Smoothening the Output Power of a Fixed Speed IG Based Wind Farm by Using Storage Device along with PMSG

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***Abstract*— The fluctuation of output parameters of a wind farm due to the randomly varying wind speed is a serious problem especially for fixed speed wind generators, like induction generator (IG). This paper presents a new technique to improve the performance of a fixed speed wind generator by using permanent magnet synchronous generator (PMSG) along with a storage device. A wind farm of a total capacity of 12 MW has been used for this purpose. It is shown that the output power of an IG based wind farm can be made smooth by including PMSG with it. In this concept, the power capacity required for a storage device can also be reduced. A low pass filter has been used to calculate the required capacity of the storage device. Simulations have been done by using the engineering software PSCAD/EMTDC. Real wind speed data have been considered for this study.**

Keywords—induction generator; permanent magnet synchronous generator; storage device; low pass filter

I. INTRODUCTION

In recent years the world consumption of energy has increased enormously due to the massive industrialization which has been intensified rapidly in some geographical areas of the world remarkably in the countries of Asia. This consumption mostly depends on nonrenewable energy sources, i.e. on fossil fuels and nuclear power resources. But these non-renewable energy sources are limited. Coal, Oil and Gas are created from organic matter, they are fossil fuels. They do have a life expectancy, so will run out. Oil: 40-45 years left Natural Gas: 50-65 years left Coal: 200-300 years left. These are the approximate number of years left for each of these energy resources. Hence, the risks of shortage of fossil fuels and their effects on the climatic change have indicated the importance of renewable energies. Wind is a promising source of renewable energy. The average annual growth rate of wind turbine installation is around 30% during last ten years. In 2010 wind energy production was over 2.5% of total worldwide electricity usage, and growing rapidly at more than 25% per annum, the monetary cost per unit of energy produced is similar to the cost for new coal and natural gas installations [1]. Worldwide there are now over two hundred thousand wind turbines operating, with a total nameplate capacity of 282,482 MW as of end 2012 [2].

With the development of wind power technologies and rapid growth of wind power capacity installed worldwide, various concepts have been developed and different wind generators have been built in the last two decades. One of them is the fixed speed wind turbine system using a multi-stage gear box and a standard squirrel cage Induction Generator (IG). Although wind is a very anticipating source of renewable energy, but randomly varying wind speed results in the variation of wind power, which in turn causes the fluctuation of power system frequency. This problem is very serious for fixed speed wind generators, like induction generator (IG). Integrating an appropriate energy storage system in conjunction with a wind generator removes the fluctuations and maximizes the reliability of power supply at the loads [3]. So, an inclusion of a storage device in an IG based wind farm improves the output response. In [4] it is shown that for a fixed speed wind farm consisting multi IG's, a storage device of a capacity of 25% of the total wind farm capacity is needed. However for a composite wind farm, energy storage capacity should be 55% as seen in [5]. In this study a composite wind farm has been considered to calculate the storage capacity. This paper proposes that, the capacity of the storage device can be further reduced if a permanent magnet synchronous generator (PMSG) is included with IG. Permanent magnet machines are characterized as having large air gaps, which reduce flux linkage even in machines with multi magnetic poles [6]. Simulation results show that PMSG is capable of decreasing the capacity of the storage device to be used. Therefore a storage device of a lower capacity can be used for the wind farm operation. This reduces the installation and maintenance cost of the farm. Inclusion of PMSG also improves the stability of the wind farm. That is PMSG not only reduces the capacity of the storage device and the cost of the wind farm, but also helps to make the system stable. This paper presents the comparative results for a wind farm driven by IG alone and a wind farm driven by both IG and PMSG. A low-pass filter is used to estimate the capacity of the storage device.

II. SYSTEM MODEL

A. Wind Turbine Model

The model of wind turbine rotor is complicated. According to the blade element theory [7] modeling of blade and shaft needs complicated and lengthy computations. Moreover, it also needs detailed and accurate information about rotor geometry. Therefore, considering only the electrical behavior of the system, a simplified method of modeling of the wind turbine blade and shaft is normally used [8]. The mathematical relation for the mechanical power extraction from the wind can be expressed as follows [7].

$$Pm = \frac{1}{2}\rho\pi R^2 V_w^3 C_P(\lambda, \beta) \tag{1}$$

Where, Pm is the mechanical power that the turbine extracts from the wind, ρ is the air density (Kg/m3), R is the blade radius (m) and C_P is the power coefficient which is a function of both, tip speed ratio, λ, and blade pitch angle, β(deg). λ and C_P are expressed as [9]:

$$\lambda = \frac{\omega R}{Vw} \tag{2}$$

Where, ω is the wind turbine angular speed (rad/s), Vw is the wind speed (m/s). The power coefficient, C_P is, [9]

$$C_P = \frac{1}{2}(\Gamma - 0.022\beta^2 - 5.6)\, e^{-0.17\Gamma} \tag{3}$$

Since, C_P is expressed in feet and mile, Γ is corrected as,

$$\Gamma = \left(\frac{R}{\lambda}\right) * \left(\frac{3600}{1609}\right) \tag{4}$$

The torque coefficient, C_T, is given by,

$$C_T = \frac{C_P(\lambda)}{\lambda} \tag{5}$$

The wind turbine torque is expressed as,

$$T_m = \frac{1}{2}\rho\pi R^3 V_w^2 C_T(\lambda) \tag{6}$$

The C_P-λ characteristics, for different values of pitch angle β are illustrated in Fig.1. The maximum value of C_P i.e. C_{Popt} = 0.48 is obtained for β = 0° and for λ = 8.1. This particular value of λ is defined as the optimal value, λopt.

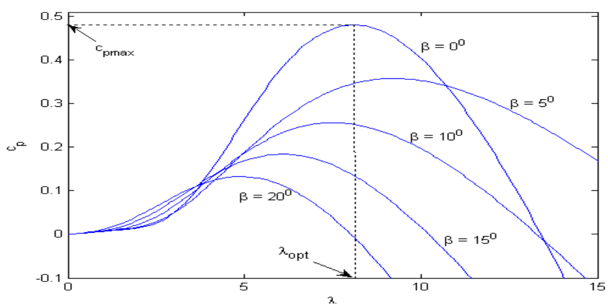

Fig. 1. Cp-λ characteristics for different pitch angle, β.

B. Generator Model

In this concept, PMSG is directly driven by a wind turbine without gearbox and it is connected to the ac power grid through the power converters. Some specific control topologies to control these power converters are provided. For PMSG, the generator speed is derived from the mechanical rotor speed ω_r and the number of poles n_p, because the generator is directly coupled to the wind turbine rotor.

$$fe = (np/2).fm = (np/2).(\omega r/2\pi) \tag{7}$$

The generation system is composed of a PMSG and a full rating power converter. In power system analysis, the magnetic flux distribution around the air gap of a synchronous generator is assumed to be sinusoidal. Therefore the flux distribution in the stator is sinusoidal, and the electromotive forces are also sinusoidal [10]. The induced voltage E_g generated by the permanent magnets can be expressed as:

$$E_g = 2\pi\, fe\Psi_m = \omega_e \Psi_m \tag{8}$$

Where, Ψ_m is the flux linkage of stator coil. A commonly used PMSG transient model is the park model. In order to get a dynamic model for the generator that easily allows us to define the generator control system, the equations of the generator are projected on a reference coordinate system rotating synchronously with the magnetic flux as shown in Fig.2.

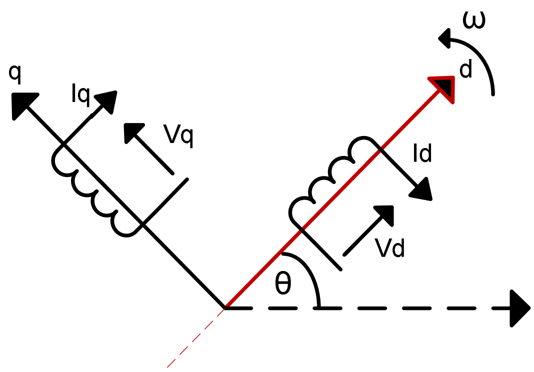

Fig. 2. The PARK Model of PMSG.

The model system shown in Fig.3 has been used for the simulation analysis of variable speed wind turbine (VSWT)-PMSG analysis. The proposed model is derived from the analytical representation of the main components: Dynamic wind turbine model, Directly-driven PMSG, AC/DC converter and the Grid Model. . In this concept, PMSG is directly driven by a wind turbine without gearbox and it is connected to the ac power grid through the power converters. Some specific control topologies to control these power converters are provided.

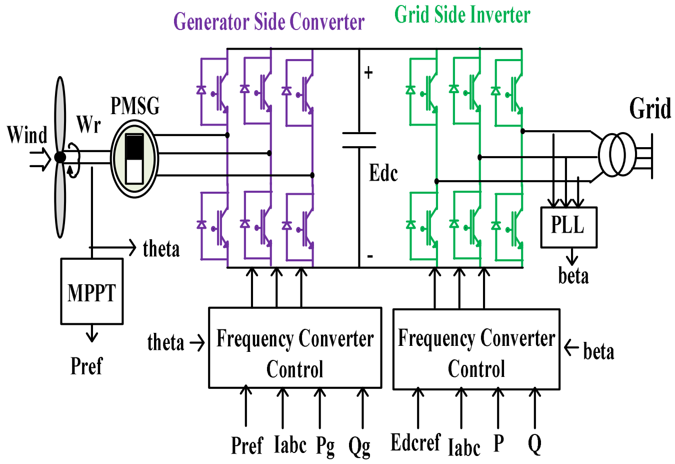

Fig. 3. Electrical Scheme of VSWT-PMSG.

Conventional IG connection scheme has been used for the simulation.

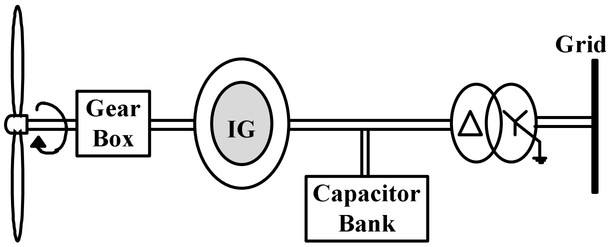

Fig. 4. Fixed speed wind farm scheme with a single IG.

In this paper, a comparison between Induction Generator (IG) and Permanent Magnet Synchronous Generator (PMSG) has been explained. Different combinations of wind farm considering IG and PMSG have been considered in this study for a total capacity of 12 MVA. The simulation results have been compared and it is seen that the performances of IG can be improved by including PMSG with IG and the storage device capacity can be reduced. The scheme used for this combination is shown in Fig. 5.

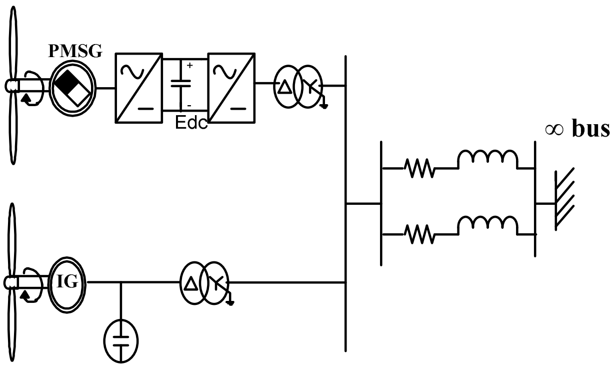

Fig. 5. Wind Farm Model with both IG and PMSG.

C. Low-Pass Filter Model[4]

Constant output power reference for wind generator output power smoothing, is not a good choice, because sufficient power cannot be obtained when wind speed is very low, hence, more energy storage capacity is needed to smooth the wind farm (WF) output power. Therefore, among the various methods, a suitable method for selection of reference line power is presented. Reference value of the transmission line power is determined by using a low pass filter (LPF) as shown in Fig. 6. It is seen that the wind power fluctuation decreases as the LPF time constant increases. The LPF suggests an increase or a decrease in the level of wind power output, which corresponds to charging or discharging of the stored energy.

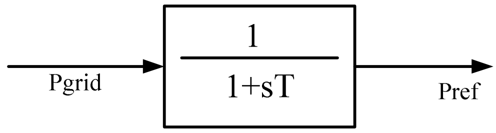

Fig. 6. Determination of reference line power by using LPF.

The first-order passive low pass filter can be mathematically described as;

$$P_G = P_{Lref} + T{*}P'_{Lref} \quad (9)$$

Where T is the filtering time constant corresponding to energy storage capacity, P_{Lref} is the filter output function corresponding to the wind turbine output together with the storage unit, P'_{Lref} is the derivative of P_{Lref} and P_G is the filter input function that corresponds to the wind turbine output without energy storage. When discrete data with a time step Δt are applied to a low pass filter and the derivative of P_{Lref} is expanded into a discrete form, (9) can be written for step k as,

$$T\frac{P_{Lref,k} - P_{Lref,k-1}}{\Delta t} + P_{Lref,k} = P_{G,k} \quad (10)$$

Solving for $P_{Lref,k}$ gives

$$P_{Lref,k} = \frac{T}{T+\Delta t}P_{Lref,k-1} + \frac{\Delta t}{T+\Delta t}P_{G,k} \quad (11)$$

Defining a constant, $\beta = \dfrac{T}{T+\Delta t}$, (11) can be written as

$$P_{Lref,k} = \beta P_{Lref,k-1} + (1-\beta)P_{G,k} \quad (12)$$

D. Method of Calculating Power System Frequency[4]

In this study, the index of smoothing effect is used in power system frequency analysis. Power system frequency fluctuation is occurred due to unbalance between supply and load power in power system. Then, the frequency fluctuation can be described by using two components, the rate of generator output variation, K_G [MW/Hz], and load variation, K_L [MW/Hz] respectively. They are representing the amount of power variation causing 1[Hz] frequency fluctuation. When generator output variation, ΔG [MW], and load variation, ΔL [MW], are occurred, frequency fluctuation of the power system, ΔF [Hz], is expressed as follows.

$$\Delta F = \frac{\Delta G - \Delta L}{K_G + K_L} \quad (13)$$

$$K = K_G + K_L \quad (14)$$

Where, K is frequency characteristic constant. In general, frequency characteristic is expressed as percentage K_G (expressed as $\%K_G$) for the total capacity of all generators and percentage K_L (expressed as $\%K_L$) for the total load. In general, it is known that $\%K_G$ and $\%K_L$ are almost constant and generally take a value of 8-15 [%MW/Hz] and 2-6[%MW/Hz] respectively. However, K_L and K_G change greatly during a day because the number of parallel generators changes depending on the amount of load during a day. And, when power imbalance ΔP is occurred in power system, frequency fluctuation ΔP/K cannot occur immediately due to the governor characteristic and generator inertia. Normally, ΔF converges to a new steady state value in 2 to 3 [sec]. In general, when ΔP is changing slowly, relationship between ΔP and ΔF can be expressed as follows:

$$\frac{\Delta F}{\Delta P} = \frac{1}{K(1+sT)} \tag{15}$$

Where, ΔP=ΔG-ΔL. Since changing load is not considered in this study, ΔL is "0". Time constant, T [sec], depending on the setting of generator governor and generator inertia, is generally 3 to 5[sec]. In this study, power system capacity is assumed to be 100[MW] and frequency characteristic K [MW/Hz] is selected to 8 [MW/Hz]. This selection means that adjustability of the system frequency is weak, resulting a severe situation. Similarly, time constant T is selected to 3 [sec]. In this study, frequency fluctuation in power system is evaluated by using (15) Therefore, frequency fluctuation, ΔF, is obtained as shown in Fig.7.

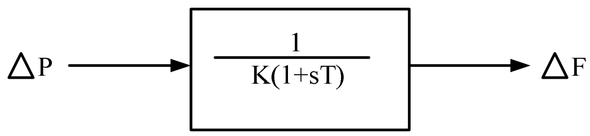

Fig. 7. Frequency calculation model.

III. Simulation Result

Simulations have been done for two cases. In Case-I, a fixed speed IG has been taken which has a capacity of 12 MVA. In Case-II, a 12 MVA wind farm is operated by the parallel combination of IG and PMSG, each having a capacity of 6 MVA. Simulations have been done by using PSCAD/EMTDC for 350 seconds. The timing step was chosen to be 0.001 sec.

A randomly varying wind data has been taken for the simulation. The maximum wind speed has been considered as 23 m/s, and minimum is 4 m/s. Fig. 8 shows the wind speed data used for the simulation.

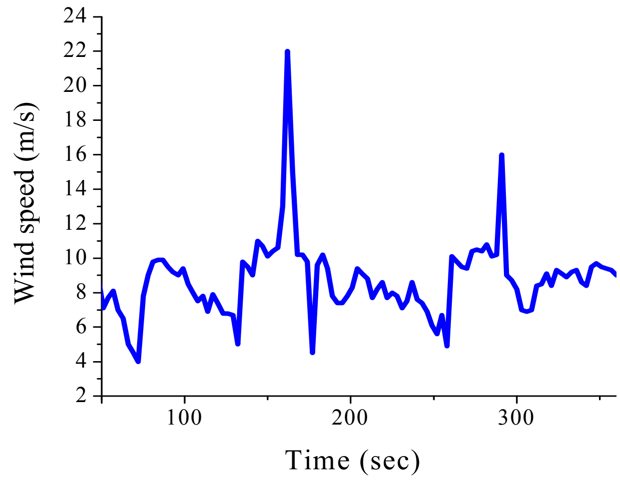

Fig.8. Wind speed data.

The smoothing effect is evaluated by using frequency fluctuation, ΔF. ΔF is calculated by using the frequency calculation model as shown in Fig. 7. Time constant suitable for each reference generation system with enough smoothing effect is investigated by using ΔF in this simulation analysis. Table I and Table II shows maximum frequency fluctuation, standard deviation and expected power compensation for each reference generation system with respect to various time constants. Frequency fluctuation decreases as time constant increases. It can be seen from these two tables that, for the same frequency deviation, a reduced capacity of storage device is needed for Case-II than that of Case-I.

TABLE I. Results for Case-I, IG (12 MVA)

Time Constant	Low-Pass Filter		
	Storage Capacity P(MW)	***Frequency Deviation ΔF(Hz)***	***Standard Deviation δ(MW)***
0	0	0.13225	0
3	5.21978	0.09986	1.2403
6	5.92569	0.06369	1.70437
9	6.00575	0.0483	1.99518
12	6.35562	0.04286	2.19343
15	6.80793	0.04243	2.33222
18	7.19784	0.03514	2.43136
21	7.52475	0.03217	2.50353
24	7.79529	0.02962	2.55699
27	8.01787	0.02742	2.59728
30	8.20119	0.02551	2.62819
33	8.35277	0.02384	2.65235
36	8.47891	0.02239	2.67161
⇨ **39**	**8.5111**	**0.0211**	**2.71099**

Time Constant	Low-Pass Filter		
	Storage Capacity P(MW)	***Frequency Deviation ΔF(Hz)***	***Standard Deviation δ(MW)***
42	8.67488	0.01996	2.71111
45	8.77011	0.01894	2.71142
48	8.87784	0.01804	2.72103
51	8.97917	0.01722	2.72953

For getting a frequency deviation of 0.0211 Hz, the storage capacity required for Case-I, is 8.5111 MW. This corresponds to 70.90% of the total wind farm capacity. At this frequency deviation, the required storage capacity is almost three times to that of the standard deviation.

TABLE II. RESULTS FOR CASE-II, IG (6MVA) + PMSG (6MVA)

Time Constant	Low-Pass Filter		
	Storage Capacity P(MW)	***Frequency Deviation ΔF(Hz)***	***Standard Deviation δ(MW)***
0	0	0.06415	0
3	2.54498	0.04809	0.56597
6	2.87074	0.03062	0.79216
9	3.01843	0.02427	0.93899
⇨ **12**	**3.229**	**0.02152**	**1.076**
15	3.49471	0.01939	1.12571
18	3.68801	0.01762	1.1931
21	3.84911	0.0161	1.25264
24	3.98152	0.01477	1.30781
27	4.08965	0.01359	1.36053
30	4.17774	0.01254	1.4118
33	4.2494	0.01158	1.46207
36	4.30756	0.01071	1.51149

But for getting this same frequency deviation, in Case-II, the required storage capacity was found to be 3.229 MW. This corresponds to 26.90% of the total wind farm capacity. So, a saving of about 5.31607 MW (44.0%) is assured by using PMSG with IG.

Fig. 9 shows the frequency deviations for Case-I and II. Fig.10 and 11 shows the standard deviations for Case-I and Case-II.

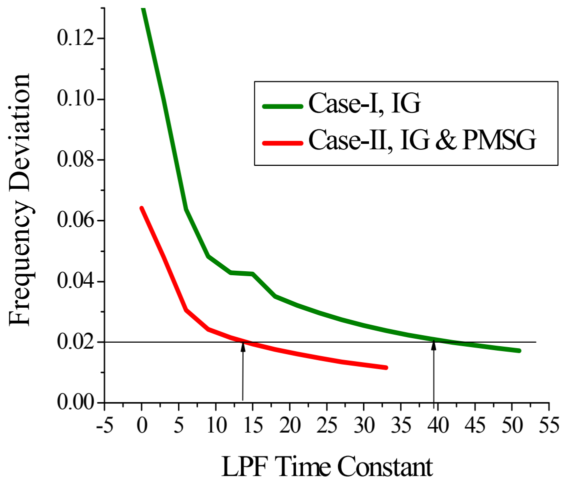

Fig. 9. Frequency deviations for the two cases.

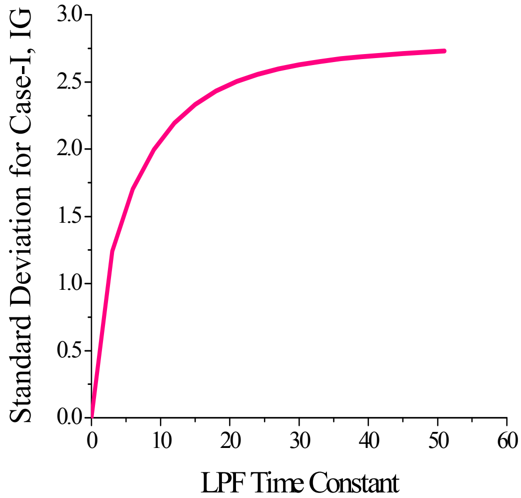

Fig. 10. Standard deviation of LPF power for Case-I.

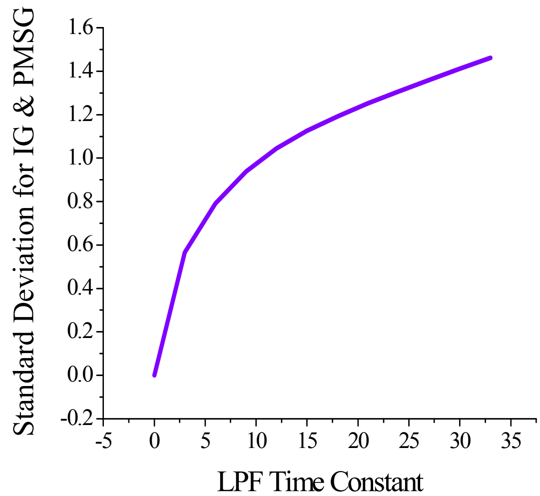

Fig. 11. Standard deviation of LPF power for Case-II.

So, from the simulation results, it can be said that inclusion of PMSG in an IG based wind farm helps to reduce the storage capacity of the storage device.

IV. CONCLUSION

For a fixed speed wind farm, smoothing the output power in spite of a randomly varying wind speed is a big problem. Storage devices can help to make the output power smooth, but the storage capacity of such devices is a big factor. It is very necessary to maintain the storage capacity minimum with respect to a maximum or allowable frequency deviation to reduce cost. This paper shows that inclusion of PMSG with IG in a composite wind farm can help to reduce the storage capacity by almost 40%. So, it ensures a reliable operation of the wind farm as well as it makes the overall system cost effective. So, the proposed system has proved its better quality and improved reliability.

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