Investigation of Possible Dynamic Interaction between DFIGs of Different Capacity Operating in the Same Wind Farm

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Abstract- **This paper explores the possibility of dynamic interaction between DFIGs of different capacity in a grid connected and islanding mode wind farm. The modeling of DFIG is presented in the paper. The case of adding 5 MW DFIGs to a wind farm with existing 1.5 MW DFIGs is considered. Grid-connected scenario is considered regarding the connection of the units. Moreover, step-up wind speed and fault at infinite bus will be introduced as disturbances to examine the possible dynamic interaction. Simulation using MATLAB and Simulink has been used to investigate all cases. To further justify the simulation results, a series of modal small perturbation analysis is also conducted.**

***Index Terms*--DFIG, dynamic interaction, grid-connected, system modeling, modal analysis**

I. Introduction

In the last 10 years, the capacity of installed global wind farm has been growing at arate of around 30% per year. Wind power is playing an increasingly significant role in global energy supply. Five types of wind turbine generators (WTG) have been employedin wind farms [1]. Among these, the Doubly Fed Induction Generator (DFIG) is currently the most efficient and therefore the most popular one. The biggest advantage of DFIG is its capability in decoupling control of active and reactive power while the machine is able to run asynchronously.

Regarding the dynamic interaction research on DFIG, there are some papers focusing on dynamic interaction of DFIG and other power sources, such as [2] which investigates the influence of DFIG control on wind farm stability and the interaction between the wind farm and power system, and [3] which simulates the dynamic interaction of DFIG and fuel cell with the AC grid. In [4], the eigenvalue analysis method is applied to observe the dynamic interaction between DFIG and synchronous generator. There are still no studies on the dynamic interaction between DFIGs of different capacity. Nowadays, the manufacture of DFIG with large capacity is developing rapidly and subsequently the capacity expansion of existing DFIG based wind farms with units of much larger capacity becomes more and more realistic. Therefore, the importance and necessity of research into the dynamic interaction between DFIGs of different capacityhas emerged.

To investigate this dynamic interaction, 5 MW DFIGs are added to a wind farm with existing 1.5 MW DFIG. For the grid connection case, sets of 5 MW and 1.5 MW DFIGs connected to infinite bus via a transmission line distributed by step-up wind speed and fault at infinite bus is simulated. The performances of 1.5 MW and 5 MW DFIGs wind farms in changing wind conditions are studied by observing their outputs of active power, reactive power, stator current and rotor speed. The responses of these two DFIGs to the faults are analysed and examined as well. A modal small signal analysis is implemented for observing the dynamic interaction by building system differential equations and obtaining eigenvalues.

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II. Doubly-Fed Induction Generator Dynamic Mathematical Model

A. DFIG Configuration

The configuration of DFIG shown in Fig. 1, consists of induction generator, wind turbine, drive train, rotor-side control, grid-side control and pitch control.

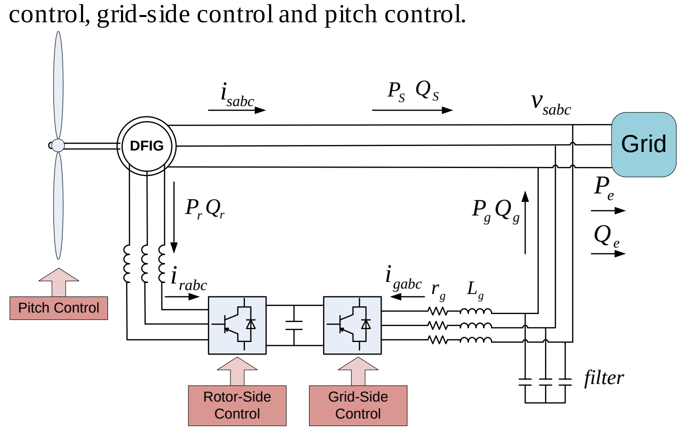

Fig.1.Configuration of a Grid-Connected Wind Turbine Double-fed Induction Generator

B. Modeling of the Induction Generator

The electrical part of the machine is represented by a fourth-order state-space model [5].All electrical variables and parameters are referred to the stator. This is indicated by the prime signs in the machine equations given below (1)~(4). All stator and rotor quantities are in the arbitrary two-axis reference frame (d/q frame).

$$V_{qs} = R_s \cdot i_{qs} + \frac{d\varphi_{qs}}{dt} + \omega \cdot \varphi_{ds} \quad (1)$$

$$V_{ds} = R_s \cdot i_{ds} + \frac{d\varphi_{ds}}{dt} - \omega \cdot \varphi_{qs} \quad (2)$$

$$V_{qr} = R_r \cdot i_{qr} + \frac{d\varphi_{qr}}{dt} + (\omega - \omega_r) \cdot \varphi_{dr} \quad (3)$$

$$V_{dr} = R_r \cdot i_{dr} + \frac{d\varphi_{dr}}{dt} - (\omega - \omega_r) \cdot \varphi_{qr} \quad (4)$$

C. Modeling of Wind Turbine Aerodynamics

The mechanical power extracted from the wind could be obtained by [6]:

$$P_m = \tfrac{1}{2}\rho A_r v_w^3 C_p \quad (5)$$

where ρ is the air density in kg/m^3; $A_r = \pi R^2$is the area swept by the rotor blades in m^2;C_p is power coefficient; λis tip-speed-ratio; andβis the blade pitch angle. $C_p(\lambda, \beta)$can be calculated as:

$$C_p = C_1\left(\frac{C_2}{\lambda + C_8\beta} - \frac{C_2 C_9}{\beta^3+1} - C_3\beta - C_4\beta^{C_5} - C_6\right) \cdot e^{-\left(\frac{C_7}{\lambda + C_8\beta} - \frac{C_7 C_9}{\beta^3+1}\right)} + C_{10}\lambda \quad (6)$$

where $C_1 \sim C_{10}$ are coefficients, and the maximum value of $C_{p-max} = 0.4382$ can be obtained by $\beta = 0$ and $\lambda = 6.325$.

D. Modeling of Drive Train

A two-mass drive train model [10] is used in this study, in which there are two separate masses to represent the low-speed turbine and the high-speed generator, and the connecting resilient shaft is modelledin (7)~(9) as a spring and a damper.

$$\frac{d}{dt}\omega_t = \frac{1}{2H_t}(T_m - T_{tg}) \quad (7)$$

$$\frac{d}{dt}\omega_m = \frac{1}{2H_g}(T_{tg} - F\omega_m - T_e) \quad (8)$$

$$T_{tg} = K_{sh}(\theta_t - \theta_m) + D(\omega_t - \omega_m) \quad (9)$$

where ω_t isthe turbine speed; ω_m is the generator speed; T_m ismechanical torque applied to the turbine; $T_e$iselectromagnetic torque of the generator; T_{tg} isthe internal torque between turbine and generator; θ_t isturbine angular position; K_{sh} isthe shaft stiffness; andDisthe mutual damping coefficient.

E. Modeling of Rotor-Side Control

The Rotor-Side control scheme consists of two cascaded control loops [7]. The inner current control loops regulate independently the d-axis and q-axis rotor current components, i_{dr} and i_{qr} , according to some synchronously rotating reference frame. The outer control loops govern both the stator active power (generator rotor speed) and reactive power separately. The basic rotor-side controller diagram is shown in Fig. 2.

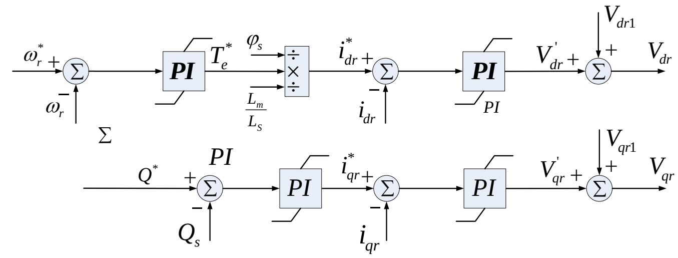

Fig. 2. The Vector Control Scheme of Rotor-Side Control

F. Modeling of Grid-Side Control

The Grid-Side Control also consists of two cascaded control loops [7], the inner current control loops regulate independently the d-axis and q-axis GSC ac-side current components, i_{dg} and i_{qg} , in the synchronously rotating reference frame. The outer control loops regulate the dc-link voltage and the reactive power exchanged between the grid-side control and the grid.

The basic grid-side controller diagram is shown in Fig. 3.

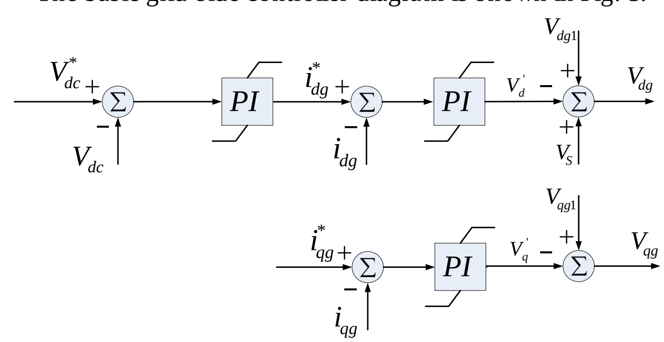

Fig. 3.The Vector Control Scheme of Grid-Side Control

G. Design of Pitch Control

The differential equation of this pitch control [11] could be expressed as (10).

$$T \cdot \frac{d\beta}{dt} = K_{p\_\beta} \cdot \frac{d\omega_r}{dt} + K_{i\_\beta} \cdot \omega_{err} \quad (10)$$

Fig.4, shows the scheme of pitch angle control loop [9];

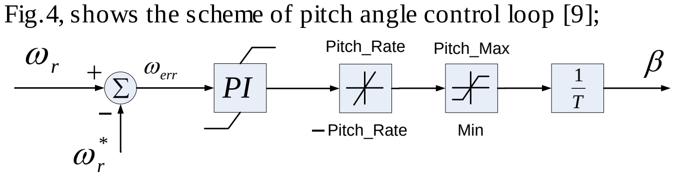

Fig. 4.Wind Turbine Pitch Angle Controller

III. SIMULATION RESULTS

To demonstrate the possible dynamic interaction between 5 MW and 1.5 MW DFIGs, a double machine grid-connected system in Fig. 5, is built for simulation studies using Matlab/Simulink. The disturbance signals like step-up wind input and self-clearing fault at infinite bus will be introduced into the system. The transmission line length varies in the case study to detect the effect of the distance of the wind farm from the grid on dynamic interaction. Both high and low level wind speeds are used as inputs in order to observe the potential interaction between these two DFIGs when they run both super-synchronously and sub-synchronously. The outputs of rotor speeds, active powers, reactive powers and stator currents of these two DFIGs are recorded for judging the possible dynamic interaction between them.

In Fig. 5, DFIG1 and DFIG2 represent 30 MW (6×5 MW) and 9 MW (6×1.5 MW) DFIGs respectively. The DFIG based wind farm is connected through a transmission line anda step-up transformerto an infinite bus.

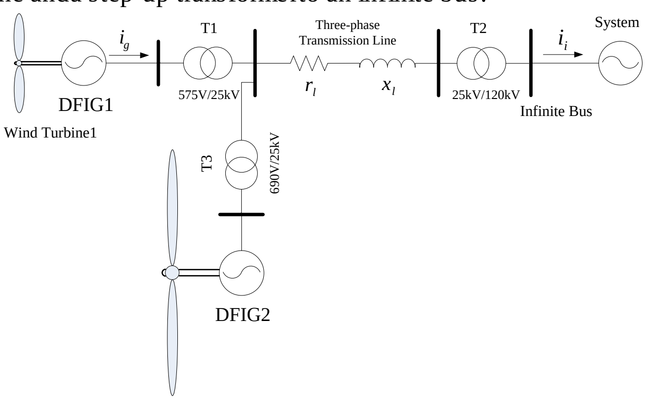

Fig. 5.Two DFIG wind farms connected to infinite bus

A. *Case I: Grid-connected 6 × 5 MW And 6 × 1.5 MW DFIGs With Step-up Wind Input*

To observe the possible dynamic interaction between 5 MW and 1.5 MW DFIGs, 6 ×5 MW and 6 × 1.5 MW DFIGs are connected to infinite bus through a 30 km transmission line. The wind speed is assumed to be a step-up signal from 13 m/s to 15 m/s at t = 1 s for both wind farms. As the wind speed is above the rated value, the pitch controller is activated all the time.The RSC reactive power is regulated at $Q_s^* = 0$ and the GSC q-axis current is set at $i_{qg}^* = 0$ respectively.

The results (Fig. 6, and Fig. 7,) indicate that there is no dynamic interaction between 5 MW and 1.5 MW DFIGs. When the pitch controller is activated, the rotor speeds and active power outputs of both DFIGs are regulated at rated values. These two DFIGs are working well together under the condition of step-up winds.

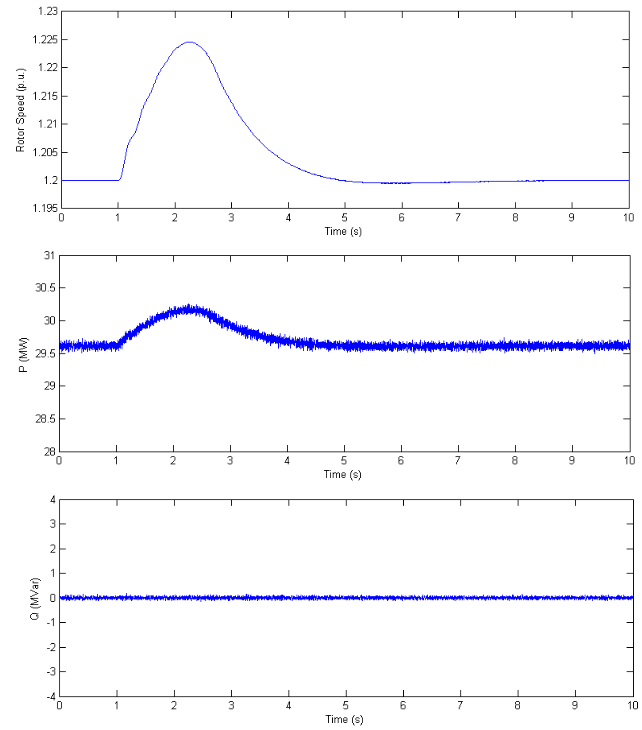

Fig. 6. Step-up wind 13 to 15 m/s: rotor speed, active power output, reactive power output of 5 MW DFIG

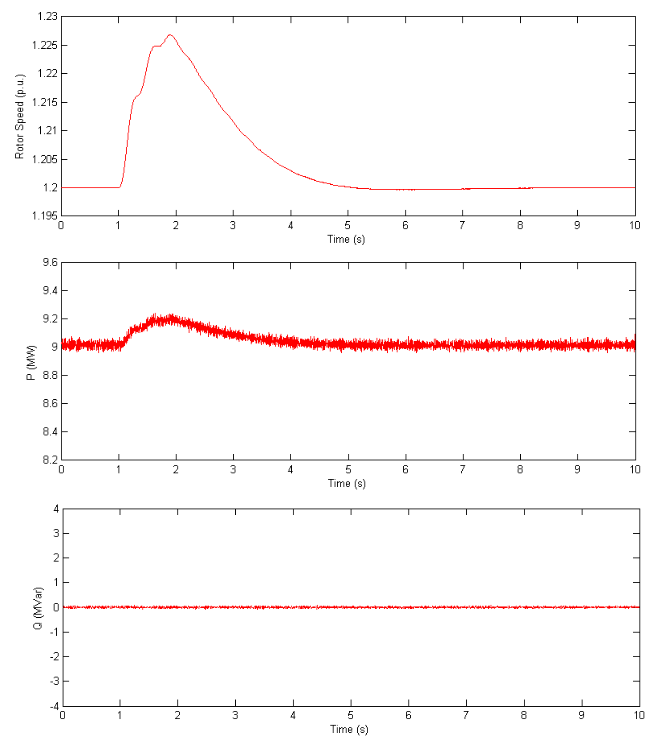

Fig. 7. Step-up wind 13 to 15 m/s: rotor speed, active power output, reactive poweroutput of 1.5 MW DFIG

B. *Case II: Grid-connected 6 × 5 MW And 6 × 1.5 MW DFIGs Under Grid Fault WithSmaller Wind Speed in Sub-synchronous State*

A 100 ms three-phase short circuit is applied to the infinite bus att = 1 s. In order to test the dynamic responses of 5 MW and 1.5 MW DFIGs in sub-synchronous state, the wind speed is assumed to be 9 m/s. During pre-fault and post-fault condition, the commands of reactive power outputs and GSC q-axis current are maintained at 0 pu.

From Fig. 8, we can see 5 MW and 1.5 MW DFIGs do not oscillate against each other under all three wind speeds. The damping speed of each output varies as different winds are carried out; however, all the outputs of both DFIGs stabilize after a short while. This can prove that 5 MW and 1.5 MW DFIGs are able to work together either in sub-synchronous or super-synchronous states.

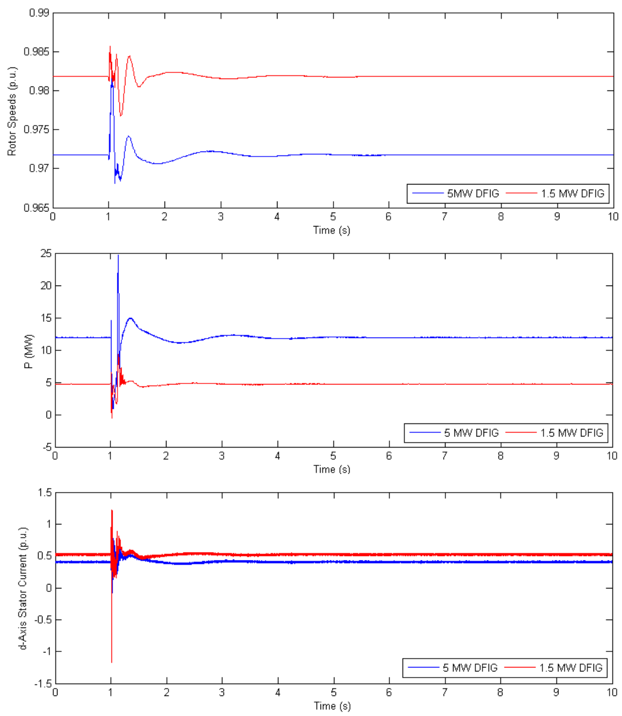

Fig. 8. Constant wind 9 m/s: rotor speeds, active power outputs and d-axis stator currents of 5 MW and 1.5 MW DFIGs

C. Case III: Grid-connected 6 × 5 MW And 6 × 1.5 MW DFIGs Under Grid Fault With Different Transmission Line Lengths

Different transmission line lengths are applied in this case, 10 km, 30 km, and 60 km. The dynamic responses of two DFIGs during and after a grid fault are presented. A 100 ms three-phase short circuit is applied to the infinite bus at t = 1 s. Wind speed is assumed to be 13 m/s. During pre-fault and post-fault condition, the reference values of reactive power outputs and GSC q-axis current are maintained at 0 pu.

It can be noted from Fig. 9 and 10 that, under the same wind conditions, the rotor speeds oscillation amplitudes of 5 MW and 1.5 MW DFIGs become larger as transmission line length increases, but the damping of active power outputs and stator currents turns faster. These two DFIGs can still work together very well, without sever dynamic interaction happening.

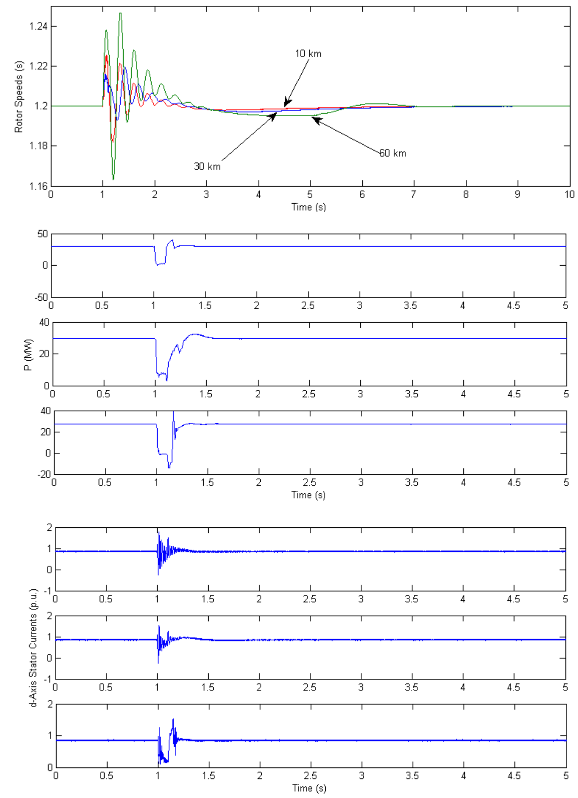

Fig. 9. Transmission line lengths 10, 30 and 60 km: rotor speeds, active power outputs and d-axis stator currents of 5 MW DFIG

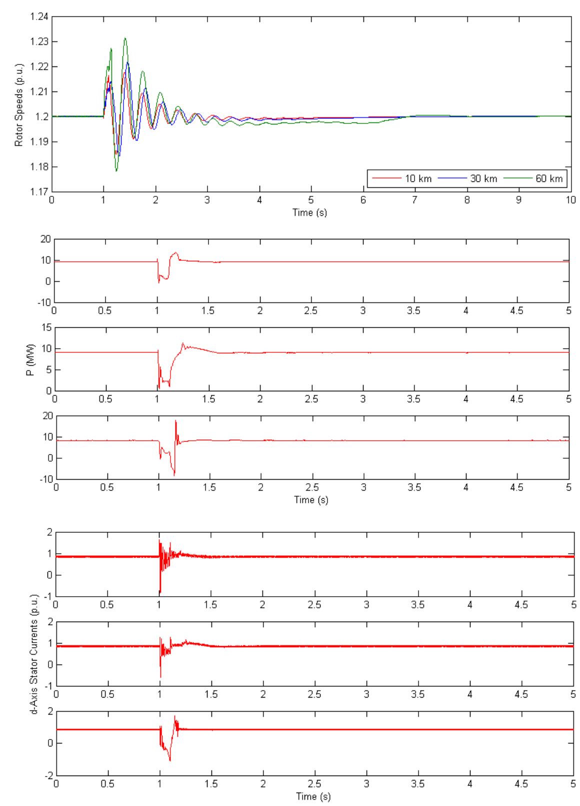

Fig. 10. Transmission line lengths 10, 30 and 60 km: rotor speeds, active power outputs and d-axis stator currents of 1.5 MW DFIG

IV. Modal Analysis

To further justify the results of case study, a set of dynamic equations of double machine grid-connected system is established for small signal modal analysis. If all the eigenvalues are located on the left half of the complex plane, the equilibrium point selected is stable [4] and therefore, no dynamic interactionbetween 5 MW and 1.5 MW DFIGs can be determined.

For system small signal stability analysis, an equivalent circuit with equivalent voltage sources is built in a d-q reference frame [5]. The generator stator and rotor voltage equations (1)-(4) can be derived as the differential equations (11)-(14) of stator current and equivalent voltage behind transient impedance as state variables [12]-[4]-[8].

$$\frac{1}{\omega_b}\frac{di_{ds}}{dt} = -\frac{\omega_s}{X_s'}\left(R_s + \frac{X_s - X_s'}{\omega_s T_0}\right) i_{ds} + \omega_s i_{qs} + \frac{\omega_r}{X_s'} e_{ds}' - \frac{1}{X_s' T_0} e_{qs}' + \frac{\omega_s L_m}{X_s' L_r} v_{dr} - \frac{\omega_s}{X_s'} v_{ds} \quad (11)$$

$$\frac{1}{\omega_b}\frac{di_{qs}}{dt} = -\omega_s i_{ds} - \frac{\omega_s}{X_s'}\left(R_s + \frac{X_s - X_s'}{\omega_s T_0}\right) i_{qs} + \frac{1}{X_s' T_0} e_{ds}' + \frac{\omega_r}{X_s'} e_{qs}' + \frac{\omega_s L_m}{X_s' L_r} v_{qr} - \frac{\omega_s}{X_s'} v_{qs} \quad (12)$$

$$\frac{1}{\omega_b}\frac{de_{ds}'}{dt} = -\frac{1}{T_0}\left[e_{ds}' - (X_s - X_s') i_{qs}\right] + (\omega_s - \omega_r) e_{qs}' - \frac{\omega_s L_m}{L_r} v_{qr} \quad (13)$$

$$\frac{1}{\omega_b}\frac{de_{qs}'}{dt} = -\frac{1}{T_0}\left[e_{qs}' + (X_s - X_s') i_{ds}\right] - (\omega_s - \omega_r) e_{ds}' - \frac{\omega_s L_m}{L_r} v_{dr} \quad (14)$$

where L_r is stator voltage vector $v_s = v_{ds} + jv_{qs}$; rotor voltage vector $v_r = v_{dr} + jv_{qr}$; $X_s = \omega_s / L_s$; $X_s' = \omega_s (L_s - L_m^2 / L_r)$; $T_0 = L_r / R_r . \omega_b$ is frequency base.The equivalent circuit of grid-connected twoDFIGs system can be presented as the graphic below:

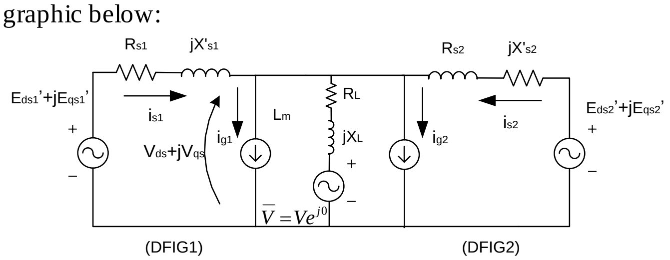

Fig. 11. Equivalent Circuit of Two DFIGs Connected to a Grid

By adding differential equations of grid-side converter and two-mass drive train (7)-(9), we can obtain a set of differential equations to present simplified grid-connected double DFIG wind turbines system. Performance of 5 MW and 1.5 MW DFIG wind turbine under small perturbation in a grid-connected mode is studied by substituting corresponding equilibrium points.

A. *Modal Analysis Case I: Grid-connected 6 × 5 MW And 6 × 1.5 MW DFIGs at Wind Speed 13m/s in Super-synchronous states*

TABLE I
EIGENVALUES FOR 5 MW DFIG AT $V_W = 13$M/S, $\Omega_R = 1.2$ PU

Eigenvalues of 5 MW DFIG	Damping Ratio	State Variables
$-109.35 \pm j578.44$	0.186	i_{ds}, i_{qs}
$-22.53 \pm j376.00$	0.060	e_{ds}', e_{qs}'
$-22.52 \pm j316.08$	0.071	i_{dg}, i_{qg}
$-27.46 \pm j341.04$	0.080	ω_r, θ_t
-1.28	1	ω_t

TABLE II
EIGENVALUES FOR 1.5 MW DFIG AT $V_W = 13$M/S, $\Omega_R = 1.2$ PU

Eigenvalues of 1.5 MW DFIG	Damping Ratio	State Variables
$-87.08 \pm j547.09$	0.157	i_{ds}, i_{qs}
$-18.36 \pm j311.43$	0.059	e_{ds}', e_{qs}'
$-15.98 \pm j355.09$	0.045	i_{dg}, i_{qg}
$-22.33 \pm j345.66$	0.065	ω_r, θ_t
-0.04	1	ω_t

From Table I and II, the eigenvalues of all the state variables of both 5 MW and 1.5 MW DFIGs are negative, There is no direct coupling happening between these two DFIGs' rotor speeds or turbine speeds. It can be proved that the generator and wind turbine systems of these two DFIGs do not have dynamic interaction.

B. *Modal Analysis Case II: Grid-connected 6 × 5 MW And 6 × 1.5 MW DFIGs at Wind Speed 9 m/s in Sub-synchronous states*

TABLE III
EIGENVALUES FOR 5 MW DFIG AT $V_W = 9$M/S, $\Omega_R = 0.972$ PU

Eigenvalues of 5 MW DFIG	Damping Ratio	State Variables
$-109.31 \pm j578.44$	0.186	i_{ds}, i_{qs}
$-22.53 \pm j376.00$	0.060	e_{ds}', e_{qs}'
$-22.46 \pm j316.10$	0.071	i_{dg}, i_{qg}
$-27.40 \pm j341.05$	0.080	ω_r, θ_t
-1.35	1	ω_t

TABLE IV
EIGENVALUES FOR 1.5 MW DFIG AT $V_W = 9M/S$, $\Omega_R = 0.982$ PU

Eigenvalues of 1.5 MW DFIG	Damping Ratio	State Variables
$-87.03 \pm j547.10$	0.157	i_{ds}, i_{qs}
$-18.29 \pm j311.43$	0.059	e'_{ds}, e'_{qs}
$-15.98 \pm j355.11$	0.045	i_{dg}, i_{qg}
$-22.28 \pm j345.67$	0.065	ω_r, θ_t
-0.04	1	ω_t

Compared this result to modal analysis Case I, we can find that as wind speed changes, the eigenvalues of stator currents, equivalent voltages and grid-side converter currents barely move. Two DFIGs of different capacity can still work together in sub-synchronous states.

C. Modal Analysis Case III: Grid-connected 6 × 5 MW And 6 × 1.5 MW DFIGs at Wind Speed 13 m/s With Transmission Line Length at 60 km

TABLE V
EIGENVALUES FOR 5 MW DFIG AT $V_W = 13M/S$, $\Omega_R = 1.2$ PU, $L = 60KM$

Eigenvalues of 5 MW DFIG	Damping Ratio	State Variables
$-210.75 \pm j720.02$	0.280	i_{ds}, i_{qs}
$-43.21 \pm j373.85$	0.115	e'_{ds}, e'_{qs}
$-36.06 \pm j299.06$	0.120	i_{dg}, i_{qg}
$-24.42 \pm j239.68$	0.101	ω_r, θ_t
-0.65	1	ω_t

TABLE VI
EIGENVALUES FOR 1.5 MW DFIG AT $V_W = 13M/S$, $\Omega_R = 1.2$ PU, $L = 60KM$

Eigenvalues of 1.5 MW DFIG	Damping Ratio	State Variables
$-163.74 \pm j671.10$	0.237	i_{ds}, i_{qs}
$25.52 \pm j334.30$	0.076	e'_{ds}, e'_{qs}
$-27.83 \pm j308.92$	0.090	i_{dg}, i_{qg}
$-14.98 \pm j222.54$	0.067	ω_r, θ_t
-0.96	1	ω_t

Most state variables of both two DFIGs have their eigenvalues move left and damping ratios increase as the transmission line distance enlarges.The performances of 5 MW and 1.5 MW DFIGs in the same wind farm are rarely affected by the transmission line distance to the grid.

V. CONCLUSION

Doubly-fed induction wind turbine generators of different capacity have good performance in grid connected mode when some disturbances are introduced to the system. The good fault-ride through capability is shown when 5 MW and 1.5 MW DFIGs are working together within the same wind farm.

There is little dynamic interaction emerging between 5 MW and 1.5 MW DFIGs.In the condition of step-up wind input, both DFIGs adapt the abrupt input change and are able to maintain the stable power outputs and rotor speed after a short term adjustment. Under faults, both DFIGs manage to be stable during post-fault period. They are demonstrated to be able to work perfectly together either sub-synchronously or super-synchronously by introducing different levels of wind speeds. The length of transmission line isn't a problem for both 5 MW and 1.5 MW DFIGs.

The modal small signal system analysis helps to explore the dynamic characteristics of double DFIGs grid-connected mode more intuitively. It can be justified that there is no direct coupling between the drive train systems of 5 MW and 1.5 DFIGs as well as their generators. Both DFIGs have negative eigenvalues for all the state variables when they work together.

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