Comparative Assessment of SVC and TCSC Controllers on the Small Signal Stability Margin of a Power System Incorporating Intermittent Wind Power Generation

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1. Introduction

The complexity of power system has increased due to high rate of growth of power demands, and the increasing penetration of renewable energy generators (REGs) on the grid in recent years has further pushed the operation of the existing transmission lines closer to their operating limit. This has necessitated the need to understand the impact of REGs on the overall stability of a power system. The output power of most REGs (wind generators, PV, small hydrogenerators, etc.) is highly variable and can have considerable effect on the dynamic behavior of a power system leading to power swing and less synchronizing coupling [1]. Wind generators have been the most proliferated REG in recent time. This is a result of its technological maturity and the availability of wind resources in many regions of the world [2]. The present and the progressive scales of integration have generated concern about the possible impact it may have on the power system grid integrity. Most of the large wind farms are located where the wind resources are found; hence they are far from the load center and are connected to relatively weak grid [3]. The presence of wind generators connected to such weak transmission networks incurs serious concern about system stability, system security, and power quality. Small signal stability is a key issue in the study of grid impact of wind power integration as a result of its intermittent nature [4, 5]. Small signal stability is concerned with the ability of a power system to ascertain a stable operating condition following a small perturbation around its operating equilibrium [6]. Modal analysis is widely recognized for the analysis of small signal stability of a power system. The analysis is carried out based on the system nonlinear equations describing the dynamic behavior of the system, linearized about a chosen operating point.

In order to take into consideration the stochastic nature of wind power, probabilistic modal analysis method via Monte Carlo simulation (MCS) is employed using MATLAB based power system toolbox (PST). The wind speeds used for the generation of intermittent wind power are drawn from Weibull distribution using Latin hypercube sampling (LHS) techniques. The use of LHS reduces the number of iterations required in traditional MCS and hence reduces computational effort and cost. The basic outline of
the procedures for generating LHS as used in this paper is
given in Appendix A. However, details on the application of
LHS techniques to probabilistic small signal stability can be
found in Ayodele et al’s work [7].

FACTS controllers have been extensively used to improve
the steady-state control problems and enhancing power sys-
tem stability in addition to the main function of power flow
control [8]. Damping electromechanical power oscillations
has been recognized as an important issue in electric power
system operation. Application of power system stabilizers
(PSS), with increasing transmission line loading over long
distances, may in many cases not provide sufficient damping
for interarea power swings. In such cases, other solutions for
power oscillation damping are needed. Fuzzy logic controlled
energy storage (energy capacitor system) has been used to
enhance the overall stability of electric power system [9].
Hossain et al. compared SVC and STATCOM in the improve-
ment of voltage stability and concluded that STATCOM
provides better response during low voltage compared to SVC
[1]. The performance of three FACTS controllers, namely,
static compensator (STATCOM), static synchronous series
compensator (SSSC), and the unified power flow controller
(UPFC), was studied in [10] using current injection model.
The model was applied to damping electromechanical modes.
According to their results, UPFC is the most effective FACTS
controller for damping interarea oscillations and SSSC is
more effective than STATCOM. Comparison of proportional
integrated derivative (PID), power system stabilizer (PSS),
and thyristor controlled dynamic brake (TCDB) in small
signal stability study has been presented by Balwinder [11].
It was concluded that combination of PID with TCDB offers
better improvement in oscillation damping. Application of
controllable series compensator (CSC) in damping power
system oscillation was investigated on the basis of Philip-
Heffron model by Swift and Wang [12]. In their work,
the capability of CSC controller was analyzed in terms of
its damping torque contribution both for single machine
infinite bus and for multimachine power system. The same
authors later compared the effectiveness of damping torque
of FACTS devices, namely, SVC, CSC, and phase shifter
(PS), to power system [13]. It was concluded that SVC and
CSC damping provide more damping torque during high
load conditions while PS damping control does not depend
on system load condition. However, none of the aforemen-
tioned study compared SVC and thyristor controlled series
 capacitor (TCSC) controllers. Moreover, none of the studies
incorporates wind power in their study. In the present study,
SVC and TCSC controllers are compared for the damping
of electromechanical mode of a wind generator connected
power system considering the intermittent nature of wind
power using probabilistic approach.

2. Model Description

Analysis of small signal stability in an interconnected power
system requires adequate model describing various compo-
nents making up the system. Therefore, this section presents
the model approach of these components.

2.1. Synchronous Generator Model. Synchronous machine
can be mathematically modeled as either elementary classical
models or detailed ones. In the detailed models, transient and
subtransient phenomena are considered [14, 15]. In this study,
detailed model is employed to model all the synchronous
generators.

The mechanical variables are linked with the electrical
variables using the following [16]:

\[
(D + T\delta) = T_m - \left( E''_q I_q + E''_d I_d \right),
\]

\[S\delta = \omega - 1,
\]

where \(D\) and \(T_j\) represent the damping constant and the
inertia time constant, respectively; \(T_m\) stands for the input
mechanical torque; \(\omega\) and \(\delta\) represent the rotational speed
and rotor angle, respectively; \(E''_d\) and \(E''_q\) correspond to
the subtransient generated voltage in the direct and quadrature
axes; and \(I_d\) and \(I_q\) stand for the armature current in the
direct and quadrature axes, respectively.

2.2. Power System Stabilizer (PSS) Model. The input signal
to PSS may be rotor speed, rotor angle, or a combination of
this signal. The linearized differential equation of PSS can be
written as follows [11]:

\[
d\Delta X_{W(PSS)} \over dt = K_{PSS} \omega - \frac{1}{T_w} \Delta X_{W(PSS)},
\]

\[
d\Delta X_{x(PSS)} \over dt = \frac{T_1}{T_2} \Delta X_{W(PSS)} + \frac{T_1}{T_2} \Delta X_{W(PSS)} - \frac{1}{T_2} \Delta X_{W(PSS)},
\]

\[
d\Delta V_{f(PSS)} \over dt = \frac{T_3}{T_4} \Delta X_{W(PSS)} + \frac{T_1}{T_2} \Delta X_{W(PSS)} - \frac{1}{T_2} \Delta V_{f(PSS)},
\]

where \(\Delta X_{W(PSS)}\) represent the output of washout filter,
\(\Delta X_{x(PSS)}\) represent the output of first lag-lead network, \(\Delta V_{f}\)
is the output signal of PSS block, and \(T_w\) is the washout
constant. \(T_1\) and \(T_3\) are lead-time constants while \(T_2\) and \(T_4\)
are the lag time constants of lag-lead network. Figure 1 depicts
the PSS block diagram design.

2.3. SVC Controller Model. Facts controllers are electronic
deVICES that are used to enhance power system performance
[17]. SVC is used to inject a controlled capacitance or inductive
current in order to control specific variables, mainly bus
voltage [18]. There are basically two configurations of SVC:
the fixed capacitor (FC) with thyristor controlled reactor
(TCR) and the thyristor switched capacitor (TSC) with TCR.
The model of SVC as implemented in PST software is depicted
in Figure 2.

![Figure 1: PSS block diagram design.](image-url)
2.4. TCSC Controller Model. TCSC has proven to be very robust and effective in the of power system oscillations. The damping effect is obtained by inserting the TCSC in the interconnecting transmission line and executing reactance modulation in phase with the speed difference between the generators connected to the two terminals of the line. The damping effect of TCSC has the following benefits [19]. The effectiveness of the TCSC for controlling power swings increases with higher levels of power transfer, the damping effect of a TCSC on an inertia is unaffected by the location of the TCSC, the damping effect is insensitive to the load characteristic, when a TCSC is utilized to damp interarea modes, and it does not excite any local modes in the process [18]. The TCSC model as implemented in this paper is shown in Figure 3 where $X_m$ is the stability control modulation reactance value which is determined by the stability or dynamic control loop, $X_s$ is the steady state reactance or set point of the TCSC whose value is determined by the steady state control loop, and $X_e$ is the equivalent capacitive reactance of the TCSC.

2.5. Wind Energy Conversion System Model

2.5.1. Wind Speed Model. The intermittent nature of wind power is a result of the stochastic nature of wind speed which is the prime mover of any wind energy conversion system; therefore, adequate model of wind speed that will capture the variability of wind power is required. In this study, the wind speed is modelled using two-parameter Weibull distribution which is found to be appropriate for modelling wind speed in many regions of the world [20–22]. Two-parameter Weibull distribution can be represented as (5) [23] where $f_W(v)$ is the probability of observing wind speed ($v$) and $k$ and $c$ are the Weibull shape and scale parameters of the distribution, respectively. The shape and the scale parameters are provided in Table 7 in the Appendix B:

$$f_W(v) = \frac{k}{c} \left(\frac{v}{c}\right)^{k-1} \exp \left[-\left(\frac{v}{c}\right)^k\right].$$

2.5.2. Wind Generator Model. The variable speed wind turbine is being considered as the most promising among the technologies for grid connection of wind generators today. However, a significant number of fixed speed wind turbines are still in operation. In this study, fixed speed wind generator made of squirrel cage induction generator (SCIG) is employed. Figure 4 gives the schematic diagram of the electrical power output ($P_e$) of a typical wind turbine. Not all the energy in the mass of moving air can be converted into electrical power. The amount of energy that can be converted into useful electrical power depends on the coefficient of the performance of the turbine, the transmission efficiency, and the generator efficiency. This can be written as

$$P_e = \frac{1}{2} \rho AC_P V_w^3,$$

where $C_p$ is the coefficient of the performance of the turbine; it is a function of the tip speed ratio and the pitch angle. Theoretically, it has a maximum value of 0.59 known as the Betz limit. $\eta_m$ is the mechanical transmission efficiency and $\eta_g$ is the generator efficiency. The generated active power of wind generator was modeled as [22]

$$P_e(v) = \begin{cases} \frac{P_{ci} - P_{co}}{v_i - v_c}, & (v_i \leq v \leq v_r), \\ \frac{P_r - P_{ci} - \frac{1}{2} \rho AC_P \eta_m \eta_g v_r^3}{v_i - v_c}, & (v_r \leq v \leq v_{co}), \\ 0, & (v_i \leq v_{ci}, v_i \geq v_{co}), \end{cases}$$

where $v_i$ is the vector of wind speeds generated according to the Weibull distribution of known parameters, $P_e(v_i)$ is the vector of active wind power generated in accordance with the stochastic wind speed and power curve of a wind turbine, $v_{ci}$ is the cut-in wind speed, $v_r$ is the rated wind speed, $v_{co}$ is the cut-out wind speed, and $P_r$ is the rated power. The parameters of the wind turbine are provided in Table 7 in Appendix B.

2.5.3. Reactive Power Model of Wind Generator. The active power injected into the grid is derived from the power curve of the wind turbine with the prior knowledge of wind speed and its distribution. The reactive power absorbed or injected from or into the grid, respectively, can be derived using the steady state equivalent circuit of an asynchronous induction generator as shown in Figure 5, where $U$ is the terminal voltage, $X_1$ is the stator reactance, $X_2$ is the rotor reactance, $X_m$ is the magnetising reactance, and $r_2$ is the rotor resistance. The stator resistance is neglected. From the circuit, the real power injected to the grid can be calculated as

$$P_e(v) = \frac{-U^2 (r_2/s_i)}{(r_2/s_i)^2 + X^2},$$

where $X = X_1 + X_2$ and $P_e(v)$ is the generated active power at different wind speeds according to the power curve in (3). The amount of reactive power absorbed from the grid depends on the rotor slip $s_i$, which also changes as the wind power varies in accordance with the variations in wind speed. Based on (8), $s_i$ was derived as (9). The reactive power $Q_{(v_i)}$ absorbed at
where \( n_k \) indicates the number of WECS of type \( k \) and \( P_{e(v)k} \) is the output electrical power of type \( k \) WECS. Similarly, the reactive power absorbed by the wind farm can be expressed as

\[
Q_{(v)wf} = \sum_{k=1}^{N} n_k Q_{(v)k},
\]

For a wind farm consisting of the same types of wind turbines, (11) and (12) become (13) and (14). Consider the following:

\[
P_{e(v)wf} = NP_{e(v)} ,
\]

\[
Q_{(v)wf} = NQ_{(v)}.
\]

### 3. Power System and Small Signal Stability Model

The dynamic model of power system with wind turbines can be modeled as a set of nonlinear differential algebraic equation:

\[
\dot{x} = f(x, y, p),
\]

\[
0 = g(x, y, p),
\]

where \( x \) is the dynamic state variable which is directly defined by (15) and \( y \) is the instantaneous variable such that the system satisfies the constraint in (16). The parameter \( p \) defines a specific system configuration and the operating condition. The state matrix can be obtained by linearizing the system power flow equations.

Choosing the equilibrium point \((x_o, y_o, p_o)\), (15) and (16) are linearized by taking the first order Taylor expansion as (17) and (18), respectively. Consider the following:

\[
\Delta x = F_x \Delta x + F_y \Delta y,
\]

\[
0 = G_x \Delta x + G_y \Delta y.
\]
If $G_y$ is nonsingular matrix, then
\[
\Delta \dot{x} = \left( F_x - F_y G_y^{-1} G_x \right) \Delta x,
\]
where $F_x, F_y, G_x,$ and $G_y$ are power flow Jacobian matrices. Hence the small signal stability analysis for the model can be obtained as
\[
\Delta \dot{x} = A \Delta x.
\]

The value of $\lambda$ that satisfies (21) is the eigenvalues of matrix $A$. It contains information about the response of the system to a small perturbation:
\[
\det (\lambda I - A) = 0.
\]

The eigenvalue can be real and/or complex. The complex eigenvalues appear in conjugate pairs if $A$ is real (22). The complex eigenvalues are referred to as oscillatory modes and they appear in conjugate:
\[
\lambda_i = \sigma_i \pm j\omega_i.
\]

Each eigenvalue represents a system mode and the relationship between this mode and the stability is given by Lyapunov’s first method [14].

The frequency of oscillation in, Hz, and the damping ratio are given by
\[
\begin{align*}

f &= \frac{\omega_i}{2\pi} , \\

\xi &= \frac{-\sigma_i}{\sqrt{\sigma_i^2 + \omega_i^2}}.
\end{align*}
\]

The contributions of states on oscillation can be observed by evaluating the participation factors (PFs) of each state on a particular mode. Participation factor gives the relationship among the states and eigenmode in a dynamic system [14].

The participation factor of mode $i$, can be computed using [24]
\[
\begin{align*}

p_i &= \begin{pmatrix}

p_{i1} \\
p_{i2} \\
\vdots \\
p_{in}
\end{pmatrix} , \\
p_{ki} &= \frac{\left| \Phi_{ki} \right| \left| \psi_{ki} \right|}{\sum_{k=1}^{m} \left| \Phi_{ki} \right| \left| \psi_{ki} \right|} ,
\end{align*}
\]

where $m$ is the number of state variables, $p_{ki}$ is the participation factor of the $k$th state variable into mode $i$, $\Phi_{ki}$ is the $k$th element of the $i$th right eigenvector of $A$, and $\Psi_{ki}$ is the $m$th element of the $i$th left eigenvector of $A$.

4. System under Study

An IEEE 4-machine, 2-area network as depicted in Figure 6 is used for the study.

The network is selected because it consists of two areas interconnected by weak tie-line which makes it suitable for studying interarea modes. Moreover, the network parameters are readily available and this will enhance repeatability of the work. The network is slightly modified to incorporate wind farm at bus 20. The wind farm consists of 50 different wind generators made of SCIG technology and each is of 2 MW. The network also consists of four conventional synchronous generators at buses 1, 2, 11, and 12. SVC is connected to bus 3 while TCSC is connected on the line connecting buses 3 and 13. The data used for the load flow can be found in [25]; the data not found in the reference due to modification to the network are provided in Appendix B.

The flow chart of Monte Carlo simulation algorithm for the analysis of small signal stability is depicted in Figure 7 and is programmed based on power system toolbox (PST) [25] in MATLAB.

The analysis begins with the generation of wind speed for the wind turbine using Weibull distribution through LHS method. An earlier study showed that, for small signal stability application, 100 runs of input variables generated using LHS are appropriate in Monte Carlo simulation to achieve reasonable results [7]. The load flow analysis is carried out next using Newton-Raphson algorithm, followed by the damping ratio computation via modal analysis. Finally, the results are analysed statistically.

5. Scenario Creation, Results, and Discussion

Four scenarios (Case A–Case D) are created in order to gain meaningful insight into the study. The description and the results of each scenario are discussed under each case.

5.1. Case A: Original Network (No Wind Farm Connected and No Controllers Connected) The base case is made up of the original network without considering the wind farm and the controllers (PSS, SVC, and TSCS). This is to know the initial state of the network in terms of small signal stability and hence the impact of the controllers when they are later added. The result of the simulation shows that there are total of 55 modes in which 24 are oscillatory which appears in
12 conjugate pairs. The results of the oscillatory mode are depicted in Table 1. In small signal stability studies, the modes of interest are the electromechanical modes. These modes must be properly damped for a small signal secured power system. Three conjugate pairs of electromechanical modes are identified and are shown in Table 2. The table depicts that there is one conjugate pair of interarea modes (modes 21 and 22) with damping ratio of 0.24% and oscillatory frequency of 0.571. Figure 8 depicts the compass plot confirming that modes 21 and 22 are interarea modes with generators in area 1 (SG1 and SG2) oscillating against generators in area 2 (SG3 and SG4). Two conjugate pairs are identified as local modes (modes 9 and 10 and modes 27 and 28) with damping ratio of 36% and 7%, respectively. All the modes are positively and strongly damped with damping ratio greater than 5% except the interarea mode which has a damping ratio of 0.24%. The interarea mode determines the stability of the system; it can therefore be concluded that the original network is weakly damped. The results were confirmed using time domain simulation. A 3-phase fault of duration 100 ms was created at the middle of the line connecting buses 3 and 101.

![Figure 8: Compass plot of interarea mode.](image)

![Figure 9: Speed deviation when 3-phase fault of duration 100 ms was created at the middle of the line connecting buses 3 and 101.](image)
The table shows that SVC has a better performance in the
was connected are presented in Figure 11. The figure confirms
the speed of the four synchronous generators when wind farm
3 to bus 13. The results showing both the electrical power and
fault of duration 100 ms at the middle of line connecting bus
network. The wind power was generated as described in the
flowchart in Figure 7. The result was statistically analysed
and presented in Table 3. From the table, it can be observed
that the interarea mode is negatively damped with mean
damping ratio of −0.015 signifying an unstable state. The
standard deviation (SD) of the damping ratio is low (0.0029).
This shows that, in all the operating condition (varying wind
power), the damping ratio is negative. Figure 10(a) shows that
the interarea mode was weakly damped (with damping ration of
0.0024) before wind farm was connected. However, the
weakly damped interarea mode became unstable (shifted to
the left side of the plane) when wind farm was connected to
the network as shown in Figure 10(b). To verify this result,
time domain simulation was carried out by creating a 3-phase
fault of duration 100 ms at the middle of line connecting bus
3 to bus 13. The results showing both the electrical power and
the speed of the four synchronous generators when wind farm
was connected are presented in Figure 11. The figure confirms
that the system is unstable when wind power was injected
into the network. This is due to the interarea mode that is
negatively damped after the wind farm was connected. The
instability resulting from this mode can be vividly observed
in Figure 11(b) with the generators in area 1 (SG1 and SG2)
swinging against generators in area 2 (SG3 and SG4).

5.2. Case B (Wind Farm Is Connected at Bus 20 to the Network in Case A). Wind farm made of 50 wind power generators
each of 2 MW was connected to bus 20. Again no controller
was considered. This will allow us to know the impact of
the wind power on the small signal stability of the original
network. The wind power was generated as described in the
flowchart in Figure 7. The result was statistically analysed
and presented in Table 3. From the table, it can be observed
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negatively damped after the wind farm was connected. The
instability resulting from this mode can be vividly observed
in Figure 11(b) with the generators in area 1 (SG1 and SG2)
swinging against generators in area 2 (SG3 and SG4).

5.3. Case C (Power System Stabilizer Is Allocated to the Generators). The main function of power system stabilizer is
to provide the synchronizing torque [14] and hence improve
the damping of a power system. However, it has to be properly
allocated to the most suitable synchronous generator in order
to provide the most effective result. The aim here is to improve
the damping of the interarea mode in Case B by allocating
PSS. The allocation of PSS has been traditionally done using
deterministic method in which a single operating condition
is considered. In this paper, probabilistic approach is used
in determining the most suitable synchronous generator
in order to allocate the PSS in order to damp the interarea mode.

5.4. Case D (SVC and TCSC Are Installed in Turns). SVC
only was first installed on bus 3 in the network of Case B.
This is to give insight into the influence of SVC on the
small signal stability of a power system. The objective is
to see its influence on the small signal stability and then
compare its performance with that of TCSC. Thereafter, SVC
was taken out and then TCSC only was installed on the line
connecting bus 3 to bus 13. Both SVC and PSS were later
installed to give insight into the combinational effect of the
duo. Finally, SVC and PSS were taken out and both TCSC
and PSS were installed. The results are presented in Table 5.
The table shows that SVC has a better performance in the

\[ \lambda = \sigma \pm j\omega \]

Number Type of mode Mean mode Damping ratio (\(\xi\)) Frequency (\(f\))
9 and 10 Area 1 local -0.547 ± 7.381i 0.065 0.007 1.177 0.0015
21 and 22 Interarea 0.061 ± 4.018i -0.015 0.0029 0.639 4.9 * 10^4
27 and 28 Area 2 local -0.534 ± 7.314i 0.076 2.84 * 10^4 1.164 0.0016

\[ \lambda = \sigma \pm j\omega \]

Table 4: Damping of interarea mode (modes 21 and 22).

<table>
<thead>
<tr>
<th>Methods</th>
<th>Allocation</th>
<th>Damping ratio ((\xi))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deterministic</td>
<td>SG3</td>
<td>0.0076</td>
</tr>
<tr>
<td>Probabilistic</td>
<td>SG1</td>
<td>0.0726</td>
</tr>
</tbody>
</table>

The result is then compared with the deterministic method.
Figure 12(a) shows the speed participation factor (PF) when
deterministic method is used (i.e., single operating condition
of wind speed is considered) while Figure 12(b) depicts the
mean speed PF using probabilistic approach (i.e., all the oper-
ating conditions of wind speed are taken into consideration
and the statistical average is determined). The result of the
deterministic method as depicted in Figure 12(a) reveals that
SG3 will be the generator that will provide the most effective
damping when PSS is allocated while Figure 12(b) shows that
SG1 should be installed with PSS for effective damping of the
interarea mode.

PSS were allocated using the two methods and the results
are presented in Table 4. The table shows that when PSS
is allocated deterministically, the interarea mode in Case B
improved from being negatively damped (−0.015) to being
weakly damped (0.0076). However, when allocated proba-
bilistically, the negatively damped interarea mode became
strongly damped (0.0726). The result is again verified using
time domain simulation and is presented in Figure 13. The
figure confirms that probabilistic method presents a better
allocation of PSS for small signal stability application.


![Graph showing frequency versus damping ratio](image1)

**Figure 10:** The plot of frequency versus damping ratio of the network: (a) without wind farm connected and (b) with wind farm connected.

![Graph showing electrical power and rotor speed](image2)

**Figure 11:** Time domain simulation showing (a) the electrical power and (b) the speed deviation when wind power was connected to the network.

damping of the interarea mode with mean damping ratio of 1.67% compared to that of TCSC with damping ratio of 0.61%. The combination of SVC and PSS provides effective damping compared to TCSC and PSS. The controllers are compared in Figure 14 for the damping of the interarea mode.

It can be viewed from the figure that the combination of SVC and PSS gives the best damping to the interarea mode with damping ratio of 15.54%. The order of performance of the controllers as used in this paper is as shown in Table 6. From the table, it can be seen that combination of SVC and PSS puts up the overall best performance followed by the combination of TCSC and PSS. It is generally observed that better results are obtained when the controllers are combined with PSS compared to when they are operated in a stand-alone mode.

<table>
<thead>
<tr>
<th>Controllers</th>
<th>Damping ratio ($\xi$) Mean</th>
<th>Frequency ($f$) Mean</th>
<th>Damping ratio ($\xi$) Std.</th>
<th>Frequency ($f$) Std.</th>
</tr>
</thead>
<tbody>
<tr>
<td>SVC only</td>
<td>0.0167</td>
<td>0.6082</td>
<td>0.0011</td>
<td>0.0038</td>
</tr>
<tr>
<td>TCSC only</td>
<td>0.0061</td>
<td>0.6343</td>
<td>0.00069</td>
<td>0.0010</td>
</tr>
<tr>
<td>SVC + PSS</td>
<td>0.1554</td>
<td>0.6288</td>
<td>0.0021</td>
<td>0.00098</td>
</tr>
<tr>
<td>TCSC + PSS</td>
<td>0.1032</td>
<td>0.6270</td>
<td>0.0030</td>
<td>0.0015</td>
</tr>
</tbody>
</table>

**Table 5:** Influence of controllers in the damping of the interarea mode (modes 21 and 22).
Figure 12: The bar plot of (a) speed participation factor using deterministic method and (b) mean speed participation factor using probabilistic method.

Figure 13: 3D plot of speed when PSS is allocated using (a) deterministic method and (b) probabilistic method.

Table 6: Order of performance of the controller(s) at damping electromechanical modes.

<table>
<thead>
<tr>
<th>S/N</th>
<th>Controllers and possible combination</th>
<th>Order of performance</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>SVC + PSS</td>
<td>1st</td>
</tr>
<tr>
<td>2</td>
<td>TCSC + PSS</td>
<td>2nd</td>
</tr>
<tr>
<td>3</td>
<td>Probabilistic allocation of PSS only</td>
<td>3rd</td>
</tr>
<tr>
<td>4</td>
<td>SCV only</td>
<td>4th</td>
</tr>
<tr>
<td>5</td>
<td>Deterministic allocation of PSS only</td>
<td>5th</td>
</tr>
<tr>
<td>6</td>
<td>TCSC only</td>
<td>6th</td>
</tr>
</tbody>
</table>

The result of the modal analysis was confirmed with time domain simulation and the result is presented in Figure 15.

6. Conclusion

Comparative assessment of SVC and TCSC controllers and their combination with PSS at improving the electromechanical modes excited by the intermittent wind power generated from wind farm made of fixed speed squirrel cage induction generators has been studied using probabilistic modal analysis. Correctness of every result obtained by the modal analysis was verified using time domain simulation. It was revealed that combination of SVC and PSS performs best at damping the electromechanical modes followed by TCSC and PSS. It can be deduced that better performance of the controllers is obtained when combined with PSS compared to...
when operating as a stand-alone controller. It has also been shown that allocation of PSS using probabilistic techniques enhances damping of electromechanical mode compared to the deterministic allocation. This is because, in probabilistic allocation, various combinations of wind power scenarios are taken into consideration unlike deterministic method that takes into consideration only single scenario. The future study will focus on the use of variable speed generator using DFIG and optimal location of SVC for effective damping of interarea mode excited by intermittent wind power. In this study, conclusions are made based on 4-machine, 2-area network; further work will consider large network that will give room for more scenario consideration.

Appendices

A. Latin Hypercube Sampling Techniques

The basic sampling procedures as applied to probabilistic small signal stability in this paper are as follows.

(i) Let $G_1, \ldots, G_N$ be the $N$ input random variables in a probability problem. The cumulative distribution of $G_n$ which belongs to $G_1, \ldots, G_N$ can be written as

$$Y_n = F_n(G_n).$$  \hfill (A.1)

For a sample size $k$, the range of $Y_n$ from $[0,1]$ is divided into $k$ nonoverlapping intervals of equivalent length; hence the length of each interval is given as $1/k$.

(ii) One sample value is chosen from each interval randomly without replacement. Then, the sampling values of $G_n$ can be calculated by the inverse function. The $n$th sample of $G_n$ can be determined by

$$G_{nk} = F_n^{-1}\left(\frac{n-0.5}{k}\right).$$ \hfill (A.2)

(iii) The sample value of $G_n$ can now be assembled in a row of the sampling matrix as given in

$$[G_{n1}, G_{n2}, \ldots, G_{nk}, \ldots, G_{nN}].$$ \hfill (A.3)

Once all the $k$ input random variables are sampled, an $N \times K$ primary sampling $G$ can be obtained. LHS can always start with the generation of uniform distributed samples in interval $[0,1]$ then inverting the cumulative distribution function (CDF) to obtain the target distribution.

B. Parameters Used in the Study

See Tables 7, 8, 9, 10, and 11.
Table 10: SVC parameters.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum susceptance (B_{svc_{\text{max}}})</td>
<td>1 pu</td>
<td>Regulator gain (K_{R})</td>
<td>10</td>
</tr>
<tr>
<td>Minimum susceptance (B_{svc_{\text{min}}})</td>
<td>~1 pu</td>
<td>Regulator time constant (T_{R})</td>
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Table 11: TCSC controller parameters.

<table>
<thead>
<tr>
<th>(T) (s)</th>
<th>(K_{W}) (pu)</th>
<th>(T_{W}) (s)</th>
<th>(T_{1}) (s)</th>
<th>(T_{2}) (s)</th>
<th>(T_{3}) (s)</th>
<th>(T_{4}) (s)</th>
<th>(X_{\text{min}}) (pu)</th>
<th>(X_{\text{max}}) (pu)</th>
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<tr>
<td>0.015</td>
<td>1.1</td>
<td>5</td>
<td>1.1</td>
<td>0.05</td>
<td>0.08</td>
<td>0.5</td>
<td>0.00527</td>
<td>0.0514</td>
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</tbody>
</table>

Conflict of Interests

The author declares that there is no conflict of interests regarding the publication of this paper.

References

