Performance Improvement of a Grid Connected Direct Drive Wind Turbine Using Super-capacitor Energy Storage

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***Abstract*—This paper investigates control and operation strategy of grid connected permanent magnet synchronous generator (PMSG) based direct drive variable speed wind turbine with a static synchronous compensator (STATCOM). The application of STATCOM enhances the system performance by improving the fault ride through capability of the wind turbine. Control strategies for generator side converter with maximum power extraction, grid side inverter and STATCOM controller are implemented in Matlab/Simpower. Extensive simulations have been conducted using supercapacitor energy storage system with STATCOM to enhance the steady state and dynamic performances of the wind energy system under grid faults or disturbances.**

***Index Terms*—direct drive variable speed wind turbine, PMSG, STATCOM, super-capacitorenergy storage.**

I. Introduction

WIND energy is growing rapidly due to technology innovation and power electronic device cost reduction. The cost of wind energy has been reduced to 4.5 cents/kWh on shore and 5 cents/kWh off shore [1].Global wind energy council statics shows that wind power capacity will reach just under 500 GW by the end of 2016[2].Stochastic behavior of wind power and there controllability is an important issue when the system is connected to the grid.Intermittent nature of wind introduces voltage sags, swells, flickers and harmonics. Integrating large amount of wind power into existing power system presents technical challenges, which requires consideration of voltage and frequency regulation, stability and power quality problems[3].Mechanical switch capacitor (MSC) bank and tap changer transformers (TCs) are used for power system stability and quality issue. These devices improve power factor of wind farm but no strong influence on other power system issue. Moreover they add additional stress on wind turbine shaft [4]. Shunt Flexible AC Transmission System (FACTS) devices such as synchronous static compensators (STATCOMs)has the ability to improve the voltage quality with its fast response capability, accurate reactive power compensation and voltage control [5]-[9]. Recent development in power electronic devices and application specific ICs and DSP system enables the introduction of low cost and faster STATCOMs.

This paper investigates the application of STATCOM with PMSG based variable speed wind turbine for uninterrupted operation during grid disturbances. Supercapacitor based energy storage and STATCOM are used to enhance the performance of the direct drive wind energy system.

II. SYSTEM OVERVIEW

Fig. 1 shows the proposed structure of the direct drive, grid connected PMSG based variable speed wind turbine with STATCOM and super-capacitor energy storage. The generator side converter is controlled using vector control scheme to regulate the speed of the generator and to extract maximum power under fluctuating wind speeds. The grid side converter is controlled using vector control scheme as well to regulate the current and active/reactive power. The STATCOM is connected to the point of common coupling to enhance the system performance under disturbances.

III. WIND TURBINE CHARACTERISTICS

Power captured by wind turbine is given by [7]

$$P_t = \frac{1}{2}\rho A v_w^3 C_p(\lambda,\beta) \quad (1)$$

where, $P_t$is the turbine power and C_p is the turbine rotor power coefficient, which is a function of tip speed ratio (λ) and pitch angle (β). ρ is the air density in kilograms per cubic meter, A is the area swept by rotor blade in square meters, v_ω is the wind speed in meter per second.The coefficient of performance of a wind turbine is influenced by the tip-speed to wind speed ratio (TSR), which is given by [7]

$$TSR = \lambda = \frac{\omega_m R}{v_w} \quad (2)$$

where, ω_m is rotational mechanical speed of turbine rotor (generator speed) in mechanical radian per second, and R is the radius of the turbine blade. So at any working wind speed there is a unique turbine rotor or generator speed where C_p is maximum to extract maximum power.

The maximum mechanical power extracted from wind turbine is given by [7]

$$P_m = 0.5\rho A C_{p\_opt}\left(\frac{\omega_{m_{opt}} R}{\lambda_{opt}}\right)^3 = K_{opt}\left(\omega_{m\_opt}\right)^3 \quad (3)$$

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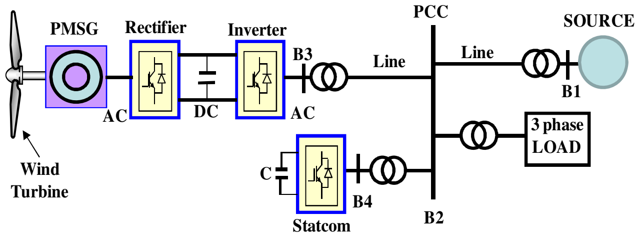

Fig.1. Grid connected wind energy system with STATCOM

IV. PMSG Model

The voltage equation of PMSG are expressed in *d*- and *q*- axis reference frame are given by [7]

$$v_d = -i_d R_s - L_d \frac{di_d}{dt} + \omega_r L_q i_q (4)$$

$$v_q = -i_q R_s - L_q \frac{di_q}{dt} - \omega_r L_d i_d + \omega_r \psi_f (5)$$

where v_d, i_d and v_q, i_q are *d*- and *q*- axis component of stator voltages and currents, R_s is the stator resistance, ω_r is the rotor speed in radian per second and ψ_f is the flux linkage. The torque equation PMSG can be given by [12]

$$T_g = -\frac{2}{3} P_n \{\psi_f i_q + (L_d - L_q) i_d i_q\} \ (6)$$

Where P_n is the pole pairs, L_d and L_q are *d*- and *q*- axis inductances. The first term in the equation (6), is the interaction torque between the magnetic field and *q*- axis current. For a surface mounted PMSG, *d*- and *q*- axis inductances are equal, so torque equation is given by

$$T_g = -\frac{2}{3} P_n \psi_f i_q \qquad (7)$$

V. STATCOM with Super-capacitor based Energy Storage System

An electric double-layer capacitor (EDLC) is known as supercapacitor.The value of a supercapacitor can be in the order of thousands of times greater than an electrolytic capacitor.Compared to conventional capacitor supercapacitorshave much lower capacitance and higher cost per energyunit. Super capacitors shows very high efficiency when they are charged and discharged in at least tens of seconds [13], [14].Supercapacitor could works at 100% depth of discharge without "memory effect". The supercapacitor contains a higher power density than the battery, which allows the supercapacitorto provide more power over a short period of time which is vital in wind energy system. Supercapacitor also is used for power smoothing of wind farms output connected to the grid. Fig.2 shows a supercapacitor model which contains inductance L_{sc}, equivalent series resistance, R_{sc} and capacitance C_{sc}. These parameters are frequency, temperature and voltage dependent [15]. In wind energy system supercapacitor operating frequency is below its self-resonant frequency, so avoiding inductance also could give enough

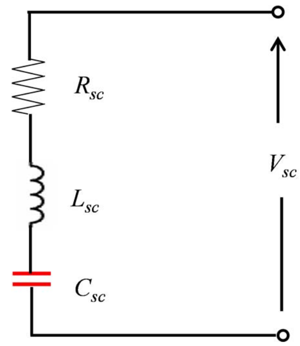

Fig.2. Supercapacitor model.

accuracy [16]. The power rating of a supercapacitor is limited by its converter. The model used in this paper is based on a 94F 75V 0.013Ω supercapacitor [17]. The supercapacitor works in the 10% to 100% state of charge (SOC) range. So effective energy for each module is 0.06609 kWh or 237.94 kJ (0.5×94F×75V^2 ×0.9). The supercapacitor storage has seven modules per stack and 25 parallel stacks, which makes energy of 13.218 kWh 525V 293F 0.00416 Ω.

Fig. 1. shows a three phase voltage source converter based STATCOM having the supercapacitor. In this paper, the STATCOM used is consists of IGBT PWM converter, three phase coupling filter and super capacitors. The STATCOM regulates the voltage at the load terminal through reactive power exchange with the system and regulates its dc bus voltage through the real power exchange with the system. STATCOM can provide transient over current in both the capacitive and inductive operating regions [18]-[20]. The STATCOM injects a compensating current to PCC, which enhance ride through capability of the wind turbine during transient disturbances in the grid.

VI. Control of PWM Rectifier

The structure of the proposed control strategy of PWM rectifier is shown in Fig.3, to obtain maximum power from variable speed wind turbine. The algorithm for gate drive of PWM rectifier is given by

- Measured wind speed v_w.
- Calculate the reference generator speed using the given equation [3]

$$\omega_r^* = K_w v_w \qquad (8)$$

Where $K_w = \frac{\lambda}{R}$

- The error between speed reference and measured speed is passed through proportional-integral (PI) to set electromagnetic torque reference T_e^*.
- Calculate the generator *q*-axis current reference i_q^*, using the given equation

- $T_e^* = -\frac{2}{3} P \psi_f i_q^* (9)$

Where *P* is the number of pole pairs.

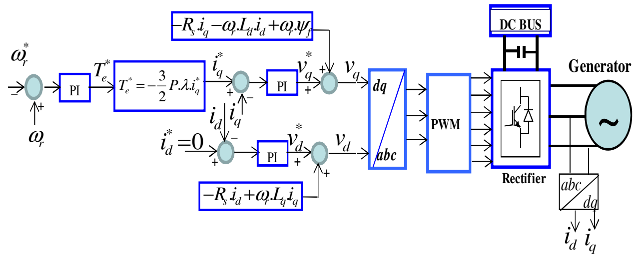

Fig.3. Vector control structure for machine side PWM converter.

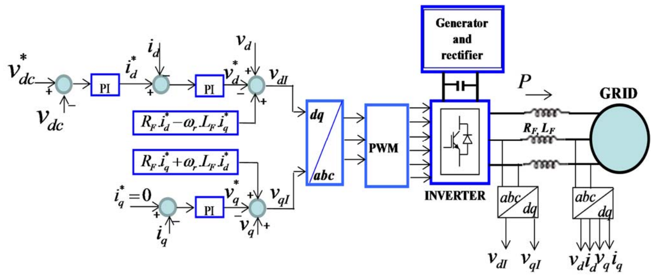

Fig.4. Vector control structure for grid side PWMconverter.

- Set d-axis generator current reference $i_d^* = 0$.

Finally d-$q$components of the rectifier voltage vector are derived from two proportional-integral (PI), which control d-$q$axis generator currents. To improve dynamic response compensation terms are added. Ziegler-Nichols tuning method was used to tune the PI controllers [21].

VII. CONTROL OF PWM INVERTER

The structure of the proposed control strategy of PWM inverter is shown in Fig.4. A reference frame rotating synchronously with the grid voltage space vector can be expressed as[9];

$$v_d = v_{d1} - R_F i_d - L_F \frac{di_d}{dt} + \omega_r L_F i_q \tag{10}$$

$$v_q = v_{q1} - R_F i_q - L_F \frac{di_q}{dt} - \omega_r L_F i_d \tag{11}$$

Using the dq transformation the active power P and reactive power Qflow to the grid can be given by[9]

$$P = \frac{2}{3}\left(v_d i_d + v_q i_q\right) \tag{12}$$

$$Q = \frac{2}{3}\left(v_d i_q + v_q i_d\right) \tag{13}$$

If reference frame is oriented along the grid voltage then $v_d = |v|$and $v_q = 0$. So active and reactive power can be written as follows

$$P = \frac{2}{3} v_d i_d \tag{14}$$
$$Q = \frac{2}{3} v_q i_q \tag{15}$$

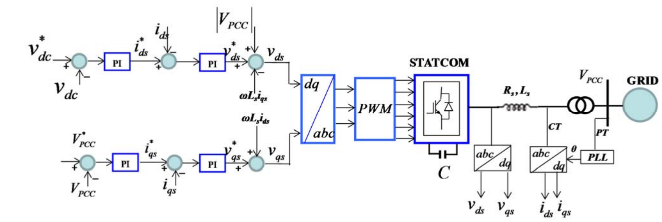

Fig.5. Control of STATCOM

Therefore, direct and quadrature components of current can control the active and reactive power respectively. In Fig. 4, the dc voltage control path is used to set the d-axis current referencei_d^*, which control active power P to the grid. The second control path used to set q-axis current reference$i_q^* = 0$, which control the reactive power to the grid. Ziegler-Nichols tuning method was used to tune the PI controllers [21].

VIII. CONTROL OF STATCOM

The vector control scheme for STATCOM is shown in Fig.5, the dc link voltage controller is used to set$d$-axis current referencei_{ds}^* and maintain dc-bus voltage of the statcom constant. First PI controller in the second control path used to set q-axis current referencei_{qs}^* and maintain the voltage at point of common coupling (PCC) at desired level. Other two PI controllers keep track of reference currents (i_{ds}^*, i_{qs}^*) and the outputs are added to the cross coupling compensation terms to produce command voltages v_{ds}, v_{qs}. Finally, voltages v_{ds}, v_{qs} are converted to abc-reference frame to produce modulating signal [5].

IX. FAULT/LV RIDE CAPABILITY OF WIND TURBINE

The ability to support the grid during deep voltage transients caused by network disturbances depends on both the technical features and load of the connected generator, and the dynamic characteristics of the grid. The factors affecting fault ride through that can be said to be attributable to the electrical system and interconnection rules are as follows [23]:

- shape of the voltage dip and absolute level of the voltage dip
- fault type and location
- fault clearance time
- grid strength (short circuit power)
- grid architecture (meshed or radial)
- active and reactive power conditions prior to the fault
- active and reactive power requirements after fault clearance
- load characteristics.

In a conventional power system, the factors affecting fault ride through that can be said to be attributable to the generating unit are; rotating inertia, generator reactance, excitation system design and AVR (autonomic voltage regulator) control, engine response and control. The electrical system can be said to be stable when the synchronous machines connected to it operate in synchronism and in parallel with each other, and there is a balance between the

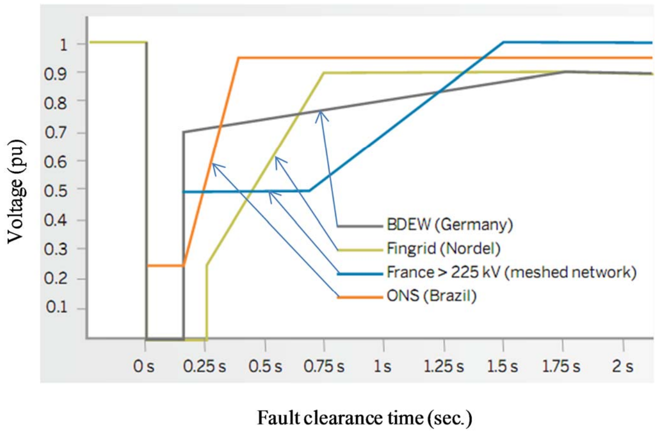

Fig.6. Fault ride through requirement for some countries.

demand and production of both active (P) and reactive (Q) power [22],[23].With the increased wind penetration, utility operators have to make sure that power system operates properly without compromising power quality and stability. The power systemshould be capable of supplying power and stay connected under any network disturbance. Wind farm should supply active and reactive powers for frequency and voltage regulation immediately after any disturbance or faults. The disturbance can be in the form of sudden load changes, faults within the transmission and distribution system, as well as loss of generation, and so forth [23]. Utility companies of some countries have introduced special grid-connection codes for wind-farm developers, covering reactive-power control, frequency response, and fault ride through in places where wind turbines provide for a significant part of the total power. Examples are Spain, Denmark, Germany and Brazil. Fig.6shows the fault ride through requirement of some countries. The grid connection codes define the operational boundary of a wind farm connected to the power grid and understandings of these codes are critical for wind turbine manufacturers, developers and utility operators. Among the grid requirement, the fault ride through is regarded as the main challenge to the wind turbine manufacturer [23], [24].

X. Results and Discussion

The direct drive wind energy system with STATCOM of Fig.1 is built using Matlab/Simpower dynamic system simulation software. The power converter and the control algorithm are also implemented and included in the model. The sampling time used for the simulation is 20 µs.

A. Three phase impedance fault with and without STATCOMat PCC

This study evaluates voltage sag during fault, voltage recovery time, voltage overshoot at recovery and the settling time. A remote fault is simulated at the PCC using a fault breaker in series with fault impedance.The value of the fault impedance has been programmed to produce 14% voltage sag at PCC. The breaker is programmed to operate at t=1 second for a duration of 8 cycles. The effect of three phase fault at different bus is investigated. The system is studied under three differentconditions atsource bus(B1), at load bus (B2), and at collector bus (B3), which are(i) without VARsupport(ii) with a 3MVAR STATCOM (iii) with a 15MVAR STATCOM.

High voltage sag (more than 10%) for more than 3 seconds may cause wind turbine to trip.Also high voltage sag or voltage swell at load bus due to fault or load changes degrades the power quality.By using the STATCOM, it is possible toavoid wind turbine trip and improve the power quality.Fig.7(a), 7(b) and 7(c) shows during three phase fault, voltage sag without VAR supportat PCC is highest almost 14%, 7% with 3MVARSTATCOM support andminimum with 15MVARSTATCOM support. By reducing voltage sag using STATCOMit is possible to keep wind turbine remain on line and enhance fault ride through capability.

It is also observed from Figure 7(a), 7(b) and 7(c) that voltage recovery time is morewithout STATCOM and less in high MVAR STATCOM. Voltage overshoot at recovery is least without STATCOM and highest with 15MVARSTATCOM. Voltage settling time is highwith 15MVAR STATCOM and less without STATCOM.

Figure 8(a) shows active power of STATCOM and 8(b) shows reactive power supplied by different STATCOM during fault.

Fig.9(a) and (b) show d- and q axis currents and their references, respectively. Fig..9(c) shows dc link voltage and reference for 15 MVAR STATCOM.

Fig.10(a)shows frequency response at PCC without VAR support,Fig.10 (b)shows frequency response at PCC with 15 MVAR STATCOM support.

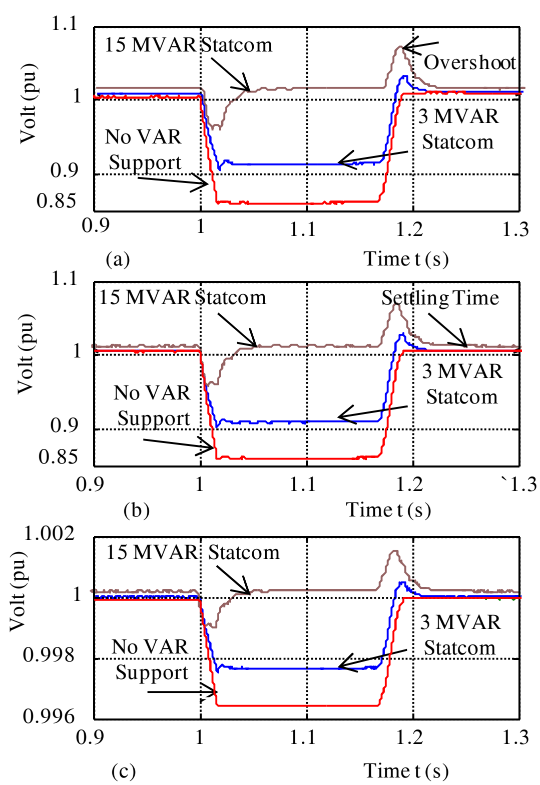

Fig. 7.Different bus voltages during fault. (a) Collector Bus (b) Load Bus (c) Source bus.

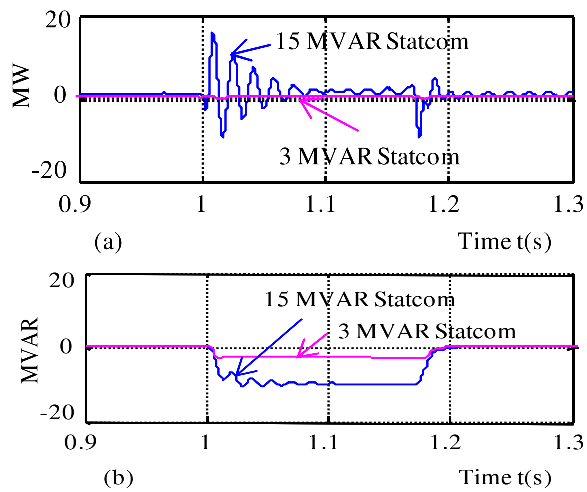

Fig. 8 (a) Active and (b) Reactive power supplied by different STATCOM

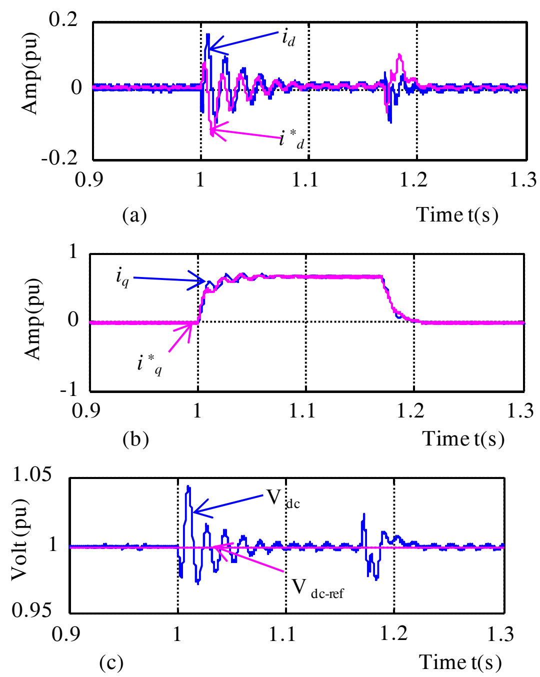

Fig.9. 15 MVA STATCOM (a)*d*-axis current and reference(b) *q*-axis current and reference (c) *dc-voltage* and reference

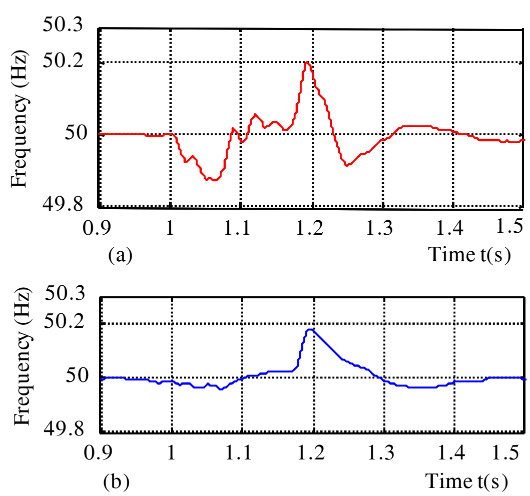

Fig.10. Frequency Respone at PCC (a)without VAR support and (b) with 15MVARstatcom.

B. Fixed capacitor were put at high voltage side of wind turbine to check voltage swell

This study evaluates voltage swell.The value of the capacitor bank has been programmed to produce 12% voltage swell at PCC. The breaker is programmed to operate at t=1 second for a duration of 8 cycles. The effect of voltage swell at different bus is studied. The system is studied under two differentconditions atsource bus(B1), at load bus (B2), and at collector bus (B3) , which are (i) without VARsupport and (ii) with a 3MVARSTATCOM. Fig.11(a) shows without VAR support load bus voltage increasesalmost 12% and with 3MVAR STATCOM voltage swell reduced to 5%.

Figure 12(a) shows active power of STATCOM and 12(b) shows reactive power supplied by 3MVARSTATCOM during voltage swell.Fig.13(a) shows d-axis current and reference, Fig.13 (b)shows *q* axis current and reference and Fig.13(c) shows dc link voltage and reference for 3 MVAR STATCOM.Fig.14(a) shows frequency response at PCC without VAR support, Fig.14 (b)shows frequency response at PCC with 3 MVAR STATCOM support.

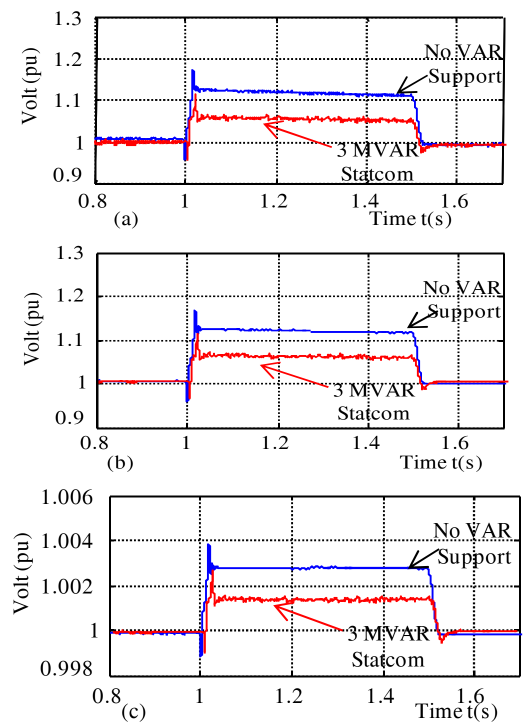

Fig. 11.Different bus voltages during Voltage swell.(a) Collector Bus (b) Load Bus (c) Source bus.

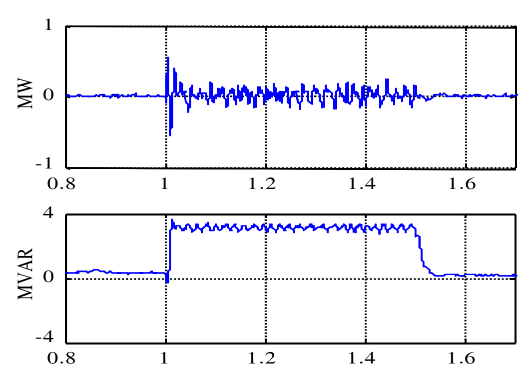

Fig.12. (a) Active and (b) Reactive power supplied by 3MVARSTATCOM.

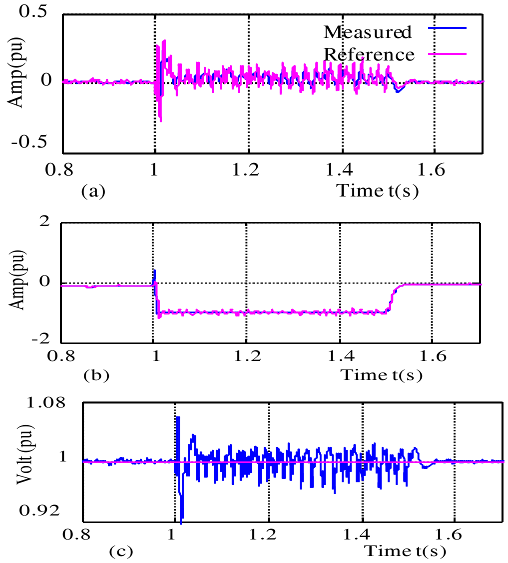

Fig.13.3 MVAR STATCOM performance during voltage swell (a) *d*-axis current and reference (b) *q*-axis current and reference (a) *dc-voltage* and reference

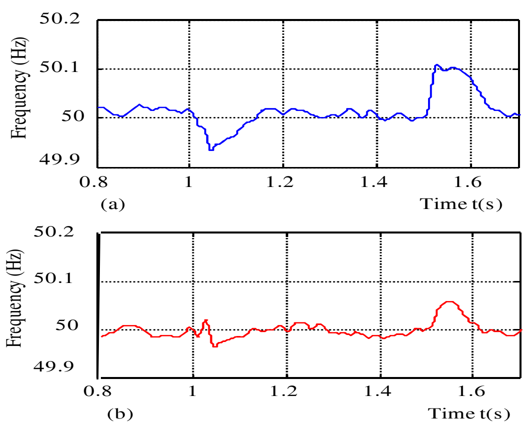

Fig.14. Frequency Respone at PCC with (a) and without(b) statcom during voltage swell.

XI. Conclusion

In this paper, control strategy for a gearless direct drive PMSG based variable speed wind turbine with STACOM and sepercapacitor based energy storage is investigated. To enhance the dynamic performance of the wind energy system, STATCOM with supercapacitor energy storage is used. Results shows that the STATCOM with supercapacitor energy storage can enhance the dynamic performance of the direct drive wind energy system. With reactive power support from STATCOM, it is possible to maintain grid voltage at PCC well above the wind farm trip voltage during grid faults and improve the LVRT capability of wind farm.

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