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Comparison of Retrofitting Techniques for Improving LVRT Capability of Variable Speed Wind Turbine Employing SCIG

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Abstract:Rapid infiltration of wind farms into central power grid has prompted authorities to insist on low voltage ride through capability (LVRT) of wind turbines to prevent cascading failures. A large number of existing wind farms still employ squirrel cage induction generators (SCIG) because of their robustness and low cost. Their main drawback is absence of LVRT capability. This paper proposes enhancing the LVRT of a variable speed wind turbine(VSWT) employing squirrel cage induction generators by three techniques, braking chopper, energy storage and STATCOM.The transient behaviour of the VSWT using retrofitting devices is analyzed and simulated in MATLAB/Simulink. The losses occurring due to lack of LVRT capability was studied by collecting data from a wind farm in India employing variable speed SCIG. A comparison of technical performance and economic feasibility of the above three techniques was also done.

Key Words: LVRT, VSWT, SCIG, chopper, energy storage device, STATCOM.

I. INTRODUCTION

India standsat fourth position, worldwide in terms of installed capacity of wind power [1]. Wind energy is free, non pollutable and renewable. The increase in wind penetration into central grid has prompted authorities to insist on LVRT of wind turbines to prevent cascading failures. An example is the cascading failure occurring in Southern grid area of India on 8th May 2013, resulting in loss of 860MW of wind generation [1]. As a result, new Indian grid code requires all existing and new wind turbines to stay interconnected to the grid even during under voltages as given in figure1.T varies from 100ms to 300ms depending on the system voltage at interconnection point in the range of 66kV to 400kV[2]

Currently most of the constant speed wind turbines are using SCIG due to their robustness, low cost and reduced maintenance .The decreased energy capture of such wind turbines can be enhanced by

attaching a full converter between generator and grid [3].Existing wind farms employing VSWT with SCIG do not have LVRT capability. When a fault occurs at PCC, sudden drop in voltage results in reduced power transfer to grid side converter, while the generator side power remains unchanged. This inequality in power transfer leads to increased DC link voltage triggering its overvoltage protection leading to subsequent disconnection of wind turbine from the grid [4, 5].In addition, reactive power has to be supplied to assist post fault grid side voltage recovery.

A range of LVRT techniques are available for variable speed wind generators like DFIG and PMSG classified under two catagories,modified controller based and external hardware based methods.[6,7].The modified controller methods include .The modified controller LVRT techniques for variable speed SCIG including internal model control, dual current control, fuzzy logic control and sliding mode controller are dealt with in[8,9,10,11]. Its drawbacks include complicated structure, improper tuning and inability to deal with deep voltage sags. For existing wind farms LVRT capability can be maintained by using additional hardware devices like STATCOM [12]. Not much discussion regarding comparative study of additional hardware devices for augmenting the LVRT of variable speed wind turbine (VSWT) with SCIG have been found in previous literatures

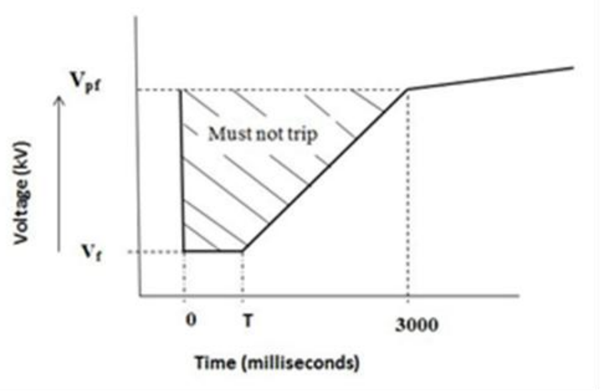

Figure 1.LVRTin India

2.Explanation of the System under study

Figure2 shows the schematic diagram of the system .The variable speed wind generator, connected to the grid though back to back (B2B) converters.MPPT control based on optimum torque control is used for obtaining maximum possible energy at different wind speed conditions [13]. As wind speed becomes greater than rated speed, pitch control is used to restrict rotor speed within safe value. For controlling generator side converter, turbine control unit is used, while grid side control unit is used to control the grid side converter. The wind generator is coupled to the grid through a 400/66kV transformer. The various devices proposed to enhance LVRT are also shown in figure.3.

2.1. Wind turbine modelling

The turbine converts the wind power into mechanical power as given by (1):

$$P_w = \frac{\rho}{2} A_w C_P(\lambda, \theta) v_w{}^3 \quad (1)$$

Where ρ is the air density, A_{wt} areasweptbythe turbine , v_w is velocity of wind, Cp is the performance coefficient, dependent on tip speed ratio λ and pitch angle θ. Cp is calculated by (2), (3) and the dynamic behaviour of rotor mechanic speed is given by (4):

$$C_p = 0,73(\frac{151}{\lambda} - 0.58\theta - 0.002\theta^{2.14} - 13.2)e^{\frac{-18.4}{\lambda_i}}$$
(2)

$$\lambda_i = \frac{1}{[(\frac{1}{\lambda - 0.02\theta}) + (\frac{0.003}{\theta^3 + 1})]} \; (3)$$

$$2H_m \frac{d\omega_m}{dt} = (T_t - T_e) \; (4)$$

$H_m$is the inertia constant,T_t and T_e are mechanical and electromagnetic torque respectively.The generator used is of squirrel cage induction generator type. The v equations of stator and rotor side voltages in the d-q frame are given from (5),(6),(7) and (8)

$$V_{ds} = -R_s i_{ds} - \omega_s \varphi_{qs} + \frac{d\varphi_{ds}}{dt} \; (5)$$

$$V_{qs} = -R_s i_{qs} + \omega_s \varphi_{ds} + \frac{d\varphi_{qs}}{dt} \; (6)$$

$$V_{dr} = 0 = -R_r i_{dr} - s\omega_s \varphi_{qr} + \frac{d\varphi_{dr}}{dt} \; (7)$$

$$V_{qr} = 0 = -R_r i_{qr} + s\omega_s \varphi_{dr} + \frac{d\varphi_{qr}}{dt} \; (8)$$

Here V_{ds},$V_{qs,}$$V_{dr}$and V_{qr} are stator d axis voltage, stator q axis voltage, rotor d axis voltage and rotor q axis voltage.$i_{ds,}$$i_{qs}$,$i_{dr}$ and i_{qr} are stator side d axis current, stator q axis current, rotor d axis current and rotor q axis currentand $\omega_r$are the synchronous speed and angularspeed of rotor respectively.φ_{ds},φ_{qs},φ_{dr} and $\varphi_{qr}$are the fluxes in stator d axis, stator q axis, rotor d axis and rotor q axis respectively[14].

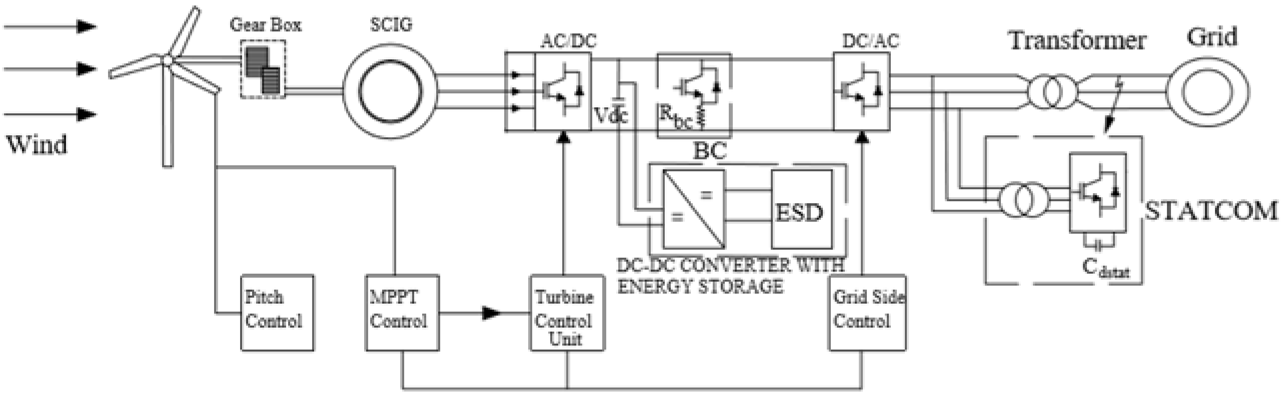

Figure 2. Configuration of the system under study

$R_s$and $R_r$are stator side and rotor side resistances.The power,bothactive and reactive, transmitted by the stator is shown in (9) and (10) while the electromagnetic torque equation is given in (11)

$$P_s = V_{ds} i_{ds} + V_{qs} i_{qs} \; (9) \quad Q_s = V_{qs} i_{ds} - V_{ds} i_{qs} \; (10)$$

$$T_e = \varphi_{qr} i_{dr} - \varphi_{dr} i_{qr} \qquad (11)$$

$\Phi_{dr}$and $\varphi_{qr}$are stator direct axis and quadrature axis flux linkages respectively.

3.1.1. Control System of Wind turbine

The generator is coupled to the grid through an B2B converter. A turbine control unit(TCU) control the turbine torque to obtain variable speed operation. The controller for turbine is shown in figure.4.Using optimal torque control method[15],the wind power capture is maximized for different wind speeds.

The optimal torque is given by (12):

$$T_{topt} = K_{opt}\omega_m^{2} \qquad (12)$$

whereTopt is the optimal torque ,λopt is the optimal value of tip speed ratio to be maintained for maximum power transfer and $K_{opt}$is the optimal torque coefficient.

2.2. Grid side control unit(GCU)

The GCU unit controls the voltage at DC link and supplies electric power at grid frequency.Vector control techniques are used for seamless operation of B2B converter system [16]. The block diagram of GCU system is shown in figure.5.The DC link voltage, power,both active and reactive exchanged with grid are given by the equations(13),(14) and (15):

$$V_{dc} = \frac{\sqrt{6}V_g}{m_a} \quad (5)$$

Where,Vdc, the voltage at DC link side,V_g, the AC voltage and m_a, the modulation index.

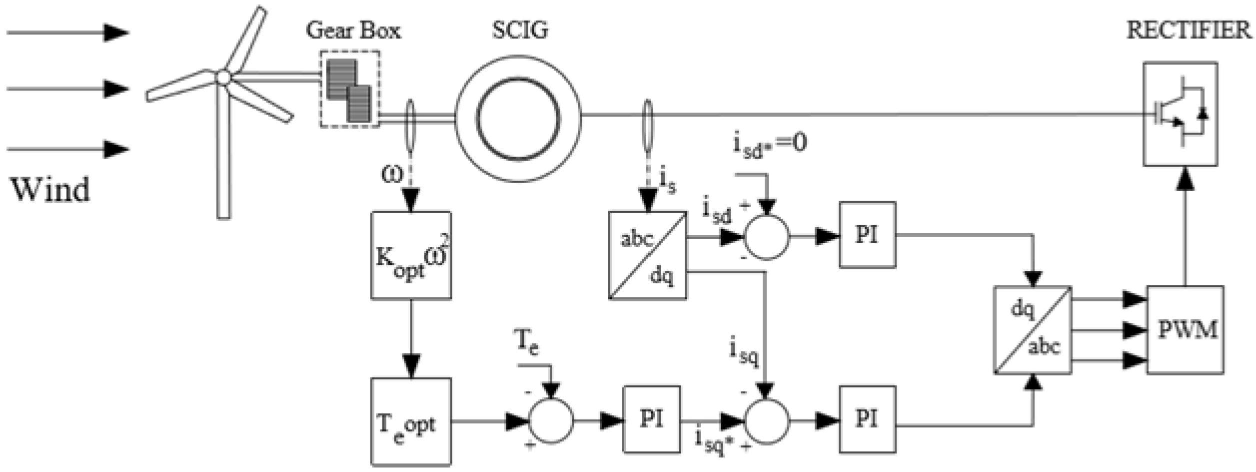

Figure 3. Turbine side control unit

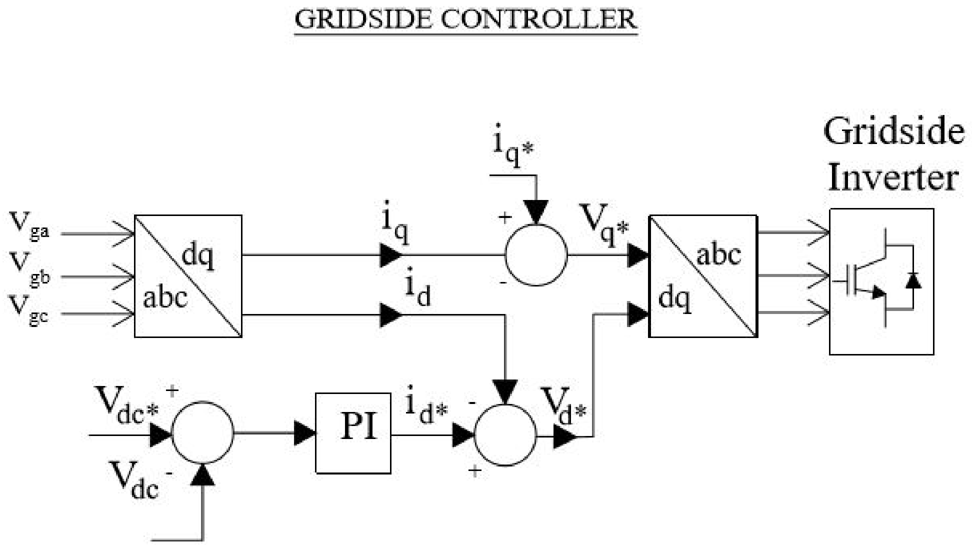

Figure 4. Grid side control unit

3. Retrofitting technologies for LVRT enhancement.

The LVRT technologies used and compared in this paper are braking chopper, energy storage device and STATCOM.

3.1. Braking chopper

Braking chopper (BC) comprises a high value of resistance in series with a fast acting IGBT switch. The surplus power, equal to the difference between power generated and power supplied to grid is dissipated by this device thus confining DC voltage to rated value during fault. The requisite switching pulses to control the IGBT switch are provided by a PI controller .The control part of BC is seen in Fig**.**6**.** Although the BC has advantages like low cost and simple controller, the excess power can only be dissipated and cannot be used for any useful purpose. The resistance of the BC is selected on the basis of power to be dissipated and the duty cycle of the switch as shown by equations (16) and (17):

$$R_{bc} = \frac{D_{sw}V_{dc}^2}{P_{bc}} \quad (16)$$

$$P_{bc} = P_{gen} - P_{grid} \quad (17)$$

Where, P_{bc} is excess power to be dissipated by the BC during faults, $P_{gen}$is the generator side voltage and $P_{grid}$is the voltage at grid side.

In this case,V_{dc}=700V,D_{sw}=1kHz and Rbc=9kohm.

3.1. Energy storage device

An energy storage device (ESD) can be used for enhancing the LVRT capability of variable speed wind generators [17].ESD can be connected across the DC link of B2B converter through DC-DC converter. ESD can absorb additional energy from the generator side under faults, limiting the DC voltage withinsafe value.

The power requirement of the ESD is given by the (18), (19) and (20):

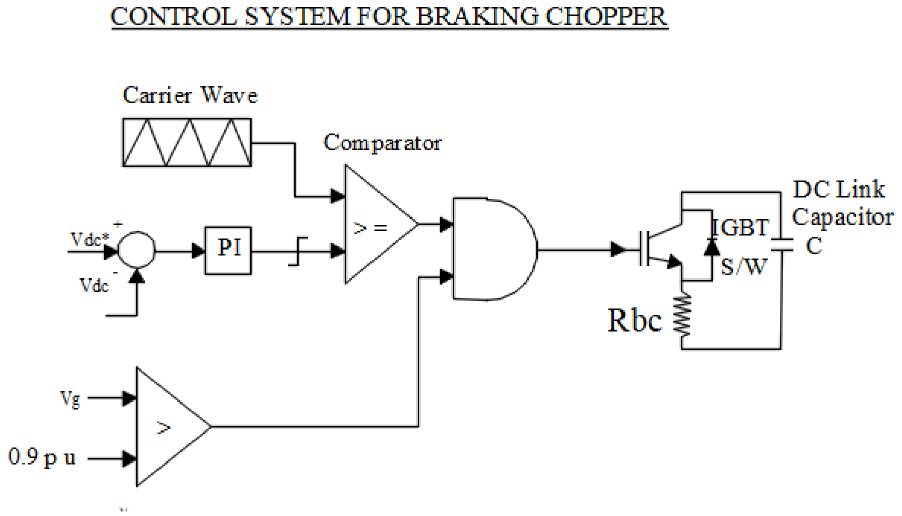

Figure 5 Braking controller

$$P_{LVRT} = (0.91V_{nom} - V_f)I_{rated} \quad (18)$$

$$0 \le t \le T$$

$$= \frac{(0.91V_{nom} - 0.15V_{nom})P_{rated}(3000 - T)}{(3000 - T)}$$

$$T \le t \le 3000 \qquad (19)$$

$$E_{LVRT} = \int_0^T (0.91 - 0.15V_{nom})I_{rated}\,dt + \frac{\int_T^{3000} (.91 - 0.15V_{nom})}{3000 - T} I_{rated}(3000 - t)$$

(20)

V_{nom} is the rated voltage,V_f is 15% of rated voltage is the time for which system should remain connected to grid ,I_{rated} is the rated current, P_{LVRT} and E_{LVRT} are the power and energy to be absorbed by the ESD during fault.

3.2. STATCOM

Both braking chopper and Energy storage device are unable to supply reactive power.STATCOM is a shuntconnected An ESD along with a buck boost converter is used for storing and releasing the excess energy [18].The controller consists of four PI controllers, two of which can be used to generate reference currents and voltage voltages in d and q axis. The STATCOM's power both active and reactive,is given by (21) and (22):

$$P_{stat} = \frac{|V_{stat}||V_g|}{X}\sin\theta \qquad (21)$$

$$Q_{stat} = \frac{|V_{stat}||V_g|\cos\theta}{X} - \frac{|V^2|}{X} \qquad (22)$$

$V_{stat}$is STATCOM output voltage,V_g is the PCC voltage ,θ is the angle in between the two voltages.

FACTdevice, which helps to limit the DC link voltage by controlling the reactive power absorbed or injected into the gridvoltages.

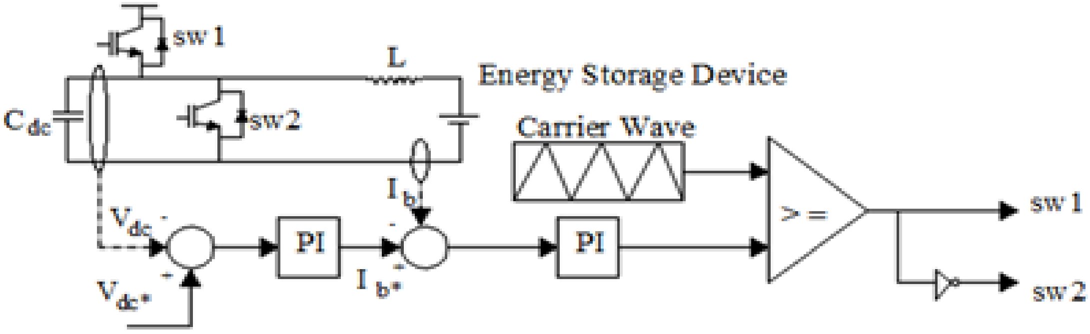

Figure 6. Control system for Energy storage device

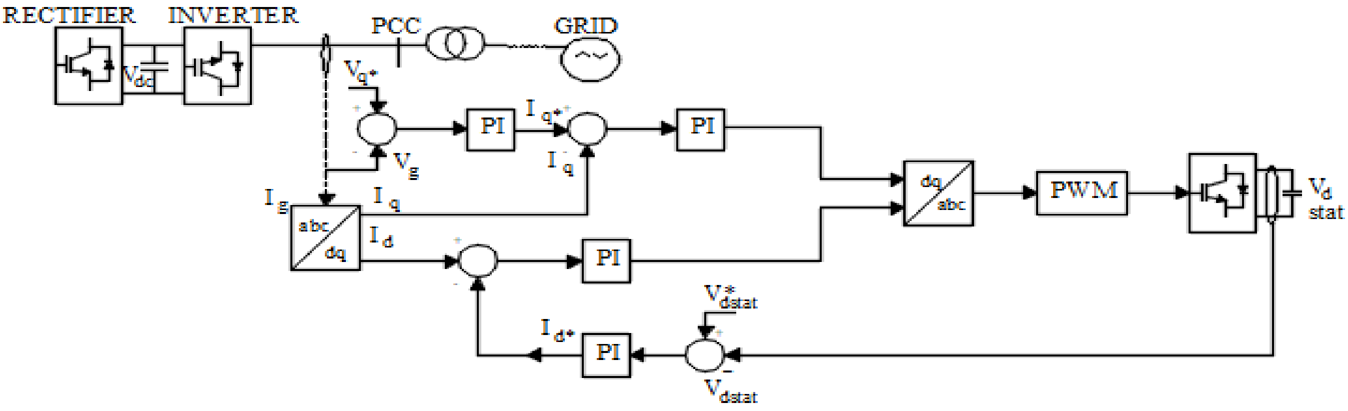

Figure 7 STATCOMcontrolunit

1. Results and Discussions

3.1 Financial losses due to Lack of LVRTCapability

A wind farm containing 177 wind turbines employing SCIGs inTamilNadu, India is studied. Each wind turbine is connected to a variable speed SCIG connected to grid through a B2B converter.

An analysis of under voltage hours of 3 wind farms for a duration of 6 months is noted as shown in table 1.It is seen that there is loss in production due to disconnection of wind turbines during fault. This result in financial losses for the company.

Above results show the necessity of implementing LVRT capability in wind farms employing variable speed wind turbines with SCIG.. The variation of under voltage hours in the wind farms is compared in figure.2.

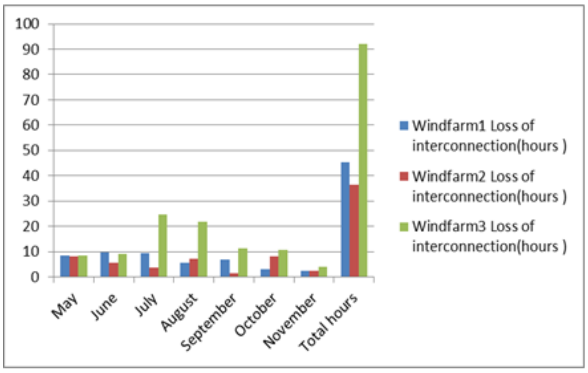

Figure 8. Loss of hours due to under voltage

The system under study is simulated bymeans of MATLAB/Simulink software. The steady state and dynamic behaviour of the system is studied and compared

Table 1

f Hours Under e msMonth (2016)	Windfarm1	Windfarm 2	Windfarm3
	Loss of interconnection(hours)	Loss of interconnection (hours)	Loss of interconnection (hours)
May	8.5	8	8.5
June	9.75	5.5	9
July	9.5	3.75	24.5
August	5.5	7.3	21.75
September	6.75	1.5	11.25
October	3	8	10.5
November	2.3	2.5	4
Total hours	45.3	36.55	92
Loss in Indian Rupees	**90,600**	**73,100**	**18,8000**

1.1 Performance under steady state conditions.

The voltage at grid side, wind speed variations, DC link voltage of the system under study are shown in figures 9,10,11and12. Voltage is remaining constant at700V.

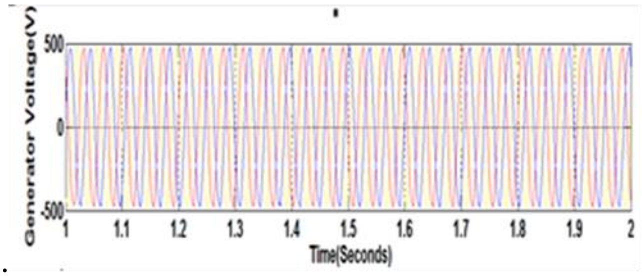

Figure 9.Grid side voltage

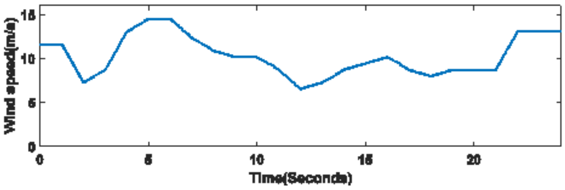

Figure 10.Wind speed variations

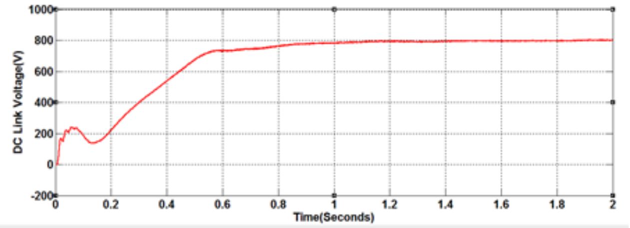

Figure 11.DC link voltage

1.2 Performance under transient conditions.

To analyze the behaviour under transient conditions, a three phase fault is applied at the point of common coupling for a period of 300 milliseconds. During fault, the voltage at DC side rises to 1300V from rated value of 800V, resulting in triggering of overvoltage protection device and subsequent disconnection of wind generator from the grid. In order to prevent this, three retrofitting devices braking chopper, energy storage device and STATCOM are connected and their performances are studied and compared.Fig.13 and 14 shows the grid side and DC link voltage during fault

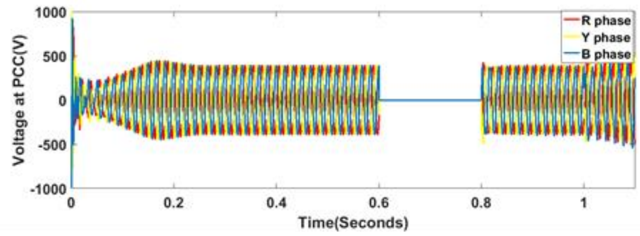

Figure 13.Grid side voltage during fault

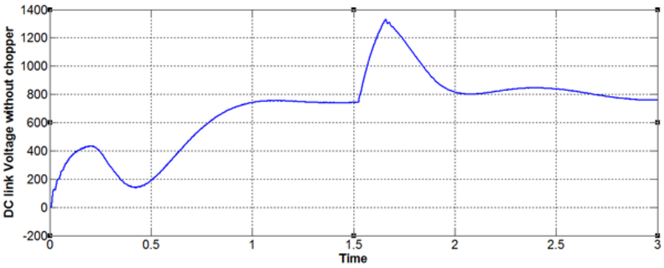

Figure 14.DC link voltage during fault

4.2. Performance using retrofitting devices

The performance of the VSWT is first studied by connecting a braking chopper across the DC link capacitor.

4.2.1. Performance using braking chopper

The DC link voltage during fault after connecting the braking chopper is shown in Fig. 15.It is seen that the DC link voltage is limited to its safe value so no disconnection is required

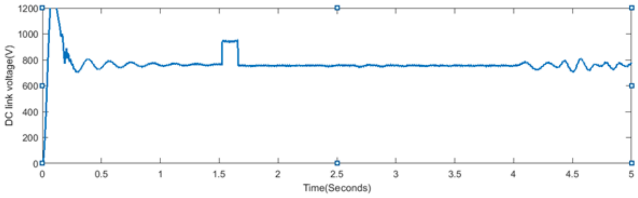

Figure 15.DC link voltage

4.2.2. Performance using ESD.

An energy storage device is connected across the DC link voltage. The state of charge (SOC) of the battery is shown in Fig 16. The voltage at DC side during fault is given by Fig.17.The energy storage device is being charged during fault and the voltage is limited to its rated value.

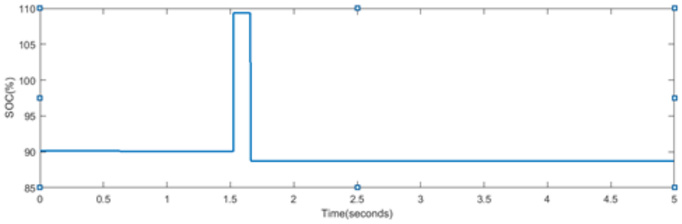

Figure 16.SOC of energy storage device

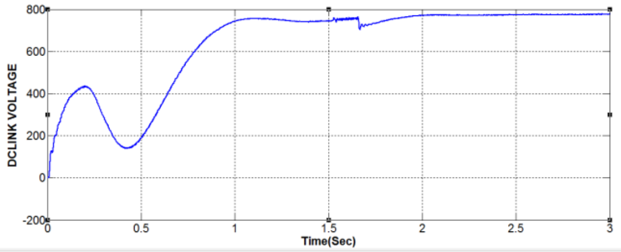

Figure 17.DC link voltage

4.2.2. Performance using STATCOM

Grid code prefers injection of reactive power into the grid by wind turbine during fault. Only STATCOM has the capability to inject reactive power as compared to braking chopper and ESD.The reactive power injected by STATCOM is shown in Fig. 18 and DC link voltage is shown in Fig.19.The DC link voltage is maintained within safe limits during fault and hence LVRT capability is maintained.

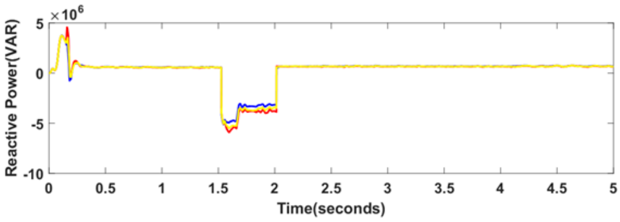

Figure 18.Reactive power of STATCOM

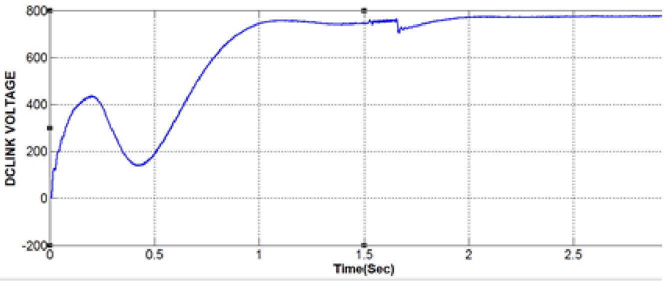

Figure 19.DC link Voltage

Table 2
Comparison of retrofitting devices

Device name	Technical feasibility	Economic feasibility
Braking chopper	Dissipation of energy	Low Cost
ESD	Excess energy can be stored	Medium cost
STATCOM	Provides reactive current injection during faults	High cost

Conclusion

In this paper, the behaviour of variable speed wind turbine with SCIG connected to grid under steady and transient conditions is analysed. Simulations are carried out using MATLAB/Simulink. Transient behaviour is studied by applying an unbalanced fault at PCC for a period of 300 milliseconds. It is seen that, when a fault occurs at the PCC, the wind turbine is disconnected from the grid due to overvoltage across DC link capacitor. Three retrofitting devices are used to enhance LVRT capability of wind turbine and their performances are compared. All three devices enhance the LVRT capability; STATCOM is having additional reactive power capability . In terms of cost, braking chopper is most economical. Energy storage device can be used additionally for wind power smoothing.

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