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Determination of Minimum Reactive Power Compensation for the Stable Operation of Type-1 WTG in Grid-Connected mode

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Abstract: ***The current energy demand scenario leads to tremendous increase in the renewable energy sector, but the integration of these renewable causes various stability issues of the system. Increasing share Wind energy has several shortages due to its energy harnessed from the wind. These shortages can be improved by compensating reactive power into the wind plant. The wind farm consist of fixed speed squirrel cage Induction generator absorbs reactive power from the grid for stable operation and it can be injected using reactive power compensator. In this context, the main aim of the research is to find the minimum reactive power compensation required for stable operation for different rating of Type-1 WTG in grid connected mode. In this paper, a detailed model of constant speed Squirrel Cage Induction Generator is carried out in MATLAB/SIMULINK-2017a to analyze the need of reactive power compensation to maintain voltage and frequency stability of the system during normal condition. The work also focuses on to investigate the impact of induction generator inertia level on compensation level. The modified IEEE 5-bus radial distribution system is used to conduct these investigations and the simulation results clearly show that: (1) The necessity and minimum additional reactive power support to the wind farm to improve and maintain stability of the system; (2) the inertia level of wind farm and reactive power compensator level both are independent each other.***

Keywords: ***IEEE 5-bus, Reactive Power Compensation, SCIG Based Wind Plant, Stability.***

I. INTRODUCTION

The limited resources of fossil fuels and recent environmental concerns, wind power plant emerging as a clean and sustainable alternate form of energy resources in fast growing power system. As per the GWEC 2018 report, 51.3 GW of new wind energy installed and the GWEC intelligence expects new installation for onshore and offshore of more than 55 GW each year till 2023[1]. Also, WWEA presents a statistics that the overall wind power capacity worldwide reaches 597 GW by the end of 2018, among that India stands in fourth place by installing 35017 MW in 2018[2]. Capacity has been doubling every three years from the last decade. Among the wind power generation systems, squirrel cage induction generator (SCIG) operating at constant speed is more feasible with respect to cost and maintenance. To produce rotating magnetic field in Induction generator an external supply should be applied to the stator windings, which clearly indicates that the induction generator consumes the reactive power and operates at poor lagging power factor. Hence, SCIG-WTG is to be connected to grid with reactive power injectors.

As a result, the SCIG can directly effects on voltage and frequency of the system. The fluctuation of this parameter in the system becomes larger, if the penetration level increases. There are different techniques are employed to study the small signal and transient stability of the system [3],[4]. The impact and need of reactive power compensation of wind plant is analyzed using P-V curve and also stated the importance of studies on ability of power system [5]. The detail modeling of SCIG-WTG is carried out and also investigates on series compensation requirement to integrate it into Grid [6]. Reference [7] presents modeling of SCIG and DFIG wind turbine and connected to IEEE 14 bus system using PSAT software. Also the impact of these WTGs on the small signal stability of the system is analyzed and concluded that the SCIG is marginally stable whereas DFIG is fully stable.

From the survey, the increase in penetration level of type-1 WTG plant effects on stability of the system as it mainly depend on grid for reactive power support. In order to overcome the burden of grid, the optimum reactive power should be calculated and compensate externally. So in this context, the proposed work is to suggest the minimum and optimum reactive power to be supplied for the different rating of type-1 wind mill to maintain the voltage and frequency stability of the system during normal operating condition. Also focuses on to analyze the impact of inertia on reactive power support and system stability considering IEEE 5 bus Modified RDS using SIMULINK.

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The paper is presented as follows: section II elaborates the detail modeling of squirrel cage induction generator type wind plant to carry out system stability analysis, followed by the system configuration details which is consider for the proposed studies in section III.

Section IV and V explains about the analysis of the voltage, frequency and rotor stability of the developed system under varying reactive power compensation level and inertia level with relevant results, followed by minimum capacitor bank to be connected in delta to supply required reactive power for different rating of type-1 wind plant is suggested in conclusion.

II. MATHEMATICAL MODELLING OF SQUIRREL CAGE INDUCTION GENERATOR

A Type 1 wind turbine is characterized by a Squirrel-Cage Induction Generator (SCIG), which is connected directly to the step up transformer as shown in Fig 1. The turbine rotates at a speed that closely follows the electrical grid frequency. The rotor speed is controlled by a pitch control and also required reactive power compensation is compensated either by using active or passive reactive power compensation device. The wind mill technical details are tabulated in Table I.

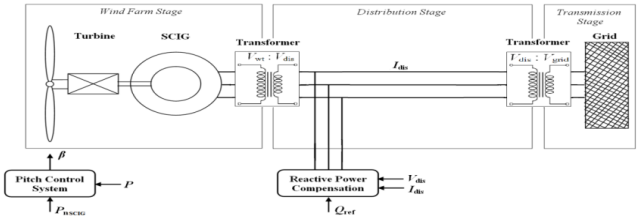

Fig.1.Type-I Wind Power Plant

Table-I: Wind Plant Parameter

Parameter	Quantity
Wind speed	10m/s
Transformer Rating	600KVA, 480/11KV
Rotor Type	Squirrel-Cage
Asynchronous Generator rated Power	100KVA
Rated Voltage	480V
Rated frequency	50Hz
Stator Resistance and Inductance (PU)	0.016,0.06
Rotor Resistance and Inductance (PU)	0.012,0.03
Mutual inductance (PU)	3.5
Pole Pairs	2
Friction factor	0

The mathematical modeling of wind turbine and induction generator which is suitable for stability studies are explained below:

A. Wind Turbine Model

The mechanical power output of a turbine ix expressed by:

$$P = \pi\rho V^3 R^2 C_p/2 \qquad (1)$$

Where, ρ is the air density, V is the wind velocity, R is the radius of rotor and C_p is the aerodynamic power coefficient. The Value of C_p is depends on wind speed, turbine speed and blade pitch angle β. The approximate equation of C_p is given as:

$$C_p = (0.44 - 0.0167\beta) * \mathrm{Sin}\left[\frac{\frac{\pi}{2}(\lambda - 3)}{7.5 - 0.15\beta}\right] - (\lambda - 3) * 0.00148\beta \qquad (2)$$

λ is the speed ratio and is defined as:

$$\lambda = \omega_H R/V \qquad (3)$$

Where ω_H is the wind turbine speed.

From (1) to (3) it can be observed that the wind turbine mechanical output power depends on the wind turbine speed, rotor blade pitch angle and wind speed

The commonly used mechanical model is two mass drive train systems for system stability studies. The dynamic equations are as follows:

$$\frac{d}{dt}(\delta_{tg}) = \omega_b(\omega_{wt} - \omega_{ge}) \qquad (4)$$

$$2H_{wt}\frac{d}{dt}(\omega_{wt}) = T_{\omega i} - K_{tg}\delta_{tg} - D_{tg}[\omega_b(\omega_{wt} - \omega_{ge})] \qquad (5)$$

$$2H_{ge}\frac{d}{dt}(\omega_{ge}) = K_{tg}\delta_{tg} + D_{tg}\omega_b(\omega_{wt} - \omega_{ge}) - T_{go}] \qquad (6)$$

Where, $T_{go} = X_m(I_{dr}I_{qs} - I_{qr}I_{ds})$ (7)

The normalized state space equation of the Wind turbine drive train system can be represented as:

$$X_T = A_T x_T + B_T u_T \qquad (8)$$

Where, $x_T = [\Delta\omega_{wt}\ \Delta\delta_{tg}\ \Delta\omega_{ge}]$ is set of state variables and $u_T = [\Delta T_{\omega i}\ \Delta T_{go}]$ is set of control or input variables. The state and control matrices of the sub-system are represented by A_T and B_T.

B. Induction Generator Model

Based on generalized flux linkages equations the single squirrel cage Induction Generator is modelled mathematically and Synchronously rotating d-q reference frame is used to develop the following equations[6].

$$\frac{1}{\omega_s}\frac{d}{dx}\lambda_{ds} = -R_s I_{ds} + \lambda_{ds} - V_{ds} \qquad (9)$$

$$\frac{1}{\omega_s}\frac{d}{dx}\lambda_{qs} = -R_s I_{qs} + \lambda_{qs} - V_{qs} \qquad (10)$$

$$\frac{1}{\omega_s}\frac{d}{dx}\lambda_{dr} = -R_r I_{dr} + s\lambda_{qr} \qquad (11)$$

$$\frac{1}{\omega_s}\frac{d}{dx}\lambda_{qr} = -R_r I_{qr} - s\lambda_{dr} \qquad (12)$$

$$\lambda_{ds} = X_s I_{ds} + X_m I_{dr} \qquad (13)$$

$$\lambda_{qs} = X_s I_{qs} + X_m I_{qr} \qquad (14)$$

$$\lambda_{dr} = X_r I_{dr} + X_m I_{ds} \qquad (15)$$

$$\lambda_{qr} = X_r I_{qr} + X_m I_{qs} \qquad (16)$$

$$X_s = X_{s\sigma} + X_m \qquad (17)$$

$$X_r = X_{r\sigma} + X_m \qquad (18)$$

The state space representation of normalised induction generator model is:

$$X_G = A_G x_G + B_G u_G \qquad (19)$$

Where, $x_G = [\Delta I_{ds}\ \Delta I_{qs}\ \Delta I_{dr}\ \Delta I_{qr}]$ and $u_G = [\Delta\omega_{ge}\ \Delta V_{ds}\ \Delta V_{qs}]$

III. SYSTEM CONFIGURATION

The stability analysis of a distribution system for various level of reactive power compensation and inertia for different ratings of SCIG wind plant are carried out by considering IEEE 5 bus modified radial distribution system. The 11KV three phase programmable voltage source 1 and the wind plant is connected to bus 1 and bus 5 respectively as shown in Fig.2.

The total active and reactive loads of the system are 755KW and 175KVAr respectively. The line and load details are tabulated in Table-II.

Table II: Load and Line data of modified IEEE 5 bus RDS

Bus No.	Bus Voltage in PU	Load		Branch	R_L in Ohms	X_L in Ohms
		KW	*KVAr*			
1	1	0	0	1-2	0.455	1.093
2	0.9927	160	60	2-3	0.494	1.184
3	0.9865	140	30	3-4	0.873	2.095
4	0.9762	155	55	4-5	1.329	3.188
5	0.9703	300	30	-	-	-

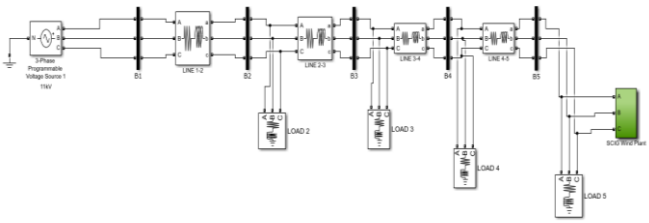

Fig.2: IEEE 5 Bus Test System with Wind Mill

IV. SIMULATION AND DISCUSSION OF RESULTS

The Modified IEEE 5 bus system and Type I wind plant suitable with different capacity and inertia to study on stability are modeled and simulated using MATLAB-SIMULINK 2017. The different rating of Type I wind Plant is connected to bus 5 with various level of inertia constant to find the minimum reactive power compensation required for the stable operation of the system during normal condition.

In this Case, the 100KW WTG are connected to the test system with various levels of reactive power compensation and inertia constant is 0.1. The analysis on stability of voltage and frequency of the system for the stable operation under normal condition is carried out and as shown in Fig.3 and Fig.4.Also the rotor speed of the turbine is observed is shown in Fig.5.

It can be observed that the voltage and frequency of all the nodes are become unstable and wind turbine speed also runs at dangerous speed when reactive power is 1KVAr, 2KVAr and 2.5KVAr. When there is enough reactive power compensation i.e. 2.8KVAr and 3KVAr, the voltage and frequency will be stable under normal operating condition and also turbine rotated at its rated value. Thus, it clearly shows that the minimum reactive power compensation for stable operation of **100KW** Type-I WTG is **2.8KVAr.**

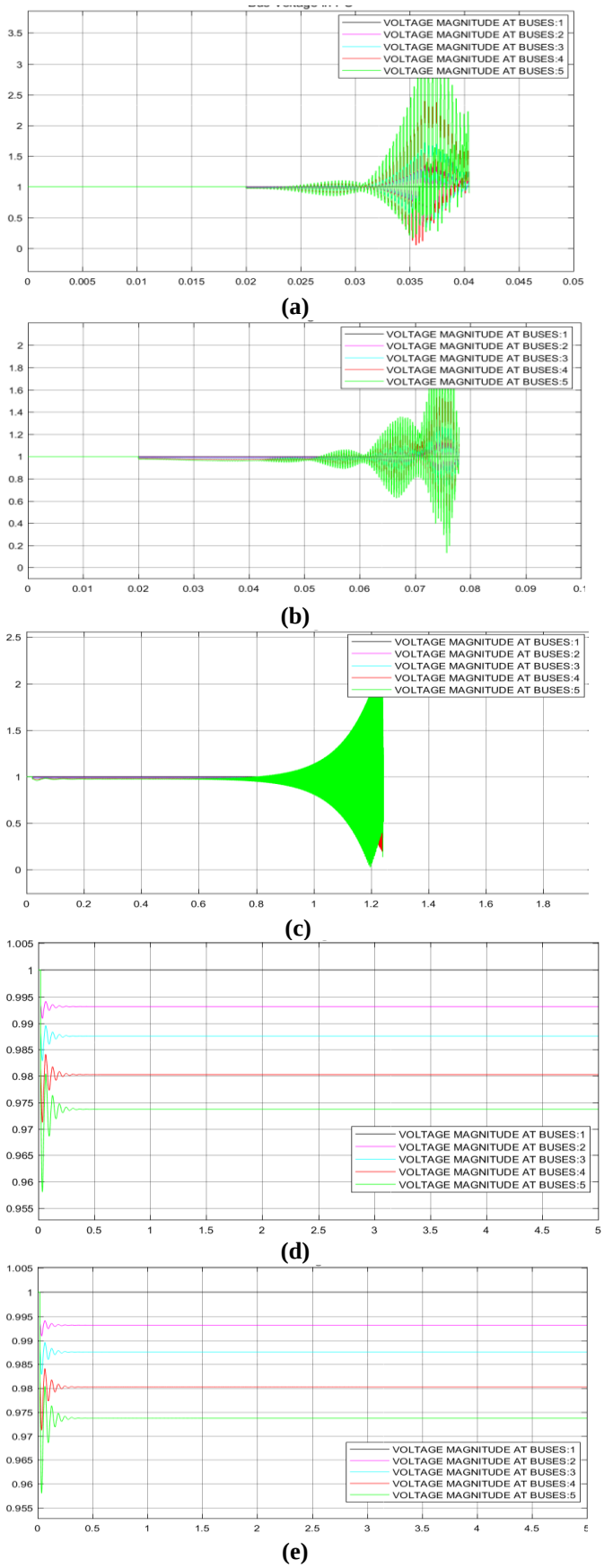

Fig.3: (a)-(e): The Bus voltages in PU when Q= 1, 2, 2.5, 2.8 & 3 KVAr at H=0.1

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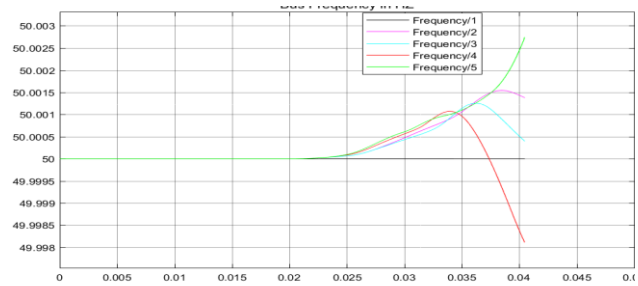

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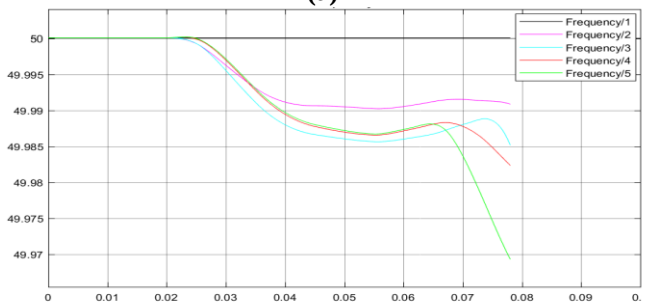

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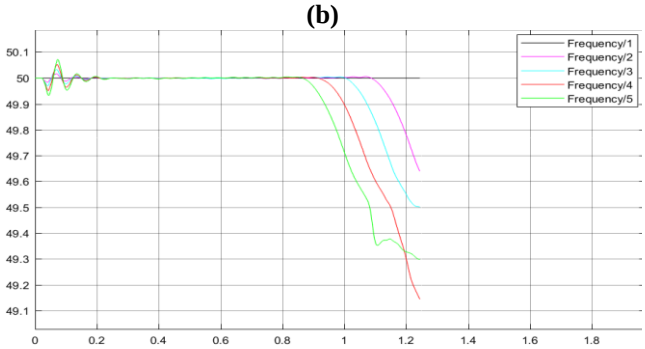

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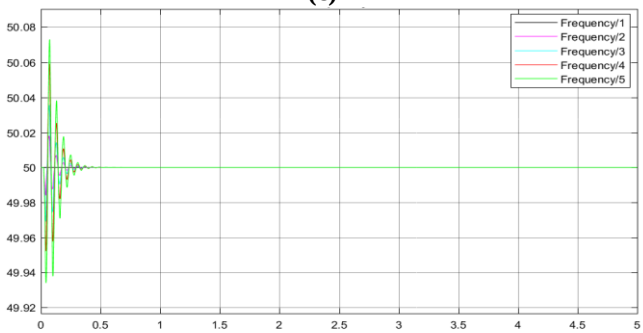

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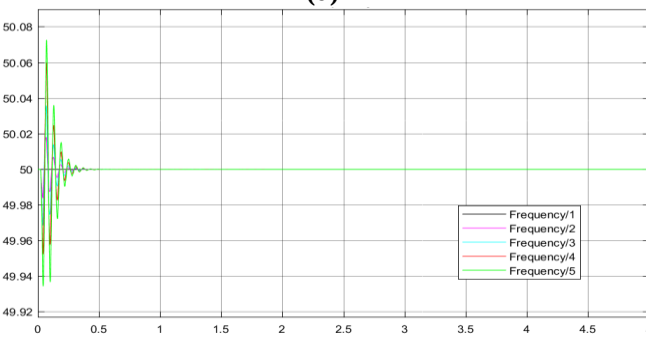
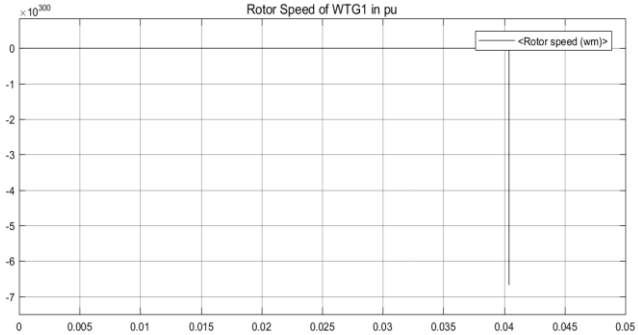
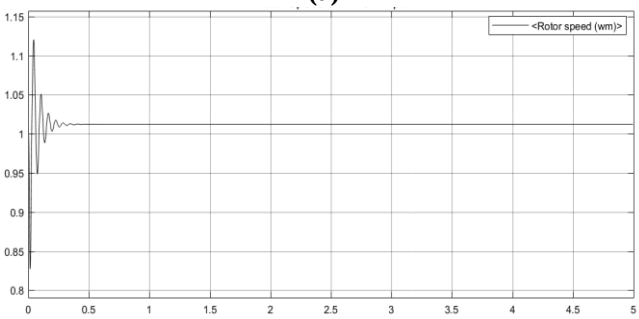


(e)

Fig.4: (a)-(e): frequency at all buses when Q= 1, 2, 2.5,2.8 & 3 KVAr at H=0.1



(a)



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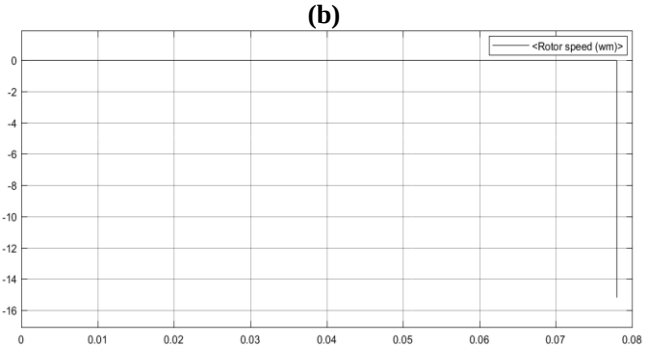

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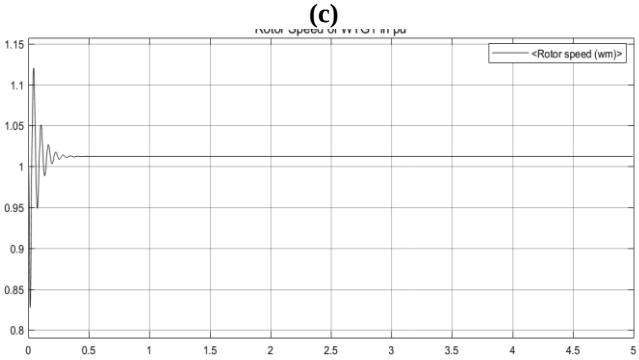

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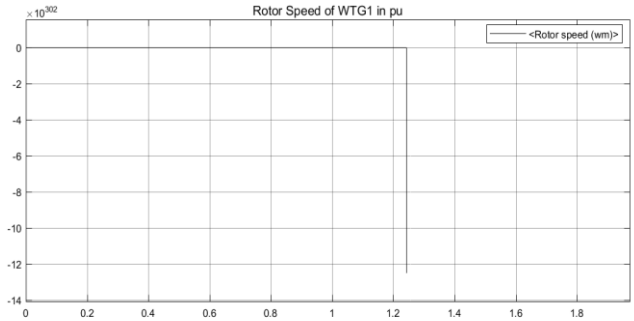

(e)

Fig.5: (a)-(e) Wind Turbine Speed when Q=1, 2, 2.5, 2.8 and 3KVAr at H=0.1.

In this scenario, 100KW wind plant is subjected to different inertia level by supplying enough constant reactive power compensation. From Table-III, It has been observed that there is no impact of inertia level on minimum reactive power compensation and it can be clearly stated that the Q_{min} is independent of inertia of the wind plant.

Table- III: Q_{min} of 100KW WTG for various Inertia levels

Sl.No	Inertia Constant	Q_{min} in KVAr
1	0.1	2.8
2	0.2	2.8
3	0.3	2.8
4	0.4	2.8
5	0.5	2.8
6	1.0	2.8

A similar analysis is carried out for different wind plant capacity and the minimum reactive power requirement for **200, 300, 400 and 500KW** of WTG are **8, 13.8, 19.8 and 27KVAr** and the same is tabulated in Table IV. The wind plant capacity versus minimum reactive power support to the plant is plotted in Fig 6.

Table IV: Q_{min} for different rating of WTG

Sl. No.	Capacity of WTG	Q_{min} in KVAr
1	100 KW	2.8
2	200 KW	8
3	300 KW	13.8
4	400 KW	19.8
5	500 KW	27

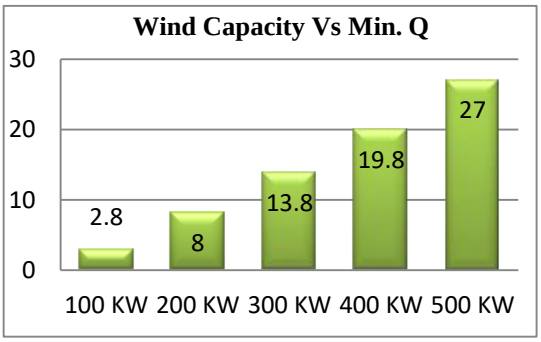

Fig.6 Wind Plant capacity Vs Q_{min}

From the above results, the relation between the wind capacity and minimum reactive power compensation can be represented approximately in (20).

$$Q_{min} = n(n+2) \quad (20)$$

Where, n is the wind plant capacity i.e n=1 for 100KW, 2 for 200KW and so on.

VI. CONCLUSION

In this paper, a detailed mathematical model of constant speed SCIG based wind plant with IEEE-5 bus RDS is developed in SIMULINK. The voltage and frequency stability of the distribution system has been studied for various reactive power compensation levels. In this, the various levels of reactive power compensation is supplied for different rating Type-I WTG to analyse the voltage and frequency stability of all nodes in the test system and also wind turbine speed has been observed. The results demonstrated that Type-1 WTG required sufficient reactive power support for the stable operation otherwise the system will become unstable. Therefore, the minimum reactive power compensation for 100KW, 200KW, 300KW, 400KW and 500KW WTG to achieve the stable operation during normal condition is 2.8KVAr, 8KVAr, 13.8KVAr, 19.8KVAr and 27KVAr respectively. From the above analysis the equation is developed to relate the wind plant capacity and minimum reactive power compensation.

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