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Small Signal Stability Performance of Power System during High Penetration of Wind Generation

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***Abstract*- The small signal stability of interconnected power systems is one of the important aspects that need to be investigated since the oscillations caused by this kind of instability have caused many incidents.**

With the increasing penetration of wind power in the power system, particularly doubly fed induction generator (DFIG), the impact on the power system small signal stability performance should be fully investigated. Because the DFIG wind turbine integration is through a fast action converter and associated control, it does not inherently participate in the electromechanical small signal oscillation. However, it influences the small signal stability by impacting active power flow paths in the network and replacing synchronous generators that have power system stabilizer (PSS).

In this paper, the IEEE 39 bus test system has been used in the analysis. Furthermore, four study cases and several operation scenarios have been conducted and analysed. The selective eigenvalue Arnoldi/lanczos's method is used to obtain the system eigenvalue in the range of frequency from 0.2 Hz to 2 Hz which is related to electromechanical oscillations.

Results show that the integration of DFIG wind turbines in a system during several study cases and operation scenarios give different influence on small signal stability performance.

***Index Terms*-Arnoldi/Lanczos method, DFIG, DIgSILENT, eigenvalue analysis, power system operation, small signal stability, transient stability.**

I. INTRODUCTION

In order to reduce greenhouse gas (GHG) emission and give concern to climate change, The Kyoto Protocol, as an international agreement has been established in Kyoto on 11 December 1997. The major concern of this agreement is to set a target for industrialized countries and the European Community to reduce GHG [1]. This agreement has encouraged industrialized countries to minimize the using of fossil fuel for power plant. The European Union has planned to increase the contribution of renewable electricity technology up to 39.80% in 2020 [2]. Furthermore, efforts are being made to use renewable sources to generate electricity. Among the various renewable sources, wind power is predicted to have the highest contribution [2].

With the increasing penetration of wind power in the power system, the impact in power system performance should be fully investigated, particularly for doubly fed induction generation (DFIG) wind turbine since this type of renewable source is gaining prominence in the power system industry. Power system stability is one of the important aspects that need to be investigated particularly small signal stability since the oscillations caused by this kind of stability have caused many incidents [3].

Several research efforts have been developed to analyse the influence of wind turbine generators on small signal stability. It is reported in article [4], the impact of DFIG wind farm penetration and voltage control loop on power system oscillation. The study used a two area and four machine power system. The DFIG control was adopted using the general electric (GE) model [5]. These results showed that, by increasing the penetration level of DFIG wind turbines, it provided significant system damping. Furthermore, the increasing gain in the voltage control loop of DFIG enhanced system damping as well.

The impact of DFIG wind farm on power system oscillations was also reported in article [6]. The results showed that by increasing the level penetration of DFIG wind farm into power system, it enhanced inter-area oscillation damping. On the other hand, with the presence of DFIG wind farm, the inter-area frequency mode was increased significantly.

Other published work that used factual equivalent Australian power system with DFIG penetration has been investigated in [7]. Different capacities of DFIG have been analysed to obtain the influence on dynamic system stability. It is observed that high levels of wind capacity influence inter area modes and when contingency is applied in the system the value of inter-area damping modes fall below an acceptable level [7].

Integration of DFIG wind turbines do not inherently participate in the electromechanical small signal oscillation mode since its operation is determined by the converter and associated control. However, the DFIG will influence small signal oscillation mode through four mechanisms, i.e.: displacing synchronous generator, impacting major paths flows, displacing synchronous generator that have power system stabilizer and DFIG control with the damping torque on nearby large synchronous generator [8].

In this paper, the small signal stability performance of the power system is analysed using IEEE 39 bus test case system. To get more detailed analysis about the benefit and detrimental effect of DFIG penetration into the small signal stability, four study cases have been implemented and analysed where each study case has its own network topology and operation scenario to reflect the influence of DFIG wind turbine on small signal performance through the first three mechanisms listed above.

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II. Test System in DIgSILENT

A. IEEE 39 Bus Test System

The IEEE 39 bus equivalent power system [9] shown in Fig. 1 has been constructed using DIgSILENT PowerFactory simulator [10] and used to analyse the small signal stability performance of power system during penetration of DFIG wind turbine. This test system is a well-known 10 machine power system. Generator G1 represents the aggregation of a large number of generators.

The IEEE 39 bus test system is divided into three generic areas as follow: area 1 has three generators G1, G2 and G3 and area 2 has three generators G8, G9 and G10 while area 3 has four generators G4, G5, G6 and G7.

It is clear from Fig. 1 that the system has 4 interconnectors connecting the areas. Area 1 and area 2 is connected via 2 interconnectors between bus 1 and bus 39 and between bus 3 and bus 4. Furthermore, two other interconnectors between bus 14 and 15 and between bus 16 and bus 17 are connecting area 1 to area 2 and area 2 to area 3 respectively.

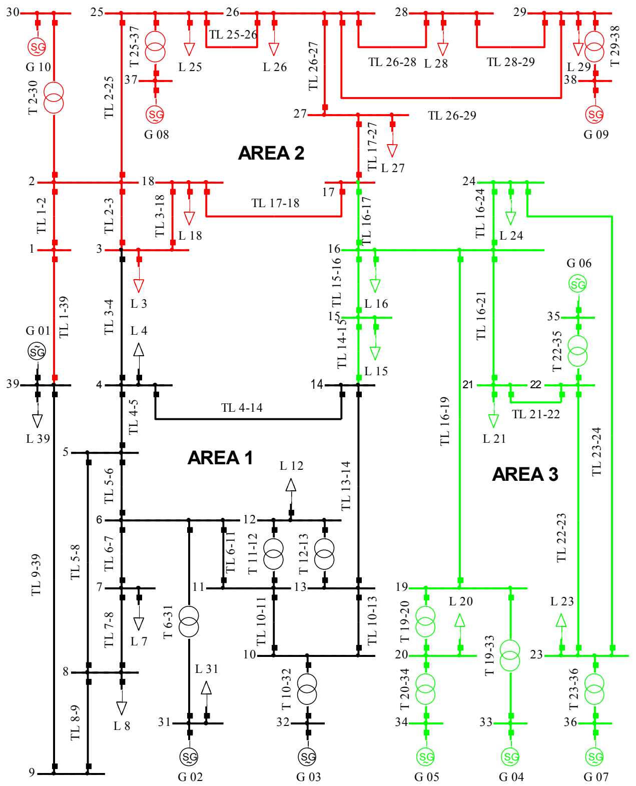

Fig. 1. IEEE 39 bus test system

In this paper, all generators are modelled as 6th order synchronous machines where the parameters are obtained from [9]. These synchronous machines data from [9] are in 4th order while DIgSILENT model requires the 6th order for the synchronous machine model thus some assumptions need to be made as follows: T_{do}'' and T_{qo}'' are set to 0.001 s while x_d'', x_q'' is set equal to $x_l(1+\varepsilon)$ where $\varepsilon = 0.001$.

B. Automatic Voltage Regulator and Power System Stabilizer Model

Each synchronous generator is equipped with an automatic voltage regulator (AVR) as represented in Fig. 2 which has been modelled using DIgSILENT Simulation Language (DSL) [11].

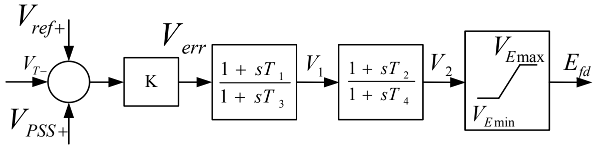

Fig. 2. AVR model

Furthermore, Fig. 3 represent the power system stabilizer (PSS) installed in each synchronous generator where the parameter data can be found in [12]. It can be seen from Fig. 3 that the PSS uses generator speed as feedback to change the input signal of the AVR.

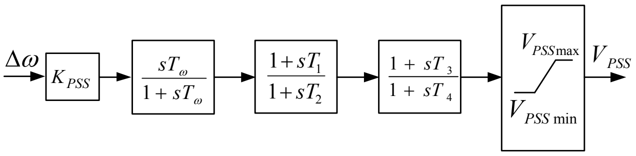

Fig. 3. PSS model

C. Doubly Fed Induction Generator Wind Turbine Simulation Model

A typical configuration of doubly fed induction generator (DFIG) wind turbine is shown in Fig. 4 [13]. Basically, several major components contribute to the dynamic performance of a DFIG wind turbine.

The frequency converter is set up by two PWM converters with an intermediate DC voltage circuit. The rotor side converter (RSC) is used to regulate the active and reactive component of the rotor current while grid side converter (GSC) can be used for optimum reactive power sharing between the generator and GSC [14]. In this paper, a generator with an output of 3.6 MW is used for building up the wind farm.

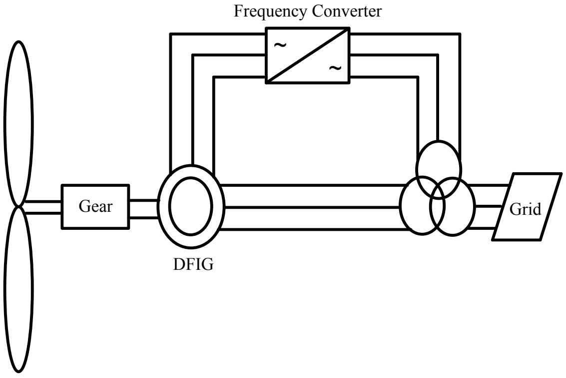

Fig. 4. Doubly Fed Induction Generator

D. Study Case and Operation Scenario

Four study cases and several operation scenarios in each study case have been analysed in this paper and a brief description of each study case is outlined below:

Case I: This is a base case operation scenario of the IEEE 39 test case as it is described in [9]. Total load in the system is 6,097.10 MW which is supplied by 10 synchronous generators.

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Case II: DFIG wind turbine is integrated at the same bus of synchronous generations. The DFIG is operated at unity power factor control mode where it only supplies active power to the system. Increasing active power (from around 10% until 40% of load demand) from the DFIG wind turbine is followed by reducing the same amount of synchronous generator active power at the same location.

Case III: All synchronous generators in each area were replaced by DFIG wind turbine alternately. The capacity of DFIG is set similar to synchronous generator capacity in that area and it operates at power and voltage control mode.

Case IV: This it is used to analyse the influence of DFIG wind turbine on small signal stability performance by impacting major paths flows. DFIG wind turbine is integrated in each area with the same capacity. Changing major paths is created by switching off two generators in each area to accommodate power supply from the wind.

III. METHOD

A. Small Signal Stability

The electromechanical oscillation that occurs in the power system is called the power system oscillation, with frequency oscillation up to a couple of Hertz. This oscillation is part of the stability criteria and is usually characterized as small signal (or small-disturbance) stability. Small signal stability is the ability of the power system to maintain synchronism under small disturbances. Such disturbances occur continually on the system because of small variations in load and generation [15].

Modal analysis is one of the methods to analyse the behaviour of small signal stability. This method is from the modal control theory where a power system may be described by a set of *n* first order nonlinear differential equations. The linearized form of the system is called the ABCD state space model.

Once the state space model is obtained, the eigenvector and eigenvalue can be computed using a state matrix A. Moreover, the oscillatory and non-oscillatory mode can be derived from eigenvalue while modes of oscillation can be obtained from eigenvector of matrix A. Real eigenvalues are non-oscillatory modes while complex eigenvalues are oscillatory modes. The oscillation is said to be asymptotically stable when complex eigenvalues have a negative real part.

Furthermore, when at least one of the eigenvalues has a positive real part, the original system is unstable. A system with the real part of the eigenvalue equal to zero means it is not possible to say anything in the general [15].

In this paper, the selective modal analysis using Arnoldi/Lanczos's method was used to obtain the small signal stability performance of the power system. This method is very useful since it has the ability to select the eigenvalue of the system in the specific predetermined range of frequency mode (i.e. from 0.1 Hz until 2 Hz in the case of electromechanical oscillation).

IV. RESULT AND ANALYSIS

A. Case I: Base Case

The case I describes a base case operation of the IEEE 39 bus system without any wind power connected to the system. Table I represents system modes related to the electromechanical low frequency oscillation. All of the modes are considered as small signal stability stable since all of the modes have damping ratio higher than 5%. It is not surprising since all of the synchronous generators have a power system stabilizer that can improve the damping ratio of the system. Mode 6 is an inter-area type mode between area 1 and area 3 with the lowest damping ratio at 12.8%.

TABLE I
FREQUENCY AND DAMPING RATIO
OF LOW FREQUENCY OSCILLATION MODES

Name	Frequency (Hz)	Damping Ratio	Mode Type
Mode 1	1.179	0.156	Inter Area 1,2
Mode 2	1.103	0.195	Inter Area 1,2,3
Mode 3	0.992	0.243	Inter Area 1,2,3
Mode 4	1.094	0.313	Inter Area 2,3
Mode 5	1.350	0.191	Intra Area 1
Mode 6	0.577	0.128	Inter Area 1,3
Mode 7	1.360	0.297	Intra Area 3
Mode 8	1.585	0.193	Local
Mode 9	1.675	0.233	Local
Mode 10	0.679	0.724	Inter Area 2,3
Mode 11	0.423	0.734	Inter Area 1,2

B. Case II: Sharing Power between Conventional Generator and DFIG

Table II presents the summary of the system active power flow and the percentage of DFIG wind turbine penetration for four different operation scenarios. Scenario I until scenario IV are the operation scenarios where DFIG wind turbine increasing from around 10% to 40% of its system demand. DFIG wind turbines were integrated in the same bus to the synchronous generators of the base case network. During this study case, DFIG wind turbines operated in unity power factor which means they only supplied active power to the network. Increasing active power coming from DFIG wind turbines in the system will be compensated by reducing the same amount of active power supplied by synchronous generators.

TABLE II
TOTAL GENERATION AND INTERCONNECTOR TRANSFER
FOR FIVE OPERATION SCENARIOS

Scenario	BC	I	II	III	IV
Active Power (MW)					
Synch Generator	6140.81	5519.09	4997.93	4277.35	3657.34
Load	6097.10	6097.10	6097.10	6097.10	6097.10
Grid Losses	43.71	41.7	38.8	37.85	37.03
Area 2 to Area 1	217.23	218.68	219.87	220.8	221.49
Area 3 to Area 2	229.68	229.83	229.94	230.01	230.05
Area 1 to Area 3	5.14	4.04	3.15	2.48	2.02
DFIG (%)	0.00	10.16	20.31	30.47	40.62

Fig. 5 describes the dynamics of the electromechanical modes of the system with different levels of DFIG wind turbine penetration in the system. It can be seen from Fig.5 that the increasing penetration of DFIG wind turbines in the system influences the oscillation modes.

Damping ratio for mode 1 and mode 2 decrease when the penetration level of DFIG wind turbines is increased. However, mode 2, mode 6 and mode 11 experienced a different influence. Their damping ratios are increased as

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level penetration increased. The frequency of mode 5 and mode 8 drops when the penetration level is increased while mode 4 and mode 10 do not have significant change in terms of frequency and damping ratio.

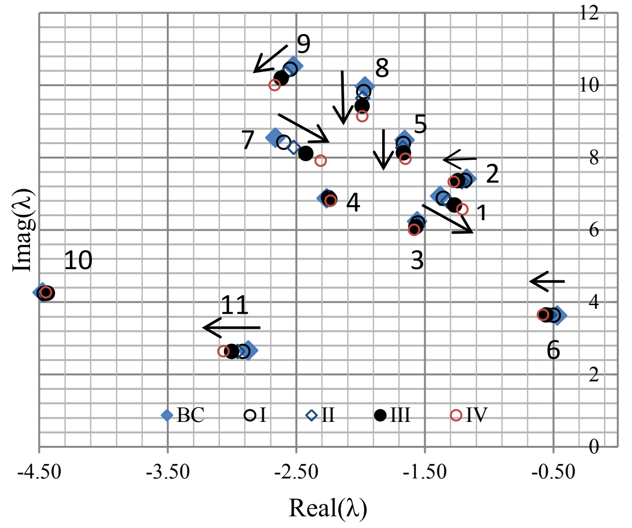

Fig. 5. System eigenvalue with different active power share between synchronous generator and DFIG wind turbine

From this result can be drawn an initial conclusion that, during the case II, integration DFIG wind turbines give different influences to the small signal stability performance of the system. Some damping ratios of electromechanical have been improved while other modes are decreasing.

C. Case III: Replacing Synchronous Generation with DFIG

Table III presents the summary of the system active power flow and the detrimental modes exist during case III.

TABLE III
TOTAL GENERATION AND INTERCONNECTOR TRANSFER FOR TWO NETWORK VARIATIONS

Scenario	**Scenario 1 DFIG Area 1**	**Scenario 2 DFIG Area 2**	**Scenario 3 DFIG Area 3**
Active Power (MW)			
Synch Generator	3940.16	4512.85	3779.7
Load	6097.10	6097.10	6097.10
Grid Losses	46.26	39.39	40.60
Area 2 to Area 1	199.97	221.83	222.69
Area 3 to Area 2	212.38	226.16	235.54
Area 1 to Area 3	17.53	1.84	0.61
DFIG (%)	36.14	26.63	36.67
Frequency (Hz)	1.104	0.555	1.148
Damping Ratio	0.173	0.057	0.151
Mode Type	Intra Area 2	Inter Area 1-3	Inter Area 1-2

Case III represents the small signal stability performance of IEEE 39 bus test system for the three different operation scenarios. Scenario 1, scenario 2 and scenario 3 are an operating condition when all synchronous generators in each area 1, area 2 and area 3 are replaced by DFIG wind turbines alternately. During case III, the DFIG operated on power and voltage control mode to allow it to absorb or supply reactive power to achieve bus bur (point connection) voltage as its voltage setting.

It can be seen from table III that the system is considered as stable since all damping ratios of detrimental modes in each scenario are higher than 5%. However, scenario 2 experienced a significant drop on damping ratio (i.e. 5.7%) compared to the small signal performance in the case I (i.e. lowest damping ratio mode is 12.8%).

The detrimental mode in scenario 2 is categorized as inter-area oscillation where synchronous generator G1 and G3 in area 1 oscillate against synchronous generator G5 in area 3. The participation factor of this oscillation is presented in Fig. 6. The highest participation comes from G1's speed state variable while the state variable from the PSS in each generator contributes to this oscillation as well. It may suggest that proper tuning of PSS parameters is needed in order to damp or improve small signal stability performance.

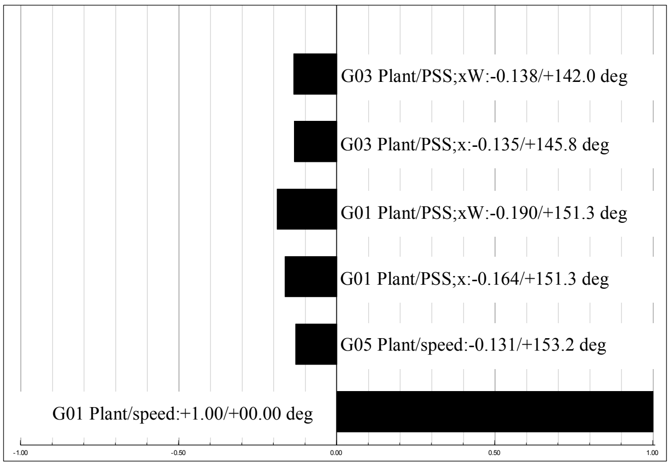

Fig. 6. Participation factor for detrimental mode during study case III scenario 2.

D. Case IV: Diversified DFIG Across the Area

During case IV, the DFIG wind turbines were integrated at four locations in each area. The DFIG wind turbine was integrated at bus 5, 7, 11, and 13 in area 1 while 8 DFIG wind farms were occupied bus 17, 18, 26 and 28 in area 2 and bus 15, 19, 21 and 24 in area 3 respectively. Total capacity of DFIG wind farm in the system is around 19.8% of system demand.

Scenario 1, scenario 2 and scenario 3 are the operation scenarios where in order to accommodate power from 12 DFIG wind farms, 2 of the synchronous generators in each area were keep off line during each scenario and one of the remaining synchronous generators in that area was selected as the slack generator to balance active power between load and generation. By switching off particular synchronous generators, it will change the active power path because at that condition, system demand get it power supply from DFIG wind turbine at different locations to an offline synchronous generator. Furthermore, the number of state variable of system is decrease since PSS and AVR and dynamic model form synchronous generator have been removed in turn it affect the A system matrix.

Table IV presents the summary of the system active power flow and the detrimental modes exist during study case IV for three different operation scenarios 1, 2 and 3. It can be seen from the table IV that the mode with the lowest damping in each scenario has significant change compared to the performance of case I.

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TABLE IV
FREQUENCY AND DAMPING RATIO OF
DETRIMENTAL MODES DURING DFIG DIVERSIFIED ACROSS THE AREA

Scenario	**1**	**2**	**3**
Offline	**G2 and G3**	**G8 and G9**	**G4 and G7**
Slack generator	**G5**	**G10**	**G5**
Active Power (MW)			
Synch Generator	4953.93	4943.46	4927.45
Load	6097.1	6097.1	6097.1
Grid Losses	66.43	55.96	39.95
Area 2 to Area 1	616.73	-155.150	92.61
Area 3 to Area 2	238.61	653.750	-292.910
Area 1 to Area 3	-380.08	-31.750	281.090
DFIG (%)	19.84	19.84	19.84
Frequency (Hz)	0.539	0.569	0.594
Damping Ratio	0.065	0.082	0.149
Mode Type	Inter Area 1&3	Inter Area 1&3	Inter Area 1&2

Although, the system is considered as stable, the damping ratio in scenario 1 (6.5%) and scenario 2 (8.2%) drop significantly compared to the lowest damping ratio during case I (12.8%). In contrast, the damping ratio is slightly higher during operation scenario 3.

The detrimental mode in the scenario 1 and 2 during study case IV are categorized as inter-area oscillation between generator in area 1 and area 3. As it is shown in Fig. 7, speed and PSS state variables from generator G1, G5 and G9 contribute to the oscillation during scenario 1 while generator G1, G3 and G5 contribute to the oscillation in scenario 2 as it is shown in Fig. 8.

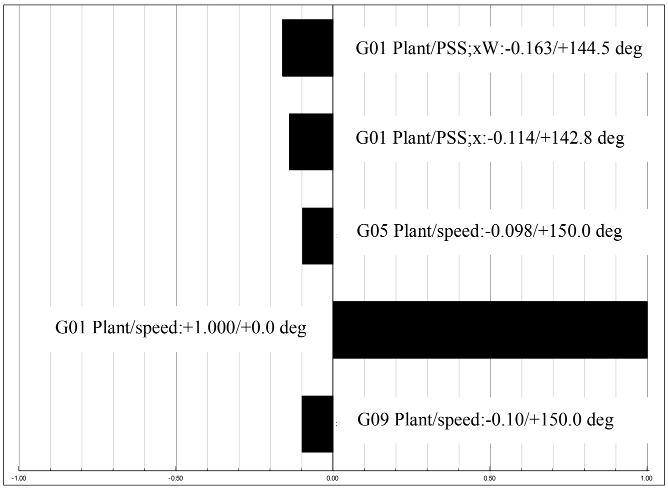

Fig. 7. Participation factor for detrimental mode during study case IV scenario 1.

Although the highest participation comes from the speed state variable, this detrimental mode could be improved by retuning the PSS which is installed in each of the synchronous generator's that are involved in the oscillation. A suitable method of PSS tuning during the integration of wind is proposed for future work.

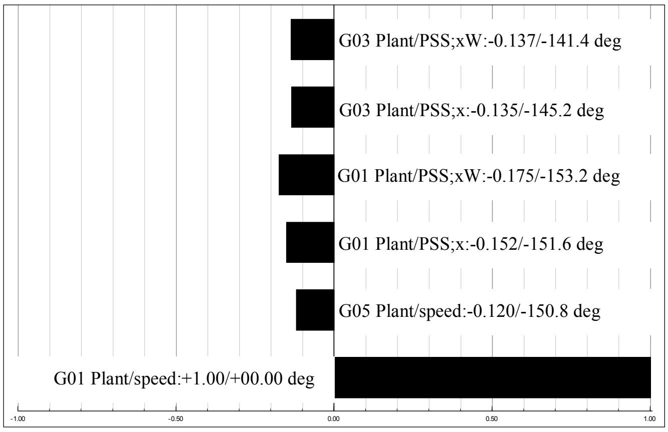

Fig. 8. Participation factor for detrimental mode during study case IV scenario 2.

V. CONCLUSION

The impacts of the DFIG wind turbine integration on small signal stability have been analysed in this paper. The presence of DFIG in the system gives different influences on the system eigenvalue depending on the study case and operational scenario.

The result from case II showed that by increasing the active power share between DFIG wind turbine and the existing synchronous generators gives different influences on the system damping where some modes experienced an increase in damping ratio while other modes decreased.

Operation scenario 2 in case III experienced a significant drop in terms of system damping. Impacting the active power flow paths and replacing some synchronous generators as it is illustrated in case IV influences small signal stability performance as well.

The presence of DFIG wind turbine in a power system changes the operation condition and network topology of power system hence existing PSS installed in particular synchronous generator is need to be re-tuned. A self-tuning PSS method seems to be suitable for the power system with wide range of operation change in order to have small signal stability performance with an optimum damping ratio.

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