# Impact of Wind Power on Power System Stability and Oscillation Damping Controller Design

M. Mandour#1, M. EL-Shimy*2, F. Bendary#3, W.M. Mansour#4
#Electric Power and Machines Department, Benha University
Shoubra Faculty of Engineering, Cairo, Egypt
1madel_ibec@yahoo.com
3fahmybendary10@gmail.com
4wagdy_ibrahim2010@yahoo.com
*Electric Power and Machines Department, Ain Shams University
Ain Shams Faculty of Enginnering, Cairo, Egypt – corresponding author
2Shimymb@yahoo.com, 002 01005639589

***Abstract* – Due to the benefits of wind power in the ecological enhancement, energy cost reduction and energy security, the use of wind power is spreading. In this paper, the impact of wind power on the dynamic stability of weakly interconnected power systems is considered. Two situations are covered. The first one is the replacement of conventional power by wind power while the second one includes the addition of wind power to an existing conventional power generation system. The considered system is composed of two weakly interconnected areas. The objectives of wind power are to reduce the dependency between the two areas and the reduction of conventional fuel use while keeping acceptable damping levels. Two popular wind energy technologies are considered which are fixed speed SCIGs and the variable speed DFIGs. The results show that the wind power causes reduction in the damping of power system oscillations. Therefore, power oscillation damping controllers (POD) are integrated with the available SVCs. These POD controllers are designed for improving the system dynamic stability to an acceptable level. The POD design is based on the frequency response method. The modal analysis and the time-domain simulation are used for validating the POD efficient design.***

***Index Terms* – FACTS; wind power, electromechanical oscillations; POD design ;modal analysis; time domain simulation.**

## I. Introduction

Due to their ecological benefits, and free availability, the renewable energy becomes a key factor in the global energy security [1]. The competitive prices of wind energy place it as a major renewable energy resource [2]. Egypt has many locations with excellent wind energy resources and large scale projects are already available [2 - 4]. In addition, future projects are currently in progress [4].

Based on the electrical topology, wind turbine generators (WTGs) can be grouped into two main categories [5 - 8]; fixed speed and variable speed WTGs. In comparison with the fixed speed technologies, the variable speed alternatives are known for their high aerodynamic efficiency, control capability, and stability.

Previous researches [9 - 11] show that the impact of wind power on the stability of power systems is highly related to the penetration level and the WTG technology. The higher the penetration level the significant the impact of wind power [10 - 12]. In fact, the dynamic behavior of a power system is largely determined by the behavior and interaction of the generators connecting to the power system. If wind turbines gradually start to replace the output of the synchronous generators, many aspects of the power system operation and control might be affected such as protection, frequency control, transient and voltage stability, among others [6, 7, 9 - 15].

Some studies have been applied to solve the power system stability problems associated with increasing penetration levels of renewable energy sources by the application of FACTS devices to enhance the dynamic and transient performance and improve the voltage stability of power systems which includes a large wind farm [16,17]. However, the presence of some FACTS devices (such as SVCs) has an adverse impact on the dynamic stability of power systems [10, 16 - 19]. Power Oscillation damping controllers are usually then designed for enhancing the system stability [20 – 22].

The objectives of this paper include studying the impact of the wind power penetration on the small signal stability of power systems. In addition, high power system oscillations are mitigated by the proper design of power oscillation dampers (PODs) integrated with the available SVCs. The major types of WTG technologies are considered while two wind power scenarios are investigated. The first one is the replacement of conventional power by wind power while the second one is the addition of wind power to the generation capacity. The Kundur two-area system [18] is considered in this study due to its suitability for the analysis of complex dynamic phenomena as well as the availability of its data.

## II. The Study System, Modeling, and Modal Analysis

### A. *The Study System*

The study system is shown in Fig.1. The system data are available at [18]. This system will be studied and analyzed with the aid of the Power System Analysis Toolbox (PSAT) version 2.1.7, the Simulink and the control system toolbox of Matlab 2012a [23 - 25].

The original four-machine, two-area study system has been taken from [18] and has been modified by replacing the old fixed capacitors at buses 7 and 9 by SVCs as shown in Fig. 2 which also shows the PSAT Simulink model of the system. Each area consists of two synchronous generator units. The rating of each synchronous generator is 900 MVA and 20 kV. Each of the units is connected through transformers to the 230 kV transmission line. There is a power transfer of 400 MW from Area 1 to Area 2. The detailed base data, the line data, and the dynamic parameters for the machines, AVRs, PSS, and loads are given in [18].

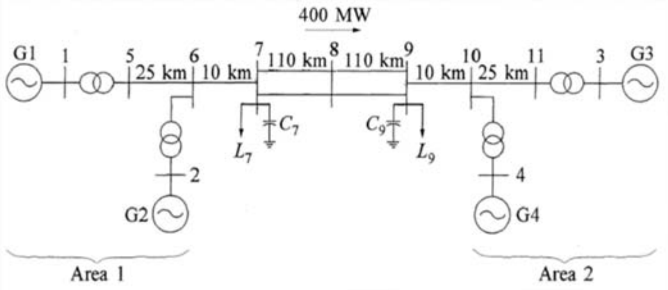



Fig. 1 The study system

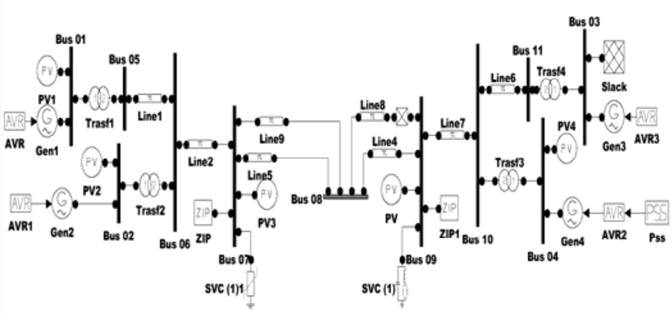



Fig. 2 The study system model in PSAT

The wind power is included in the system considering two scenarios where two situations are considered in each scenario. A scenario is associated with the WTG technology while a situation is associated with the way at which the wind power is included. The first scenario considers the fixed-speed SCIG while the second one considers the variable-speed DFIG. For both scenarios the following situations are considered.

- *Situation 1*: the wind power will be used to replace a specific amount of the conventional generation in area 1. The objectives here are to reduce the ecological impact of the conventional generation and to reduce the dependency on fossil fuels.
- *Situation 2*: The wind power will be added to the conventional generation capacity available in area 2. The main objective in this case is to reduce the dependency of area 2 on area 1 i.e. the minimization of the power transfer over the weak tie-link.

As will be illustrated, the maximum or allowable amounts of wind power for both scenarios and both situations will be determined based on the modal analysis of the system. In addition, the PODs will be designed while the wind power is very close to its allowable limits.

*B. Power system modelling and modal analysis*

The power systems are dynamic systems that can be represented by differential algebraic equations in combination with non-linear algebraic equations. Hence, a power system can be dynamically described by a set of $n$ first order nonlinear ordinary differential equations that are to be solved simultaneously. In vector-matrix notation, these equations are expressed as follows [18, 20, 26]:

$$\dot{x} = f(x,u) \tag{1}$$

$$y = g(x,u) \tag{2}$$

where: $x = [x_1, x_2 \cdots x_n]^t$, $u = [u_1, u_2 \cdots u_r]^t$, $f = [f_1, f_2 \cdots f_n]^t$ , $y = [y_1, y_2 \cdots y_m]^t$ , $g = [g_1, g_2 \cdots g_m]^t$,

$n$ is the order of the system, $r$ is the number of inputs, and $m$ is the number of outputs. The column vector $x$ is called the state vector and its entries are the state variables. The vector $u$ is the vector of inputs to the system, which are external signals that have an impact on the performance of the system. The output variables $y$ are those that can be observed in the system. The column vector y is the system output vector and $g$ is the vector of nonlinear functions defining the output variables in terms of state and input variables.

The design of POD controllers is based on linear system techniques. After solving the power flow problem, a modal analysis is carried out by computing the eigenvalues and the participation factors of the state matrix of the system. The dynamic system is put into state space form as a combination of coupled first order, linearized differential equations that take the form,

$$\Delta\dot{x} = A\Delta x + B\Delta u \tag{3}$$

$$y = C\Delta x + D\Delta u \tag{4}$$

where $\Delta$ represents a small deviation, $A$ is the state matrix of size $n \times n$, $B$ is the control matrix of size $n \times r$, $C$ is the output matrix of size $m \times n$, and $D$ is the feed forward matrix of size $m \times r$. The values of the matrix $D$ define the proportion of input, which appears directly in the output.

The eigenvalues $\lambda$ of the state matrix $A$ can be determined by solving $\det[A - \lambda I] = 0$. If $\lambda_i = \sigma_i \pm j\omega_i$ denotes the $i^{th}$ eigenvalue of the state matrix $A$, then the real part gives the damping, and the imaginary part gives the frequency of oscillation. The relative damping ratio is then given by:

$$\xi_i = -\sigma_i / \sqrt{\sigma_i^2 + \omega_i^2} \tag{5}$$

A damping ratio between 5% to 10% is acceptable for most power systems; however, the 10% value is recommended for secure system operation [20, 28].

The models of SVC, SCIG and DFIG are described in [23, 24, 28].

## III. POD Design

A variety of design methods can be used for tuning POD parameters. The most common techniques are based on frequency response [29], pole placement [30], eigenvalues sensitivity [30, 31] and residue method [32].

Due to their popularity and efficiency, POD designs are presented in this paper using the frequency domain which is described in [20, 27] and the POD will be designed near the maximum wind penetration points. A flowchart showing the POD design process is shown in the Appendix. The main design objective is to achieve a predefined damping acceptable level of the electromechanical oscillations to improve the system performance. The general control diagram of the power system controlled by the POD is shown in Fig. 3 and 4. As shown in Fig. 4, The structure of the POD controller is similar to the classical power system stabilizer (PSS). The controller consists of a stabilizer gain, a washout filter, and phase compensator blocks. The gain $K_w$ determines the amount of damping introduced by the POD and the phase compensator blocks provides the appropriate phase lead-lag compensation of the input signal.

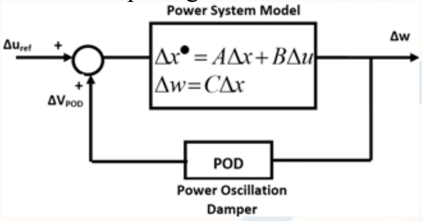



Fig.3 General feedback control system

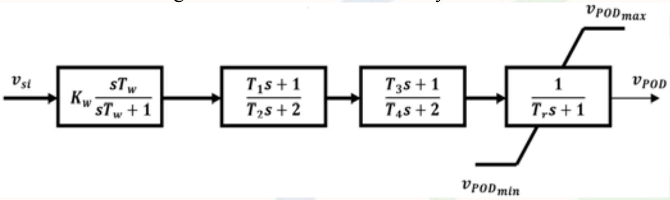



Fig.4: Scheme of the POD controller

## IV. Results and Discussion

The results will be presented through studying the system described in Fig.1 considering the scenarios and situations explained in section II. The maximum wind penetration that can be replaced or added is determined based on the eigenvalues criteria. Near the maximum penetration point, POD will be designed using the frequency response method to improve the system dynamic performance when the system is subjected to a small disturbance (disconnection of line 8 for 100 msec after 1 sec operation in the initial steady state conditions). The data of the SCIG wind turbine can be found in [33] while the DFIG data are available at [34].

*1) Scenario 1: SCIG:*

*A) Power Replacement*

the SCIG will be added to area 1 on bus 12 as shown in Fig.5 for the purpose of replacing the generated power of synchronous generators by wind power till reaching the maximum wind penetration

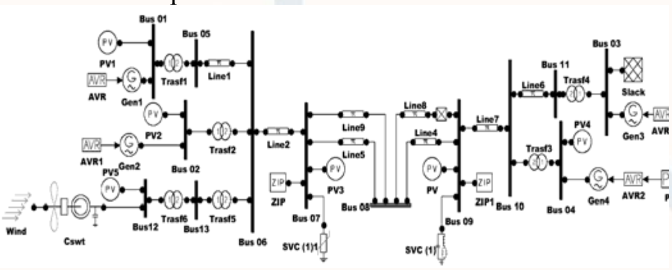


Fig.5 Two-area test system with SCIG added to Area 1 connected to bus 12

The eigenvalues with low damping ratios are shown in Table I. According to the results in Table I, The maximum generated power in area 1 that can be replaced by wind power equals 140 MW (10% of the total generated power by synchronous generators in Area 1) and after this value the system will be unstable as there is an existence of an eigenvalue located in the unstable region.

TABLE I
SCENARIO 1.A - DOMINANT EIGENVALUES AND PARTICIPATION

| | Eigenvalues | f (Hz) | ξ (%) | Most associated states | Eigenvalue Status |
|---|---|---|---|---|---|
| $P_1+P_2$=1260MW $P_{12}$=140MW | -0.59442±j6.5443 | ١,٠٤٥٨ | 9.04% | δ2 ,ω2 | Unacceptable |
| | -0.15025±j3.821 | ٠,٦٠٨٦ | 3.9% | δ3 ,ω3 | Critical |
| $P_1+P_2$=1250MW $P_{12}$=150MW | -0.57982±j6.5303 | ١,٠٤٣٤ | 8.88% | δ2 ,ω2 | unacceptable |
| | -0.14699±j3.8239 | ٠,٦٠٩٠٣ | 3.86% | δ3 ,ω3 | Critical |
| | -0.42722±j7.0026 | ١,١١٦٦ | 6.08% | omega_t_Cswt_1, gamma_Cswt | unacceptable |
| | 0.12483+j0 | 0 | ------- | e1m_Cswt_1 | +ve Eigenvalue |

The POD is then designed near the maximum wind penetration point ($P_{12}$=140 MW) with the objective of increasing the damping ratios of the eigenvalues to an acceptable level. According to Table I, at $P_{12}$ = 140 MW, there is a critical eigenvalue with damping ratio 3.9% and an unacceptable eigenvalue with damping ratio 9.04%. These damping ratios can be increased to acceptable levels (≥10%) by designing a POD. The sending current between Bus 5 and Bus 6 is used as a stabilizing signal to the POD. The POD gain ($K_w$) is selected based on the root-locus of the system as shown in Fig. 6. It is shown that with a again of 0.114 the 3.9% damping ratio becomes 23.88% while the 9.04% damping ratio becomes 10.7%. Therefore, this gain value results in acceptable damping ratios.

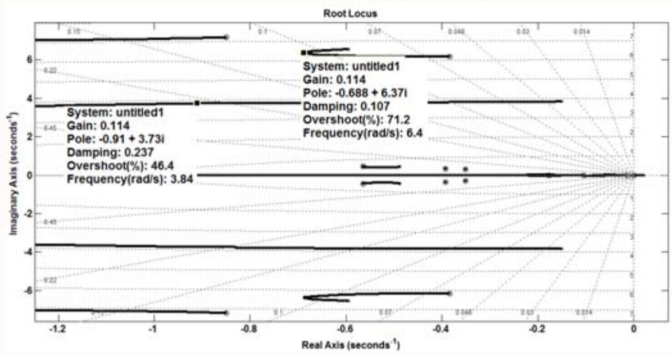



Fig. 6 Root locus of the compensated system and selection of the gain *Kw* for Scenario 1.A

Using the frequency domain POD design method [20, 27], the rest of the POD parameters are determined. The transfer function of the POD is, then takes the form

$$POD(s) = 0.114 \left[\frac{s}{s+1}\right] \left[\frac{0.3186s+1}{0.215s+1}\right]^2 \quad (6)$$

With the POD connected to the system shown in Fig. 5 as shown in Fig. 7, the design will be evaluated by both the eigenvalue analysis and the TDS of the compensated system. The results of the eigenvalue analysis of the compensated system indicate that the minimum damping ratios of the critical and unacceptable eigenvalues are improved as desired to 23.88% & 10.7% respectively. This ensures the success of the POD design for improving the damping of the system.

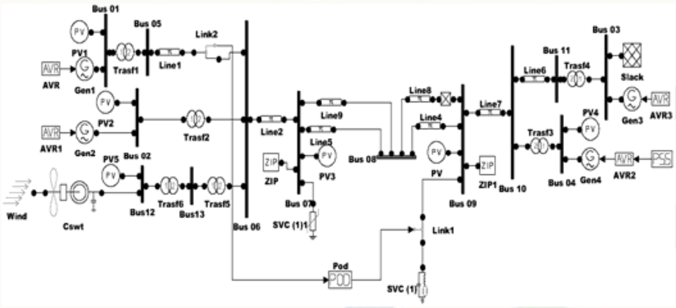
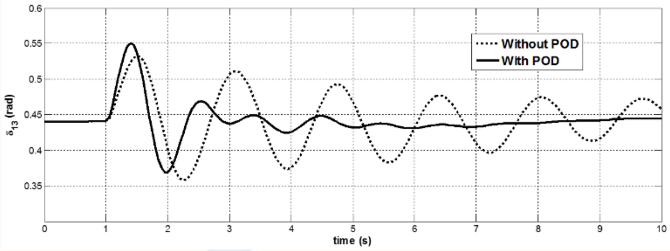
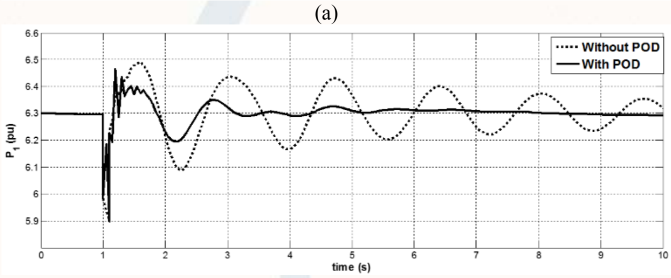


Fig.7 Two area test system with SCIG added to Area 1 and POD

The TDS is performed considering a disconnection of line 8 for 100 msec. This disturbance started at t = 1 sec. The simulation is performed using the Matlab control system toolbox. The responses of the system with and without POD are compared as shown in Fig. 8.




(a)




(b)

Fig. 8 TDS for 100msec disconnection of line8: (a) Rotor angle of G1; (b) Active power of G1.

It is depicted from Fig. 8 that the POD improves the dynamic performance of the system through increasing the system damping, and decreasing the settling time.

*B) Power Addition:*

The SCIG in this section will be added to area 2 on bus 12 for the purpose of reducing the power transfer from area 1 to area 2 by adding generated power by SCIG in area 2 till reaching the maximum wind penetration.

The eigenvalues with low damping ratios will be tabulated in Table II as follow:

TABLE II

SCENARIO 1.B - DOMINANT EIGENVALUES AND PARTICIPATION FACTORS

| | Eigenvalues | f (Hz) | ξ (%) | Most associated states | Eigenvalue Status |
|---|---|---|---|---|---|
| $P_{12}$=140 MW | -0.59524±j6.5765 | ١,٠٥١ | 9.02% | δ2 ,ω2 | Unacceptable |
| | -0.17052±j3.9459 | ٠,٦٢٨٦ | 4.31% | δ3 ,ω3 | Critical |
| $P_{12}$=150 MW | -0.60136±j6.5699 | ١,٠٥ | 9% | δ2 ,ω2 | unacceptable |
| | -0.16879±j3.9522 | ٠,٦٢٩٥٨ | 4.3% | δ3 ,ω3 | Critical |
| | -0.57935±j6.9841 | ١,١١٥٤ | 8.28% | gamma_Cswt_1, e1m_Cswt_1 | unacceptable |
| | 0.17508+j0 | 0 | ------- | e1m_Cswt_1 | +ve Eigenvalue |

According to the results in Table II, The maximum wind power that can be added to area 2 equals also to 140 MW and the system will be unstable when the generated power by SCIG equals 150 MW.

The POD is then designed near the maximum wind penetration point ($P_{12}$=140 MW) with the objective of increasing the damping ratios of the eigenvalues to an acceptable level. According to Table II, at $P_{12}$ = 140 MW, there is a critical eigenvalue with damping ratio 4.31% and an unacceptable eigenvalue with damping ratio 9.02%. These damping ratios can be increased to acceptable levels by designing a POD. The sending current between Bus 5 and Bus 6 is used as a stabilizing signal to the POD. The POD gain (Kw) is selected based on the root-locus. For a gain of 0.062, the 4.31% damping ratio becomes 17.2% while the 9.02% damping ratio becomes 10.16%. Therefore, this gain value results in acceptable damping ratios.

In this case, the transfer function of the POD will take the form:

$$POD(s) = 0.062\left[\frac{s}{s+1}\right]\left[\frac{0.3097s+1}{0.2074s+1}\right]^2 \qquad (7)$$

With the POD connected to the system as shown in Fig. 9, the design will be evaluated by the eigenvalue analysis, which indicates that the minimum damping ratios of the critical and unacceptable eigenvalues are improved as desired to 17.23% & 10.16% respectively.

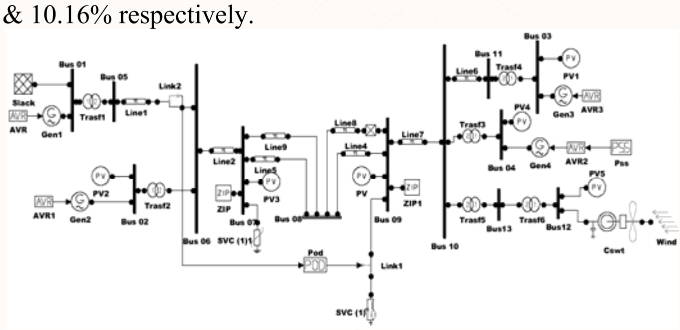
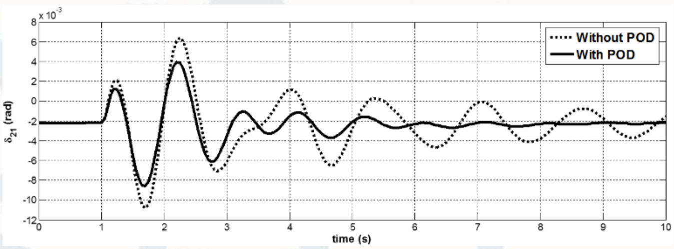
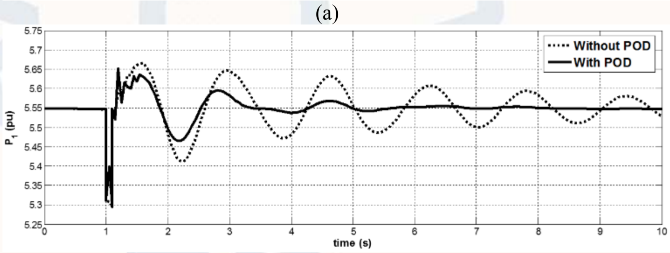


Fig.9 Two area test system with SCIG added to Area 2 and POD

The TDS of the compensated system is shown in Fig.10 considering the same disturbance to show the impact of POD on improving the damping of the system.




(a)




(b)

Fig. 10 TDS for 100msec disconnection of line8: (a) Rotor angle of G2; (b) Active power of G1.

*2) Scenario 2 with DFIG:*

### A) *Power Replacement:*

the DFIG will be added to area 1 on bus 12 for the purpose of replacing the conventional power by wind power till reaching the maximum wind penetration

The eigenvalues with low damping ratios will be tabulated in Table III as follow:

TABLE III

SCENARIO 2.A - DOMINANT EIGENVALUES AND PARTICIPATION FACTORS

| | Eigenvalues | f (Hz) | ξ (%) | Most associated states | Eigenvalue Status |
|---|---|---|---|---|---|
| $P_1+P_2$=900MW $P_{12}$=500MW | -0.81087±j6.2776 | ١,٠٠٧٤ | 12.8% | δ2 ,ω2 | acceptable |
| | -0.20784±j4.0177 | ٠,٦٤٠٢٨ | 5.16% | δ1 ,ω1 | Critical |
| $P_1+P_2$=850MW $P_{12}$=550MW | -0.85172±j6.2167 | ٠,٩٩٨٦٦ | 13.5% | δ2 ,ω2 | acceptable |
| | -0.22005±j4.0365 | ٠,٦٤٣٣٩ | 5.4% | δ1 ,ω1 | Critical |
| | -0.12055±j1.7216 | ٠,٢٧٤٦٧ | 7.04% | δ3 ,ω3 | unacceptable |
| | 0.008 ±j0 | 0 | ------ | omega_m_Dfig_1 | +ve eigenvalue |

According to the results in Table III, The maximum generated power in area 1 that can be replaced by wind power equals 500 MW (35.7% of the total generated power by synchronous generators in Area 1) and after this value the system will be unstable.

The POD is then designed near the maximum wind penetration point ($P_{12}$=500 MW) with the objective of increasing the damping ratios of the eigenvalues to an acceptable level. According to Table III, at $P_{12}$ = 500 MW, there is a critical eigenvalue with damping ratio 5.16%. This damping ratio can be increased to an acceptable level by designing a POD. The sending current between Bus 5 and Bus 6 is used as a stabilizing signal to the POD. The POD gain (Kw) is selected based on the root-locus. For a gain of 0.0283, the 5.16% damping ratio becomes 10%. Therefore, this gain value results in acceptable damping ratio.

In this case, the transfer function of the POD will be as follow:

$$POD(s) = 0.0283\left[\frac{s}{s+1}\right]\left[\frac{0.2871s+1}{0.2158s+1}\right]^2 \qquad (8)$$

With the POD connected to the system as shown in Fig. 11, the design will be evaluated by the eigenvalue analysis which indicates that the minimum damping ratios of the critical is improved as desired to 10%. the TDS of the compensated system is shown in Fig.12 to show the impact of POD on improving the damping of the system.

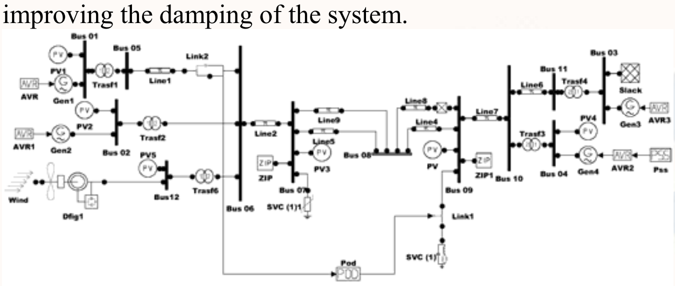
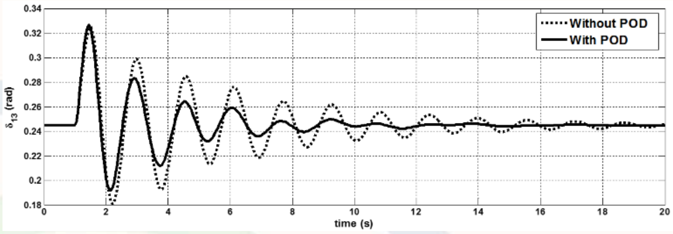
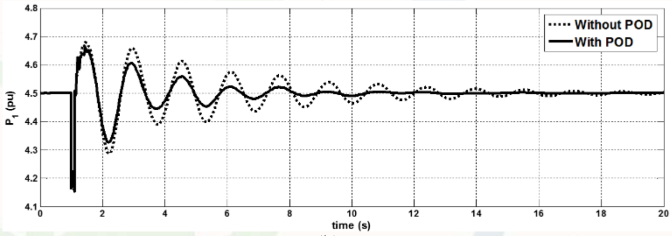



Fig.11 Two area test system with DFIG added to Area 1 and POD




(a)




(b)

Fig. 12 TDS for 100msec disconnection of line8: (a) Rotor angle of G1; (b) Active power of G1.

### B) *Power Addition:*

The DFIG in this section will be added to area 2 on bus 12 for the purpose of reducing the power transfer from area 1 to area 2 by adding generated power by DFIG in area 2 till reaching the maximum wind penetration. The eigenvalues with low damping ratios will be tabulated in Table IV as follow:

TABLE IV

SCENARIO 2.B - DOMINANT EIGENVALUES AND PARTICIPATION FACTORS

| | Eigenvalues | f (Hz) | ξ (%) | Most associated states | Eigenvalue Status |
|---|---|---|---|---|---|
| $P_{12}$=350 MW | -0.78117±j6.3636 | ١,٠٢٠٤ | 12.3% | δ2 ,ω2 | acceptable |
| | -0.27893±j4.182 | ٠,٦٦٧٠٦ | 6.65% | δ3 ,ω3 | Critical |
| $P_{12}$=400 MW | -0.83732±j6.2965 | ١,٠١٠٩ | 13.0%6 | δ2 ,ω2 | acceptable |
| | -0.30421±j4.2103 | ٠,٦٧١٨٣ | 7.1% | δ3 ,ω3 | Critical |
| | -0.22003±j1.3624 | ٠,٢١٩٦٤ | 16.6% | δ1 ,ω1 | acceptable |
| | -0.00074±j0 | --------- | -------- | omega_m_Dfig_1 | +ve eigenvalue |

According to the results in Table IV, The maximum wind power that can be added to area 2 equals 350 MW and after this value the system will be unstable.

The POD is then designed near the maximum wind penetration point ($P_{12}$=350 MW) with the objective of increasing the damping ratios of the eigenvalues to an acceptable level. According to Table IV, at $P_{12}$ = 350 MW, there is a critical eigenvalue with damping ratio 6.65%. This damping ratio can be increased to an acceptable level by designing a POD. The sending current between Bus 5 and Bus 6 is used as a stabilizing signal to the POD. The POD gain (Kw) is selected based on the root-locus. For a gain of 0.03, the 6.65% damping ratio becomes 18%. Therefore, this gain value results in acceptable damping ratio.

the transfer function of the POD will take the form:

$$POD(s) = 0.03\left[\frac{s}{s+1}\right]\left[\frac{0.3365s+1}{0.1699s+1}\right]^2 \qquad (9)$$

With the POD connected to the system as shown in Fig. 13, the design will be evaluated by the eigenvalue analysis, which indicates that the minimum damping ratios of the critical is improved as desired to 18%. The TDS of the compensated system is shown in Fig.14 to show the impact of POD on improving the damping of the system.

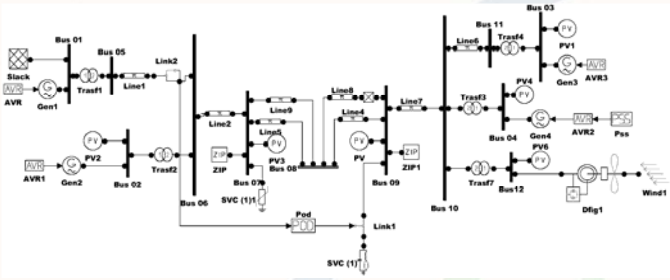
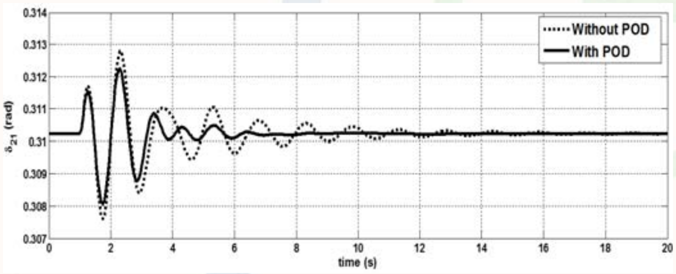
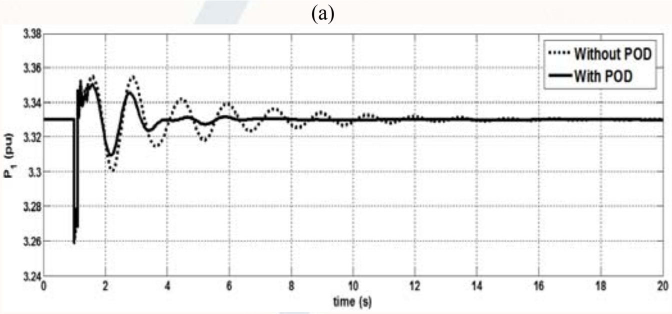


Fig.13 Two area test system with DFIG added to Area 2 and POD




(a)




(b)

Fig. 14 TDS for 100msec disconnection of line8: (a) Rotor angle of G2; (b) Active power of G1.

## V. Conclusions

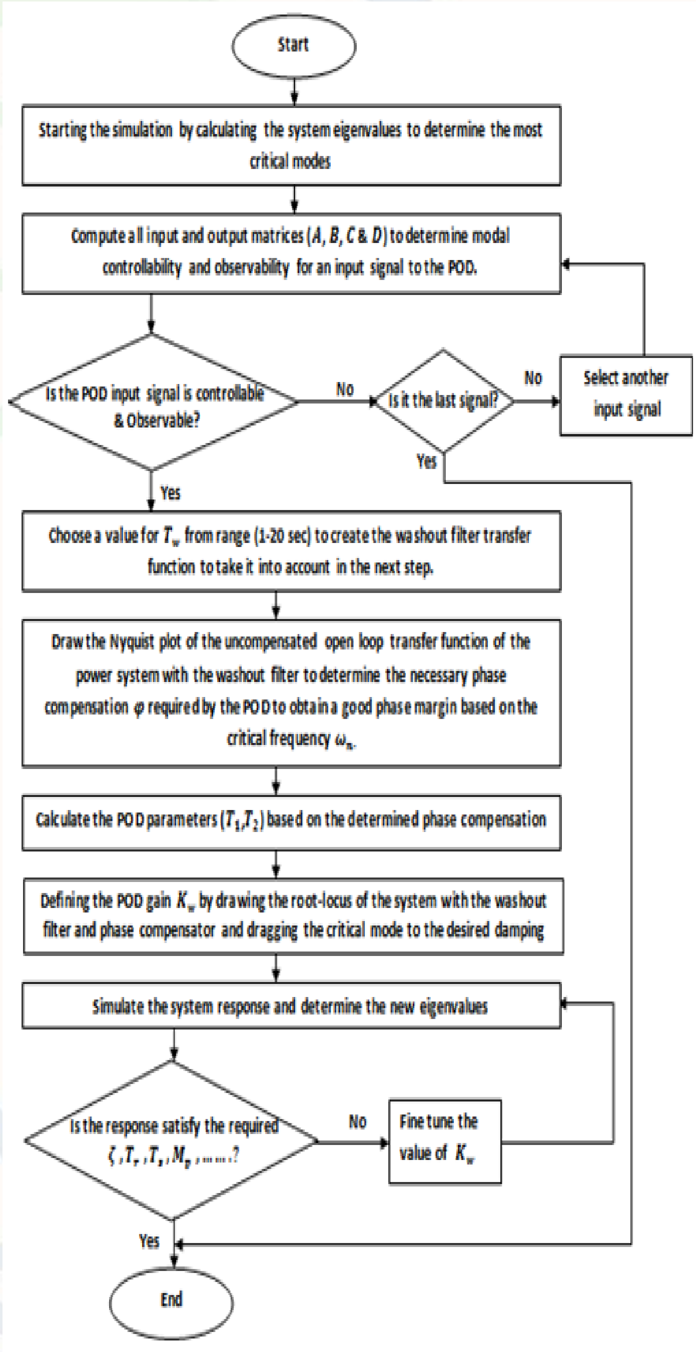
The increasing penetration of renewable energy sources has caused new challenges to the operation, control and stability of modern electric power systems. This paper investigates the application of the POD based FACTs devices to enhance the dynamic performance of power systems which includes wind farm.

The POD has been designed using the frequency response method in the two area test system which includes FACTS-SVCs and two types of WTGs which are SCIG and DFIG. The design steps of POD have been achieved near the maximum penetration points which have been evaluated using two different criteria (replacement and addition).

Results show that the maximum wind penetration of the power system, including DFIG is more than that which includes SCIG. The POD in both cases provides an effective mean to enhance the small signal stability of the power system which is subjected to small disturbance the results were confirmed by both the eigenvalues and time domain simulation.

## Appendix

POD design by the frequency response method – flowchart.



## References

[1] M. EL-Shimy. "Viability Analysis of PV Power Plants in Egypt," Renewable Energy, Vol. 34, No. 10, 2009, pp. 2187-2196.

[2] M. EL-Shimy. "Optimal site matching of wind turbine generator: case study of the Gulf of Suez region in Egypt," Renewable Energy, Vol. 35, No. 8, 2010, pp. 1870-1878.

[3] M. EL-Shimy. "Adequacy-Based Placement of WECS in Egypt," presented at the MEPCON'08 IEEE International Conference, Aswan, Egypt, 2008.

[4] New & Renewable Energy Authority (NREA) of Egypt. Available: http://nrea.gov.eg/english1.html

[5] M. EL-Shimy, "Probable Power Production in Optimally Matched Wind Power Systems," International journal of Sustainable Energy Technologies and Assessments (SETA).2, pp. 55–66, 2013.

[6] M. EL-Shimy, "Wind Energy Conversion Systems: Reliability Prospective," *Encyclopedia of Energy Engineering and Technology*, vol. 2, pp. 2184 - 2206, 2014.

[7] M. EL-Shimy and N. Ghaly, "Grid-Connected Wind Energy Conversion Systems: Transient Response," Taylor & Francis - Encyclopedia of Energy Engineering and Technology, CRC Press, 2014.

[8] R. Zavadil, N. Miller, A. Ellis and E. Muljadi., "Queuing up," Power and Energy Magazine, IEEE, vol. 5, pp. 47-58, Nov.-Dec 2007.

[9] J. Slootweg and W. Kling, "The impact of large scale wind power generation on power system oscillations," Electric Power Systems Research, vol. 67, pp. 9-20, October 2003.

[10] EL-Shimy M, Badr MAL, Rassem OM. Impact of Large Scale Wind Power on Power System Stability. MEPCON'08 IEEE International Conference; 12 – 15 March 2008; Aswan, Egypt, 2008. p. 630 – 636.

[11] P. Ledesma and C. Gallardo, "Contribution of variable-speed wind farms to damping of power system oscillations," presented at the Power Tech, 2007 IEEE Lausanne, Lausanne, 2007.

[12] N. Ghaly, M. EL-Shimy, M. Abdelhamed, "Consistence of Wind Power Technologies with the Fault Ride-through Capability Requirements," presented at the MEPCON'14 IEEE International Conference, Cairo, Egypt, 2014.

[13] Z. Chen, "Issues of connecting wind farms into power systems," presented at the Transmission and Distribution Conference and Exhibition: Asia and Pacific, 2005 IEEE/PES, Dalian, 2005.

[14] M. EL-Shimy, "Modeling and analysis of reactive power in grid-connected onshore and offshore DFIG-based wind farms," *Wind Energy*, vol. 17, no. 2, pp. 279–295, 2014

[15] M. Ahmed, M. EL-Shimy, and M. Badr, "Advanced modeling and analysis of the loading capability limits of doubly-fed induction generators," Sustainable Energy Technologies and Assessments, vol. 7, pp. 79-90, 2014.

[16] W. Qiao, Harley, R.G. and Venayagamoorthy, G.K., "Effects of FACTS Devices on a Power System Which Includes a Large Wind Farm," presented at the Power Systems Conference and Exposition, 2006. PSCE '06. 2006 IEEE PES, Atlanta, GA, 2006.

[17] M. Fazli, A.R. Shafighi, A. Fazli and H.A. Shayanfar, "Effects of STATCOM on wind turbines equipped with DFIGs during grid faults," presented at the World Non-Grid-Connected Wind Power and Energy Conference (WNWEC), Nanjing, 2010.

[18] P. Kundur, "Power system stability and control", New York: McGrew Hill, (1994).

[19] T. Ackermann, Wind power in power systems vol. 140. Chichester, UK: John Wiley, 2005.

[20] M. Mandour, M. EL-Shimy, F. Bendary, and W.M.Mansour , "Damping of Power Systems Oscillations using FACTS Power Oscillation Damper – Design and Performance Analysis", MEPCON'14 IEEE International Conference; Dec. 23 – 15, 2014, Cairo, Egypt, 2014.

[21] R. Sadikovic, P. Korba and G. Andersson, "Application of FACTS devices for damping of power system oscillations," presented at the IEEE Power Tech, St. Petersburg, Russia, June 2005

[22] Martins, Nelson, H. J. C. P. Pinto, and John J. Paserba, "Using a TCSC for line power scheduling and system oscillation damping-small signal and transient stability studies," *Proceedings of IEEE PES Winter Meeting*. Vol. 2. 2000.

[23] F. Milano. PSAT version 2.1.7 Available: http://www3.uclm.es/profesorado/federico.milano/psat.htm.

[24] F. Milano, "An Open Source Power System Analysis Toolbox" IEEE Transactions on Power Systems," IEEE Transactions on Power Systems, vol. 20, Aug 2005.

[25] I. The MathWorks. MATLAB and Simulink R2012a. Available: http://www.mathworks.com

[26] C. E. Ugalde-Loo, et al., "Multi-machine power system state-space modelling for small-signal stability assessments," Applied Mathematical Modelling, vol. 37, pp. 10141-10161, 15 December 2013.

[27] H. M. Ayres, I. Kopcak, M. S. Castro, F. Milano and V. F. d. Costa, "A didactic procedure for designing power oscillation damper of facts devices", Simulation Modelling Practice and Theory, vol.18, no.6 June 2010.

[28] F. Milano, Power System Analysis Toolbox – Documentation for PSAT Version 2.0.0, Feb 2008.

[29] N. Martins and L. Lima, "Eigenvalue and Frequency Domain Analysis of Small-Signal Electromechanical Stability Problems," IEEE Symposium on Application of Eigenanalysis and Frequency Domain Method for System Dynamic Performance, 1989.

[30] B. C. Pal, "Robust pole placement versus root-locus approach in the context of damping interarea oscillations in power systems," IEE Proceedings on Generation, Transmission and Distribution, vol. 149, Nov 2002.

[31] R. Rouco and F. L. Pagola, "An eigenvalue sensitivity approach to location and controller design of controllable series capacitors for damping power system oscillations," IEEE Transactions on Power Systems, vol. 12, Nov 1997.

[32] R. Sadikovic, et al., "Application of FACTS devices for damping of power system oscillations," presented at the IEEE Power Tech, St. Petersburg, Russia, June 2005.

[33] J. C. Munoz and C. A. Canizares, "Comparative stability analysis of DFIG-based wind farms and conventional synchronous generators," presented at the Power Systems Conference and Exposition (PSCE), 2011 IEEE/PES, Phoenix, AZ, 2011.

[34] B. Mehta, et al., "Small signal stability analysis of power systems with DFIG based wind power penetration," International Journal of Electrical Power & Energy Systems, vol. 58, pp. 64-74, June 2014