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Mathematical Modeling of DFIG for Reactive Power Loss Analysis and Controlling

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Abstract

The output of wind farms depends on the wind resource and cannot be conventionally controlled. This demand in development towards the balancing power for wind farm networks. Network reconfiguration is the process of the altering topological structures of distribution feeders by changing the open or close statues of the sectionalizing and switches. During normal operation of a power transmission networks are reconfigured to reduce the system real power losses and to relieve overloads in the networks. The former is referred to as network reconfiguration for loss reduction and the lateral load balancing. In the work a network reconfiguration approach is proposed for load balancing and loss reduction in wind power energy system. As the wind power generation is a variable source it is a challenging task to deliver the required load with least load unbalancing.

Keywords: Mathematical modeling, Reactive power loss, analysis, controlling

Introduction

A maximum output control of wind power generation system considering loss minimization of machines. The wind turbine has its own optimum rotational speed, which produce the maximum power conversion for give dimension and wind speed. Even at this optimum speed, the generator cannot produce the maximum output power due to the useless machine loss. In general, the decreasing the flux level, resulting in the significant reduction of the core loss, can reduce the machine loss. For vector controlled induction machine drives, the d-axis current controls the excitation level and the q axis current controls the generator is controlled according to the variation of the wind speed in order to produce the maximum output power. The generator reference speed is adjusted according to optimum tip-speed ratio. The generated power flows into the utility grid through the back-to-back PWM converter. The grid-side converter controls the dc link voltage and the line-side power factor by the q-axis current control, respectively.

This method is applied to the flux control of the cage-type induction generator for grid connected wind power [1] systems. The generator is operated in indirect vector control mode, where the d axis current controls the flux level and the q-axis current controls the machine speed which is determined so as to capture the maximum energy from the wind. For grid connection, a back-to-back PWM converter is used between the machine terminal and the grid. The grid-side converter is also controlled in d-q vector frame. The q axis current is controlled to keep the dc link voltage constant and d-axis current is controlled to zero for unity power factor.

According to the aero dynamic characteristics of wind turbine blade, there is an optimum rotating speed to give maximum wind energy [1 7] capture. The theoretical power obtainable from the wind passing through a circular area is

$$P_{air} = 0.5\rho A v^3$$

The power conversion coefficient of the rotor is defined as the ratio between the mechanical power available at the turbine shaft and the power available in the wind. Neglecting the friction losses, the mechanical power available to be converted by generator is given by

$$P_m = 0.5\rho C_p v^3$$

The power conversion coefficient is a function of the tip speed ratioλ, which is defined as

$$\lambda = \frac{\omega_m}{\upsilon} R$$

Torque of wind turbine (Twt) = (0.5)*(ρ)*(π)*(Rwt)*(Rwt)*(V) ^{3}*(Cp)/ (ω)

When a synchronous machine is operated as a generator, a prime mover is required to drive the generator. In steady state, the mechanical torque of the prime mover should balance with the electromagnetic torque produced by the generator and the mechanical loss torque due to friction and wind age.

$$T_{pm}=T+T_{loss}$$

Multiplying the synchronous speed to both sides of the torque equation, we have the power balance equation as

P*pm*=P*em*+P*loss*

Ppm=Tpm(t)syn is the mechanical power supplied by the prime mover

P*em*=Tw*syn*

is the electromagnetic power of the generator

P*loss*=T*loss (t) syn*

is the mechanical power losses of the system.

The electromagnetic power is the power being converted into the electrical power in the three phase stator windings.

$$P_{em} = T\omega_{syn} = 3E_a I_a \cos\varphi_{E_a I_a}$$

Where Q is the angle between phasorsE*a*and I*a*.

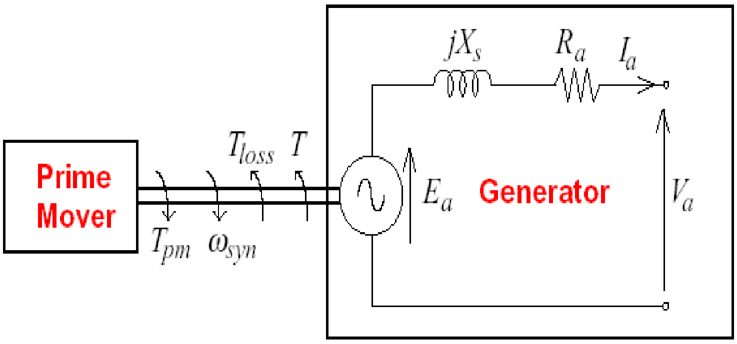


Figure 1: Synchronous Machine operated as generator

For larger synchronous generators, the winding resistance is generally much smaller than the synchronous reactance and thus the per phase circuit equation can be approximately written as

$$\mathbf{V}_a = \mathbf{E}_a - jX_s\mathbf{I}_a$$

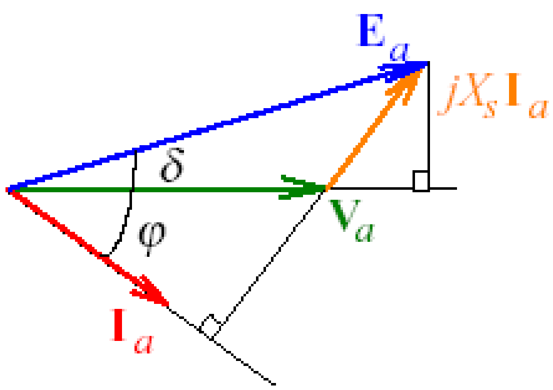


Figure 2: Generator Phase Diagram.

Active Power (P) = (Vr)*(Vr)*(cos (φ)) / (Zr)
Reactive Power (Q) = (Vr)*(Vr)*(sin (φ)) / (Zr)

Stator cupper losses: $i_{ds}^2 R_s + i_{qs}^2 R_s$

Rotor cupper losses: $i_{dr}^2 R_r + i_{qr}^2 R_r$

Stator iron losses: $K_h \omega_e \lambda_r^2 + K_c \omega_e^2 \lambda_r^2$

Rotor iron losses: $K_h \omega_{sl} \lambda_r^2 + K_c \omega_{sl}^2 \lambda_r^2$

Rotor /Grid Side Converters

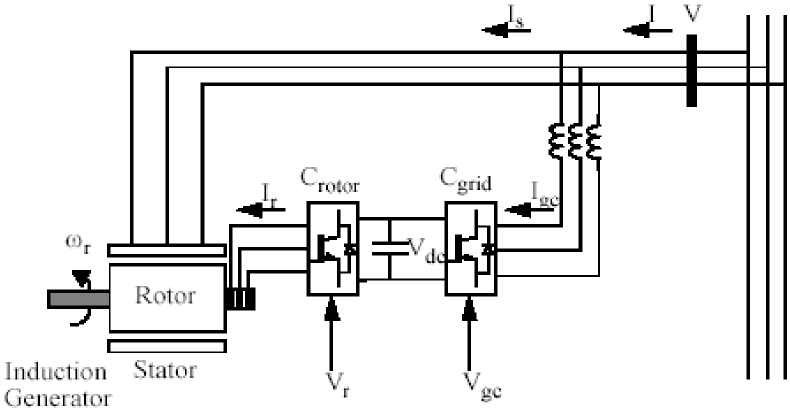


Figure 3: Rotor-side and grid side converters.

The absolute value of slip is much lower than 1 and consequently, Pr is only a fraction of Ps. Since Tm is positive for power generation and since ωsis positive and constant for a constant frequency grid voltage, the sign of Pr is a function of the s5lip sign. Pr is positive for negative slip (speed greater than synchronous speed) and it is negative for positive slip (speed lower than synchronous speed). For super synchronous speed operation, Pr is transmitted to DC bus capacitor and tends to rise the DC voltage. For sub-synchronous speed operation, Pr is taken out of DC bus capacitor and tends to decrease the DC voltage. C grid is used to generate or absorb the power Pgc in order to keep the DC voltage constant. In steady state for a loss less AC/DC/AC converter Pgc is equal to Pr and the speed of the wind turbine is determined by the power Pr absorbed or generated by C rotor. The phase-sequence of the AC voltage generated by C rotor is positive for sub-synchronous speed and negative for super synchronous speed. The frequency of this voltage is equal to the product of the grid frequency and the absolute value of the slip. C rotor and C grid have the capability for generating or absorbing reactive power [2 8 9] and could be used to control the Reactive power or the voltage at the grid terminals.

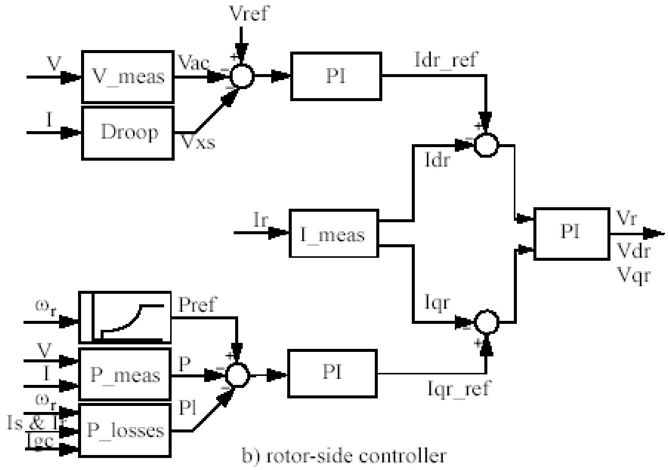


Figure 4: Rotor-side controller.

Rotor Control System

The rotor-side converter is used to control the wind turbine output power and the voltage measured at the grid terminals. The power is controlled in order to follow a pre-defined power-speed characteristic, named tracking characteristic. This characteristic is superimposed to the mechanical power characteristics of the turbine obtained at different wind speeds. The actual speed of the turbine ωr is measured and the corresponding mechanical Power of the tracking characteristic is used as the reference power for the power control loop. The tracking characteristic is defined by four points: A, B, C and D. From zero speed to speed of point A the reference power is zero. Between point A and point B the tracking characteristic is a straight line. Between point B and point C the tracking characteristic is the locus of the maximum power of the turbine (maxima of the turbine power vs turbine speed curves). The tracking characteristic is a straight line from point C and point D. The power at point D is one per unit (1 p.u.). Beyond point D the reference power is a constant equal to one per unit (1 p.u.).The generic power control loop is illustrated in Fig. 4b).

For the rotor-side controller the d-axis of the rotating reference frame used for d-q transformation is aligned with air-gap flux. The actual electrical output power, measured at the grid terminals of the wind turbine, is added to the total power losses (mechanical and electrical) and is compared with the reference power obtained from the tracking characteristic. A Proportional-Integral (PI) regulator is used to reduce the power error to zero. The output of this regulator is the reference rotor current I*qr*-ref that must be injected in the rotor by converter C rotor.

This is the current component that produces the electromagnetic torque Tem. The actual I qr component is compared to Iqr-ref and the error is reduced to zero by a current regulator (PI). The output of this current controller is the voltage Vqr generated by C rotor. The current regulator is assisted by feed forward terms which predict Vqr. The voltage at grid terminals is controlled by the reactive power generated or absorbed by the converter C rotor. The reactive power [2] is exchanged between CRotor and the grid, through the generator. In the exchange process the generator absorbs reactive power to supply its mutual and leakage inductances. The excess of reactive power is sent to the grid or to CRotor.

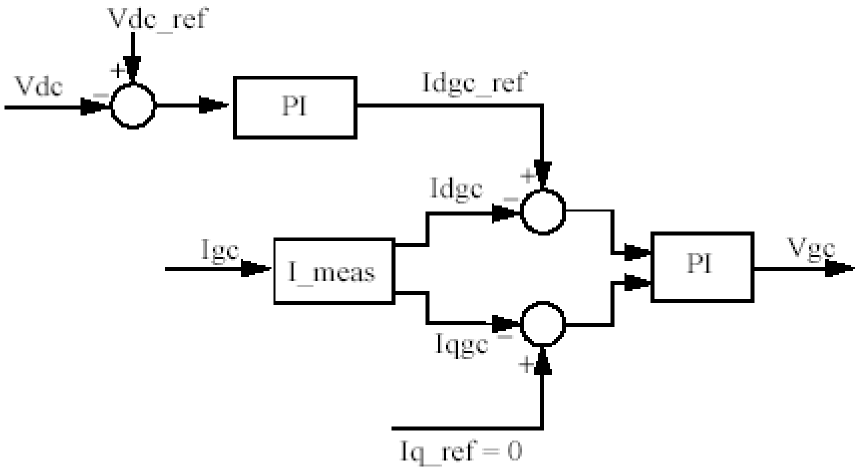


Figure 5: Grid-side controller.

Grid Control System

The converter C grid is used to regulate the voltage of the DC bus capacitor. For the grid-side controller the d-axis of the rotating reference frame used for d-q transformation is aligned with the positive sequence of grid voltage. This controller consists of:

1. A measurement system measuring the d and q components of AC currents to be controlled as well as the DC voltage Vdc.
2. An outer regulation loop consisting of a DC voltage regulator. The output of the DC voltage regulator is the reference current Idgc-ref for the current regulator (Idgc =current in phase with grid voltage which controls active power flow).
3. An inner current regulation loop consisting of a current regulator. The current regulator controls the magnitude and phase of the voltage generated by converter C grid (Vgc) from the Idgc_ref produced by the DC voltage regulator and specified Iq_ref reference. The current regulator is assisted byFeed forward terms which predict the Cgrid output voltage.

Mathematical Analysis

Density (ρ)	= 1.08 Kg/m^3;
Radius of Wind turbine	= 45m;
Optimal tip speed ratio	= 10;
Impedance	= 5ohm;
Phase Angle	= 30degrees;

Stator direct axis current	= 2amp;
Stator quadrature axis current	= 2amp;
Rotor direct axis current	= 3amp;
Rotor quadrature axis current	= 3amp;
Hysteresis loss coefficent	= 0.4;
Eddy current loss coefficient	= 0.5;
Turbine operating speed	= 40r.p.m;
Current	= 60amp;
Wind Speed	= 12m/sec;
Vmeasurement	= 230;
idroop	= 5.8;
vxs	= 45;
vref	= 800;
wr	= 315;
v	= 250;
Is	= 4.5;
s	= 2*3.14*f;
w_e	= 0.5;
w_{sl}	= 0.3;

Constant Speed Wind Turbine

1. Total Power available in the wind = $(0.5)*(\rho)*(\pi/4)*(d^2)*(v)^3$;
=0.5*(1.08)*(3.14/4)*$(90)^2$*$(12)^3$
=5933KW

2. Torque = (Density)*(Rwt)*(ws)*(ws)*(ws)/((Nsyn)*(4));
= (1.08)*(45)*(12)*(12)*(12)/((40/60)*(4))
=31.4K*N-M*

3. Voltage = ((T)*(2*3.14*(Nsyn)))/(3*(Ia)*(cos(O))));
= (31.4)*(1000)*(2)*(3.14)*(40/60)/((3*(60)*(cos(30))
=4.7Kv

4. Active Power = $((v)^2/Z)$*cos(O);
= ((4.7)*(4.7)/(3))*(0.866)*(1000)
=6.3KW;

5. Reactvie Power = $((v)^2/Z)$*(sin (O));
= ((4.7)*(4.7)/ (3))*(0.5)*(1000)
=3.6KW

Variable Speed Case

6. Synchronous Speed (N_{syn})	= (120*f)/ (60*p); = (120*50)/ (60*12)= 8.3336rps
7. Torque	= (density)*(Rwt)*(ws)* (ws)*(ws)/((Nsyn)*(4)); = (1.08)*(45)*(12)*(12)*(12)/((8.336)*(4)) = 2.58K*N-M*
8. Voltage	= (((T)*(2*3.14*(Nsyn)))/(3*(Ia)*(cos(O)))); = (2.584)*(1000)*(2)*(3.14)* (8.336)/((3*(60)*(cos(30)) =4.8Kv
9. Active Power	= $((v)^2/Z)$*cos(O); = ((4.8)*(4.8)/(3))*(0.866)*(1000) = 6.65Kv
10. Reactive Power	= $((v)^2/Z$ *(sinO); = ((4.8)*(4.8)/(3))*(0.5)*(1000) = 3.8KW
11. Maximum power	= $(0.59)*(0.5)*(\rho)*(\pi/4)*(d^2)*(v)^3$; (0.5)*(0.59)*(1.08)*(3.14/4)*(90)* (90)*(12)*(12)*(12) =3.5Kw
12.Stator copper losses	=(ids)*(ids)*(Rs)+(iqs)*(iqs)*(Rs); =(2)*(2)*(3)+(2)*(2)*(3) = 24 W
13.Rotor copper losses	=(idr)*(idr)*(Rr)+(iqr)*(iqr)*(Rr); = (2)*(2)*(3)+(2)*(2)*(3) = 24 W
14.Stator iron losses	= $((kh)*(w_e)*(lr)*(lr))+((ke)*(w_e)*(lr)*(lr))$; =((0.4)*(0.5)*(10)*(10)+(0.5)* (0.5)*(10)*(10)) = 45W
15. Rotor iron losses	= $(k_h)*(ws_l)*(ws_l)*(lr)*$ (lr)+(ke)*(ws1)*(ws1)*(lr)*(lr); =((0.4)*(0.3)*(0.3)*(10)*(10)+(0.4)* (0.3)*(0.3)*(10)*(10)) =7.2;

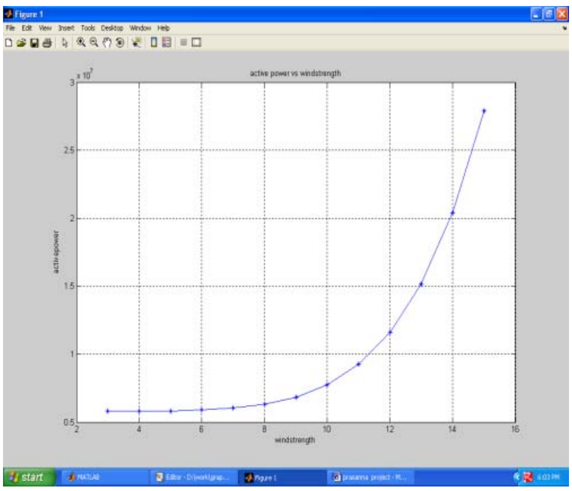
16.Total losses = 24+24+45+7.2
= 100.2W

PARAMETER DEFINITONS

P_m	Mechanical power captured by the wind turbine and transmitted to the rotor
P_s, Q_s	Stator active and reactive power output
P_r, Q_r	Rotor active and reactive power output
P_{gc}, Q_{gc}	C_{grid} active and reactive power output
T_m	Mechanical torque applied to rotor
T_{em}	Electromagnetic torque applied to the rotor by the generator
ω_r	Rotational speed of rotor
ω_s	Rotational speed of the magnetic flux in the air-gap of the generator. This synchronous speed is proportional to the frequency of the grid voltage and to the number of generator poles.
J	Combined rotor and wind turbine moment of inertia

Wind turbines [4 8] use complex technologies including power electronic converters and sophisticated control systems. Electromagnetic transients in Power systems need to be simulated and analyzed in order to study the impact of these new power generators on the power systems.

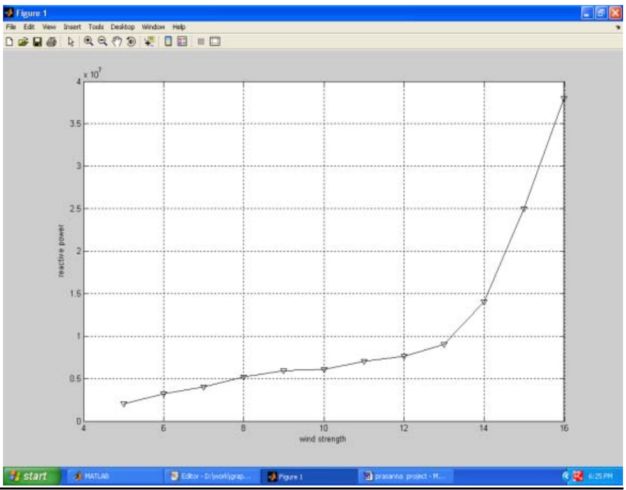
Result Analysis



Wind Strength / Active Power

Table 1:

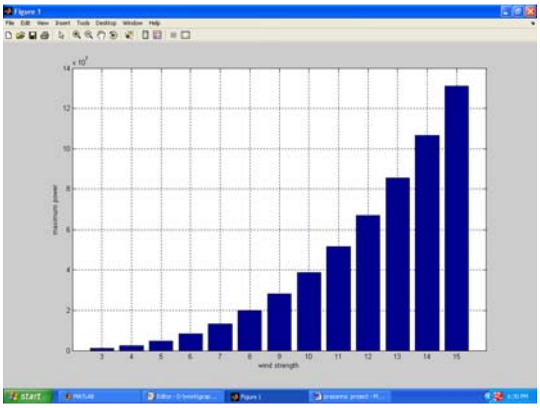
S.no	Wind Strength (m/sec)	Active Power (MW)
1	4	5.2
2	6	7.1
3	8	7.9
4	10	9.1
5	12	13.4
6	14	21.5
7	16	30



Wind Strength / Reactive Power

Table 2:

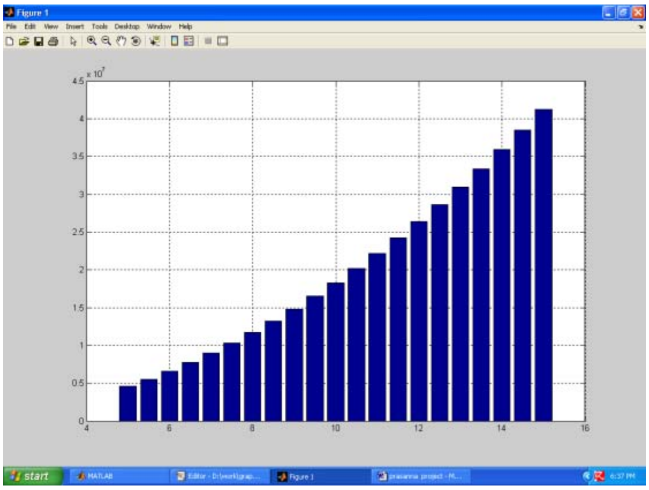
S.no	Wind Strength (m/sec)	Reactive Power (MW)
1	4	2.2
2	6	3.1
3	8	5.1
4	10	6.9
5	12	8.6
6	14	13.2
7	16	38



Wind Strength / Maximum Power

Table 3:

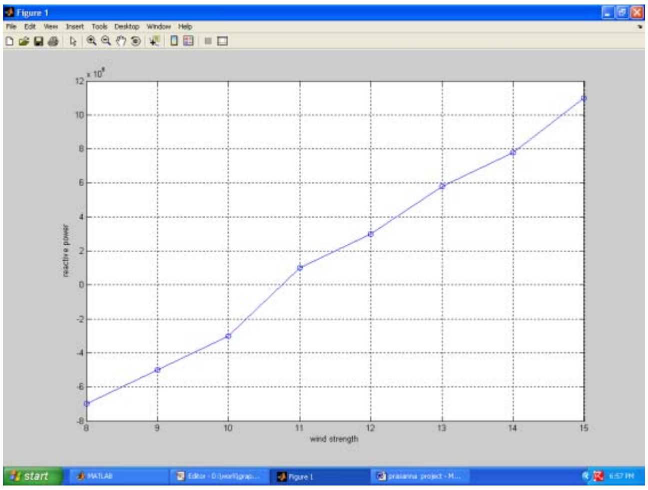
S.no	Wind Strength (m/sec)	Maximum Power (MW)
1	4	8
2	6	14
3	8	19
4	10	37
5	12	61
6	14	103
7	16	135



Wind strength / Torque

Table 4:

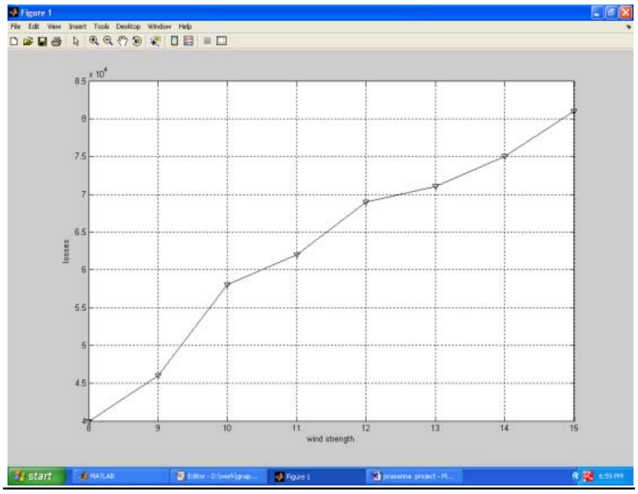
S.No	Wind Strength (m/sec)	TORQUE ($*10^6$ N-M)
1	4	4.2
2	6	6.3
3	8	14
4	10	18
5	12	27
6	14	36
7	16	45



Wind Strength / Reactive Power

Table 5:

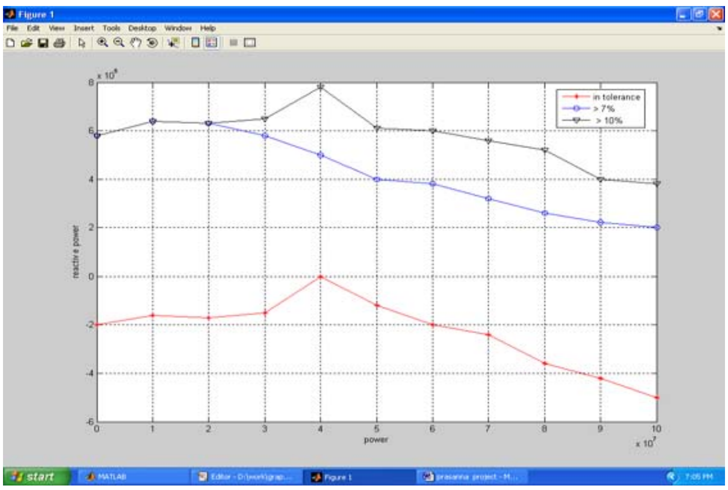
S.no	Wind Strength (m/sec)	Reactive Power (MW)
1	8	-7.4
2	9	-5.4
3	10	-2.8
4	11	1.5
5	12	3.4
6	13	5.7
7	14	7.8



Wind Strength / Losses

Table 6:

S.no	Wind Strength (m/sec)	LOSSES (KW)
1	8	4.0
2	9	4.7
3	10	5.8
4	11	6.2
5	12	6.9
6	13	7.2
7	14	7.5



Total Power / Reactive Power

Table 7:

S.No	total power (MW)	reactive power (with 7% tolerance)	Reactive power (with 10%tolerance)
1	20	6.5	6.5
2	30	5.8	6.7
3	40	4.9	7.9
4	50	4.0	6.1
5	70	2.8	5.6
6	80	2.5	4.7
7	90	2.2	4.0

Conclusion

The work presents the importance of power control in wind farm network and advantages offered by rotor side and grid side converters to control reactive power. The main objective of this work to get reactive power optimization and minimization of internal losses in wind farm network having both constant speed & variable speed wind turbines.

The considered wind farm consists of 10 wind energy converters (WEC) with a nominal capacity of 1250 kWeach.5WEC's are of a conventional design fixed speed, asynchronous generator directly coupled to the grid. The remaining 5 units are equipped with electronic power converters allowing variable speed operation this uncommon combination of technologies offers new opportunities for wind farm operation and control.

The real power is obtained from the wind turbine power curve, giving the wind speed as input. Crotor and Cgrid have the capability for generating or absorbing reactive power and could be used to control the reactive power or the voltage at the grid terminals. The rotor-side converter is used to control the wind turbine output power and the voltage measured at the grid terminals. The converter Cgrid is used to regulate the voltage of the DC bus capacitor. As the active power output decreases the grid-side converters of the 5Variable-speed WEC's can dedicate more kVA capability to generation / absorption of reactive power and the Q control range increases. The tolerated voltage rise in the wind farm network determines the available Q control range. In case the voltage rise is limited to 7% the Q control range is limited significantly. Because reactive power generation leads to increase of losses. Finally it can be concluded that to get the maximum power output & minimization of losses control of reactive power by using rotor side and grid side converters in variable speed wind turbines of a wind farm network.

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