# Impact of hybrid FACTS devices on the stability of the Kenyan power system

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**ABSTRACT**

Flexible alternating current transmission system (FACTS) devices are deployed for improving power system's stability either singly or as a combination. This research investigates hybrid FACTS devices and studies their impact on voltage, small-signal and transient stability simultaneously under various system disturbances. The simulations were done using five FACTS devices-static var compensator (SVC), static synchronous compensator (STATCOM), static synchronous series compensators (SSSC), thyristor controlled series compensator (TCSC) and unified power flow controller (UPFC) in MATLAB's power system analysis toolbox (PSAT). These five devices were grouped into ten pairs and tested on Kenya's transmission network under specific contingencies: the loss of a major generating machine and/or transmission line. The UPFC-STATCOM pair performed the best in all the three aspects under study. The settling times were 3 seconds and 3.05 seconds respectively for voltage and rotor angle improvement on the loss of a major generator at normal operation. The same pair gave settling times of 2.11 seconds and 3.12 seconds for voltage and rotor angle stability improvement respectively on the loss of a major transmission line at 140% system loading. From the study, two novel techniques were developed: A performance-based ranking system and classification for FACTS devices.



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## 1. INTRODUCTION

The demand for quality and reliable energy is growing rapidly across the world. Rapid expansion of energy generation has inevitably resulted in an increase in power quality challenges mainly because of the growing long-distance between generation and load centers. This has resulted in the voltage collapse of heavily stressed power systems across the world [1].

The huge capital investment required for new power infrastructure coupled with rising strain on land has necessitaed the use of alternative power system stability improvement methods to enable optimization of the existing network. Arising from their versatility, high speed control and flexibility FACTS devices provide an excellent method for improving a power system rotor and voltage stability and power transfer capability. The best location and utilization of flexible alternating current transmission system (FACTS) devices for given system constraints is critical owing to their high initial installation and maintenance costs [2]. Past research in voltage and rotor angle stability improvement using FACTS devices has mainly been done using a single device or a comparative study of two or more devices whilst looking at either voltage or rotor angle stability separately. There has not been any research on the use of a combinations (hybrid) of FACTS devices in a co-ordinated manner for simultaneous study on the improvement of voltage and rotor angle stability. In a real power system, both parameters are imparted at the same time. This is part of the motivation of carrying out this study. The remainder of the paper flows as: section 2 handles the literature review, the next section 3 presents the simulation method, section 4 details the results obtained and section 5 has an analysis of the results obtained. Lastly, section 6 gives a conclusion of the work.

## 2. LITERATURE REVIEW

Power system stability is the characteristic that enables the system to remain balanced under all operating conditions [3]. FACTS devices are power electronic-based devices that provide control of one or more power system parameters to enhance system controllability and improve system stability. This is done by appropriate adjustment of the three variables of voltage, angle and impedance [4], [5]. FACTS devices are classified using a number of criteria that includes but is not limited to: i) mode of connection to the power system [6], ii) age of the FACTS devices [7], and iii) switching technology [8].

The static var compensator (SVC) is made up of a thyristor controlled reactor coupled with a capacitor. It is a variable impedance device used for voltage control and damping of undesirable electromechanical oscillations [9]. For a SVC connected at bus k, the reactive power is expressed in (1):

$$Q_{svc} = Q_k = -V_k^2 Q_{svc} V_k \quad (1)$$

where
$Q_{svc}$= SVC reactive power output
$Q_k$= Reactive power injected at bus k
$V_k$= Voltage at bus k
$Q_{svc}$= Susceptance of the SVC

The highest compensating current of the SVC is inversely proportional to the system voltage. The maximum reactive power is an inverse function of the voltage thus their usefulness decreases when they are needed the most in a power system. The use of the SVC to improve a power system's voltage stability under normal and during system disturbances such as line outages and line faults [10] and for rotor angle stability improvement [11] have been widely studied. The static synchronous compensator (STATCOM) is based on the DC-AC switching converter. It generates/absorbs reactive power by the use of capacitor and reactors for voltage control and damping of system oscillations as shown in (2), (3) [12]:

$$P = \frac{VV_o}{X}\sin\delta \quad (2)$$

$$Q = \frac{V(V-V_o\ \sin\delta)}{X} \quad (3)$$

where
$V$= Power system voltage
$V_O$= Voltage generated by the voltage source converter
$X$= Reactance of the connecting transformers and filters

The (2) and (3) show that if the maximum displacement of the STATCOM voltage is more than that of the system, the converter generates reactive (capacitive) power for the power system. Else, it absorbs reactive power (inductive) from the system. A key advantage of the STATCOM over the SVC is that it provides full reactive power compensation regardless of the system voltage.The STATCOM has been extensively researched on for voltage [13] and rotor angle [14] stability improvement. In a comparative study of the SVC and STATCOM, the latter performed better in improvement of the system voltage profiles [15] and on transient stability improvement [16]. The adjustment of the thyristor controlled series capacitor (TCSC) capacitor frequency using the thyristor firing angle changes the series reactance to increase/decrease the active power flow through the line [17], it provides inherent protection against over voltages by being a source/sink of reactive power. The impedance of the TCSC is computed as in (4).

$$Z_{TCSC} = \frac{-jX_C.jX_{TCR}}{j(X_{TCR}-X_C)} = \frac{-jX_C}{(1-\frac{X_C}{X_{TCR}})} \quad (4)$$

The current through the thyristor controlled reactor ($I_{TCR}$) is given as in (5):

$$I_{TCR} = \frac{-jX_C}{j(X_{TCR} - X_C)} I_L = \frac{I_L}{(1 - \frac{X_{TCR}}{X_C})} \quad (5)$$

where
$Z_{TCSC}$= Impedance of the TCSC
$X_C$= Capacitive reactance
$X_{TCR}$= Reactance of the thyristor controlled reactor
$I_{TCR}$= Current through the thyristor controlled reactor
$I_L$= Inductive current

Since the losses are very small, the impedance of the TCSC can be approximated as purely reactive as in (6).

$$Q_{svc} = Q_k = -V_k^2 B_{svc} \quad (6)$$

$X_{TCSC}$ is capacitive as long as $X_C < X_{TCR}$.

The power flow equations at the sending end bus of the bus are:

$$P_{sr} = V_s V_r B_{sr} \sin(\theta_s - \theta_r) \quad (7)$$

$$Q_{sr} = -V_s^2 B_{ss} - V_s V_r B_{sr} \cos(\theta_s - \theta_r) \quad (8)$$

where
s and r = The sending and receiving ends respectively
$P_{sr}$= Active power flow from the two ends of the bus
$Q_{sr}$= Reactive power flow from both ends
$V_s V_r$= Voltage at both ends
$B_{sr}$= Susceptance between the sending and receiving ends
$\theta$= Transmission angle.

The TCSC has been shown to do an excellent job in the improvement of power flow [18], voltage stability [19], mitigation of sub-synchronous resonance [20] and improvement of power system transient stability [21]. The main drawback of capacitor compensation is that their reactive power is inversely proportional to the system voltage. This means that their usefulness decreases rapidly when they are needed the most during power system faults. The TCSC was shown to perform much better than the SVC in the improvement of the system transient stability [22]. On the other hand, the STATCOM achieved a higher level of oscillation damping as compared to the TCSC [23]. The static synchronous series compensator (SSSC) works as a voltage source that injects capacitive/inductive compensating voltage for transmission angle control and voltage stability improvement [24]. Its real and reactive power flows are:

$$P = \frac{V_s V_r}{X_L} \sin(\delta_s - \delta_r) = \frac{V^2}{X_L} \sin \delta \quad (9)$$

$$Q = \frac{V_s V_r}{X_L} \{1 - \cos(\delta_s - \delta_r) = \frac{V^2}{X_L} (1 - \cos \delta) \quad (10)$$

where
$X_L$= The effective line reactance
s and r = The sending and receiving ends respectively
$\delta$= The transmission angle.

A comparative study of the static voltage stability improvement using both the STATCOM and the SSSC has also been done with the former giving better results [25]. The SSSC was shown to perform better than the SVC in damping of power system oscillations [26]. The unified power flow controller (UPFC) is made up of the STATCOM and SSSC. The STATCOM injects reactive power for voltage control [27]. The SSSC is used to control the power flow by injecting an adjustable voltage $V_{pq}$ through the series transformer for the range $0 \leq V_{pq} \leq V_{pqmax}$ and $0 \leq \rho \leq 2\pi$ respectively. The power at the receiving end is expressed as in (11):

$$P(\delta,\rho) = P_o(\delta) + P_{pq}(\rho) = \frac{V^2}{X}\sin\delta - \frac{VV_{pq}}{X}\cos(\frac{\delta}{2}+\rho) \quad (11)$$

$$Q(\delta,\rho) = Q_o(\delta) + Q_{pq}(\rho) = \frac{V^2}{X}(1-\cos\delta) - \frac{VV_{pq}}{X}\sin(\frac{\delta}{2}+\rho) \quad (12)$$

where
$P_o(\delta)$ = Real power transmission of the line before compensation at a given angle δ
$Q_o(\delta)$= Reactive power transmission of the line before compensation at a given angle δ

The superior ability of the UPFC allows for power control for any transmission angle δ as in (13) and (14). Past research work has shown the UPFC to tremendously improve the voltage [28] and rotor angle stability [29], [30]. A relative study of the SVC, STATCOM and UPFC on the improvement of the transient stability during large system disturbances showed that the UPFC gave much better performance followed closely by the STATCOM [31]. Again the UPFC did better than both the STATCOM and the SSSC in the minimization of the unwanted disturbances for the transient stability improvement [32], [33]. In a similar comparative analysis, the UPFC performed much better than the SSSC, TCSC, SVC and the STATCOM in rotor angle stability improvement [34].

$$P_o(\delta) - \frac{VV_{pqmax}}{X_o\frac{VV_{pqmax}}{X}} \quad (13)$$

$$Q_o(\delta) - \frac{VV_{pq_{max}}}{X} \leq Q_o(\delta) + \frac{VV_{pq_{max}}}{X} \quad (14)$$

From the foregoing analysis, it is evident that research in the voltage and rotor angle stability improvement using FACTS devices has mostly been done using a single device or a comparative analysis of two or more devices and looking at either rotor angle or voltage stability at a time. There has not been research on the use of hybrid (combinations) of FACTS devices for simultaneous improvement of voltage and rotor angle stability.

In summary, the novelty of this work lies in:
a) The use of two or more FACTS devices (hybrid) in a co-ordinated manner during system disturbances for the improvement of power system stability [35]-[39]
b) Simultaneous study of the voltage and rotor angle stability improvement using combination(s) of two or more FACTS devices
c) Development of a performance-based ranking system for the hybrid FACTS devices
d) Development of a new method of classification of FACTS devices based on the results obtained from the above study.

## 3. SIMULATION METHOD

The study began with the optimal placement of FACTS devices on Kenya's transmission network using the filter feeding allogenic engineering (FFAE) algorithm, the whale optimization algorithm (WOA) and the fast voltage stability index (FVSI) for comparison purposes. The results obtained for each transmission bus voltage deviation and the active power loss as a percentage of peak demand were used to rank the buses from the weakest to the strongest for purposes of optimal placement of FACTS devices. The top five weakest buses were Kisumu 132 kV, Lessos 132 kV, Nrbn 220 kV, Juja 132 kV and Nairobi North 220 kV respectively. The required shunt and series compensating reactive power was determined by running the continuation power flow in PSAT so as to determine the load ability margin of the weakest bus (Kisumu 132 kV). The Simulink model developed is as shown in Figure 1.

The load ability margin was determined to be 175 MVar for both shunt and series FACTS devices [38]. The power system stability improvement simulations were done in MATLAB's PSAT platform using the five available FACTS devices, namely the SVC, UPFC, TCSC, SSSC and STATCOM and tested on Kenya's transmission network. The devices were paired up as shown in Table 1. The voltage and rotor angle stability improvement were studied for the system disturbances below:
a) Simultaneous transient and voltage stability study on the loss of a major generator during normal system loading using the paired FACTS devices in Table 1. This was done by the insertion of a three phase fault at Gitaru generator (216 MW output), which has the largest amount of generation besides Olkaria V (305 MW output) generator that serves as the slack bus for the system.

b) Simultaneous voltage and small signal stability study for 140% system loading on the loss of a major transmission line using the paired FACTS devices in Table 1. The peak system loading of 1960 MW recorded during Kenya's peak demand hour of 2000 hours was used as the normal system loading. We used the Olkaria II-Nairobi north 220 kV, double circuit, 500 MVA*69 KM transmission line that evacuates the bulk of geothermal power from the central part of the country to the load center of the capital city Nairobi.

Time domain simulation was used for the transient stability studies whose study period of interest was limited to 7 seconds after the disturbances and outlined above. The introduction of three phase faults at the buses was done at 1 second and cleared after 1.3 seconds. We used the Kisumu 132 kV (weakest bus) and Nairobi North 220 kV (third weakest bus) buses for the simultaneous installation of FACTS devices and study on the impact on power system stability. We did not use the Lessos 132 kV bus although it is next best candidate because of the geographical proximity to the Kisumu 132 kV bus.

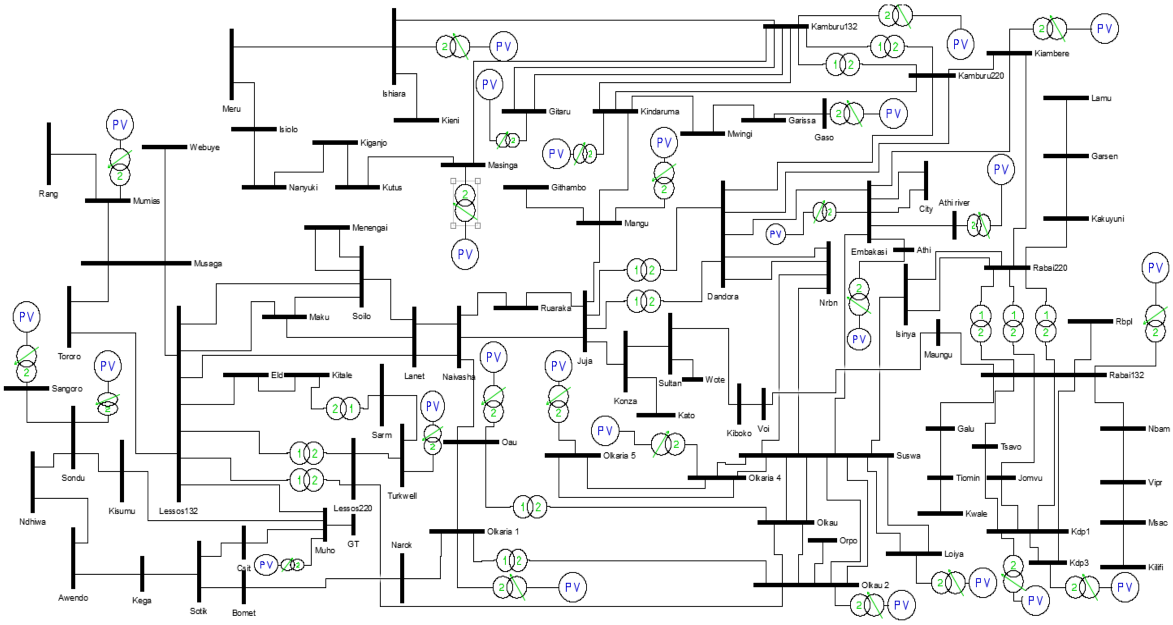


Figure 1. Kenya's 87-bus, 25-generator data 132 kV and 220 kV transmission network modelled in MATLAB's Simulink

Table 1. Pairing of the FACTS devices

| FACTS Devices Pair |
|---|
| STATCOM-UPFC |
| SSSC-UPFC |
| STATCOM-SSSC |
| TCSC-UPFC |
| TCSC-SSSC |
| STATCOM-TCSC |
| SVC-UPFC |
| SVC-STATCOM |
| SVC-SSSC |
| SVC-TCSC |

## 4. RESULTS OBTAINED

Table 2 shows the results obtained for the simultaneous study of voltage and transient stability improvement using FACTS devices on the loss of 216 MW Gitaru generator. The Table 3 shows the results obtained for the simultaneous study of voltage and small signal stability improvement using FACTS devices for 140% system loading on the loss of Olkaria II-Nairobi north 220 kV, double circuit, 500 MVA*69 KM transmission line. The plots of the voltage, small signal and transient stability studies for the two studies were as shown in Figures 2 to 5. From the results, we developed a performance ranking for the FACTS devices, both individual and paired up devices, as shown in Table 4.

Table 2. Performance of Hybrid FACTS devices on the loss of a major generator

| Hybrid FACTS Devices | Voltage (pu) | Improvement in power transfer (%) | Voltage Settling time after loss of 216 MW Gitaru Generator (s) | Settling time for rotor angle oscillations after loss of 216 MW Gitaru Generator (s) |
|---|---|---|---|---|
| Uncompensated system | 0.83 | - | - | - |
| SVC-TCSC | 0.844 | 1.687 | 3.52 | 3.66 |
| SVC-SSSC | 0.853 | 2.771 | 3.5 | 3.61 |
| SVC-STATCOM | 0.861 | 3.735 | 3.5 | 3.56 |
| SVC-UPFC | 0.863 | 3.976 | 3.49 | 3.53 |
| STATCOM-TCSC | 0.866 | 4.337 | 3.44 | 3.48 |
| TCSC-SSSC | 0.871 | 4.940 | 3.3 | 3.33 |
| TCSC-UPFC | 0.875 | 5.422 | 3.2 | 3.24 |
| STATCOM-SSSC | 0.881 | 6.145 | 3.1 | 3.15 |
| SSSC-UPFC | 0.886 | 6.747 | 3.1 | 3.1 |
| STATCOM-UPFC | 0.903 | 8.795 | 3 | 3.05 |

Table 3. Performance of Hybrid FACTS devices on the loss of a major transmission line

| Hybrid FACTS Devices | Voltage on normal load (pu) | Voltage on 140% Loading (pu) | Voltage drop (%) | Settling time for rotor angle oscillations after loss of Olkaria II-Nairobi North Line (s) | Settling time for voltage after loss of Olkaria II- Nairobi North Line (s) |
|---|---|---|---|---|---|
| Uncompensated system | 0.83 | 0.77 | 7.229 | - | 2.5 |
| SVC-TCSC | 0.844 | 0.82 | 2.844 | 3.94 | 2.39 |
| SVC-SSSC | 0.853 | 0.835 | 2.110 | 3.75 | 2.36 |
| SVC-STATCOM | 0.861 | 0.849 | 1.394 | 3.68 | 2.34 |
| SVC-UPFC | 0.863 | 0.852 | 1.275 | 3.62 | 2.33 |
| STATCOM-TCSC | 0.866 | 0.858 | 0.924 | 3.55 | 2.31 |
| TCSC-SSSC | 0.871 | 0.865 | 0.689 | 3.4 | 2.29 |
| TCSC-UPFC | 0.875 | 0.873 | 0.229 | 3.3 | 2.25 |
| STATCOM-SSSC | 0.881 | 0.881 | 0 | 3.24 | 2.18 |
| SSSC-UPFC | 0.886 | 0.886 | 0 | 3.2 | 2.15 |
| STATCOM-UPFC | 0.903 | 0.903 | 0 | 3.12 | 2.11 |

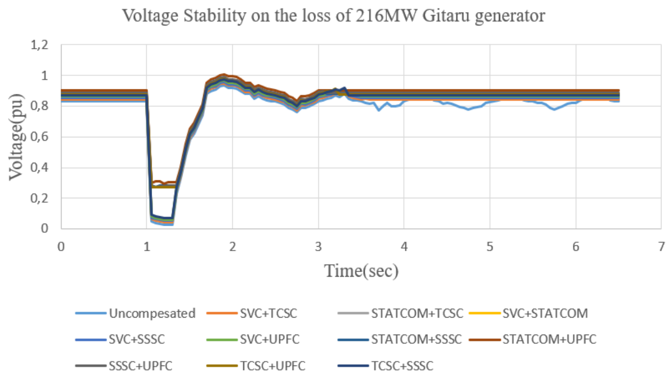


Figure 2. Voltage stability on the loss of a major generator

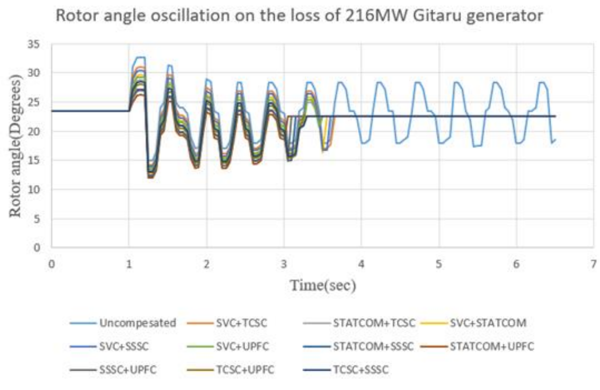


Figure 3. Rotor angle oscillations on the loss of a major generator

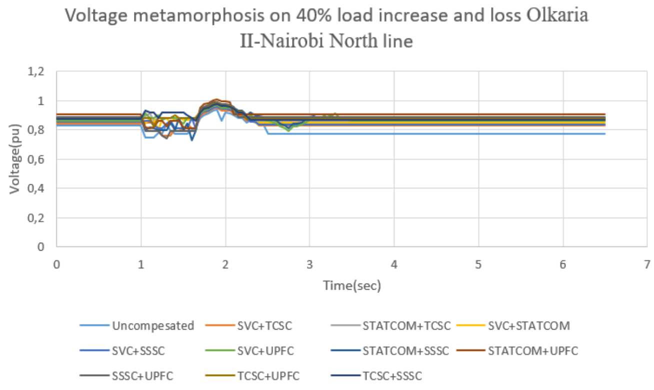


Figure 4. Voltage stability on the loss of a major transmission line

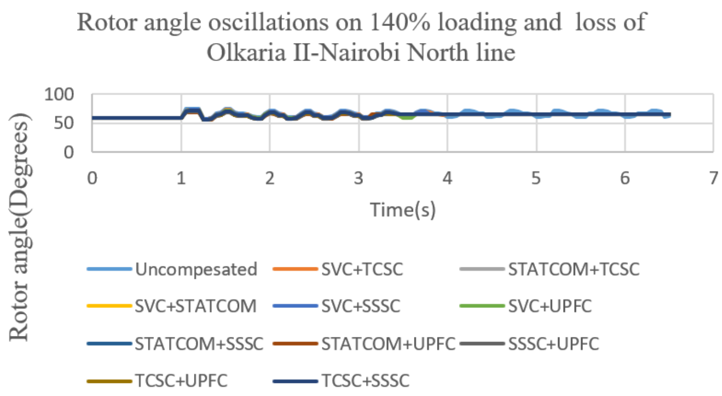


Figure 5. Rotor angle oscillations on the loss of a major transmission line

## 5. DISCUSSION

Optimal placement of paired FACTS devices provided the required damping thus enhancing the voltage and rotor angle system stability which leads to reduction in the system settling time. This should be a pioneering study on the simultaneous studies of the voltage and rotor angle stability improvement. The UPFC-STATCOM pair gave the best performance in all the three areas under this study. The settling times were 3 seconds and 3.05 seconds respectively for voltage and rotor angle improvement on the loss of a major generator at normal system operation as can be seen in Table 2. The same pair had settling times of 2.11 seconds and 3.12 seconds for voltage and rotor angle stability improvement respectively on the loss of a major transmission line at 140% of system loading as can be seen in Table 3. This is best illustrated in Figures 2 to 5. The same pair resulted in 8.79% improvement in power transfer capability at the existing system and loading conditions. This is what led to the development of performance ranking Tables 4 and 5.

The voltage stability study on the loss of the 216 MW Gitaru generator as illustrated in Figure 2 showed that the top performing four FACTS devices pairs, namely the STATC0M-UPFC, SSSC-UPFC, STATCOM-SSSC and the TCSC-UPFC did not allow the voltage to drop to zero during the fault due to the VSC converter output in the SSSC, STATCOM and UPFC. The reactive power compensation of the three does not depend on the power system voltage as can be seen in the reactive power output (3), (10) and (14). This is in sharp contrast to the SVC and TCSC which tend to behave like fixed capacitors at full output as shown in (1) and (8). Their reactive power output is severely degraded when they are most needed (during system faults) as the reactive power output of capacitors depends on the system voltage. The inhibition zone of the TCSC further degrades its performance during system disturbances. However, the TCSC performed much better than the SVC because its reactive power output has an additional component that is a function of the system voltage, susceptance and transmission angle as shown in (8).

It is good to note that the performance of the paired devices is far much better when compared to the individual devices. This should inform better utilization of the devices in future whilst taking care of other technical and financial considerations. The results led to the development of a performance-based ranking of FACTS devices as shown in Table 4 where the UPFC performed best on all the areas under study.

The results in Tables 4 and 5 further helped us to get a deeper understanding and appreciation of the existing methods of classification of FACTS devices. A look at Tables 4 and 5 reveals that the mode of connection is not a major factor in the overall performance of the devices. The classification of FACTS devices using switching technology closely mirrors the results in Tables 4 and 5. Ultimately, mechanically switched devices perform worse than VSC-switched devices as seen earlier and can also be seen in the classification done on the age of the devices. Table 5 thus becomes our new classification of hybrid (paired) FACTS devices based on the performance of the said devices.

Table 4. Performance ranking of FACTS devices

| FACTS Device | Ranking |
|---|---|
| UPFC | 1 |
| STATCOM | 2 |
| SSSC | 3 |
| TCSC | 4 |
| SVC | 5 |

Table 5. Performance ranking of hybrid FACTS devices

| FACTS Devices pair | Ranking |
|---|---|
| STATCOM-UPFC | 1 |
| SSSC-UPFC | 2 |
| STATCOM-SSSC | 3 |
| TCSC-UPFC | 4 |
| TCSC-SSSC | 5 |
| STATCOM-TCSC | 6 |
| SVC-UPFC | 7 |
| SVC-STATCOM | 8 |
| SVC-SSSC | 9 |
| SVC-TCSC | 10 |

## 6. CONCLUSION

This work resulted to the development of a performance-based ranking system of FACTS devices as well as the development of a new method of classification of paired FACTS devices. These findings on the performance of paired up FACTS devices for improved power system stability should inspire more research in future as well as the design and development of more versatile FACTS devices that will be able to perform much better than the existing ones. The development of new FACTS devices should be done hand in hand with financial considerations as this becomes important besides the technical performance when making investment decisions.

The STATCOM-UPFC pair was the best performer in all the aspects under study, namely the transient, small signal and voltage stability improvement or otherwise on the loss of a major generator and transmission line. The STATCOM gives full reactive power compensation regardless of the system voltage. This is a major plus over the TCSC and the SVC both of which have capacitor compensation whose output goes down with the system voltage. The UPFC is a combination of both the STATCOM and the SSSC making it very versatile. There is a need for more research on the hybrid switched FACTS devices such as the STATCOM+Storage, fault current limiter (FCL) and thyristor-controlled voltage limiter (TCVL). As power systems become bigger, more stressed, interconnected and complex, this is an area worth exploring. As part of future research work, there is need to model the above results into mathematical and technical models for further understanding of the results. This will also inform better research into the development of more versatile and better performing FACTS devices.

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