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Influence of Renewable Energy based Microgrid on Low Frequency Oscillation of Power Systems

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***Abstract*— Increase proliferation of microgrid (MG) technologies with extended use of renewable energy sources (RES) can affect the system stability performance since dynamic characteristics of this kind of MG are different from conventional generation. Sharing certain portion of or entire generated power from synchronous generator with MG results in decrease of total system inertia. On the other hand, connecting RES based MG near a central load eventually enhance system performance due to improvement in reliability, reduction of power loss and congestion on transmission line. This paper investigates the impact of RES based MG on local and inter-area oscillatory modes of power systems. This study focuses on low oscillatory eigenvalues in the frequency range of 0.1-2 Hz. Eigenvalues analysis is performed to observe damping ratios and stability margins of the system due to MG integration. Furthermore, time domain simulation is then carried out to validate the result from eigenvalues analysis.**

***Index Terms*—Microgrid, low oscillatory eigenvalues, damping, stability.**

I. INTRODUCTION

Penetration levels of distributed power generation based on renewable energy resources (RES) have been increasing significantly in recent years. This increase was mainly due to the rapid development of power electronics devices and material technologies for harnessing electricity from natural resources, which offered much better efficiency and performance of distributed generation (DG). Furthermore, to ensure stable operation and reliable supply, complementary DG, potentially a diesel unit and/ or a storage system need to be combined to form a small power system popularly referred to MicroGrid (MG). In general, MG can be defined as a small-scale power system that consists of cluster of loads and small generating units with or without energy storage devices (ESD). MG can be operated in a controlled and coordinated manner to bring wide variety of technical and economic benefits, either while tied to the main power network or isolated from the grid.

Though MG allows seamless integration of RES, reduces losses and enhances reliability of electricity supply, it brings novel challenges to the operation of entire power network. Conventionally, synchronous generators are responsible to provide synchronizing and damping torque to overcome oscillation problem in power system. Increased penetration of MG can affect the system stability performance since dynamics of MG are different from that of synchronous generator. As there are many power electronic interface in MG, dominant modes within MG system are situated in the range of higher frequency than the classic electromechanical oscillation [1, 2]. Moreover, due to less physical inertia characteristic of MG and the interaction of MG with the rest of the system, it may alter the trajectories and damping characteristic of the system low frequency modes [3].

Sensitivity analysis of local and inter-area modes respect to system inertia are conducted in [4] to quantify impact of wind energy conversion system (WECS) penetration in power systems. In [5, 6], impact of different wind power integration level and location on small signal stability are considered. It was found that doubly fed induction generator (DFIG) based WECS can have both beneficial and detrimental effects to the electromechanical of oscillation modes. Contribution of WECS in inter-area damping control is thoroughly investigated in [7]. Conversely, influence of increased tie-line power transfer and penetration level of WECS deteriorate inter-area oscillatory modes and eventually tend to instability as presented in [8].

Impact of PV penetration to small signal stability performance were investigated in [9]. The study results show that the presence of PV can improve the oscillatory system stability by adding damping on critical modes. Moreover, PV may bring either advantage or adverse impact, depending on its penetration level and location. In [10], two types of PV system; roof-top and utility scale are added to a large system to simulate a case of high PV penetration. It was monitored that reduced inertia due to replacement of synchronous generator with PV units resulted in adverse effects on electromechanical modes of oscillation.

The aforementioned studies have analysed the local and inter-area eigenvalues due to penetration of RES based power generations. However, only one type of RES was considered separately in each study. This paper will investigate impact of MG consisting of wind and PV DG unit on the small signal stability performance of a power system for varying penetration levels of renewable energy generation. A comprehensive modal analysis and trajectories of critical eigenvalues are carried out to identify interaction of low frequency local and inter-area mode of the system to assess system stability.

II. RENEWABLE ENERGY BASED MICROGRID

The configuration of the investigated MG system mainly consist of PV and wind energy DG units as depicted in Fig.1. Fully rated WECS comprising of induction generator and back-to-back AC-DC-AC power converter and two stages PV system consisting of DC-DC and DC-AC are implemented to the proposed MG system. This architecture facilitates full power conversion and variable speed operation capability of induction generator in wind DG units. While, stable operation of PV system is ensured by two stages DC-DC and DC-AC configuration.

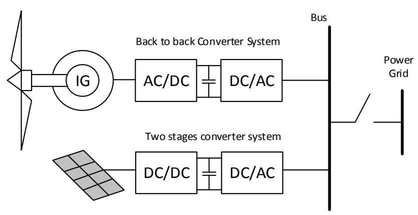

Figure 1. Microgrid architecture.

Typical control strategies for PV and WECS is shown in Fig.2.

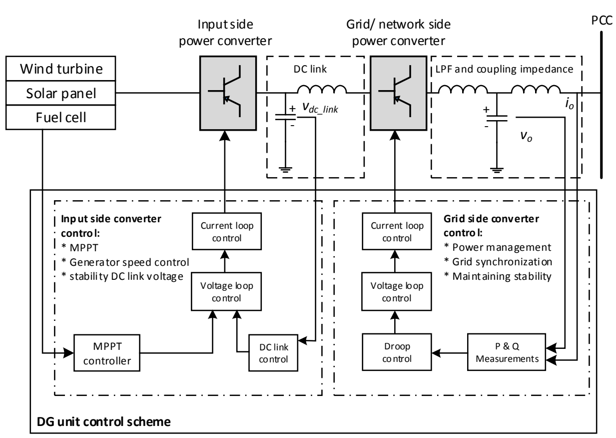

Figure 2. Control strategies for PV and WECS.

Maximum Power Point Tracking (MPPT) and droop control method are employed to the input and grid side power converter, respectively. Input side controller is responsible to make sure optimal power extraction from wind speed and solar irradiance, maintain stability voltage of DC link and perform generator speed control in WECS. While, providing power transfer from and to the grid, maintaining stability, and synchronization among DG units were the main tasks of grid side controller. To mitigate high order harmonics and provide additional damping, low pass filter and coupling impedance were connected to the output of DG units.

III. LOW FREQUENCY OSCILLATION IN POWER SYSTEM

Small signal stability is related to the ability of power system to maintain a stable condition after being subjected to small disturbance or fluctuation. Instability condition that may result can be steady increase in generator rotor angle or rotor oscillation due to insufficient of synchronizing and damping torques [11]. Oscillation associated with single generator is defined as local modes while, those which involved group of synchronous generator is commonly defined as inter-area modes of oscillation. Local and inter-area modes are characterized by oscillatory frequency in the range of 0.7 to 2 Hz and 0.1 to 0.8 Hz respectively [12]. Furthermore, increasing of oscillation amplitude could lead to partial or full black out of power system.

Eigenvalues (λ) analysis is conducted to investigate small signal stability performance of the critical modes and time domain response during small disturbance. Complex eigenvalues furthermore, indicate frequency oscillation (f) and damping ratio (ς) of the modes, which can be stated as

$$\lambda_i = \sigma_i \pm j\omega_i \tag{1}$$

$$f = \frac{\omega_i}{2\pi} \tag{2}$$

$$\varsigma_i = -\frac{\sigma_i}{\sqrt{\sigma_i^2 + \omega_i^2}} \tag{3}$$

Stable condition of the system is achieved when all of the eigenvalues have negative real part. This corresponds to the damped condition of the oscillatory modes. Sensitivity and participation factor analysis are conducted to investigate correlation between critical eigenvalues and system state variables. Participation factor analysis provide information regarding the relationship between the states variables and modes which are independent from units and scaling associated with state variables. Higher participation factor values show more relevant state variables to the modes. The participation factor of *i*-th state variables and the *j*-th modes is given by

$$p_{ij} = \phi_{ij}\psi_{ij} \tag{4}$$

Where $\emptyset_{ki}$ and Ψ_{ik} are the element on the right eigenvector and left eigenvector respectively.

IV. CASE STUDY

A. Test Bed System

Single line diagram of the 9 bus 230 kV Western Electricity Coordinating Council (WECC) test system is depicted in Fig.3. The test system comprises of three generators, equipped with governor and exciter system, supplying 315 MW and 115 MVar total load demand. The proposed MG system, analyzed in this paper, comprising of 50% WECS and 50% PV, is connected at bus 6. To investigate impact of MG penetration, injected active power from MG will be increased gradually from 10 to 80 MW to replace generated active power from generator 1. It is assumed that power output of RES based DG unit in the MG system correspond to the available power from a certain wind speed and solar irradiance conditions. Modal analysis and trajectories of local and inter-area modes are then carried out to investigate small signal stability performance and damping characteristic of the system.

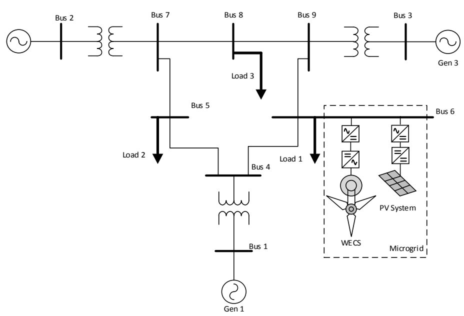

Figure 3. 9 BUS-WECC test system with microgrid.

B. Eigenvalues Analysis

Modal analysis is performed using DigSilent Power Factory analytical software package. Trajectories of critical low frequency eigenvalues is then conducted to observe the stability and damping performance of the system under various MG penetration level. The eigenvalues plot of the system in base case condition is depicted in Fig. 4. The investigated system has several critical eigenvalues correlated with electromechanical and control modes of the synchronous generators, WECS and PV system as shown in Fig. 4. However, only low frequency modes are considered in this study aiming to investigate impact of MG penetration in power system. The analysis is focused on control and electromechanical local and inter-area modes in frequency range of 0.1-2 Hz. Table I present local and inter-area modes of the base case without MG penetration. Participation factor analysis for these modes shows that the local modes correspond to the rotor angle (δ_{G3}) and speed (ω_{G3}) of generator 3. While, interaction between generators 1 and 2 is presented as inter-area modes, associated with rotor angle (δ_{G2}) and speed (ω_{G2}) of generator 2 and speed (ω_{G1}) and rotor angle (δ_{G1}) of generator 1.

Table II and III, respectively, present the results of the eigenvalues analysis of the local and inter-area modes for all considered MG penetration level. The penetration level of MG can alter critical low frequency modes. It is well known that oscillatory concerns in power system are originated from synchronous generator in terms of rotor angle and mechanical speed oscillation. The existing electromechanical oscillatory modes might be no longer exist or experienced path changes due to substitution of generated power from synchronous generator to RES based DG unit in MG[5]. Replacing a certain portion of power generated from synchronous generators with MG results in decrease of total system inertia, which can worsen small signal stability performance of the respective power system.

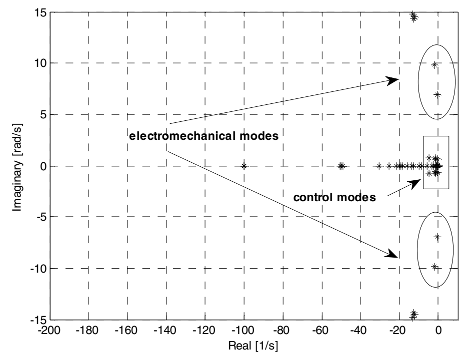

Figure 4. System eigenvalues in base case condition.

TABLE I. LOCAL AND INTER-AREA MODES IN THE BASE CASE

Real Part (1/s)	Imaginary Part (rad/s)	Frequency (Hz)	Damping Ratio (%)	State Variables
-1.82	± 9.84	1.57	18.2	δ_{G3},ω_{G3}
-0.49	± 6.90	1.10	7.1	$\delta_{G2},\omega_{G2},\omega_{G1},\delta_{G1}$

TABLE II. LOCAL MODE AFFECTED BY MG PENETRATION

MG penetration (MW)	Real Part (1/s)	Imaginary Part (rad/s)	Frequency (Hz)	Damping Ratio (%)
0	-1.82	± 9.84	1.57	18.2
10	-2.10	± 10.57	1.68	19.5
40	-2.19	± 10.66	1.70	20.2
80	-2.30	± 10.78	1.72	20.8

TABLE III. INTER-AREA MODE AFFECTED BY MG PENETRATION

MG penetration (MW)	Real Part (1/s)	Imaginary Part (rad/s)	Frequency (Hz)	Damping Ratio (%)
0	-0.49	± 6.90	1.10	7.1
10	-0.52	± 6.94	1.10	7.5
40	-0.53	± 6.95	1.12	7.6
80	-0.56	± 6.97	1.15	8.0

Conversely, connecting MG near a central load has the potential to enhance system stability performance due to reduction of power loss and congestion on transmission line. Simulation results indicate that the critical low frequency modes become more stable and damping performance of the local and inter-area modes are improved when generated active power from synchronous generator G1 is gradually displaced by MG. This is indicated by more negative values of real parts and increase of the damping ratio in both of critical eigenvalues. The influence of MG in local mode is significant, it is affecting both the frequency of oscillation and damping ratio. As MG penetration increases, the damping ratio of the local mode improved by 2.6% from 18.2% to 20.8% and oscillatory frequency become 1.65 Hz higher than its initial condition. However this is not the case in inter-area mode as presented in table III. The effect is small in that case. The damping ratio of inter-area modes only increased by 0.9% and frequency of oscillation become 0.05 Hz higher than the condition without MG.

C. Time Domain Analysis

Time domain simulations were carried out to validate the previously discussed small signal stability impact analysis results for increased MG penetration in power system. To observe the response of critical modes and system performance during small variation, load change scenarios were employed. Moreover, three-phase fault conditions were applied to investigate fault ride through capabilities and the effect of increased MG generation on system stability in general and on oscillation of system critical modes in particular.

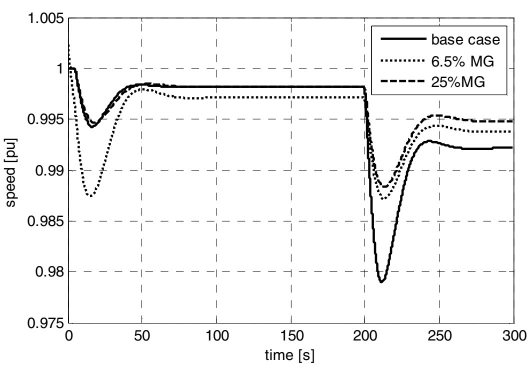

Figure 5. Speed of generator 3 following the load changes.

Fig. 5 presents the speed response of the generator connected to bus 3 following the determined load change. As depicted in Fig. 5, at low levels, penetration of MG did not significantly contribute to the damping performance of the system during 5.5% change of load demand. However, as demand increases further to 10% from its initial condition, at higher MG penetration levels, more damped condition of generator speed is observed. This monitored result validated enhancement of damping performance of the system due to integration of MG in eigenvalues analysis. At a MG active power injection of 25%, the generator speed become more stable during load change indicated by lower undershoot magnitude compared with condition before integration of MG.

Fig. 6 presents the rotor angle of generator 3, subject to the fluctuation of demand to 5.5% and 10% sequentially. It can be observed that without MG connected to the system, the rotor angle of generator 3 experiences a short period of oscillation during the load variations. However, due to integration of MG, generator 3's rotor angle becomes more stable and is not oscillating remarkably during the load change scenarios. Moreover, there is not much difference in oscillatory conditions of the rotor angle in the 6.5% and 25% MG penetration level scenario, as presented in Fig. 6. This indicates that various penetration level of MG have only slight influence on the dynamic conditions of generator rotor angle.

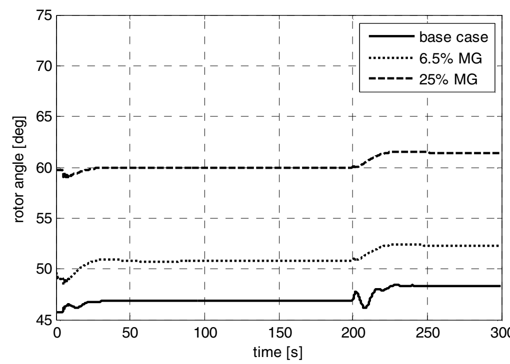

Figure 6. Rotor angle of generator 3 following the load changes.

Modal analysis and small load change scenarios have been conducted to assess the beneficial influence of increasing MG penetration in the existing power network in terms of damping ratio and stability margin improvement during small variation. To provide a more complete picture regarding dynamic behavior of critical local and inter-area modes, time domain response during severe fault condition is investigated. Moreover, response and fault ride through capability of the system with and without various MG active power injection levels during fault condition are be thoroughly analyzed. To deal with this objective, a three-phase fault is applied at bus 5 and it is assumed that the fault will be cleared after 150 ms.

Fig. 7 shows the dynamic response of generator 3's speed during the three-phase fault condition at bus 5. The MG brings valuable impact to the transient performance of the system under fault condition. As depicted in the Fig 7, transient response of the generator speed is significantly improved. It is important to note that critical modes with 0.07 Hz frequency of oscillation, depicted by the solid line in base case scenario without MG is completely disappeared due to MG. These oscillatory modes correspond to state variables of the generator control and excitation system. Gradual replacement of power injection from synchronous generator with DG units in MG significantly reduces the magnitude of electromechanical oscillatory modes in transient conditions. At higher MG penetration level, the amplitude of the 1.2 Hz oscillatory mechanical modes becomes smaller. However, these modes do not introduce further adverse impact for system stability.

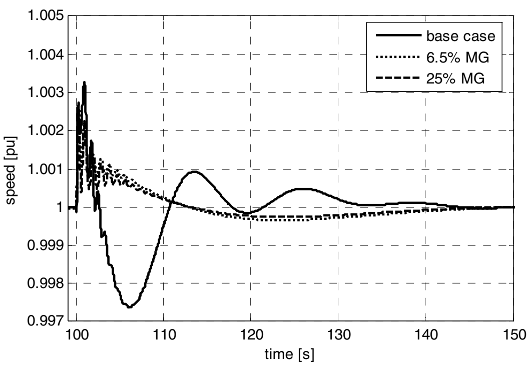

Figure 7. Speed of generator 3 following three phase fault.

Beneficial influence of the MG penetration, which result in more damped oscillation condition of generator rotor angle during three-phase fault is also observed in Fig. 8. Similar to the previous result, low frequency modes from generator control and excitation system state variables no longer exist and mechanical oscillation modes become more damped as higher MG penetration level is connected. From conducted transient studies, it can be seen that damping performance of the system is greatly improved due to integration of MG.

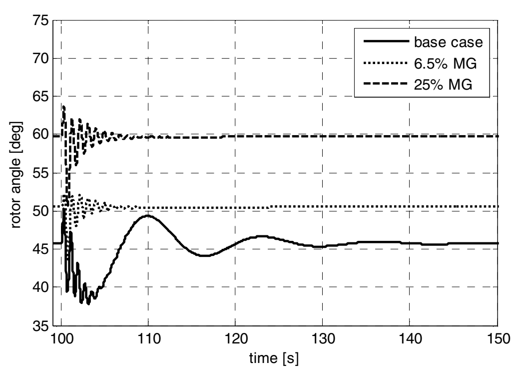

Figure 8. Rotor angle of generator 3 following three phase fault.

V. CONCLUSIONS

In this paper, PV and WECS are applied in MG system to investigate the impact of increasing MG penetration on power system low frequency oscillation. Modal analysis is performed to observe dynamic of local and inter-area modes under various MG penetration levels. It is revealed that at higher active power injection from MG, damping performance is enhanced and the power system becomes more stable. This is indicated by more negative real part of local and inter-area modes and higher damping ratio as MG penetration increased.

Time domain analysis is performed to validate eigenvalues analysis and provide more complete picture of beneficial impacts of MG integration during system transient condition. It is interesting to note that MG significantly contribute to improve transient performance of the system both due to small fluctuation and severe fault condition. It is observed that the control and excitation modes with a very low frequency around 0.07 Hz from synchronous generator are completely compensated. The amplitudes of oscillatory mechanical modes are reduced moderately at higher MG penetration level. It is shown that damping performance of generator speed and rotor angle are greatly improved during transient condition.

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