damping inter-area oscillations in case when only local measurement is realized for feedback control. To the best of authors' knowledge, this kind of comparative study of VSC based FACTS devices such as STATCOM, SSSC, IPFC, and UPFC on inter-area oscillation damping for Kundur 2-Area system has not been studied yet. The paper is organized as follows: Section 2 summarizes the working principles and the control functions of the FACTS devices which were mentioned in this study. Section 3 presents the simulation cases of Kundur 2-Area system when inter-area oscillations are formed by applying faults to the system and the discussion is made for the results of the simulations. Finally, conclusion of the work is given at the end.

## 2. FACTS DEVICES

This section briefly reviews the working principles and usual control schemes of one/two VSC based second generation FACTS devices which are proposed in this study. These FACTS devices are STATCOM, SSSC, IPFC, and UPFC.

### 2.1. Static Synchronous Compensator (STATCOM)

STATCOM consists of a VSC and a coupling transformer/reactor which has better characteristics such as faster response, smaller in size, and modularity when compared to static var compensator (SVC) and fixed capacitor/inductor compensation. STATCOM is mainly used for dynamic voltage/VAR control and it can inject controllable capacitive/inductive current into the system by varying the AC voltage of its VSC. Even in voltage sags, STATCOM is still able to supply the required capacitive current to restore the system voltage, since the magnitude of the STATCOM current is independent of the system voltage. But, in case of SVC or fixed compensation, the capacitive current is a function of system voltage and drops linearly as system voltage reduces where it is needed mostly. The simplified STATCOM configuration as well as its operating modes are shown in Figure 1 [6].

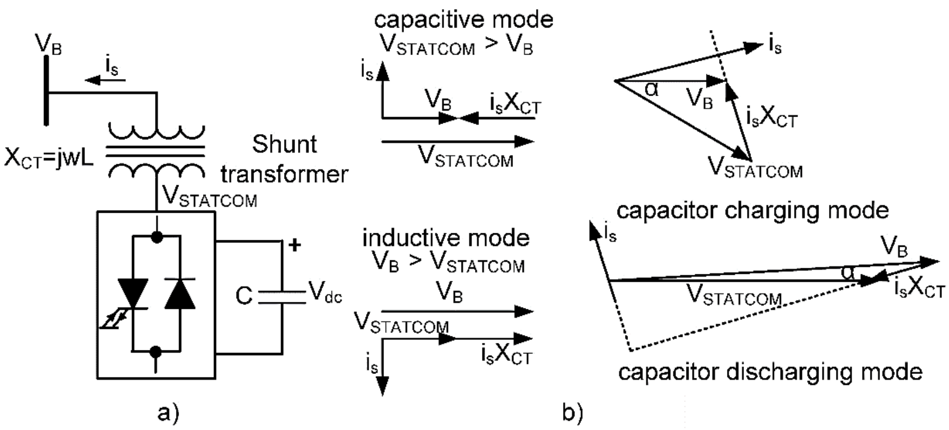


**Figure 1.** The simplified configuration of STATCOM: (a) arrangement (b) operating modes [6].

Figure 2 illustrates the basic control diagram of STATCOM [18]. There are two possible control modes for STATCOM. AC system voltage where the STATCOM is connected in the power system or alternatively reactive power injection by the STATCOM can be controlled at the connection point. At the same time, for proper VSC operation, DC link voltage must also be regulated at its reference value regardless of the STATCOM's control mode. In this work, STATCOM's AC voltage controller is of PI type and activated for the case when STATCOM is functioned for damping inter-area oscillations.

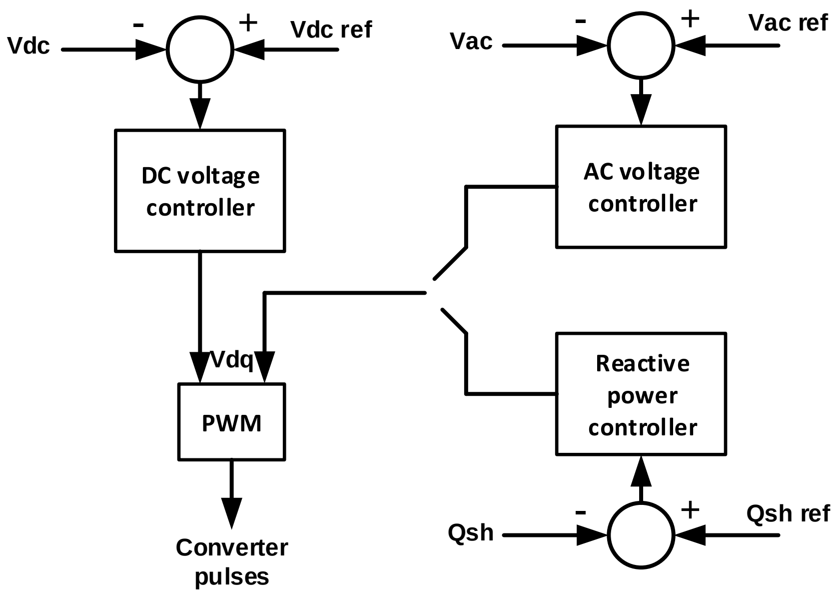


**Figure 2.** Basic control diagram of STATCOM [18].

## 2.2. Static Series Synchronous Compensator (SSSC)

From structural point of view, SSSC is similar to STATCOM except the connection style of the VSC with the power system. As seen in Figure 3, SSSC is connected to the transmission line in series with a series-coupling transformer [6]. SSSC is able to generate a controllable series voltage whose phase angle is perpendicular to the line current. With this way, the required amount of series compensation becomes possible by varying the line reactance. With SSSC, it is possible to control active/reactive power flows on the transmission line as shown in Figure 4. On the other hand, the DC link voltage controller of the SSSC is similar to that of STATCOM. In case when the injected series voltage ($V_{SSSC}$) lags line current ($I_L$), a capacitive effect is emulated and the effective reactance of the line is decreased. This function is necessary for long lines in order to increase power transfer capacity. On the other hand, in case when $V_{SSSC}$ leads $I_L$, an inductive effect is emulated and the effective reactance of the line is increased. This function is necessary especially in order to decrease the power flow in a dynamical way to damp power system oscillations.

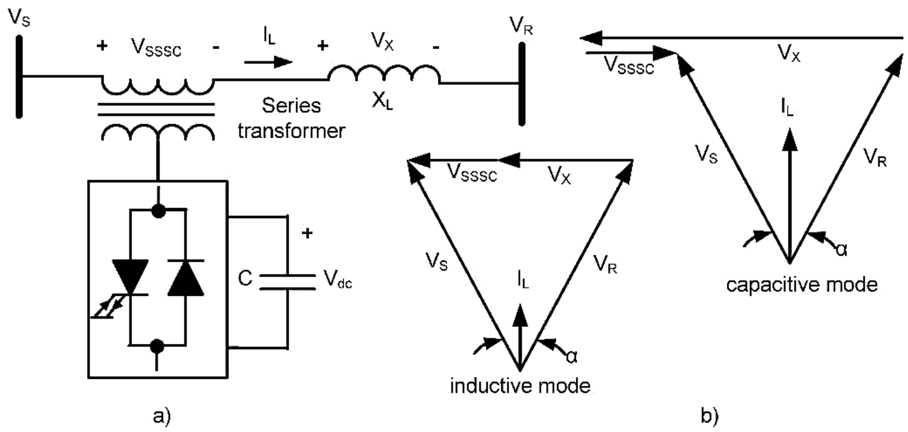


**Figure 3.** The simplified configuration of SSSC: (a) arrangement (b) operating modes [6].

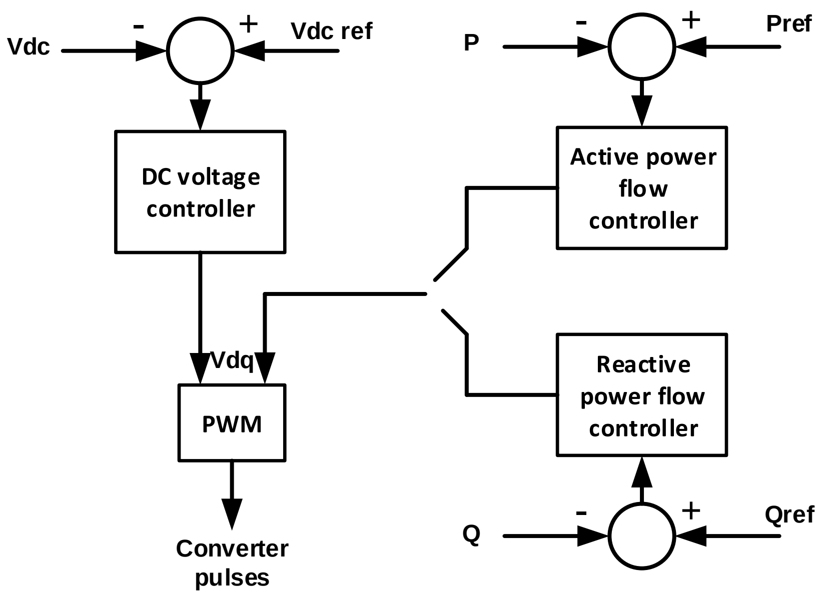


Figure 4. Basic control diagram of SSSC [6].

## 2.3. Interline Power Flow Controller (IPFC)

IPFC is one type of two-VSC based FACTS devices that is installed on two separate transmission lines as shown in Figure 5. Each VSC is connected to one transmission line via a series insertion transformer. With this regard, an IPFC can be regarded as the combination of two SSSCs with a common DC link that enables real power exchange among VSCs. Due to the real power exchange feature, the phase angle of the AC voltage of one VSC ($V_{pq2}$) can be freely controlled together with the AC voltage magnitude control. Since there are two independent controllable parameters for one VSC, the real and reactive power flows can be independently and simultaneously controlled on the transmission line to which this VSC is connected (*Line* 2). The functions of other VSC are to regulate the common DC link voltage and the reactive power flow control on the other line (*Line 1*).

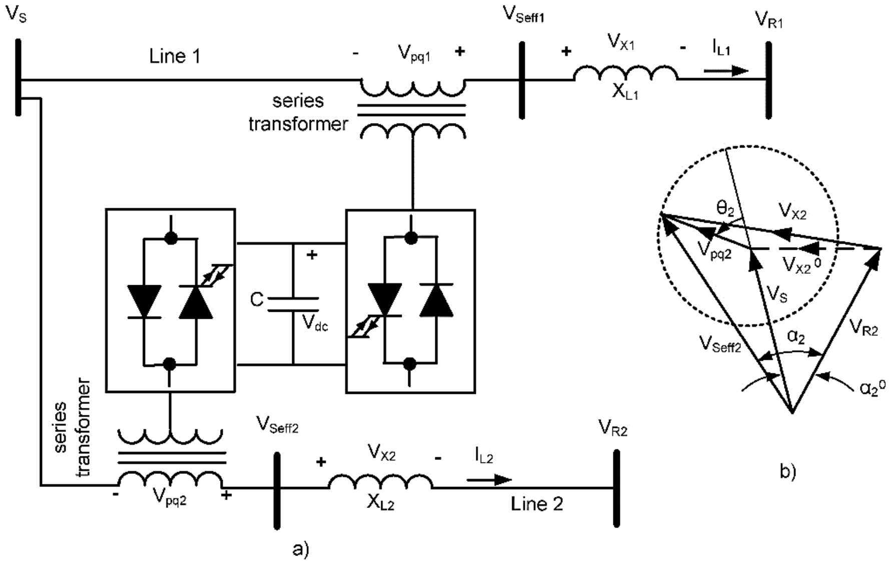


**Figure 5.** The simplified configuration of IPFC: (a) arrangement (b) voltage phasors [6].

Figure 6 briefly shows the control block diagrams of IPFC based on *dq* coordinate transformation. VSC2 is responsible from the control of real/reactive power flows on the transmission line to which it is connected. On the other hand, VSC1 regulates DC link voltage and reactive power flow on the other line. In this study conventional PI controllers are used and no modification are made to the controllers to damp inter-area oscillations.

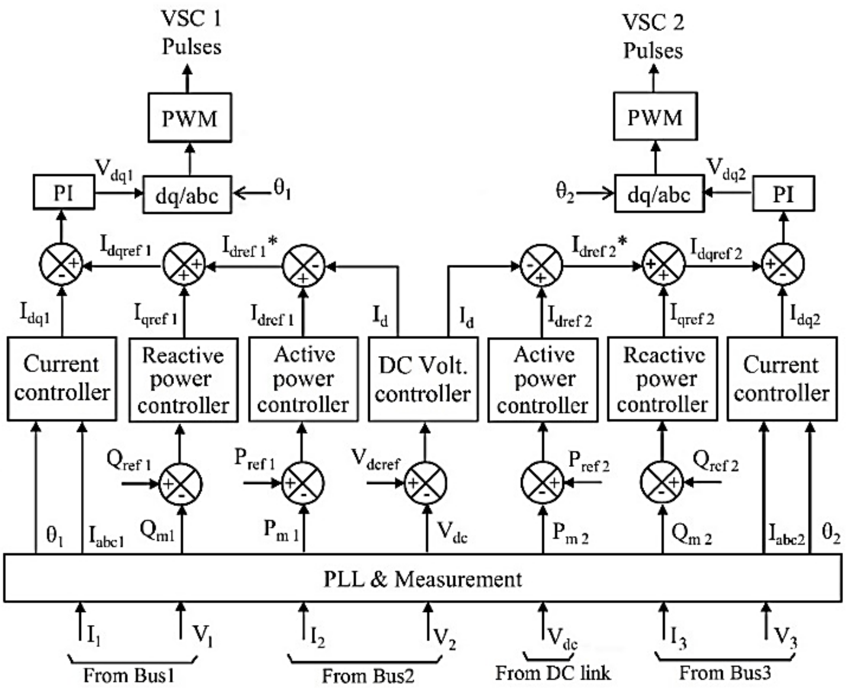


**Figure 6.** Basic control diagram of IPFC [6].

## 2.4. Unified Power Flow Controller (UPFC)

UPFC is another member of two-VSC based FACTS devices as shown in Figure 7. UPFC can be considered as the combination of STATCOM and SSSC with a common DC link that connects both VSCs from their DC sides. Series VSC is connected to a selected transmission line through a series coupling transformer. By this way, the real and reactive power flows of this transmission line in which series coupling transformer is inserted, can be independently and simultaneously controlled by full control of the series inserted voltage ($V_{pq}$). On the other hand, the other VSC is connected to a selected bus in shunt through a shunt coupling transformer. The function of the shunt VSC is to regulate the common DC link voltage and reactive power injection into the point where shunt VSC is connected through shunt coupling transformer or AC voltage control ($V_s$) for this point.

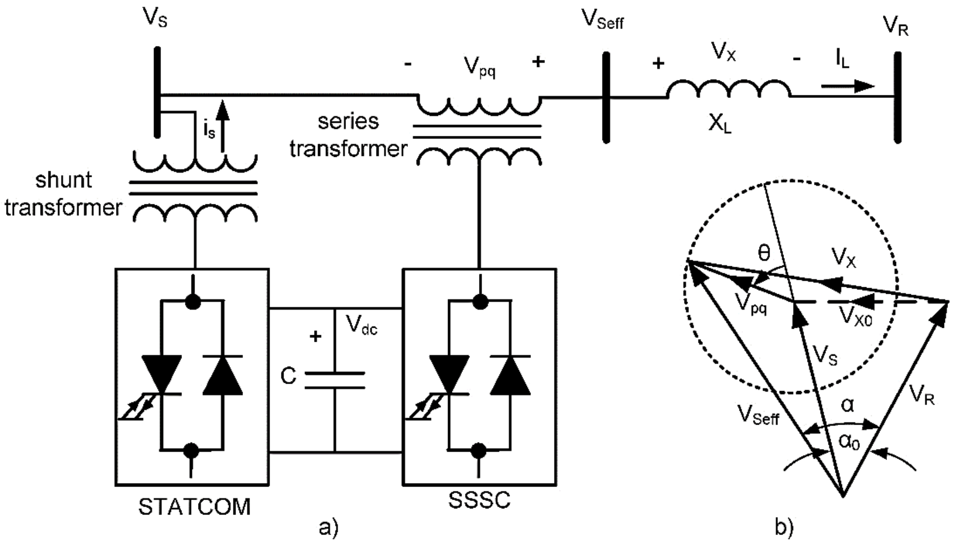


**Figure 7.** The simplified configuration of UPFC: (a) typical arrangement (b) voltage phasors [6].

Figure 8 shows the simplified control diagram of UPFC. Like IPFC, active and reactive power flow controllers regulate the flows on the line in which series VSC is connected. Reactive power controller or AC voltage controller is optionally selected for the shunt VSC. DC voltage controller is necessary for regulating the common DC link voltage. The UPFC control scheme used in this work is of PI type which is based on *dq* coordinate transformation.

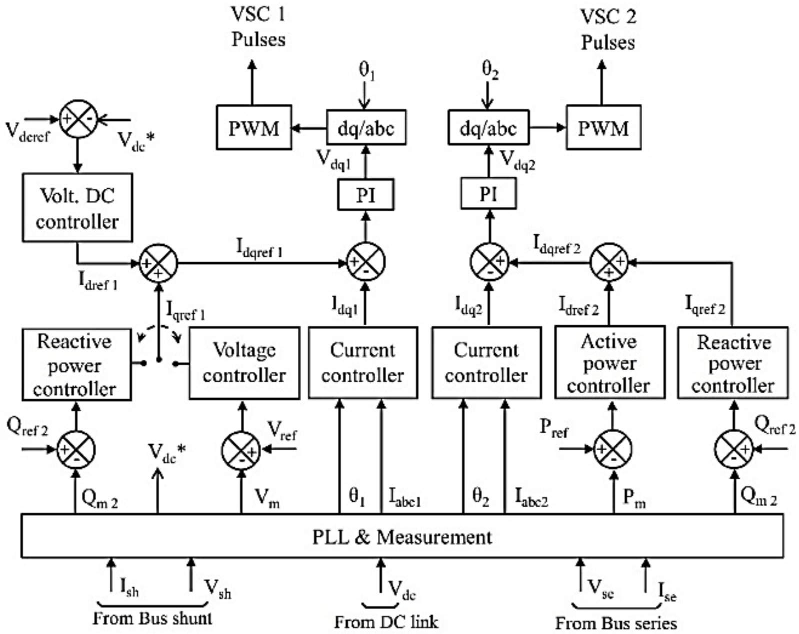


**Figure 8.** Basic control diagram of UPFC [6].

## 3. SIMULATION RESULTS

As shown in Figure 9, Kundur system is used in this work as the test system to evaluate and compare the dynamic performances of different FACTS devices (STATCOM, SSSC, IPFC, UPFC) for damping inter-area oscillations. Kundur system is a commonly used test system for performing small-signal and transient stability studies of power systems [19]. The fundamental frequency of Kundur system is 60 Hz. This test system consists of eleven buses and two generation areas which are connected to each other by three 220 km transmission lines. Each generation area has two identical generators, with a rating of 20 kV and 900 MVA for each. Two loads are connected at bus 7 and 9 with a total consumption of 1816 MW. There are also two shunt capacitors connected at bus 7 and 9, respectively. The length of other transmission lines are specified in Figure 9. There are five case studies performed on the test system as listed in Table 1. In these case studies, the STATCOM or the shunt VSC of the UPFC is connected at bus 8. The SSSC or series VSC of the UPFC is connected to one of the parallel lines near bus 8. The VSCs of the IPFC are connected to both of the parallel lines near bus 8. The case study result of each FACTS device is compared with the uncompensated case of the test system.

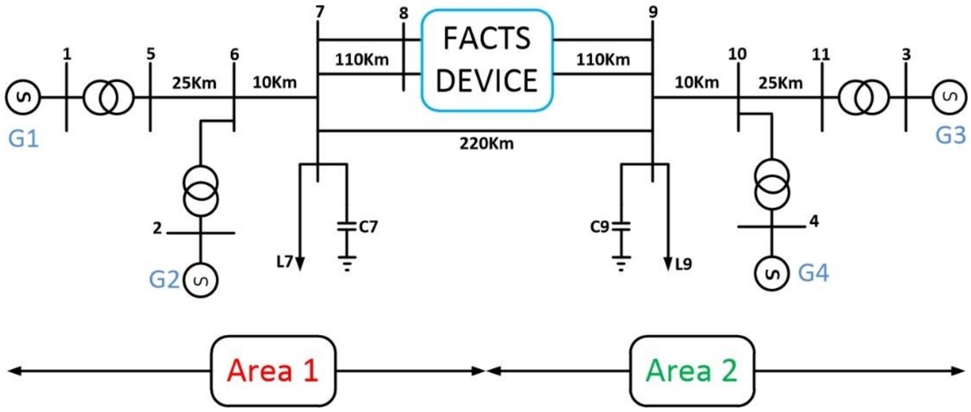


**Figure 9.** Single-line diagram of Kundur system [19].

**Table 1.** List of case studies and FACTS device locations.

| Case Number | FACTS Device | Location of FACTS Device |
|---|---|---|
| 1 | No compensation | - |
| 2 | STATCOM | At bus 8 |
| 3 | SSSC | On one of parallel line |
| 4 | IPFC | On both parallel lines |
| 5 | UPFC | At bus 8 and on one of parallel lines |

## 3.1. Case 1

In this case study, at first, the test system is simulated in order to obtain its steady-state operating point without any FACTS device. It is found that under steady-state conditions, 182 MW of real power flow per line is transferred from area 1 to area 2. Then, while in steady-state operating conditions, bus 9 is subjected to a three-phase to ground fault for a duration of 100 ms in order to get an inter-area oscillation between area 1 and area 2. Figure 10 shows that following after the cleaning of this fault, there happens relatively large oscillations of real power flow (black dashed line), even higher than 350 MW at the first swing on one of the parallel lines between bus 7 and 9. This large power oscillation is due to no effective damping or very weak damping provided by the synchronous generators. On the other hand, reactive power flow oscillation (black dashed line) on the same line is shown in Figure 11. It is concluded that the reactive power flow oscillation is resulted from no or inadequate reactive power support provided by the synchronous generators. The rotor angular speed and rotor angle differences between generator-1 (in area 1) and generator-3 (in area 2) are also shown in Figures 12 and 13 (black dashed lines), respectively. It is observed that these oscillations last for more than 12 seconds and both generators could hardly regain their stable operation after cleaning the three-phase fault. Case 1 shows that without an effective damping solution such as a FACTS device, the test system is exposed to strong inter-area oscillations following after a serious fault and the system hardly regains its stable operating point.

### 3.2. Case 2

In this case study, STATCOM is activated by connecting it at bus 8 and STATCOM is operated under AC voltage control mode. The same fault with exactly the same parameters is applied to Kundur test system as in case 1 to evaluate the dynamic performance of the STATCOM under such a three-phase to ground fault at bus 9. Figure 10 shows that following clearing of the fault, STATCOM partially compensates the inter-area oscillation of real power flow between area 1 and area 2 (green line). The partial damping function of the STATCOM is due to the dynamic reactive power injection at bus 8. Moreover, when Figure 10 and 11 are compared for STATCOM, it is observed that STATCOM is able to act better on reactive power oscillation than real power oscillation on the same line. This fact is due to the instantaneous reactive power support of STATCOM. On the other hand, Figure 12 and 13 respectively illustrate that the rotor angular speed and rotor angle oscillations of generator-1 against generator-3 (green lines) are poorly damped by STATCOM after cleaning the fault. It can be finally concluded for this case study is that the STATCOM can partially suppress the inter-area oscillations with a relatively poor damping. Although STATCOM is primarily used for AC voltage or reactive power injection control at a specific bus, it can partially help system engineers in reducing any possible inter-area oscillations by injecting the reactive power to where it is connected.

### 3.3. Case 3

This case study is carried out in order to examine the dynamic performance of SSSC when inter-area oscillations occur following after the fault in the test system. In order to make a fair comparison between FACTS devices, the fault properties are unchanged and these parameters are exactly same as in case of case study 1 and 2. In this case study, SSSC is located on one of the parallel transmission lines interconnecting the two areas of the test system. SSSC is considered when it is conventionally regulating the real power flow of the line in which it is inserted in series. The damping characteristics of the SSSC on real power flow fluctuations (purple line) is shown in Figure 10 when the set point of the real power flow controller of the SSSC is set to a value which is equal to the one as in case of the uncompensated case. It is clear from Figure 10 that SSSC performs better than STATCOM in damping out real power oscillations on the line. Since SSSC is in real power flow control mode, the oscillations following after the fault are detected instantly and the related PI controller of the SSSC would try to decrease the error signal by real-time modification of the effective line reactance. Since line reactance is directly related to the amount of real power flow on an AC line, SSSC can be preferred over STATCOM if only damping of real power oscillations is the primary control target. Moreover, Figure 11 shows that SSSC again performs better than STATCOM in reducing reactive power oscillations of the line (purple line). This is due to the fact that on an AC line real and reactive power flows are coupled and if one of them is controlled by the FACTS device, the other one becomes indirectly controlled so that in general, SSSC is a better FACTS device only if inter-area oscillations of the real and reactive power flow are matter of concern. Finally, Figure 12 and 13 show that how the parameters of two synchronous generators, namely as, rotor speed and rotor position fluctuate (purple lines) following after the fault and damped by SSSC.

### 3.4. Case 4

In this case study, one of the two-VSC based FACTS devices, namely IPFC is evaluated in terms of its inter-area oscillation damping capability for Kundur test system. IPFC is located on the parallel lines of weak tie between bus 7 and 9 by inserting its each VSC in series with each line, respectively. The fault properties are unchanged and these parameters are exactly the same as in case of previous case studies. The controllers of the IPFC are activated for simultaneously regulating two parameters of one of the parallel lines and one parameter of the other line of the parallel lines. These are the real and reactive power flows of one line and the reactive power flow of the other line. In order to make a valid performance comparison of IPFC with the other FACTS devices, the set point of real power flow controller is adjusted the same as in case of SSSC, whereas the set point of reactive power flow controllers are adjusted to the values which are obtained in case 1, namely, under no compensation mode. It is apparent from Figure 10 that IPFC performs better than previous FACTS devices and the real power flow fluctuations (blue line) is effectively damped out thanks to the multi-parameter regulation capacity of IPFC with its two VSC controllers. It is also observed in Figure 10 that the real power oscillation is almost ended after 10 seconds and the system is recovered effectively after this time. Since IPFC controls more line parameters than SSSC, besides real power oscillation damping, the reactive power oscillations following after the fault is also clearly suppressed by the IPFC better than SSSC. This situation is clearly shown in Figure 11 (blue line). Multi line parameter control feature of IPFC helps generator-1 and generator-3 when recovering from the disturbance. The simulated waveforms in Figure 12 and 13, respectively presents how the swings of rotor angular speed and rotor angle differences between the generators are damped by IPFC (blue line). After 10 seconds, almost all shaft oscillations die out.

### 3.5. Case 5

This is the last case study in this work and it evaluates and compares the dynamic performance of the other two-VSC based FACTS device, namely UPFC for suppressing inter-area oscillations of Kundur test system. In this case, the shunt VSC of UPFC is coupled at bus 8, while the series VSC of UPFC is connected to one of the parallel lines of the weak tie between bus 7 and 9. The fault type and its characteristics are exactly same with the ones which are applied in previous case studies of Kundur test system. To regulate the voltage magnitude of bus 8, the shunt VSC controller parameters of the UPFC are exactly the same with the settings of STATCOM controller. On the other hand, the series VSC controller of the UPFC is activated for simultaneously regulating real and reactive power flows of one of the parallel transmission lines of the tie line. Here, the reference of real power flow controller of UPFC is adjusted the same as in case of SSSC and IPFC, whereas the reference of reactive power flow controller of the UPFC is set to the value as in case of IPFC operation. By this way it is aimed to make a valid and fair comparison of UPFC with the other FACTS devices. With the addition of the shunt VSC, the reactive power injection support becomes available by UPFC and this feature clearly shows how UPFC impressively damps out the fluctuations of the system. Figure 10 shows that real power oscillations are strongly suppressed by the UPFC in almost 5 seconds after the fault is cleared. This is the best performance result obtained in all case studies. On the other hand, Figure 11 shows that reactive power oscillation is almost finished by UPFC in a duration of 6 seconds. Finally, Figure 12 and 13 clearly show that the rotor angular and rotor angle deviations of the generator-1 and generator-3 are effectively suppressed in 4 seconds after the fault is cleared. The results of this case study show that inter-area oscillations of Kundur test system are effectively damped out by UPFC due to its capability of controlling multi power system parameters in an independent and simultaneous manner.

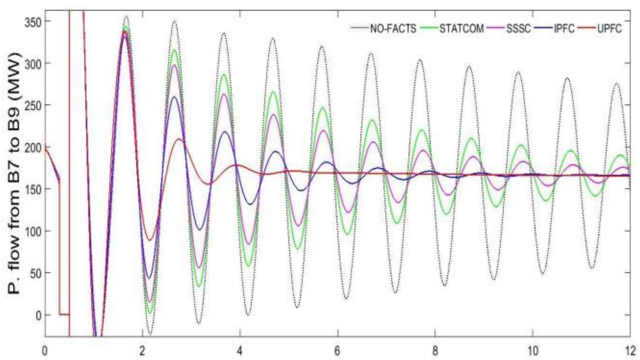


**Figure 10.** Active power flow from bus 7 to 9 for all cases.

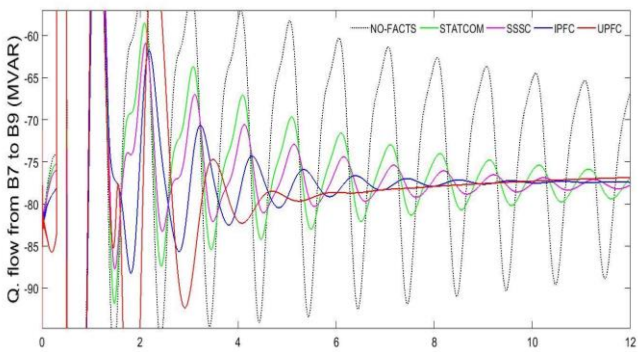


**Figure 11.** Reactive power flow from bus 7 to 9 for all cases.

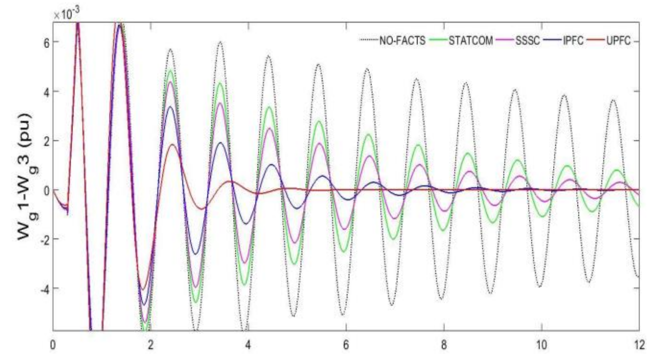


**Figure 12.** Difference of rotor angular speeds of generator-1 and 3 for all cases.

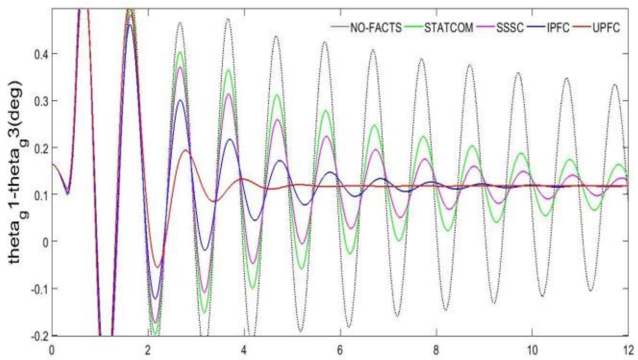


**Figure 13.** Difference of rotor angular positions of generator-1 and 3 for all cases.

## 3.6. Quantitative Comparison of Case Studies

Besides visual examining of the simulation results which have been previously done in the above case studies, it is also necessary to quantitatively evaluate the performance of each FACTS device in suppressing inter-area oscillations. To do this, the oscillation modes of a power system can be clarified by a formal method which is known as modal or eigenvalue analysis [1]. Eigenvalue analysis is a frequency domain technique that needs linearization of the system model. Assume that the linearized power system model around its operating point is obtained as

$$\begin{cases} \Delta\dot{x} = A\Delta x + B\Delta u \\ \Delta y = C\Delta x + D\Delta u \end{cases} \tag{1}$$

where $x$, $u$, $y$, and $ABCD$ are state vector, input vector, output vector, and state-space matrices, respectively. After applying Laplace transform, system equations in s-domain can be obtained as

$$\begin{cases} x(s) = (sI - A)^{-1}[x(0) + Bu(s)] \\ y(s) = C(sI - A)^{-1}[x(0) + Bu(s)] + Du(s) \end{cases} \quad (2)$$

where $x(0)$, $s$ and $I$ are initial state vector, Laplace operator and identity matrix, respectively. After this step, the eigenvalues ($\lambda_1$, $\lambda_2$,..., $\lambda_n$) of the power system can be obtained by solving the characteristic equation ($\det(A-\lambda I)=0$) of the system. If the eigenvalue is a complex number such that $\lambda=\sigma\pm j2\pi f$, it describes an oscillatory mode. Here, $\sigma$ and $f$ are the damping factor and the oscillation frequency of the complex conjugate pair, respectively. Then, the damping ratio can be defined as

$$\xi = \frac{-\sigma}{\sqrt{\sigma^2 + w^2}} \quad (3)$$

where $w=2\pi f$. Damping ratio $\xi$ is a quantitative measure that relates the oscillation decaying following after a disturbance. In inter-area oscillation damping studies, the mode is called "critical" which should be usually suppressed by a compensator such as FACTS device, if its damping ratio is less than 5 % [20], [21], [22]. Table 2 lists the oscillation frequency and the damping ratio of each case study. It is found that in all cases with a FACTS device, the damping ratio is greater than 5 % except case no 1.

In this case, a critical mode which is around 4% is observed in the Kundur test system after applying and clearing the fault. This means that a suitable compensating device such as a FACTS device should be activated to cope with this critical mode oscillation. Moreover, Table 2 shows that UPFC seems to be the best FACTS device in damping out inter-area oscillations. The damping ratio in the case study involving UPFC is 11.32% and the respective oscillation frequency is found as 0.5528 Hz, which is the minimum one of all case studies. IPFC comes as the second FACTS device after UPFC that has better damping characteristics when compared with SSSC and STATCOM. And then, SSSC comes after IPFC which has better damping characteristics when compared with STATCOM. By combining the results of both examining the simulated waveforms presented in previous figures and Table 2 reveal that a FACTS device having multi-system parameter control capability gives better damping characteristics.

Especially, if the controlled power system parameter by the FACTS device is a transmission line parameter, such as, real or reactive power flow, this FACTS device (for example IPFC or UPFC) gives relatively better damping characteristics to cope with inter-area oscillations.

**Table 2.** Comparison of oscillation frequency and damping ratio for each FACTS device

| Case No | FACTS Device | Oscillation Frequency (*f*) | Damping Ratio ($\xi$) |
|---|---|---|---|
| 1 | No FACTS | 0.7671 | 0.0409 |
| 2 | STATCOM | 0.6786 | 0.0705 |
| 3 | SSSC | 0.6422 | 0.0817 |
| 4 | IPFC | 0.5913 | 0.1026 |
| 5 | UPFC | 0.5528 | 0.1132 |

## 4. CONCLUSION

Low-frequency oscillations such as inter-area oscillations always pose a threat for the power systems due to their maximum power transfer limiting and stability threatened dynamics. They cannot be effectively controlled by conventional power system stabilizers which do not have any direct control action capability on the power system parameters. It is already reported that inter-area oscillations can even cause large blackouts if control actions are not taken immediately.

This paper presents a comparative performance evaluation of major FACTS devices when damping out inter-area oscillations in a test system. The studied FACTS devices are second generation ones, namely as, STATCOM, SSSC, IPFC, and UPFC. These devices have at least one VSC and are versatile with different control capabilities. At first, the aforementioned FACTS devices are briefly reviewed with simplified operation and basic control diagrams.

After that each of the FACTS devices is installed at a critical place in Kundur test system to evaluate its dynamic performance on damping out major power system parameter oscillations following and clearing after a three-phase fault. It is shown both by simulated time-domain waveforms and modal analysis that the FACTS device, such as IPFC and UPFC, having a real power flow controller, gives always better damping characteristics when compared to other types of FACTS devices.

It is also inferred that UPFC is better than IPFC since it has an extra reactive power injection capability owing to its shunt VSC. The application of different FACTS devices in evolving power systems is continuously rising in all over the world especially due to the recent advancements in power electronic technology. So it is strongly anticipated that the FACTS devices will be actors to cope with different types of major problems, such as inter-area oscillations in the near future.

## REFERENCES

[1] Vural, A. M., “Contribution of high voltage direct current transmission systems to inter-area oscillation damping: A review”, Renewable & Sustainable Energy Reviews, 57: 892-915, (2016).

[2] Prakash, T., Singh, V. P. and Mohanty S R., “A synchrophasor measurement based wide-area power system stabilizer design for inter-area oscillation damping considering variable time-delays”, International Journal of Electrical Power & Energy Systems, 105:131-141, (2019).

[3] Pal, B. and Chaudhuri, B., Robust control in Power Systems Series: Power Electronics and Power Systems, Springer, New York, (2005).

[4] Shakarami, M. R. and Kazemi, A., “Assessment of effect of SSSC stabilizer in different control channels on damping inter-area oscillations”, Energy Conversion and Management; 52(3):1622-1629, (2011).

[5] Hingorani, N. G., “FACTS Technology - State of the Art, Current Challenges and the Future Prospects”, 2007 IEEE Power Engineering Society General Meeting, Florida, 1-4, (2007).

[6] Vural, A. M., “Modeling of Multi-Converter FACTS (Flexible Alternating Current Transmission System”, Phd.Thesis, Cukurova University, Adana, (2012).

[7] Rajeev, A. and Nandakumar, M., “Mitigation of Low Frequency Oscillations in Two Area System Using STATCOM with PODC”, 2018 International CET Conference on Control Communication and Computing , Thiruvananthapuram, 1-5, (2018).

[8] Bhukya, J. and Mahajan, V., “Optimization of damping controller for PSS and SSSC to improve stability of interconnected system with DFIG based wind farm”, International Journal of Electrical Power & Energy Systems, 108: 314-335 (2019).

[9] Rezaei, N., Kalantar, M., Shayanfar, H. A. and Alipouri, Y., Safari A., “Optimal IPFC signal selection and damping controller design using a novel current injection model in a multi-machine power system”, International Journal of Electrical Power & Energy Systems, 44(1): 461-470, (2013).

[10] Zahid, M., Li, Y., Chen, J., Zuo, J. and Waqar, A., “Inter-area oscillation damping and voltage regulation by using UPFC for 500 kV transmission network”, 2017 2nd International Conference on Control and Robotics Engineering, Bangkok, 165-169, (2017).

[11] Arabi, S., Hamadanizadeh, H. and Fardanesh B. B., "Convertible static compensator performance studies on the NY state transmission system", IEEE Transactions on Power Systems, 17(3): 701-706, (2002).

[12] Srivastava, I. P. and Singh, Y. K., "A Comparative Analysis of Facts Devices for Damping of Inter Area Oscillation", International Journal of Engineering Science and Computing, 7(11):15515-15520, (2017).

[13] Jiang, S., "Investigation of Small Signal Dynamic Performance of IPFC and UPFC Devices Embedded in AC Networks", Phd.Thesis, University of Manitoba, Manitoba, (2010).

[14] Majeed, A., Ahmad, B. and Singh, Y., "Power System Stability, Efficiency and Controllability Improvement using Facts Devices", International Journal of Engineering Science and Computing, 9(1):19590-19596, (2019).

[15] Khatoon, N. and Shaik, S. A., "Survey on Different types of Flexible AC Transmission Systems (FACTS) Controllers", International Journal of Engineering Development and Research, 5(4):796-814, (2017).

[16] Fadhil, S. T. and Vural, A. M., "Comparison of dynamic performances of TCSC, Statcom, SSSC on inter-area oscillations", 2018 5th International Conference on Electrical and Electronic Engineering, Istanbul, 138-142, (2018).

[17] Vural, A. M. and Hamad, M. S., "Comparison of dynamic performances of IPFC, UPFC and back to back HVDC transmission on local and inter-area oscillation damping in power systems", 5th International Conference on Electrical and Electronic Engineering, Istanbul, 31-35, (2018).

[18] Cakir, G. and Radman, G., "Placement and performance analysis of STATCOM and SVC for damping oscillation", 3rd International Conference on Electric Power and Energy Conversion Systems, Istanbul, 1-5, (2013).

[19] Kundur, P., Power System Stability and Control, Mc Graw-Hill, New York, (1994).

[20] Graham, R., Power system oscillations, Springer, New York, (2000).

[21] Preece, R., Milanovic, J. V., Almutairi, A. M. and Marjanovic, O., "Damping of inter-area oscillations in mixed AC/DC networks using WAMS based supplementary controller", IEEE T POWER SYST, 28(2):1160-1169, (2013).

[22] Kerahroudi, S. K., Rabbani, R., Fan, L., Taylor, G., Alamuti, M. M. and Bradley, M., "Power system stability enhancement of the future GB transmission system using HVDC link", Proceeding of the 49th International universities power engineering conference, Napoca, 1-6, (2014).