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Small Signal Stability Analysis of Multi-Machine Power Systems Interfaced with Micro Grid

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***Abstract*— This paper work presents a study of small signal stability analysis of multi-machine power systems interfaced with micro grid. Modeling of DFIG for Wind Energy Conversion System (WECS), marine current energy system and, and PV module is presented. A procedure for incorporating Wind Energy Conversion System, Marine Current Energy System and PV system into multi-machine power systems is presented. A program is developed in MATLAB environment and effectiveness of developed program is tested in a standard IEEE-9 bus system. The small signal stability of the multi-machine power systems interfaced with micro grid is analyzed and the results are presented.**

Keywords— Wind Energy Conversion System, Marine Current Energy Conversion System, PV System, Multi-Machine Power Systems, Eigen-Value Analysis, Small Signal Stability Analysis

I. INTRODUCTION

Renewable energy is one of the sizzling themes in the entire world today due to the fast and huge consumption of fossil fuels. The ocean covers more than 70% surface of the earth, the wind energy above the sea surface and oceanic energy under the seawater can be captured simultaneously to generate large electric power[2,4,11,12]. The wind energy and oceanic energy can be effectively integrated together to deliver electric power to the loads. The utilization of marine current turbines offers an exciting proposition for the extraction of energy from marine currents[1]. Wind, tidal and PV system has a higher reliability for maintaining a continuous power than any other individual sources[2,14]. Compared to external grid, micro-grid is a single controllable unit, that link multiple distributed power generation sources into a small network The modelling of PV cell in simplified equivalent circuit with output elements and the stability of PV system using Eigen-value analysis was discussed by Hun-Chul Seo . Shan ying li presented the analysis of small signal stability of grid-connected doubly fed induction generators .The detailed model of grid-connected DFIG wind turbine is firstly established, and the Eigen-values are classified and characterized based on participation factors.

This paper presents a modeling of power system and micro grid for small signal stability analysis, step by step procedure for small signal stability analysis of micro grid interfaced with multi-machine system and state space model for multi-machine system with micro grid. The small signal stability analysis of multi-machine system with micro grid is presented using Eigen-value analysis.

This paper comprises of the following sections: Section 2 deals with the modeling of power system. In section 3, the small signal stability analysis of multi-machine system with micro grid is presented. In section 4, the results and discussion of the test system are presented. Conclusion is presented in section 5.

II. POWER SYSTEM MODELING

In this section, modeling of synchronous generator in power system and micro grid components for small signal stability analysis are presented.

A. Synchronous Generator Model

In multi-machine model, a synchronous machine or group of synchronous machines connected to a larger system through one or more power lines as shown in Fig-1.

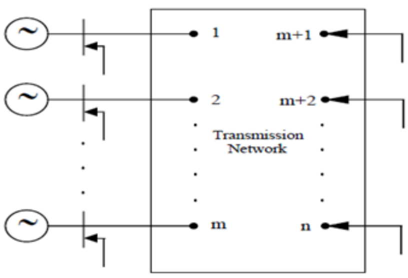

Fig-1: General m machine n bus system

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Synchronous Generators in multi-machine power systems are modeled as classical machine model and variable voltage behind transient reactance model.

Neglecting saliency, the stator of a synchronous machine is represented by the equivalent circuit shown in Fig-2. The block diagram of excitation system is shown in Fig-3.

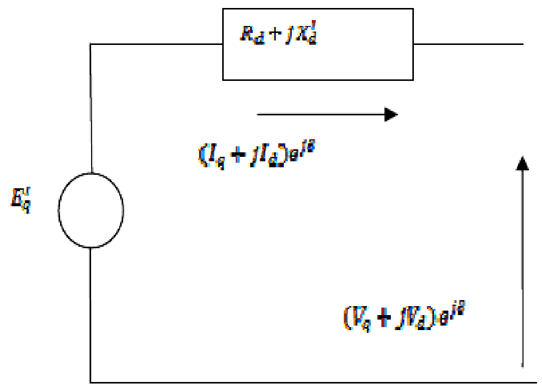

Fig-2: Stator equivalent circuit

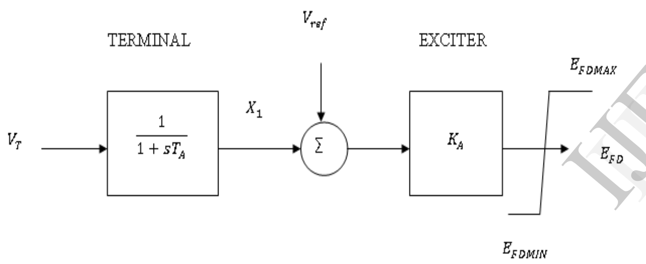

Fig-3: Simplified block diagram of excitation system

The linearized equations of classical machine model for the small signal stability analysis in state variable form are represented by the following equations[6,7,8]

$$\Delta\dot{\omega}_{12} = \frac{-K_D}{2H}\Delta\omega_{12} - \left(\frac{T_{12}}{2H_1} - \frac{T_{22}}{2H_2}\right)\Delta\delta_{12} \quad (1)$$

$$\Delta\dot{\delta}_{12} = \omega_s\Delta\omega_{12} \quad (2)$$

The linearized equations of variable voltage behind transient reactance model for the small signal stability analysis in state variable form are represented by the following equations[6,7,8]

$$\Delta\dot{\omega}_{12} = \frac{-K_D}{2H}\Delta\omega_{12} - \left(\frac{T_{12}}{2H_1} - \frac{T_{22}}{2H_2}\right)\Delta\delta_{12} - \left(\frac{T_{11}}{2H_1} - \frac{T_{21}}{2H_2}\right)\Delta E'_{q1} \quad (3)$$

$$\Delta\dot{\delta}_{12} = \omega_s\Delta\omega_{12} \quad (4)$$

$$\Delta\dot{E}'_{q1} = E_1\Delta\delta_{12} + E_{11}\Delta E'_{q1} - \frac{K_A}{T'_{d01}}\Delta X_1 \quad (5)$$

$$\Delta\dot{X}_1 = \frac{p_{12}}{T_R}\Delta\delta_{12} + \frac{p_{11}}{T_R}\Delta E'_{q1} - \frac{1}{T_R}\Delta X_1 \quad (6)$$

Where δ and ω refers rotor angle and speed, E'_q is quadrature voltage behind transient reactance, X_1 is terminal voltage transducer, H is inertia constant, K_D is damping coefficient.

Where,

$$E_{11} = -\frac{1}{T'_{do1}}[1 - B_{11}(X_{d1} - X'_{d1})] \quad (7)$$

$$E_{13} = -\frac{1}{T'_{do1}}(X_{d1} - X'_{d1})(G_{12}\cos\delta_{12,0} + B_{12}\sin\delta_{12,0})E'_{q10} \quad (8)$$

$$p_{11} = \left(\frac{V_{q10}}{V_{T10}}\right)(1 + d_{11}X'_{d1}) - \left(\frac{V_{d10}}{V_{T10}}\right)q_{11}X_{q1} \quad (9)$$

$$p_{13} = \left(\frac{V_{q10}}{V_{T10}}\right)(d_{13}X'_{d1}) - \left(\frac{V_{d10}}{V_{T10}}\right)q_{13}X_{q1} \quad (10)$$

$$d_{11} = B_{11} \quad (11)$$

$$d_{13} = -(G_{12}\cos\delta_{12,0} + B_{12}\sin\delta_{12,0})E'_{q10} \quad (12)$$

Where X_{d1} refers direct axis synchronous reactance, X'_{d1} is direct axis transient reactance, T'_{d01} is direct axis open circuit transient time constant and X_{q1} refers quadrature axis synchronous reactance, B is susceptance and G is conductance.

B. Doubly Fed Induction Generator Model for Wind and Marine Farm

DFIG is an induction-type generator. The d-axis and q-axis equivalent circuit of doubly fed induction generator for wind and marine farm is shown in Fig-4 (a) and (b).

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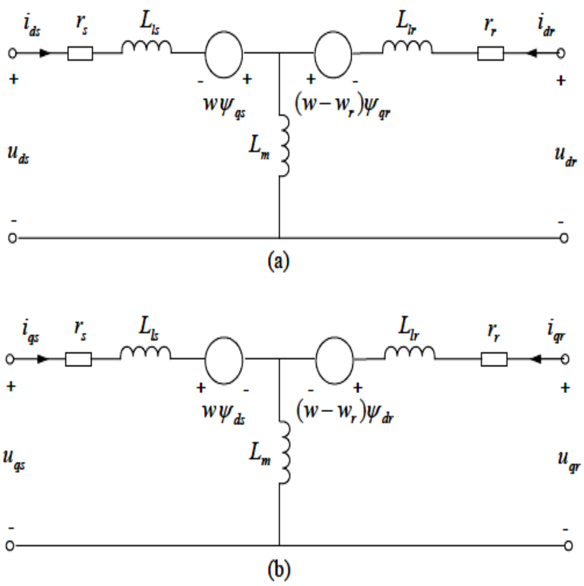

Fig-4: (a) d-axis equivalent circuit of doubly fed Induction generator
(b) q-axis equivalent circuit of doubly fed induction generator

1) Electrical Equations

The linearized electrical differential equations of DFIG in wind farm for small signal stability analysis in state variable form are represented by the following equations

$$\Delta i_{dsw} = \frac{\omega_b}{L_s^{\prime}}\left[-r_s\Delta i_{dsw} + \omega_r L_s \Delta i_{qsw} + \frac{L_m r_r}{L_r}\Delta i_{drw} + \omega_r L_m \Delta i_{qrw} + \Delta V_{ds}\right] \quad (13)$$

$$\Delta i_{qsw} = \frac{\omega_b}{L_s^{\prime}}\left[-\omega_r L_s \Delta i_{dsw} - r_s\Delta i_{qsw} - \omega_r L_m \Delta i_{drw} + \frac{L_m r_r}{L_r}\Delta i_{qrw} + \Delta V_{qs}\right] \quad (14)$$

$$\Delta i_{drw} = \frac{\omega_b}{L_s^{\prime}}\left[\frac{L_m r_s}{L_r}\Delta i_{dsw} - \frac{\omega_r L_m L_s}{L_r}\Delta i_{qsw} - \left(\frac{L_m^2}{L_r^2} + \frac{L_s^{\prime}}{L_r}\right) r_r \Delta i_{drw} - \frac{\omega_r L_m^2}{L_r}\Delta i_{qrw} - \frac{L_m}{L_r}\Delta V_{ds}\right] \quad (15)$$

$$\Delta i_{qrw} = \frac{\omega_b}{L_s^{\prime}}\left[\frac{\omega_r L_m L_s}{L_r}\Delta i_{dsw} + \frac{L_m r_s}{L_r}\Delta i_{qsw} + \frac{\omega_r L_m^2}{L_r}\Delta i_{drw} - \left(\frac{L_m^2}{L_r^2} + \frac{L_s^{\prime}}{L_r}\right) r_r \Delta i_{qrw} - \frac{L_m}{L_r}\Delta V_{qs}\right] \quad (16)$$

Where, ω_{elB} - electrical base speed, ω_s- synchronous speed, v_{qs} and v_{ds} - q-axis and d-axis voltage of stator, i_{qsw} and i_{dsw} - q-axis and d-axis current of stator for wind farm, i_{qrw} and i_{drw} - q-axis and d-axis current of rotor for wind farm, L_s and L_r - stator and rotor inductances for wind farm, L_m- mutual inductances for wind farm, r_r and r_s - rotor and stator resistances for wind farm.

The linearized electrical differential equations of DFIG in marine farm for small signal stability analysis in state variable form are represented by the following equations

$$\Delta i_{dsm} = \frac{\omega_b}{L_s^{\prime}}\left[-r_s\Delta i_{dsm} + \omega_r L_s \Delta i_{qsm} + \frac{L_m r_r}{L_r}\Delta i_{drm} + \omega_r L_m \Delta i_{qrm} + \Delta V_{ds}\right] \quad (17)$$

$$\Delta i_{qsm} = \frac{\omega_b}{L_s^{\prime}}\left[-\omega_r L_s \Delta i_{dsm} - r_s\Delta i_{qsm} - \omega_r L_m \Delta i_{drm} + \frac{L_m r_r}{L_r}\Delta i_{qrm} + \Delta V_{qs}\right] \quad (18)$$

$$\Delta i_{drm} = \frac{\omega_b}{L_s^{\prime}}\left[\frac{L_m r_s}{L_r}\Delta i_{dsm} - \frac{\omega_r L_m L_s}{L_r}\Delta i_{qsm} - \left(\frac{L_m^2}{L_r^2} + \frac{L_s^{\prime}}{L_r}\right) r_r \Delta i_{drm} - \frac{\omega_r L_m^2}{L_r}\Delta i_{qrm} - \frac{L_m}{L_r}\Delta V_{ds}\right] \quad (19)$$

$$\Delta i_{qrm} = \frac{\omega_b}{L_s^{\prime}}\left[\frac{\omega_r L_m L_s}{L_r}\Delta i_{dsm} + \frac{L_m r_s}{L_r}\Delta i_{qsm} + \frac{\omega_r L_m^2}{L_r}\Delta i_{drm} - \left(\frac{L_m^2}{L_r^2} + \frac{L_s^{\prime}}{L_r}\right) r_r \Delta i_{qrm} - \frac{L_m}{L_r}\Delta V_{qs}\right] \quad (20)$$

Where, ω_{elB} - electrical base speed, ω_s- synchronous speed, v_{qs} and v_{ds} - q-axis and d-axis voltage of stator, i_{qsm} and i_{dsm} - q-axis and d-axis current of stator for marine farm, i_{qmr} and i_{drm} - q-axis and d-axis current of rotor for marine farm, L_s and L_r- stator and rotor inductances for marine farm, L_m- mutual inductances for marine farm, r_r and r_s - rotor and stator resistances for marine farm.

2) Mechanical Equations

A two-mass drive train model is used to get a more accurate response from the wind turbine and marine turbine. Two mass drive train model is shown in Fig-5.

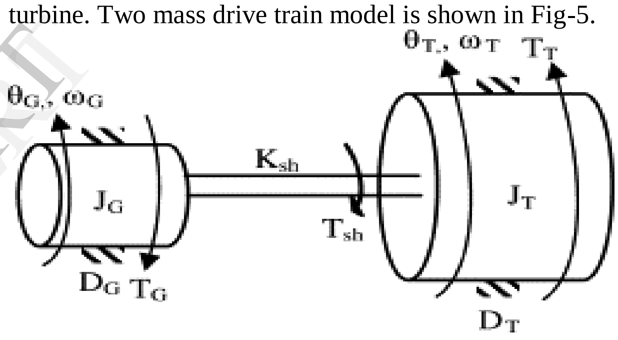

Fig- 5: Two mass drive train model

The linearized mechanical differential equations of DFIG in wind farm for small signal stability analysis in state variable form are represented by the following equations

$$\Delta\dot{\omega}_{hw} = \frac{\Delta T_{mw}}{2H_{hw}} - \frac{D_{hgw}}{2H_{hw}}\Delta\omega_{hw} - \frac{K_{hgw}}{2H_{hw}}\Delta\theta_{hgw} \quad (21)$$

$$\Delta\dot{\omega}_{gw} = \frac{D_{hgw}}{2H_{gw}}\Delta\omega_{gw} + \frac{K_{hgw}}{2H_{gw}}\Delta\theta_{hgw} - \frac{\Delta T_{ew}}{2H_{gw}} \quad (22)$$

$$\Delta\dot{\theta}_{hgw} = \omega_b\Delta\omega_{hw} - \omega_b\Delta\omega_{gw} \quad (23)$$

Where, ω_{hw} and ω_{gw} – turbine and rotor speeds for wind farm, θ_{hgw} - shaft torsional angle for wind farm, D_{hgw} and K_{hgw} -drive train damping coefficient and shaft stiffness for wind farm, H_{hw} and H_{gw} – turbine and generator inertia for wind farm, T_{mw} -mechanical torque for wind farm, T_{ew} - electrical torque for wind farm.

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The linearized mechanical differential equations of DFIG in marine farm for small signal stability analysis in state variable form are represented by the following equations

$$\Delta\dot{\omega}_{hm} = \frac{\Delta T_{mm}}{2H_{hm}} - \frac{D_{hgm}}{2H_{hm}}\Delta\omega_{hm} - \frac{K_{hgm}}{2H_{hm}}\Delta\theta_{hgm} \quad (24)$$

$$\Delta\dot{\omega}_{gm} = \frac{D_{hgm}}{2H_{gm}}\Delta\omega_{gm} + \frac{K_{hgm}}{2H_{gm}}\Delta\theta_{hgm} - \frac{\Delta T_{em}}{2H_{gm}} \quad (25)$$

$$\Delta\dot{\theta}_{hgm} = \omega_b\Delta\omega_{hm} - \omega_b\Delta\omega_{gm} \quad (26)$$

Where, ω_{hm} and ω_{gm} – turbine and rotor speeds for marine farm, θ_{hgm} - shaft torsional angle for marine farm, D_{hgm} and K_{hgm} -drive train damping coefficient and shaft stiffness for marine farm, H_{hm} and H_{gm} – turbine and generator inertia for marine farm, T_{mm} - mechanical torque for marine farm, T_{em} – electrical torque for marine farm.

C. PV Cell Model

PV arrays are built up with combined series/parallel combinations of PV solar cells, which are usually represented by a simplified equivalent circuit model such as the one given in Fig-6.

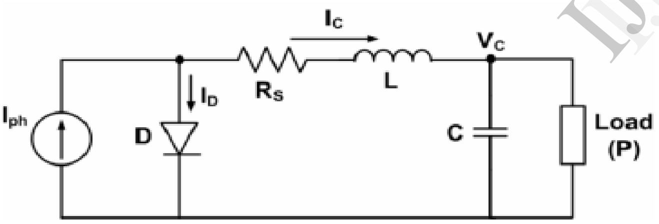

Fig-6: Simplified equivalent circuit of PV cell

The linearized differential equations of PV cell for small signal stability analysis in state variable form are represented by the following equations

$$\frac{d\Delta I_C}{dt} = -\frac{1}{\alpha L}\left(\frac{1}{I_{ph} - I_C + I_0}\right)\Delta I_C - \frac{1}{L}\Delta V_C \quad (27)$$

$$\frac{d\Delta V_C}{dt} = \frac{1}{C}\Delta I_C + \frac{P}{CV_C^2}\Delta V_C \quad (28)$$

Where, R_s- array resistance, I_{ph} , I_0 , α are constants, I_C and V_C are current and voltage through PV cell.

D. Load Model

The load is modeled as constant impedance load. The load (P + jQ) is represented as constant impedance load. The equation of load for small signal stability analysis are represented by equation (29).

ZL=VL/IL (29)

Where VL = Load Voltage, IL = Load Current, Z_L = Load impedance.

III. SMALL SIGNAL STABILITY ANALYSIS

Small signal stability analysis is performed by linearizing the system equations at the operating point and Eigen-value analysis. The system equations are described in the following general form

X=f(X,Z,U), **Z**=g(X,U) (30)

Where X, Z and U are the vectors of state variables, control variables and input variables respectively. After performing the linearization, the following relation is derived.

$$\Delta\dot{X} = A\Delta X + BU \quad (31)$$

The state variable X is given as

Classical machine model:

X=

$$[\omega_1\ \delta_1\ \omega_2\ \delta_2\ \omega_3\ \delta_3\ i_{dsw}\ i_{qsw}\ i_{drw}\ i_{qrw}\ \omega_{gw}\ \theta_{hgw}\ \omega_{hw}\ i_{dsm}\ i_{qsm}\ i_{drm}\ i_{qrm}\ \omega_{gm}\ \theta_{hgm}\ \omega_{hm} I_c V_c]^t$$

Variable voltage behind transient reactance model

X=

$$[\omega_1\delta_1 E'_{q1}X_1\ \omega_2\ \delta_2 E'_{q2}X_2\omega_3\ \delta_3 E'_{q3}X_3 i_{dsw} i_{qsw}\ i_{drw} i_{qrw}\omega_{gw}\theta_{hgw}\ \omega_{hw} i_{dsm} i_{qsm} i_{drm} i_{qrm}\omega_{gm}\theta_{hgm}\omega_{hm} I_c V_c]^t$$

Where A is the system state matrix. This matrix is then used for calculating the system Eigen-values.

IV. RESULTS AND DISCUSSION

In this section, results of small signal stability analysis of multi-machine power systems interfaced with micro grid carried out on standard IEEE 9 bus system.

A. IEEE-9 bus system

In this paper, standard IEEE-9 bus system is considered for small signal stability analysis. Data for the 9 bus system is provided in appendix. The single line diagram of micro grid interfaced standard IEEE- 9 bus system is shown in Fig- 7.

The load is represented by constant impedance load. The losses in transmission lines are neglected .The mechanical power is assumed to be constant.

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The small signal stability analysis is carried out by interfacing micro grid including WT, MCT and PV module between 7 and 8 bus of IEEE-9 bus system. The small signal stability analysis result with and without micro grid obtained for classical machine model and variable voltage behind transient reactance model in synchronous generator is tabulated in Table-1 and Table-2.

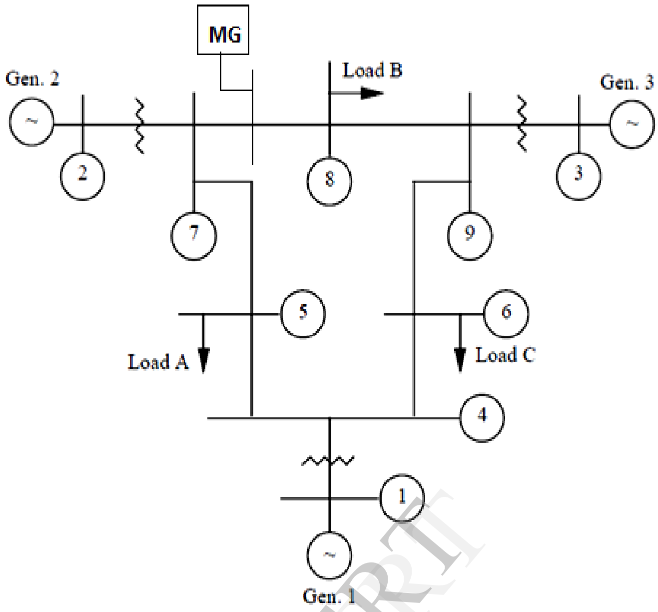

Fig-8: Single line diagram of micro grid interfaced in IEEE-9bus system

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Table -1: Eigen-values for IEEE-9 bus system without micro grid

No of state variables	Eigen-values for classical machine model	Damping ratio	Eigen-values for variable voltage behind transient reactance model	Damping ratio
1	0		0	
2	-0.5236		-0.5236	
3	0		0	
4	-1.5015		-1.5015	
5	0		0	
6	-2.1276		-2.1276	
7			-8.3491 + 3.1436i	0.9358
8			-8.3491 - 3.1436i	0.9358
9			-2.5634	
10			-14.2615	
11			-8.4882 + 3.8651i	0.9358
12			-8.4882 - 3.8651i	0.9358

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Table-2: Eigen-values for IEEE-9 bus system with micro grid

No of state variables	Eigen-values for classical machine model *10^4	Damping ratio	Eigen-values for variable voltage behind transient reactance model*10^4	Damping ratio
1	-0.0000 + 0.0007i		0	
2	-0.0000 - 0.0007i		-0.0001	
3	-0.0003		0	
4	-0.0044 + 1.0329i	0.0042	-0.0002	
5	-0.0044 - 1.0329i	0.0042	0	
6	-0.0012 + 1.0781i	0.0011	-0.0002	
7	-0.0012 - 1.0781i	0.0011	-0.0006	
8	-1.5458		-0.0011	
9	-0.0123		-0.0003	
10	-0.0003 + 0.6060i	0.0004	-0.0014	
11	-0.0003 - 0.6060i	0.0004	-0.0006	
12	-0.0011 + 0.5608i	0.0019	-0.0011	
13	-0.0011 - 0.5608i	0.0019	-0.0003 + 0.6060i	0.0004
14	-0.0000 + 0.0006i		-0.0003 - 0.6060i	0.0004
15	-0.0000 - 0.0006i		-0.0011 + 0.5608i	0.0019
16	-0.0174		-0.0011 - 0.5608i	0.0019
17	0		-0.0000 + 0.0006i	
18	-0.0001		-0.0000 - 0.0006i	
19	0		-0.0174	
20	-0.0002		-0.0012 + 1.0781i	0.0011
21	0		-0.0012 - 1.0781i	0.0011
22	-0.0002		-0.0044 + 1.0329i	0.0042
23			-0.0044 - 1.0329i	0.0042
24			-0.0000 + 0.0007i	
25			-0.0000 - 0.0007i	
26			-0.0003	
27			-0.0123	
28			-1.5458	

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From Table-3 and Table-4, it is observed that the system remains stable after interfacing micro grid into the system. Based on the Eigen-values, it is concluded that the small signal stability of the system is affected after interfacing micro grid into the system.

V. Conclusion

In the project work, the small signal stability analysis of multi-machine power systems interfaced with micro grid is presented. A program is developed using MATLAB .The effectiveness of the developed program is tested using a standard IEEE-9 bus system. The small signal stability results show that the system remains stable and stability of the system is affected after interfacing micro grid into the system.

APPENDIX

IEEE-9 BUS SYSTEM DATA

Generator Data

Gen No	P	Q	V	Xd
	(p.u.)	(p.u.)	(p.u.)	(p.u.)
1	0.716	0.27	1.04	0.146
2	0.163	0.067	1.01+0.165i	0.895
3	0.85	-0.109	1.02+0.083i	1.312

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Bus Data

Name	Vmag	Vang
	(p.u.)	(deg)
Bus 4	1.026	-2.2
Bus 5	0.9959	-3.9882
Bus 6	1.0127	-3.6869
Bus 7	1.026	3.7
Bus 8	1.0159	0.7278
Bus 9	1.032	2.0

Line Data

From	To	R (p.u.)	X (p.u.)
4	5	0.01	0.085
4	6	0.017	0.092
5	7	0.032	0.161
6	9	0.039	0.17
7	8	0.0085	0.072
8	9	0.0119	0.1008
1	4	0	0.0576
2	7	0	0.0625
3	9	0	0.0586

Stored Energy H1 = 9.55sec

H2 = 3.33sec

H3 = 2.35sec

Frequency f = 60Hz

MICRO GRID DATA

Wind Farm Data:

Air density=1.223Kg/ m3; Blade pitch angle =30 degree; Power coefficients C1=0.5, C2=116, C3=0.4, C5=5, C6=21 ;P=2MW; Rs=0.00706 p.u.; Xls=0.171 p.u; Xm=2.9p.u; Rr=0.005p.u; Xlr=0.156 p.u ; Hhw - 3.5s; Hgw - 0.5s; Dhgw- 0.1p.u ; Khgw -0.1p.u.

Marine Current Farm Data:

Water density=1025 Kg/ m3; Blade pitch angle =0 degree; Power coefficientsd1=0.18;d2=85;d3=0.38;d4=0.25;d5=0.5; d6=11;d7=10.9;d8=0.08;d9=0.01;P=2.5MW;Rs=0.01619p.u;Xls=0.1335 p.u; Xm=3.99p.u; Rr=0.12p.u; Xlr=0.1121p.u; Hhm - 2.5s; Hgm - 0.5s; Dhgm- 0.1p.u ; Khgm -0.1p.u.

PV Generation System Data

e= 1.602*10^-19 C; K = 1.38*10^-23 J/K; P=130 w; Tc=298K; Iph=5.14;I0=0.0002A; Rs=0.001ohm; L=1 ; C=10mH.

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