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Enhancement of Fault Ride through Capability of FSIG Based Wind Farm using Mechanically Switched Shunt Capacitors

Prashanth.N.A, K.S.R.Anjaneyulu, R.S.Shivakumara Aradhya

Abstract— Fault Ride through capability in FSIG based Wind Farm is essential to preserve voltage stability. This paper investigates the significance of short circuit levels of the grid on the fault ride through capability of the wind farm equipped with Fixed Speed Induction Generators. The minimum short circuit level of the grid required for uninterrupted operation of FSIG based wind farm during three phase fault is determined. Inadequate VAR support or reactive power support could result in low voltage levels and ultimately instability of the wind power systems. A balanced three phase fault is simulated at WT3 in MATLAB/Simulink with Mechanically switched shunt capacitors and without Mechanically switched shunt capacitors at the 33kV bus for different short circuit levels of the grid. The results shows that with Mechanically Switched Capacitors, fault ride through capability of the FSIG based wind farm increases and also improves the transient voltage stability therefore helps the wind farm to remain in service during faults. The results also show that the three phase grid faults closer to PCC are more severe compared to other types of faults like Line to Ground Fault(LG) and Double-Line to Ground fault(LLG).

Index Terms— Critical Short Circuit Level (CSCL), fixed speed induction generator (FSIG), point of common coupling (PCC), Squirrel cage induction generator (SCIG), Wind Turbine (WT).

1 Introduction

DURING last decade, there has been a continuous increase in installed wind power generation capacity throughout the world and it is expected to grow in future in order to fulfill the energy shortage and to avoid dependency on fossil fuel resources. Wind power, which is the fastest-growing non conventional energy source of electrical energy generation, is now proved to be potential source of electrical power generation with minimal environmental impact. It is reported that India has significant growth in wind power installation during last decade along with the world. Today India has the fifth largest installed wind power capacity in the world. In 2009-10 India's wind farm growth rate was highest among other top four countries. By the end of August 2012, wind power installations in India had reached 17.9GW [1]. Typically wind farms are located in remote areas, driven by wind and weather patterns with little analysis given to the existing transmission network in a given location. These locations tend to be weaker portions of the grid, which means they are also much more sensitive to fluctuations in reactive power demand [2]. These transmission lines in remote areas operate at lower voltages and with higher impedances than stronger parts of the grid. Such lines are poorly suited to accommodating wind power. According to ohm's law, higher impedance lines will incur higher voltage drops from one end of the line to the other for the same amount of power flow.

In addition to the above mentioned problem, majority of the wind turbines installed in India have induction generators, which are directly connected to the grid. These generators require reactive power from the grid for excitation. This may create low-voltage difficulties in the power system, especially if the wind farm is connected to the weak grid [3].

Depending on the severity of the voltage problem, utilities may choose to install fixed capacitor banks, which inject near-constant reactive power regardless of variations in system voltage levels, or they may use much more expensive switched capacitor banks, where different amounts of capacitance are mechanically switched in and out to regulate the system voltages to set values[4].

In this paper we analyze the effect of low short circuit levels of the 132kV grid on the performance of the wind farm equipped with squirrel-cage induction generators and propose a compensation strategy using mechanically switched shunt capacitors at the 33kV bus.

2 System Description

A wind farm consisting of three 1.5-MW wind turbines is connected to a 33-kV distribution system exports power to a 132-kV grid through a 30-km 132-kV feeder. Wind turbines use squirrel-cage induction generators (IG). The stator winding is connected directly to the 50 Hz grid and the rotor

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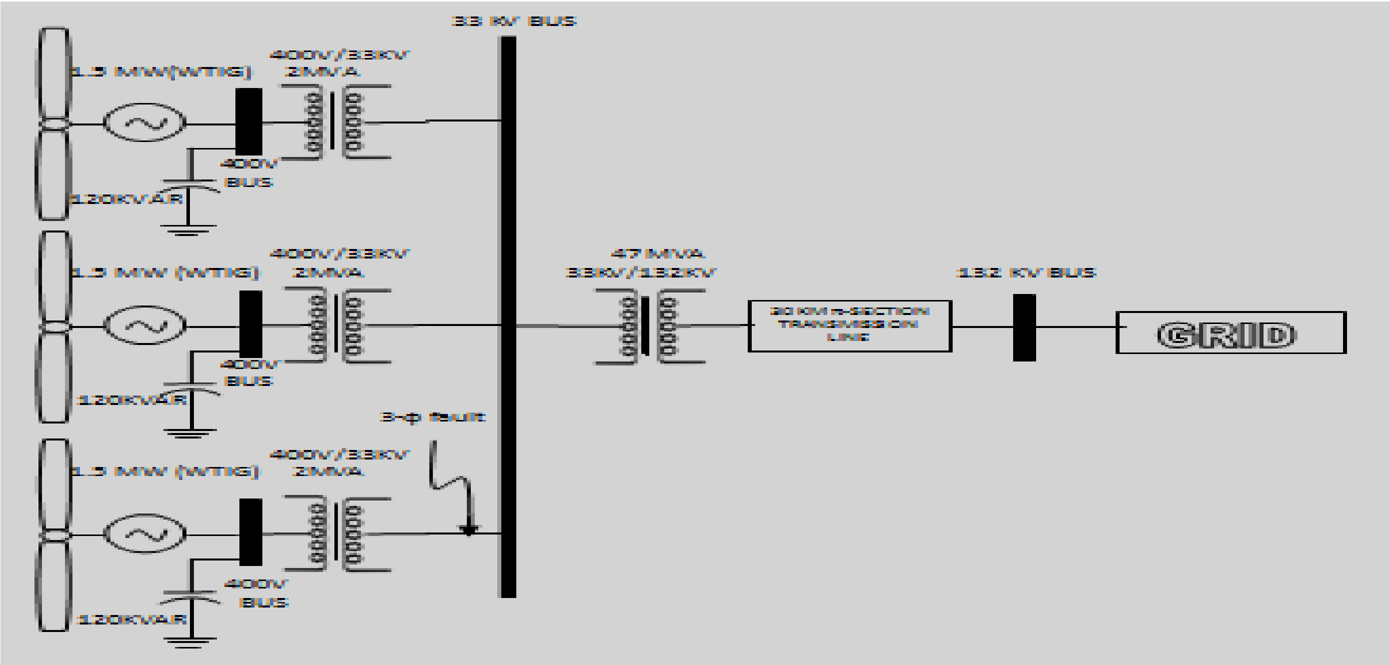

Fig. 1. Network layout used for simulation

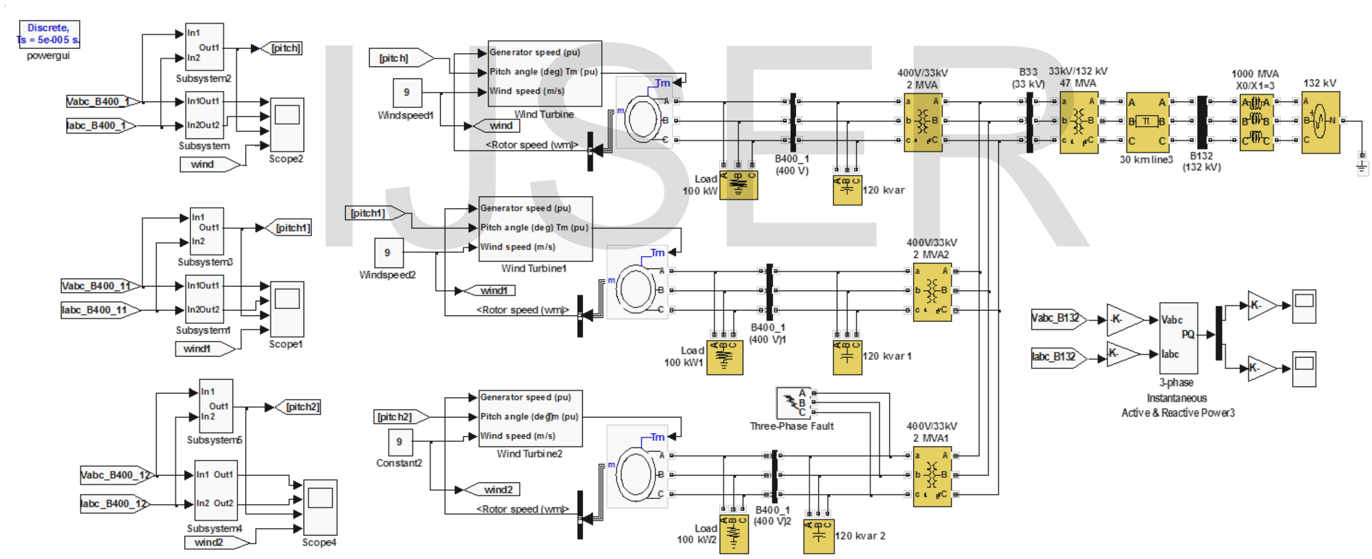

Fig. 2. Simulink Model of Wind Farm connected to 132kV Grid

driven by a variable-pitch wind turbine. The pitch angle is controlled in order to limit the generator output power at its nominal value for winds exceeding the nominal speed (9 m/s). In order to generate power the IG speed must be slightly above the synchronous speed. The Network Layout used for simulation is shown in Figure 1. Simulink Model of wind farm employing three WTs of 1.5MW each is shown in Figure 2.

3 Simulation Studies and Results

Test System 1. Wind Farm without Mechanically Switched Shunt Capacitors at 33kV bus

Case 1. Wind Farm with three Wind Turbine Generators (4.5MW Capacity) connected to 132kV Grid with Short Circuit Level of 23MVA

The wind speed input to each wind turbine is maintained constant at 9m/s. A balanced three-phase to ground fault was simulated near WT3 at t = 12 secs, with a clearance time of 12.5 cycles i.e. 250 ms. The typical short circuit levels of the 132kV grid is around 2000MVA. A 4.5MW Capacity wind farm can ride through the fault and regain stability for a short circuit level as low as 24MVA for a 132kV grid. Grid parameters representing turbine connection to a weak network of short circuit power level of 23 MVA is considered initially.

Figures 3 to 6 shows the post fault performance of the wind farm. As seen from these oscillograms, during the fault, there is a significant decrease in the active power at the 132kV bus, while the reactive power consumption increases at the 132kV bus. This leads to collapse of voltage and higher current at the 33kV bus. It is observed from the oscillogram that the post-fault voltage at the 33kV bus is only 0.62pu and is not able to recover to the pre-fault value due to insufficient supply of reactive power from the weak grid having a low short circuit level of 23MVA.

It is observed that for short circuit levels of 132kV grid below 24MVA, the system is not able to ride through the fault. This is due to the fact that, in general, induction generators tends to slow down voltage restoration after a voltage collapse during fault and this can lead to voltage and rotor instability. When the voltage restores, the generator will consume reactive power, impeding the voltage restoration. When the voltage does not return quickly enough, the generator continues to accelerate and consumes even larger amount of reactive power. This process eventually leads to voltage and rotor speed instability if the wind turbines are connected to a weak grid. The weak grid is not capable of supplying reactive power demanded by induction generators.

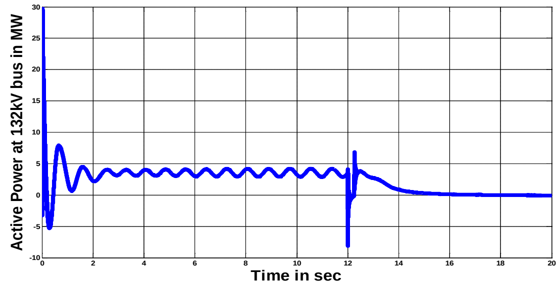

Fig. 3. Active Power during three phase fault at 132kV bus in MW

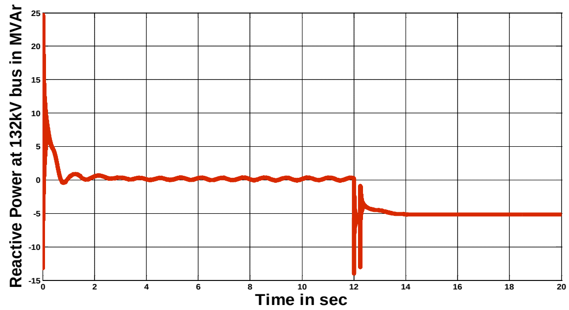

Fig. 4. Reactive Power during three phase fault at 132kV bus in MVAR

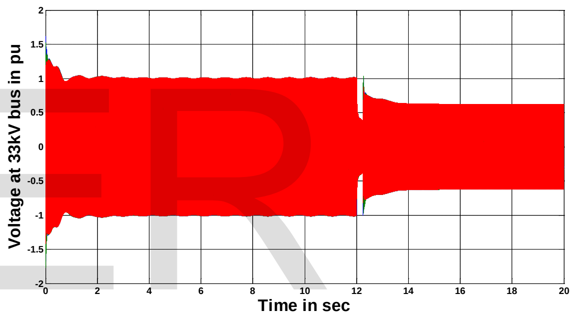

Fig. 5. 33kV bus voltage during three phase fault in pu

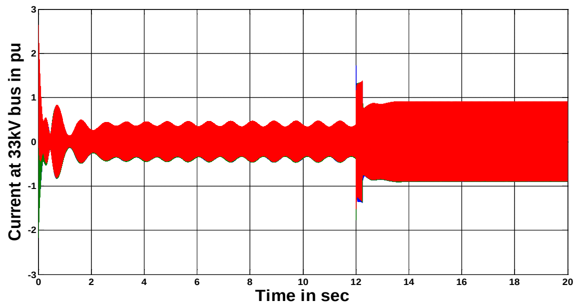

Fig. 6. 33kV bus current during three phase fault in pu

Case 2. Wind Farm with three Wind Turbine Generators (4.5MW Capacity) connected to 132kV Grid with Short Circuit Level of 24MVA

Simulation studies are carried out for the same system by increasing the short circuit level of the grid to 24MVA.

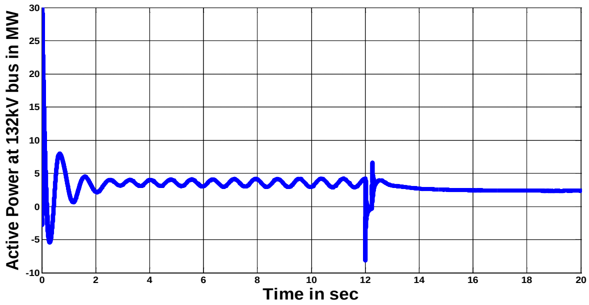

Fig. 7. Active Power at 132kV bus during three phase fault in MW

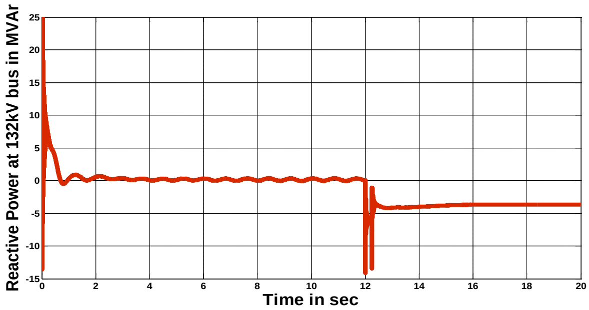

Fig. 8. Reactive Power at 132kV bus during three phase fault in MVAR

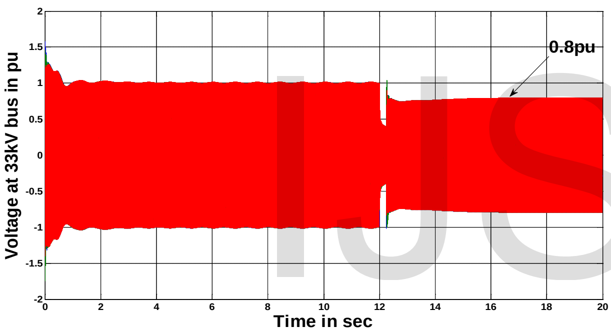

Fig. 9. 33kV bus voltage during three phase fault in pu

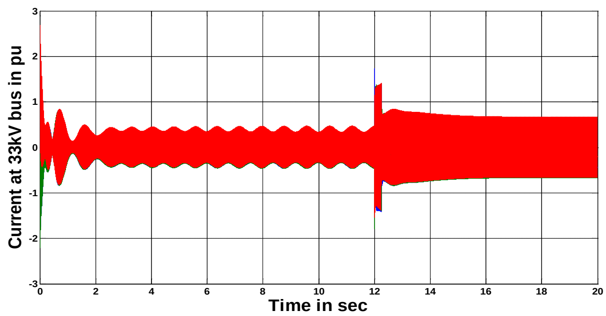

Fig. 10. 33kV bus current during three phase fault in pu

Figures 7 to 10 shows the post fault performance of the wind farm connected to the grid with short circuit level of 24MVA. It is observed from the above oscillograms that, even though during the fault the active power reduces to zero, the wind farm continues to inject active power into the 132kV grid after the fault.

It can be observed that the voltage at the 33kV bus recovers to 0.8pu after the fault. This is due to slight increase in reactive power supplied by the grid having the short circuit level of 24MVA. This short circuit level (24MVA for 4.5MW wind farm capacity) of the grid for which the system is able to ride through the fault is termed as "Critical Short Circuit Level"(CSCL) of the grid for a given size of the wind farm. When the capacity of the Wind farm is increased, system events like faults, voltage sags results in unstable operation of the network. In order to maintain stability, the short circuit level of the grid must be increased to provide necessary reactive power support. The minimum short circuit level of the grid at which the system rides through the fault is termed as "Critical Short Circuit Level". The Critical Short Circuit Level is determined for each case by increasing the number of wind turbine generators. A graph of Critical Short Circuit Level vs. Capacity of the wind farm in MW is plotted and a fourth degree polynomial curve is fitted.

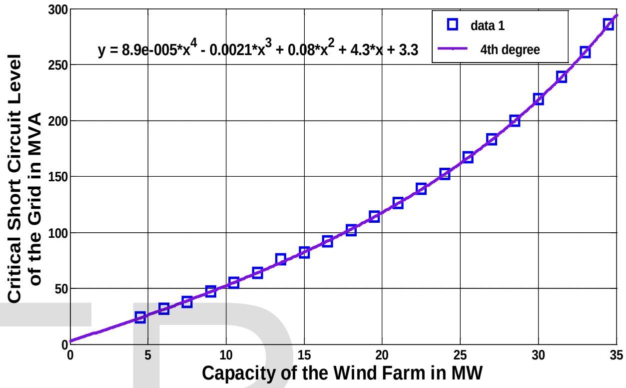

Fig. 11. Capacity of the Wind Farm in MW vs. Critical SCL of the Grid in MVA

It is observed from the graph that the Critical Short Circuit Level of the Grid increases with the increase in capacity of the wind farm. The relationship follows the equation:

$$y = 8.9e\text{-}005x^4 - 0.0021x^3 + 0.08x^2 + 4.3x + 3.3$$

From the above equation, for a wind farm of 100MW capacity, the critical short circuit level of the grid is 8033.3MVA.

Case 3. Post-Fault Reactive Power absorbed from the grid for different capacities of the wind farm connected to system with its own CSCL

For each of the above case the post-fault reactive power absorbed from the grid is measured at 132kV bus. Figure 12. shows the variation of Reactive power absorbed from the grid at the 132kV bus for the wind farm with eleven wind turbines (16.5MW capacity) connected to the grid with a short circuit level of 92MVA. From the graph, it is observed that the post fault reactive power absorbed from the grid is 11.21MVar.

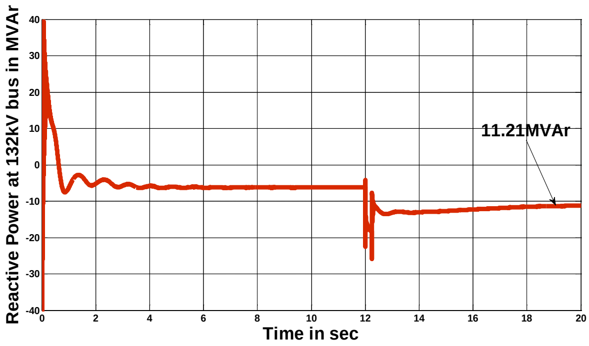

Fig. 12. Post-Fault Reactive power at 132kV bus for 16.5 MW wind farm during three phase fault

A graph of Capacity of the Wind Farm in MW versus post-fault Reactive Power in MVAR measured at the 132kV bus is plotted.

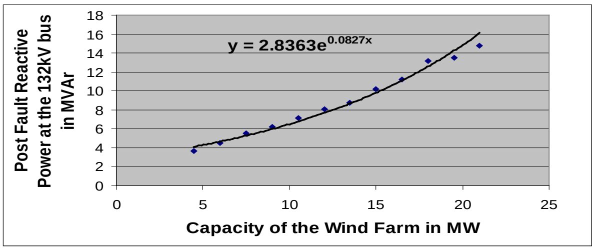

Fig. 13. Graph of Capacity of the Wind Farm in MW vs. Post Fault Reactive Power at the 132kV bus during in MVAR

From the above graph it is clear that, the Post-Fault reactive power absorbed from the grid increases with the increase in capacity of the wind farm, as the reactive power requirement of the wind farm increases with active power generation. It can be inferred that if CSCL is maintained the reactive power required to overcome the voltage instability problem will be automatically addressed. Even then the 33kV bus voltage in all the cases is observed to be lower than one p.u.

Table no.1 gives the 33kV bus voltage after clearance of fault for different capacity of wind farms.

TABLE I. 33KV BUS VOLTAGE AFTER THE CLEARANCE OF FAULT

No. of Wind Turbines	***Capacity of the Wind Farm in MW***	***33kV bus voltage in pu***
3	4.5	0.7939
4	6	0.8088
5	7.5	0.7929
6	9	0.8106
7	10.5	0.8111
8	12	0.8143
9	13.5	0.8287
10	15	0.8089
11	16.5	0.8083
12	18	0.7892
13	19.5	0.8051
14	21	0.8
15	22.5	0.8014
16	24	0.7826
17	25.5	0.7887
18	27	0.7888
19	28.5	0.7821
20	30	0.7871

It is necessary to maintain the 33kV bus voltage to near unity from supply quality point of view and improved system performance by use of Variable Reactive Compensation.

In this study switchable shunt capacitors are used to demonstrate that it is possible to restore bus voltage to acceptable level after fault is cleared.

Table No. 2 gives the value of MVAr to be provided by the switchable shunt capacitors for different MW rating of the wind farm.

TABLE II. MVAR OF SWITCHABLE SHUNT CAPACITOR

No. of Wind Turbines	***Capacity of the Wind Farm in MW***	***MVAr of Switchable shunt capacitor***
3	4.5	6.2
4	6	6.3
5	7.5	6.4
6	9	6.9
7	10.5	7.1
8	12	7.1
9	13.5	7.1
10	15	7.8
11	16.5	8
12	18	8
13	19.5	8.5
14	21	8.9
15	22.5	9.1
16	24	9.9
17	25.5	10

No. of Wind Turbines	*Capacity of the Wind Farm in MW*	*MVAr of Switchable shunt capacitor*
18	27	11
19	28.5	11.9
20	30	12.1

Test System 2. Final value of switchable shunt reactor to restore 33kV bus voltage to pre-fault voltage level with critical short circuit(CSCL) level of the Grid

TABLE III.FINAL MVAR VALUE OF SWITCHABLE SHUNT CAPACITOR

No. of Wind Turbines	*Capacity of the Wind Farm in MW*	*MVAr of Switchable shunt capacitor*
3	4.5	7
4	6	7
5	7.5	7
6	9	7
7	10.5	8
8	12	8
9	13.5	8
10	15	8
11	16.5	8
12	18	8
13	19.5	9
14	21	9
15	22.5	10
16	24	10
17	25.5	10
18	27	11
19	28.5	12
20	30	13

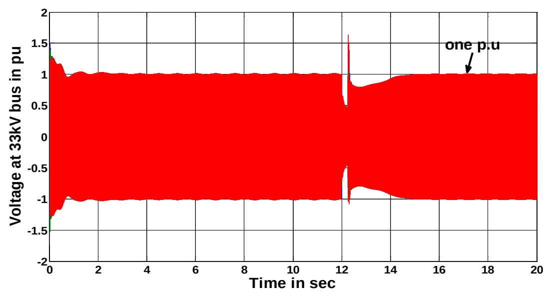

Fig. 14. 33kV bus voltage during three phase fault in pu

It can be observed from the graph that, with appropriate value of shunt connected capacitor at 33kv bus and with the short circuit level of the grid maintained at the critical level(CSCL) the voltage at the 33kV bus after the clearance of the fault recovers to one p.u or pre-fault voltage level.

The voltage level at the 33kV bus without shunt capacitors after the fault clearance depends on the short circuit level of the grid. With lower short circuit levels of the grid, the post-fault voltage level at the 33kV bus is also low. Simulation studies are carried out to determine the short circuit level of the grid required to maintain the voltage at the 33kV bus after the fault to the pre-fault voltage level for different capacities of the wind farm. A graph of Capacity of the wind farm versus short circuit level of the grid required to maintain 33kV bus voltage to the pre-fault voltage level is plotted.

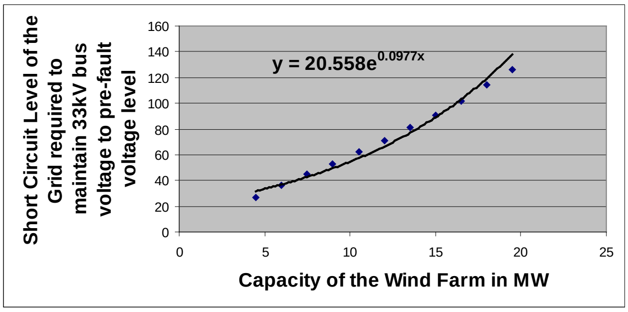

Fig. 15. Graph of Short Circuit Level of the grid required to maintain 33kV bus voltage to pre-fault voltage level vs. Capacity of the wind farm in MW

4 GRID FAULTS

Electrical faults such as grid faults produce high amplitude, rapid electrical transients and wind turbine designers increasingly need to take them into account. A balanced three-phase to ground fault was simulated at sending(after 2km) end, middle(after 15km) and receiving end(after 28km) of the 30 km π-section 132kV transmission line with a clearance time of 12.5 cycles i.e. 250 ms. Simulation studies are carried out to determine the Critical Short Circuit Level of the grid for different capacities of the wind farm.

TABLE IV. CRITICAL SHORT CIRCUIT LEVEL OF THE GRID FOR THREE PHASE FAULT

No. of Wind Generators	**CSCL of the grid for three phase fault at the sending end**	**CSCL of the grid for three phase fault at the middle**	**CSCL of the grid for three phase fault at the receiving end**
3(4.5MW)	75	75	75
4(6MW)	118	118	117
5(7.5MW)	177	175	174
6(9MW)	256	253	248
7(10.5MW)	371	365	360
8(12MW)	620	608	598
9(13.5MW)	1021	990	968

No. of Wind Generators	CSCL of the grid for three phase fault at the sending end	CSCL of the grid for three phase fault at the middle	CSCL of the grid for three phase fault at the receiving end
10(15MW)	1991	1862	1788
11(16.5MW)	7792	5803	5797

A graph of Capacity of the wind farm versus Critical Short Circuit Level of the grid is plotted.

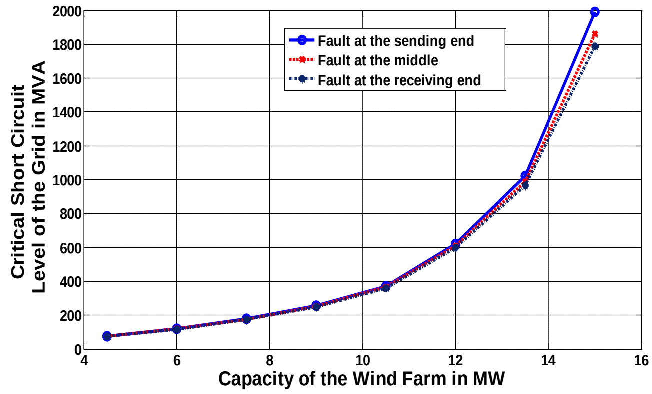

Fig. 16. Capacity of the Wind Farm in MW vs. Critical SCL of the Grid in MVA for Three Phase Fault

It can be observed from the graph that short circuit level of the grid required to ride-through the faults at sending end is more than for faults at the middle and receiving end of the 132kV transmission line. This is because, for a three phase fault at the sending end of the 132kV transmission line, the effective impedance from the point of common coupling to the point of fault occurrence will be less compared to the faults at the middle and receiving end of the transmission line. Therefore, the magnitude of sending end fault current will be more than the middle and receiving end fault current. Hence the short circuit level of the grid required to ride through the faults at the sending end will be more compared to the faults at the middle and receiving end.

Similarly a double line to ground fault(LLG) and single line to ground fault were simulated at sending(after 2km) end, middle(after 15km) and receiving end(after 28km) of the 30 km π-section 132kV transmission line with a clearance time of 12.5 cycles i.e. 250 ms. Simulation studies are carried out to determine the Critical Short Circuit Level of the grid for different capacities of the wind farm.

TABLE V. CRITICAL SHORT CIRCUIT LEVEL OF THE GRID FOR DOUBLE LINE TO GROUND FAULT

No. of Wind Generators	CSCL of the grid for double line to ground fault at the sending end	CSCL of the grid for double line to ground fault at the middle	CSCL of the grid for double line to ground fault at the receiving end
3(4.5MW)	46	45	43
4(6MW)	64	60	54
5(7.5MW)	81	75	70
6(9MW)	99	92	86
7(10.5MW)	121	110	104
8(12MW)	139	129	123
9(13.5MW)	161	150	143
10(15MW)	182	169	162
11(16.5MW)	214	197	185

A graph of Capacity of the wind farm versus Critical Short Circuit Level of the grid for double line to ground fault is plotted.

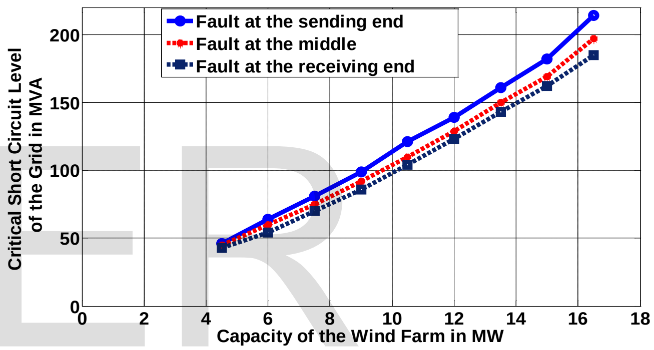

Fig. 17. Capacity of the Wind Farm in MW vs. Critical SCL of the Grid in MVA for Double Line to Ground Fault

TABLE VI. CRITICAL SHORT CIRCUIT LEVEL OF THE GRID FOR SINGLE LINE TO GROUND FAULT

No. of Wind Generators	CSCL of the grid for single line to ground fault at the sending end	CSCL of the grid for single line to ground fault at the middle	CSCL of the grid for single line to ground fault at the receiving end
3(4.5MW)	20	20	20
4(6MW)	27	27	27
5(7.5MW)	36	35	35
6(9MW)	45	45	44
7(10.5MW)	55	54	54
8(12MW)	66	64	63
9(13.5MW)	77	75	73

No. of Wind Generators	CSCL of the grid for single line to ground fault at the sending end	CSCL of the grid for single line to ground fault at the middle	CSCL of the grid for single line to ground fault at the receiving end
10(15MW)	88	86	84
11(16.5MW)	100	98	96

A graph of Capacity of the wind farm versus Critical Short Circuit Level of the grid for single line to ground fault is plotted.

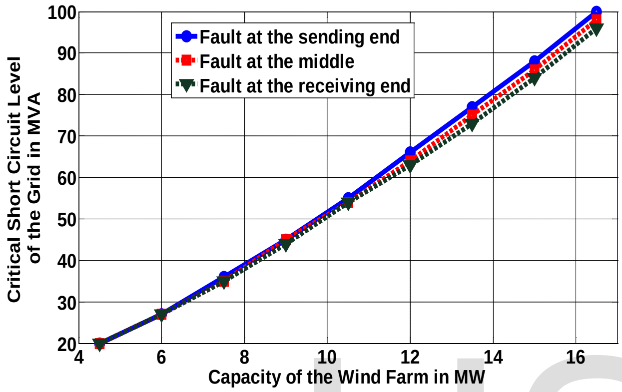

Fig. 18. Capacity of the Wind Farm in MW vs. Critical SCL of the Grid in MVA for Single Line to Ground Fault.

5 Conclusions

This paper presented an evaluation study about the impact of short circuit levels of the grid on wind farms comprising of mainly Fixed Speed Induction Generators. The wind farm terminal volage, voltages at different buses, the active power exported and the reactive power absorbed are monitored during fault state condition for different short circuit levels of the grid. It has been observed that if the wind farm is connected to weak grid with short circuit levels below a certain Critical Value (CSCL), the Wind Farm cannot ride through the three phase faults occurring near wind turbine generator terminals. This is because of insufficient supply of reactive power from weak grids with low short circuit levels below the CSCL. The effect of increasing the number of wind turbines on the short circuit level of the grid is studied. From the above studies it is clear that, larger capacity wind farms cannot ride through the faults and maintain voltage stability, if they are connected to grid with low short circuit levels. The strength of main grid will limit the penetration of the wind farm; from a certain low strength the wind farm will be instable.

Simulation studies also show that with mechanically switched shunt capacitors at 33kV bus, the wind farm is able to ride through the fault for the same short circuit level of the grid. This is due to the additional reactive power compensation provided by the switchable shunt capacitor banks. Also it is clear that the three phase faults at the sending end of the high voltage transmission lines are more severe than at the middle and receiving end and hence the short circuit power level of the grid required to ride through sending end faults is more compared to the middle and receiving end faults. This is accounted due to the low value of network impedance from PCC to the point of fault occurrence. From the present simulation studies, it is clear that the ability of the grid to absorb disturbances is directly related to its short circuit power level and short circuit power level of the grid is a very important parameter that determines the stability of the wind power system.

Appendix

TABLE I. Wind Generator Parameters

SI. No.	Wind Turbine Induction Generator Parameters		
	Parameter	*Value*	*Unit*
1.	P nominal	1.5/0.9	MW
2.	V nominal	400	V
3.	F nominal	50	Hz
4.	Stator Resistance	0.0048436	pu
5.	Stator Inductance	0.1248	pu
6.	Rotor Resistance	0.004377	pu
7.	Rotor Inductance	0.1791	pu
8.	Magnetizing Inductance	6.77	pu
9.	Inertia Constant-H	5.04	---

References

[1] Ministry of New and Renewable Energy, Government of India, "Indian Wind Energy Outlook 2012." November 2012.

[2] A. Kehrli and M. Ross, "Understanding grid integration issues at wind farms and solutions using voltage source converter FACTS technology," in Proc. IEEE PES General Meeting, 2003, pp. 1822–1828.

[3] W. Freitas, A. Morelato et al., "Comparative Analysis Between Synchronous and Induction Machines for Distributed Generation Applications," IEEE transactions on Power Systems, Vol.21, No.1, February 2006.

[4] Rose J.D. and Hiskens I.A., "Challenges of Integrating Large amounts of Wind Power",Systems Conference, 2007 1st Annual IEEE, On page(s):1 - 7.

[5] N.Dinic, B. Fox, D.Flynn, L.Xu and A.Kennedy, "Increasing wind farm capacity" IEE Proc. –Gener. Transm. Distrib., Vol.153, No.4, July 2006.

[6] P. Pourbeik, R. J. Koessler, D. L. Dickmander Member and W.Wong Me Oka, "Integration of Large Wind Farms into Utility Grids(Part 2 – Performance Issues)", IEEE transactions on Power, 2003.

[7] R. Jayashri, R.P. Kumudini Devi, "Analysis of the Impact of Interconnecting Wind Turbine Generators to the Utility Grid",Wind Engineering Journal, Volume 30, No.4, 2006, pp 303 – 316.

SI. No.	Wind Turbine Induction Generator Parameters		
	Parameter	***Value***	***Unit***
10.	Friction Factor	0.01	---
11.	Number of pairs of poles	3	---
12.	P nominal (Turbine)	1.5e6	MW
13.	Base Wind Speed	9	m/sec
14.	Pitch angle controller gain K_p	5	---
15.	Pitch angle controller gain K_i	25	---
16.	Maximum rate of change of Pitch Angle(deg/sec)	5	deg/sec

TABLE II. PI SECTION TRANSMISSION LINE SPECIFICATIONS

SI. No.	PI Section Transmission Line Specifications		
	Parameter	***Value***	***Unit***
1.	Frequency	50	Hz
2.	Positive sequence resistance[R1]	0.1153	Ohms/km
3.	Zero sequence resistance[R0]	0.413	Ohms/km
4.	Positive sequence inductance[L1]	1.05e-3	H/km
5.	Zero sequence inductance[L0]	3.32e-3	H/km
6.	Positive sequence capacitance[C1]	11.33e-009	F/km
7.	Zero sequence capacitance[C0]	5.01e-009	F/km
8.	Length	30	km

TABLE III. TURBINE TRANSFORMER SPECIFICATIONS

SI. No.	Turbine Transformer Specifications		
	Parameter	***Value***	***Unit***
1.	Nominal Power	2	MVA
2.	Frequency	50	Hz
3.	HV winding voltage	33	kV
4.	LV winding voltage	400	V
5.	HV winding resistance	0.025/30	pu
6.	HV winding inductance	0.025	pu
7.	LV winding resistance	0.025/30	pu
8.	LV winding inductance	0.025	pu
9.	Magnetization Resistance	500	pu
10.	Magnetization inductance	maximum	

TABLE IV. GRID SIDE TRANSFORMER SPECIFICATIONS

SI. No.	Grid side Transformer Specifications		
	Parameter	***Value***	***Unit***
1.	Nominal Power	47	MVA
2.	Frequency	50	Hz
3.	HV winding voltage	132	kV
4.	LV winding voltage	33	kV
5.	HV winding resistance	0.00267	pu
6.	HV winding inductance	0.08	pu
7.	LV winding resistance	0.00267	pu
8.	LV winding inductance	0.08	pu
9.	Magnetization Resistance	500	pu
10.	Magnetization inductance	maximum	