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Harmonic Distortion Control and Reactive Power Compensation in a Large Wind Mill Generation Plant

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SUMMARY

The renewable sources of energy are already on the rise; solar and wind power being the most prominent sources of green energy. Yet, their operation, controls and integration in the grid systems has its own specific problems. The paper discusses the reactive power compensation and harmonic analysis in a 100 MW wind generation plant. There are stringent requirements for the power factor of operation for wind power plants and reactive power compensation is invariably required. Passive harmonic filters are one choice, while static var compensators like STATCOM, the other. The paper describes theoretical aspects of DFIG (Doubly fed induction generator), its models, and general controls of wind power generating stations. It picks up a grid source with ambient harmonic pollution, and provides in-depth analyses of the various iterative designs and study steps to limit the harmonic distortions at the PCC (point of common coupling) with the limits specified in IEEE Guide 519.

KEYWORDS

Harmonic analysis, wind farms, Harmonic filters, STATCOM, reactive power compensation, harmonic emission limits.

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1. INTRODUCTION

More than 94 GW of wind power generation has been added worldwide by the end of 2007, out of which over 12 GW is in the USA and 22GW in Germany alone. Looking at energy penetration levels (ratio of wind power delivered by total energy delivered), Denmark leads, reaching a level of 20% or more; followed by Germany. In some hours of the year the wind energy penetration exceeds 100%, with excess sold to Germany and NordPool. Nineteen off-shore projects operate in Europe producing 900 MW. US off shore wind energy resources are abundant.

Renewable Energy Laboratory (DOE/NREL) took an investigation how 20% of energy from wind will look like in 2030. Some considerations are:

- Harmonics and resonance
- Reactive power compensation
- Fault and undervoltage ride through performance
- Congestion management
- Long term and short-term voltage stability
- Transient stability and low-voltage ride through capability
- Green house gas reduction and
- Power flow control

Harmonics, resonance and reactive compensation are the subject of this paper.

With respect to single unit wind turbines in USA, there has been progressive increase in the ratings from 100 kW in 1980s to 5 MW planned for offshore units. World wide, an 8 MW geared single unit with 80 m long blades has been commissioned in Jan 2014.

The US now ranks 2nd in the world for installed wind capacity, equal to approximately 4.5% of the total electrical demand. Between 2003 and 2013 a total of 842 MW of wind turbines were installed in distributed applications, reflecting nearly 72,000 units, Fig 1. Note the increasing addition of turbines of less than 100 kW. DOE Wind Program encourages anyone interested in purchasing small or medium sized turbines to consider using a certified product, and public funds can only be expanded on certified machines. In 2013 the wind power additions have been comparatively low, but in the years to come larger installed capacity is expected. An interesting trend in that in 2012 the exports stood at 8 MW and these increased to 13.6 MW in 2013. Growth after 2015 remains uncertain, dictated in part by future natural gas prices, fossil plant retirements, and policy decisions. The total US wind power installed capacity as in 2013 is approximately 65GW (DOE, 2013 report).

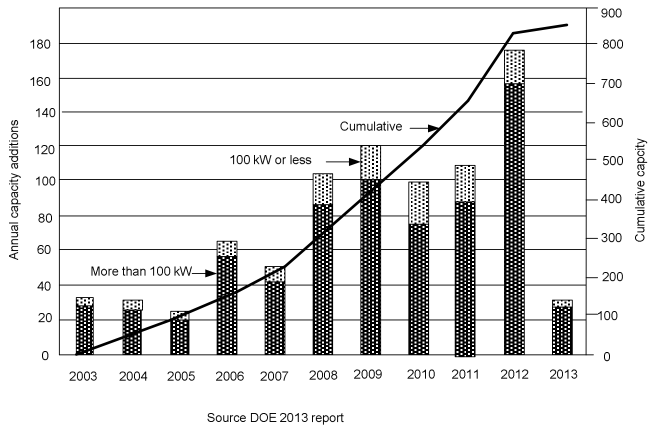

Fig 1. Installed wind power in USA

2. CONNECTIONS TO THE GRID

Fig 2 shows typical grid connections of wind generators.

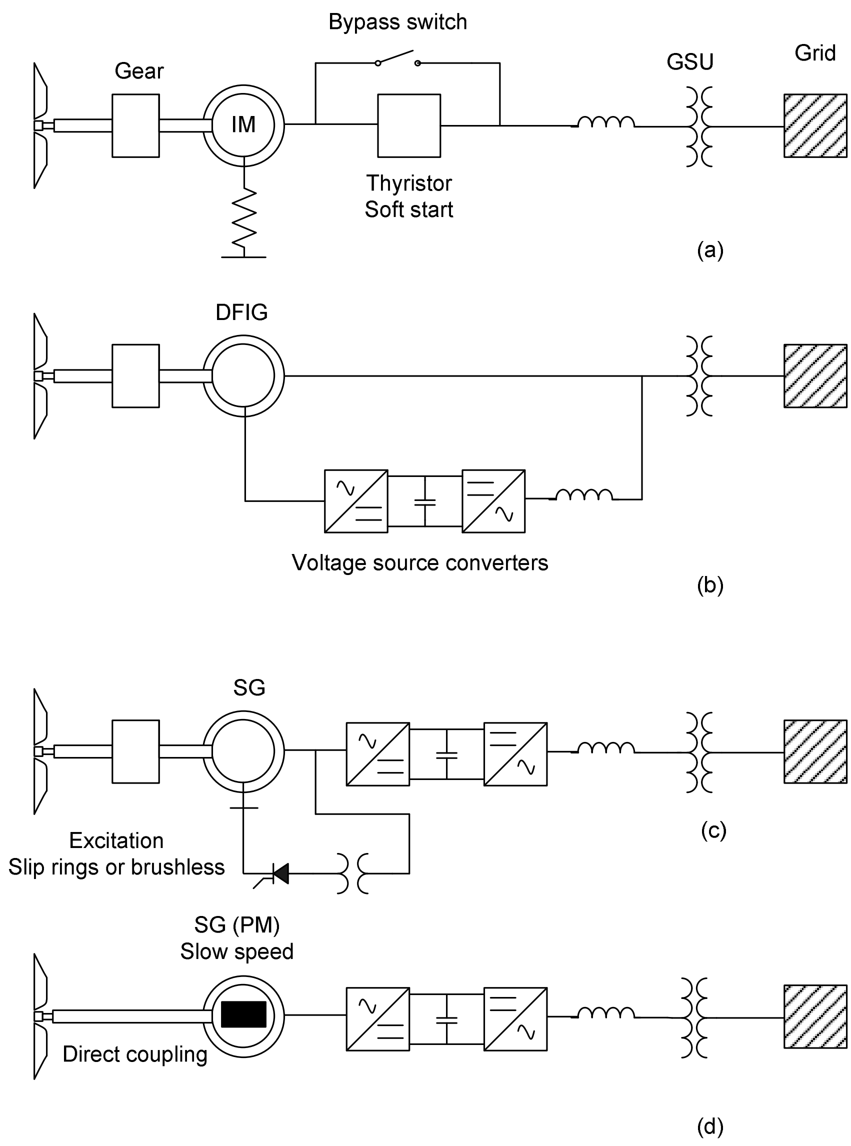

Fig.2 Typical wind power connections to the grid.

Direct Coupled Induction Generator

The direct coupled induction machine is generally of 4-pole type, a gear box transforms the rotor speed to a higher speed for generator operation above synchronous speed. It requires reactive power from grid or ancillary sources, and starting after a blackout may be a problem. Wind dependent power surges produce voltage drops and flicker. The connection to the grid is made through thyristor switches which are by-passed after start. A wound rotor machine has the capability of adjusting the slip and torque characteristics by inserting resistors in the rotor circuit and the slip can be increased at an expense of more losses, heavier weight, Fig. 2(a). The system will not meet the current regulations of connection to grid and may be acceptable for isolated systems.

Induction Generator Connected to Grid through Full Size Converter

The induction generator is connected to the grid through two back-to-back voltage source converters. Because of full power rating of the inverter, the cost of electronics is high. The wind dependent power spikes are damped by the DC link. The grid side inverter need not be switched in and out so frequently and harmonic pollution occurs.

Doubly Fed Induction Generator

The stator of the induction machine is directly connected to the grid, while the rotor is connected through voltage source converter, Fig. 2(b) The energy flow over the converter in the rotor circuit is bidirectional. In subsynchronous mode the energy flows to the rotor and in super synchronous mode it flows from rotor to the grid. The ratings of the converter are much reduced, generally 1/3rd of the full power and depend upon the speed range of turbine. The power rating is:

$$P = P_s \pm P_r \tag{1}$$

where P_s and P_r are the stator and rotor powers. But the rotor has only the slip frequency induced in its windings, therefore, we can write:

$$P_r = P_a \times s \tag{2}$$

where s is the slip.

For a speed range of $\pm$ 30%, the slip is $\pm$ 0.3, and a third of converter power is required. Also we can write:

$$n_s = \frac{f_r \pm f}{p} 120 \tag{3}$$

where p are the number of pair of poles.

Synchronous Generators

Synchronous generators can be brush type, brushless type of permanent magnet excitation systems. These are also connected to the grid much alike asynchronous machines. The excitation power has to be drawn from the source, unless the generator is of permanent magnet type. Fig. 2 (c) and (d) show typical connections.

3. INDUCTION GENERATORS

The induction generators are popular for wind generation. The characteristics of an induction machine for negative slip are depicted in Fig. 3. The equivalent circuit can be drawn akin to an induction motor, Fig.4

An induction motor will act as induction generator with negative slip. At s=0, the induction motor torque is zero and if it is driven above its synchronous speed, the slip becomes negative and generator operation results. The maximum torque can be written as:

$$T_m = \frac{v_s^2}{2\left[\sqrt{\left(r_s^2 + (X_s + X_r\right)^2} \pm r_s\right]} \tag{4}$$

The negative r_s in Eq.(4) represent the maximum torque required to drive the machine as generator. The maximum torque is independent of the rotor resistance. For subsynchronous operation, the rotor resistance does affect the slip at which the maximum torque occurs. For maximum torque at starting, s=1, and

$$r_r \approx \sqrt{r_s^2 + (X_s + X_r)^2} \tag{5}$$

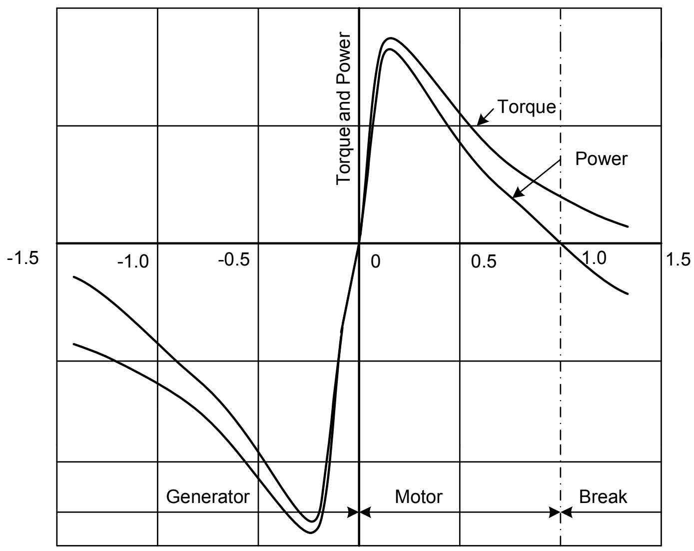

Fig. 3. Torque speed characteristics of an induction machine.

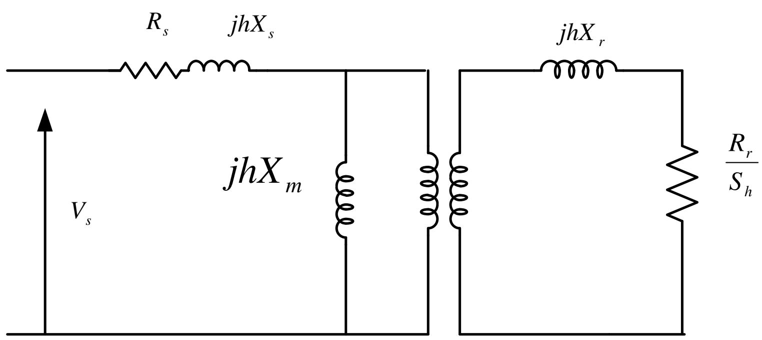

Fig.4 Equivalent circuit model of an induction generator.

For super synchronous operation (generator operation), the maximum torque is independent of r_r, same as for motor operation, but increases with reduction of stator and rotor reactance's, both. Therefore, we can write:

$$\frac{T_{m,gen}(\text{supersyn.})}{T_{m,motor}(\text{subsyn.})} = \frac{\sqrt{r_s^2 + (X_s + X_r)^2} + r_s}{\sqrt{r_s^2 + (X_s + X_r)^2} - r_s} \approx \frac{X_s + X_r + r_s}{X_s + X_r - r_s} \tag{6}$$

The approximation holds as long as $r_s << X_s$. The torque-speed characteristics of the machine above synchronism are similar to that for running as an induction motor. If the prime mover develops a greater driving torque than the maximum counter torque, the speed rises into an unstable region and the slip increases. At some high value of slip, the generating effect ceases and the machine becomes a brake.

Induction generators do not need synchronizing and can run in parallel without hunting and at any frequency, the speed variations of the prime mover are relatively unimportant. Thus, these machines are applied for wind power generation.

An induction generator must draw its excitation from the supply system, which is mostly reactive power requirement. On a sudden short-circuit the excitation fails, and with it the generator output; so in a way the generator is self protecting.

As the rotor speed rises above synchronous speed, the rotor EMF becomes in phase opposition to its subsynchronous position, because the rotor conductors are moving faster than the stator rotating field. This reverses the rotor current also and the stator component reverses. The rotor current locus is a complete circle. The stator current is clearly a leading current of definite phase angle. The output cannot be made to supply a lagging load.

An induction generator can be self excited through a capacitor bank, but the frequency and generated voltage will be affected by speed, load and capacitor rating. For an inductive load the magnetic energy circulation must be dealt with by the capacitor bank as induction generator cannot do so.

For wind power applications generators are either squirrel cage or wound rotor induction types with rotating field windings. The coupling with the grid, directly or through inverters is of significance.

The induction generator must draw its reactive power requirement from the grid source. When capacitors, SVC's, rotary phase shifters are connected, the operational capabilities can be parallel with synchronous machines, though resonance with grid inductance is a possibility. Induction generators produce harmonic and synchronous pulsating torques, akin to induction motors. A synchronous machine provides control of operating conditions, leading or lagging by excitation control

Strict regulations apply to the connections of wind power plants to the utility grids, with respect to voltage control, fault clearance times and the time duration of voltage dips should comply with the recommendations of WECC (Western Electricity Coordinating Council) Wind Generation Task Force (WGTF); not completely discussed here. Thus, a prior reactive power compensation study is undertaken. As we have previously seen the reactive power compensation, power factor and voltage profiles are interrelated, the system impedance playing an important role. With reference to Fig.4, equivalent circuit, the reactive power required by an induction generator can be written as:

$$Q = \frac{-b}{2a} V_1^2 + \frac{\sqrt{(b^2 - 4ac)V_1^4 + 4aPV_1^2}}{2a} \tag{7}$$

where

$$X_s = X_1 + X_m, \quad a = \frac{R_r X_s^2}{X_m \sin^2\phi}, \quad b = \frac{2R_r X_s}{X_m^2} + \frac{1-s}{\tan\phi}, \quad c = \frac{R_r}{X_m^2} \tag{8}$$

P is active power and ϕ is power factor angle.

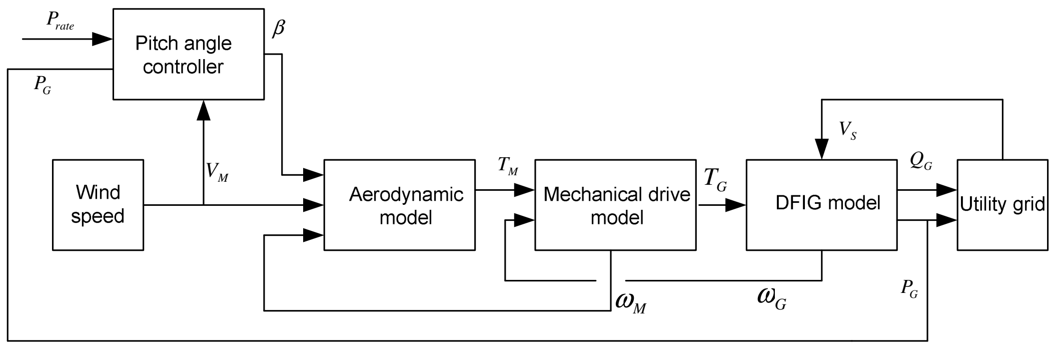

Fig. 5. Components of main control circuit of wind power generation.

The wind turbine dynamic models consist of pitch angle-control, active and reactive power control, the drive train model and the generator model. These models are considered the proprietary of the turbine manufacturer and can be obtained only under confidentiality agreements. Some efforts have been directed by WECC towards generic models, which are now available in some commercial software packages.

The overall control system diagram of a wind generation using DFIG is shown in Fig. 16.53. It has four major control components:

- Pitch angle control model
- Vector decoupling control system of DFIG
- Grid VSC control model
- Rotor VSC control system

Wind turbines are not able to maintain the voltage level and the required power factor. According to one regulation, it should be capable of supplying rated MW at any point between 0.95 power factor lagging to leading at the PCC. The reactive power limits defined at rated MW at lagging power factor will apply at all active power output levels above 20% of the rated MW output. Also the reactive power limits defined at rated MW at leading power factor will apply at all active power output levels above 50% of the rated MW output. See Fig, 6 for further details; this figure is for interconnection at the grid, PCC, *and not for individual operating units*.

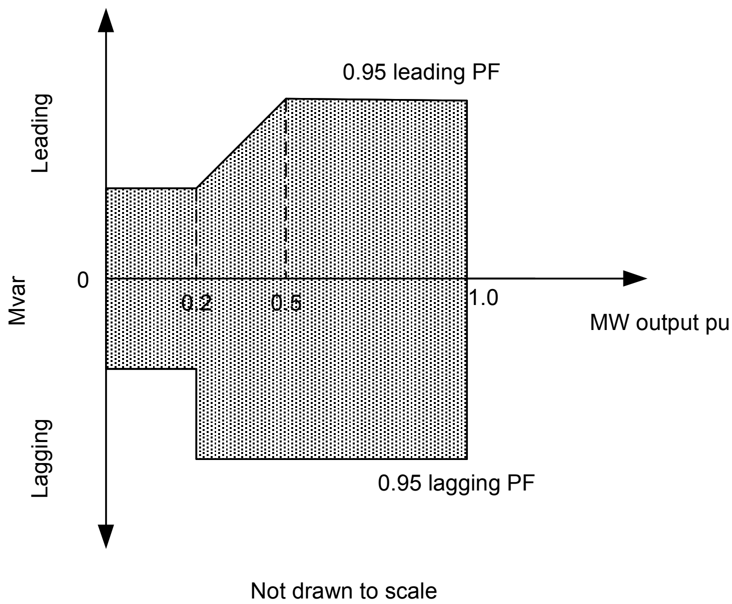

Fig. 6. Operational requirements of a wind generating plant for connections at the utility source, output versus power factor.

Thus, the reactive power compensation, fault levels and short-circuit analysis, the variations in the active power due to wind speed in the particular area over the course of a day, month-to-month, peak and lowest raw electricity that will be generated are the first set of studies performed in the planning stage. These allow fundamental equipment ratings to be selected and protection system designs. The considerations like cables versus overhead lines for connection of collector buses to grid step up transformer also arise. Further need for dynamic studies, voltage profiles, fault clearance times, studies documenting the grid connection requirements also arise. In fact wind power generation and utility interconnections required extensive studies apart from harmonic considerations.

Due to the stochastic nature of wind turbine harmonics, probability concepts have been applied. ARMA—Autoregressive moving average model is the statistical analysis of time series and provides parsimonious description of a stationary stochastic process in terms of two polynomials, one for auto regression and the other for moving average.

The mathematical model of a variable speed constant frequency generator under a *dq* synchronous rotating coordinate system is given by:

$$\begin{vmatrix} v_{sd} \\ v_{sq} \\ v_{rd} \\ v_{rq} \end{vmatrix} = \begin{vmatrix} pL_s + R_s & -\omega_1 L_s & pL_m & -\omega_1 L_m \\ \omega_1 L_s & pL_s + R_s & \omega_1 L_m & pL_m \\ pL_m & -(\omega_1 - \omega_r)L_m & pL_r + R_r & -(\omega_1 - \omega_r)L_r \\ (\omega_1 - \omega_r)L_m & pL_m & (\omega_1 - \omega_r)L_r & pL_r - R_r \end{vmatrix} \begin{vmatrix} i_{sd} \\ i_{sq} \\ i_{rd} \\ i_{rq} \end{vmatrix} \tag{9}$$

The subscripts *s* and *r* denote stator and rotor, and *p* is he differential operator

Generator flux is given by:

$$\begin{vmatrix}\varphi_{sd}\\ \varphi_{sq}\\ \varphi_{rd}\\ \varphi_{rq}\end{vmatrix} = \begin{vmatrix}L_s & 0 & L_m & 0\\ 0 & L_s & 0 & L_m\\ L_m & 0 & L_r & 0\\ 0 & L_m & 0 & L_r\end{vmatrix}\begin{vmatrix}i_{sd}\\ i_{sq}\\ i_{rd}\\ i_{rq}\end{vmatrix} \tag{10}$$

If stator flux linkage is in the same direction as *d*-axis of rotating coordinate system, then φ_{sd} =0, Then

$$\begin{aligned}\varphi_{sd} &= \varphi_s\\ \varphi_{sq} &= 0\end{aligned} \tag{11}$$

If stator coil resistance is ignored:

$$\begin{aligned}v_{sd} &= 0\\ v_{sq} &= |v_s|\end{aligned} \tag{12}$$

The generator side active and reactive powers are:

$$\begin{aligned}P_s &= v_{sd}i_{sd} + v_{sq}i_{sq} = v_{sq}i_{sq}\\ Q_s &= v_{sq}i_{sd}\end{aligned} \tag{13}$$

The P_s and Q_s can be decoupled using above equations.

The crowbar protection is specific to DFIG. The rotor side converter must be protected in case of nearby faults. When the currents exceed a certain limit the rotor side converter is bypassed to avoid any damage.

4. MODEL FOR HARMONIC STUDIES

For harmonic power flow analysis, the harmonic currents are modeled in parallel with the asynchronous machine model. A resistive load in parallel with the generator and current source is placed to model turbine auxiliary loads.

Considerable lengths of cables are involved and modeling of cable capacitance is important. Consider:

- Capacitance of the turbine capacitor bank, if provided
- Capacitance of the collector cables
- Capacitance of the substation capacitors.

Some simplifying assumptions can be made, that is: triplen harmonics will be trapped by transformer windings, even harmonics are eliminated due to waveform symmetry, the harmonic currents produced by all turbines can be assumed to have same phase angles.

For harmonic analysis, the harmonic spectrums are best obtained from a manufacturer for the specific installation. The output filters impact the harmonic emission passed on to the AC lines.

5. WIND GENERATION PLANT CONFIGURATIONFOR HARMONIC ANALYSIS

Fig. 7 shows a 100 MW wind farm generation for harmonic analysis. (1000 MW wind generation in a single location are being planned). The length and sizes of cables are indicated and also the source impedance and transformer impedances.

Table 1 shows the planning level of harmonics recommended by Energy Network Association (UK). The harmonic current spectrums are usually supplied by the manufacturer; Table 2 shows harmonic emissions from a WTG. Third harmonics need not be modeled.

Also some harmonic pollution in the grid connection itself is modeled:

- 5^{th} harmonic voltage =3%
- 7^{th} harmonic voltage =2.0%
- 11^{th} harmonic voltage =1.5%
- 13^{th} harmonic voltage =1.0%
- 17^{th} harmonic voltage =0.5%

This gives an ambient harmonic distortion at the utility source = 4.06% and makes the design of filters difficult.

The capacitive reactive power demand is a total of 30 Mvar, shown in the form of shunt capacitors at main substation bus. There are no additional capacitors at the collector bus.

To avoid resonance problems, ST (Single Tuned), DT (Double Tuned), LP (Low Pass), and Type C filters have been used in the wind farms. Also STATCOM (Static Compensator) and SVC's (Static var Controllers) are employed—these give less of a harmonic pollution and less of resonance problems

The study is conducted in the following steps:

- Establish ambient harmonics without 30 Mvar capacitor bank.
- Ascertain the harmonic resonance when 30 MVA banks is switched in service
- Provide filters to bring harmonic distortion levels to acceptable limits.
- Is 30 Mvar capacitor bank/filters a proper choice for this application?

With ambient conditions (without 30 Mvar bank) and with 30 Mvar capacitors, the results are documented in the following figures and Tables.

Fig. 8(a) and (b) are frequency scans: impedance angle and modulus without 30 Mvar capacitor bank, and Figs 8(c) and 8(d) with 30 Mvar capacitor bank

Fig. 9(a) and (b) are voltage harmonic spectrum and its waveform at PCC without 30 Mvar capacitor bank and Figs 9(c) and (d) with 30 Mvar capacitor bank.

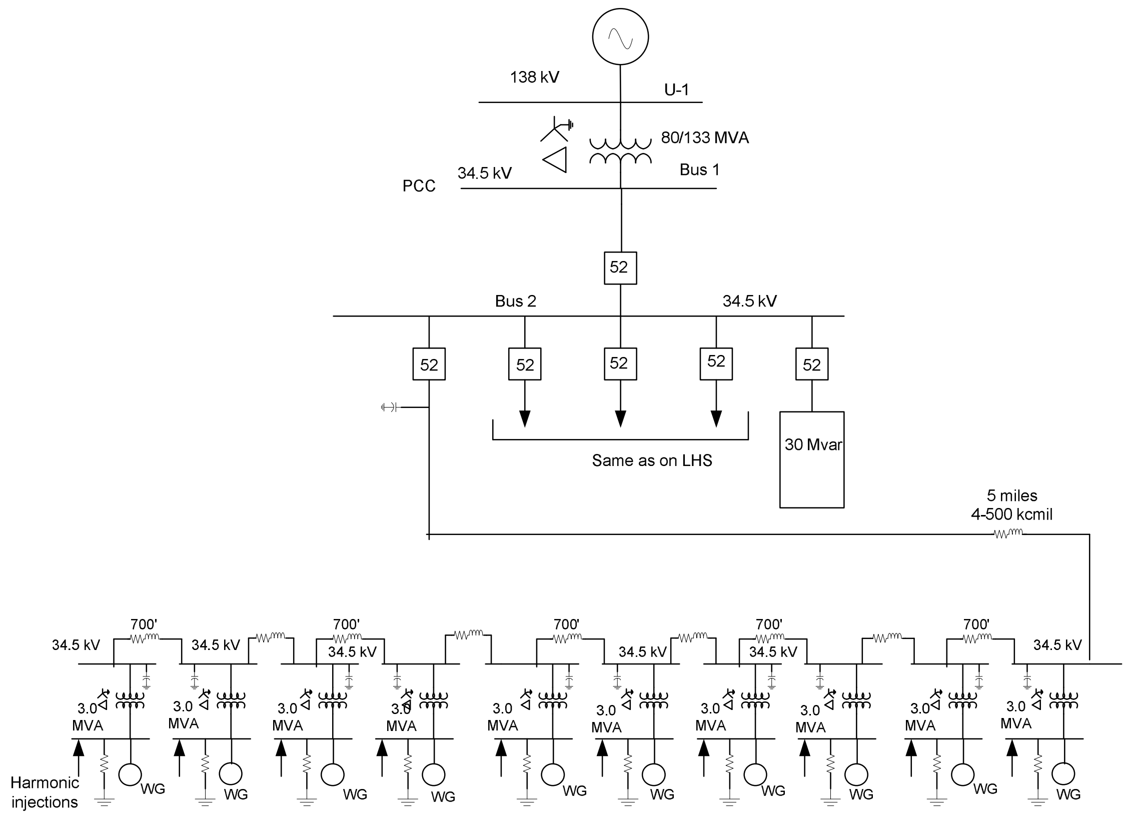

Fig.7 Configuration of a 100 MW wind generating plant.

Table 1

Planning Levels for Harmonic Voltages in Systems >20 kV and <145 kV.

Odd Harmonics		Triplen Harmonics		Even Harmonics	
Order	Voltage %	Order	Voltage %	Order	Voltage %
5	2.0	3	2.0	2	1.0
7	2.0	9	1.0	4	0.8
11	1.5	15	0.3	6	0.5
13	1.5	21	0.2	8	0.4
17	1.0	>21	0.2	10	0.4
19	1.0			12	0.2
23	0.7			>12	0.2
25	0.7				
>25	0.2+0.5(25/h)				

Table 2. Harmonic Emission from a Typical DFIG

Harmonic Order	Harmonic Current % of fundamental	Harmonic Order	Harmonic Current % of fundamental
2	1.0	17	0.76
3	0.51	19	0.42
4	0.43	22	0.33
5	1.32	23	0.41
6	0.42	25	0.24
7	1.11	26	0.2
8	0.42	28	0.15
10	0.61	29	0.27
11	1.52	31	0.24
13	1.91	35	0.35
14	0.50	37	0.26
16	0.37		

Fig. 10(a) and (b) are current distortions at PCC and its waveform at without 30 Mvar bank and Figs 10(c) and (d) with 30 Mvar bank.

Also the results of current and voltage distortions are plotted in Tables 3 and 4.

Summary of Study Results

- The study results show that with 30 Mvar capacitor bank in service resonance occurs at 5th harmonic, it is 73.70 percent of nominal voltage and 43.82 percent of fundamental current. The distorted waveforms in Figs. 9(d) and 10(d) illustrate this situation.
- Fig 8(b) without capacitor bank shows resonance at a higher frequency of approximately 35th harmonic and lower frequency of 7th harmonic. These resonance points shift to lower frequencies in Fig 8(d). This is an expected result.
- As a result of this resonance high current and voltage distortions occur, Tables 3 and 4.
- Before passive harmonic filter designs are attempted it is necessary to establish harmonic resonance frequencies.
- The study indicates that as a first step, 30 Mvar capacitor bank can be turned into a 5th harmonic filter.

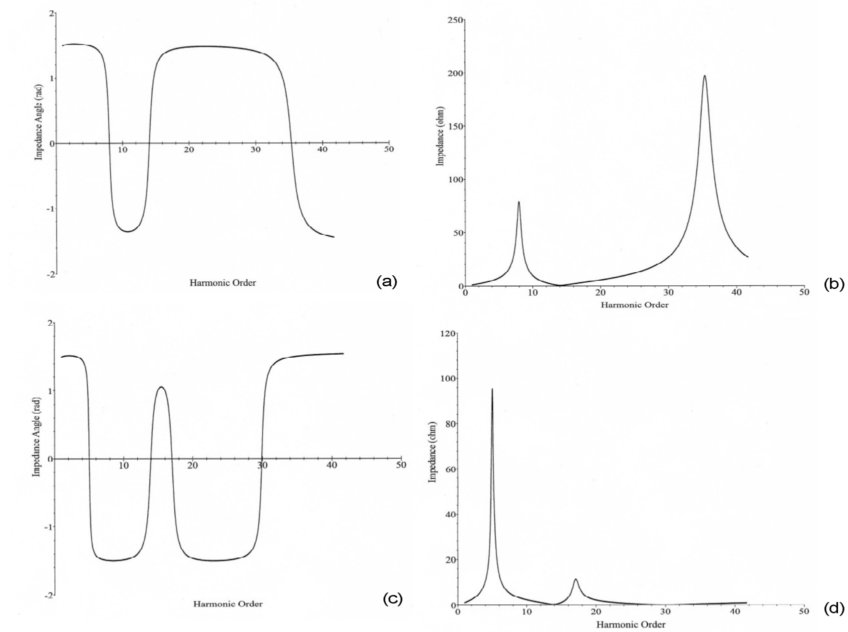

Fig 8 (a) and (b) Frequency scan, phase angle and impedance modulus, ambient harmonics (without 30 Mvar bank): (c), (d) with 30 Mvar bank.

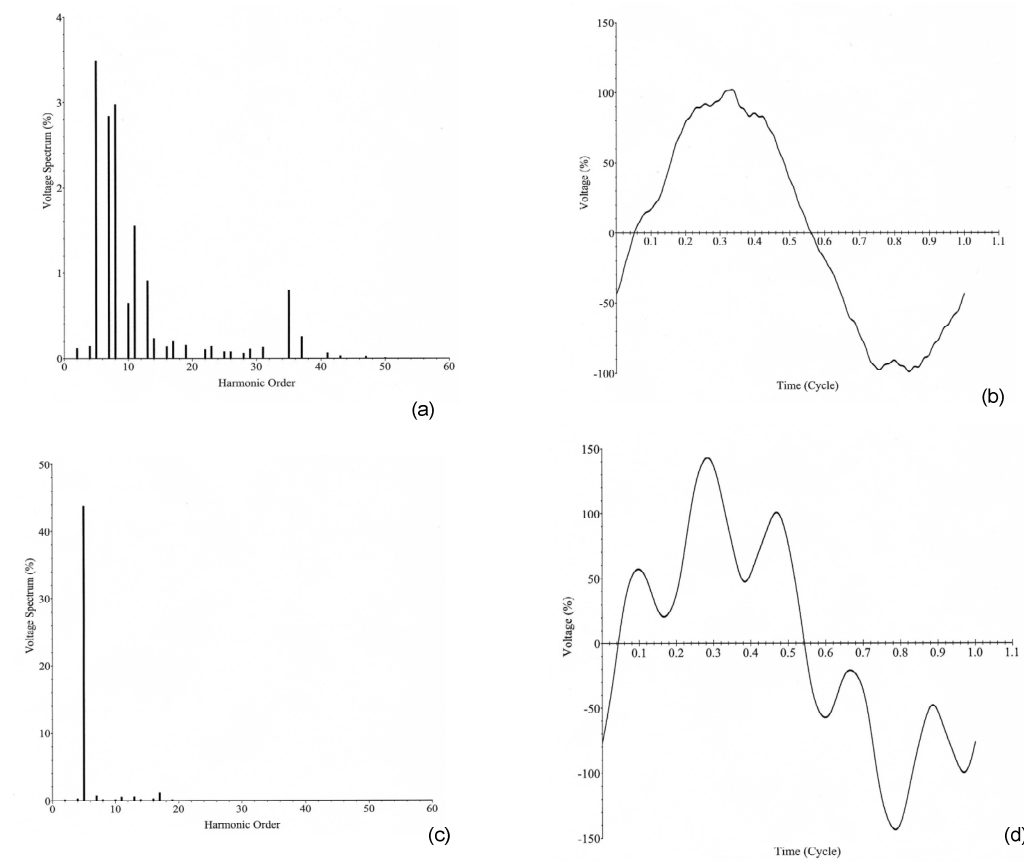

Fig 9 (a) and (b) Harmonic voltage spectrum and waveform , ambient harmonics (without 30 Mvar bank): (c), (d) with 30 Mvar bank.

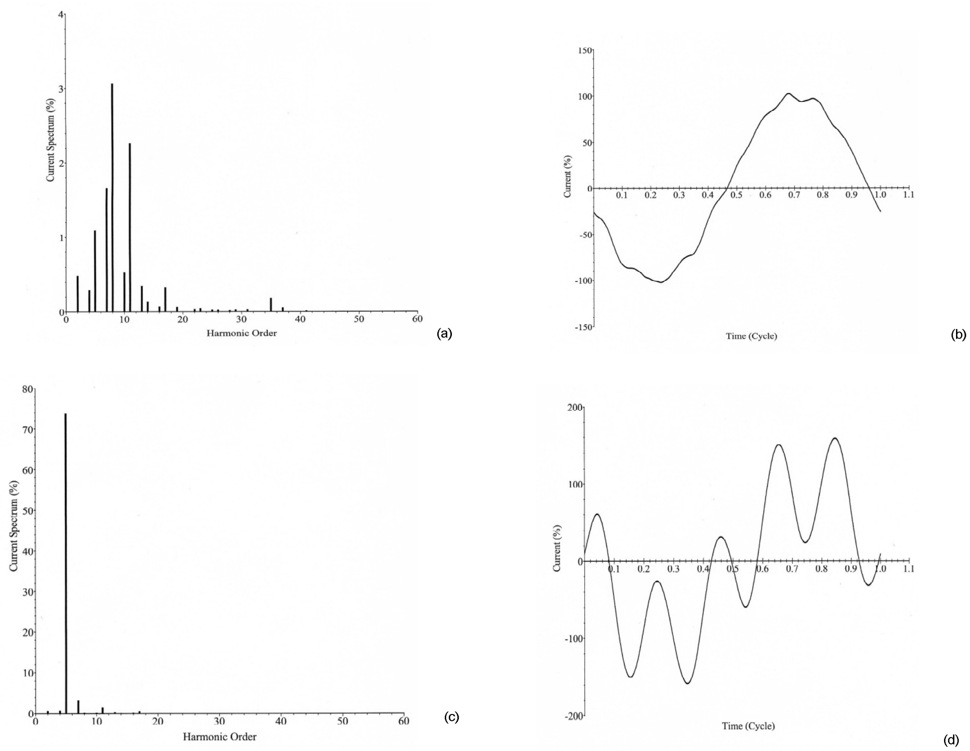

Fig 10 (a) and (b) Harmonic current spectrum and current waveform, ambient harmonics (without 30 Mvar bank): (c), (d) with 30 Mvar bank.

Study with Passive Harmonic Filters

The details of harmonic filter designs are not discussed, only the results are presented.

If the 30 Mvar capacitor bank is turned in to 5th harmonic ST (single tuned filter) filer, the results of current distortion at PCC are shown in Fig. 11(a).

It is well documented that ST filters do not eliminate resonance but shift it to a frequency lower than the tuned frequency of the filter. If this frequency happens to be close to a harmonic, resonance will occur.

In the process of ST filter designs various tuning frequencies are often tried, to escape that the shifted resonance point moves away from a harmonic that is already present.

Considerable harmonic amplification occurs at 2nd and 4th harmonics. Change in tuning frequency in this study controls these harmonics only slightly.

Though ST filters are very commonly used in HV networks, this limitation of shifted resonance frequencies must be considered.

A high pass damped filter does not give rise to shifted harmonic frequency, but is not so efficient. A size at least twice the size of ST filters or more may be required.

The various strategies of sizing the filters and their types are tried.

Two ST filters with a damped filter give the best results. However, the size of the three filters amounts to 60 Mvar. The design of filters is also impacted by harmonic voltages modeled in the 138 kV source. The current distortion at PCC with these filters in place is illustrated in Fig. 11(b).

It is not the intent of this paper to deliberate into the complex filed of passive harmonic filter designs.

Table 3
Harmonic Current Distortion at PCC, 34.5 kV

Harmonic Order	30 Mvar Capacitor out of Service	30 Mvar Capacitor in Service	IEEE Limits
Fundamental	1572.3A (100%)	1533.8A (100%)	
2	0.49	0.58	1.0
4	0.29	0.66	1.0
5	1.09	**73.70**	**4.0**
7	1.65	3.27	4.0
8	**3.06**	0.19	**1.0**
10	0.53	0.15	1.0
11	**2.26**	1.53	**2.0**
13	0.34	0.30	2.0
14	0.13	0.11	0.5
16	0.07	0.15	0.5
17	0.32	0.45	1.5
19	0.07	0.07	1.5
22	0.04	0.01	0.375
23	0.05	0.01	0.6
25	0.03	0	0.6
26	0.02	0	0.15
28	0.02	0	0.15
29	0.03	0	0.6
31	0.03	0	0.6
35	0.17	0	0.3
37	0.05	0	0.3
41	0.01	0	0.3
43	0	0	0.3
47	0	0	0.3
50	0	0	0.075

- Total permissible TDD=5%
- Without 30 Mvar capacitor bank TDD= 4.39%
- With 30 Mvar capacitor bank TDD= 73.80%
- The TDD stands for "Total Demand Distortion" according to IEEE standard 519.
- The calculations are based on IEEE standard 519
- The maximum limits of harmonic distortions in this Table and other Tables are according to IEEE 519.

Table 4
Harmonic Voltage Distortion, PCC, 34.5 kV

Harmonic Order	30 Mvar Capacitor out of Service	30 Mvar capacitor in service
2	0.12	0.14
4	0.14	0.31
5	3.49	**43.82**
7	2.84	0.72
8	2.98	0.18
10	0.65	0.18
11	1.56	0.55
13	0.91	0.58
14	0.23	0.19
16	0.21	0.30
17	0.35	1.20
19	0.11	0.16
22	0.14	0.04
23	0.08	0.04
25	0.08	0.01
26	0.06	0.01
28	0.11	0
29	0.13	0.01
31	0.79	0.01
35	0.26	0
37	0.06	0
41	0.03	0
43	0.02	0
47	0.01	0
50	0.01	0
THD_V	5.90	44.25

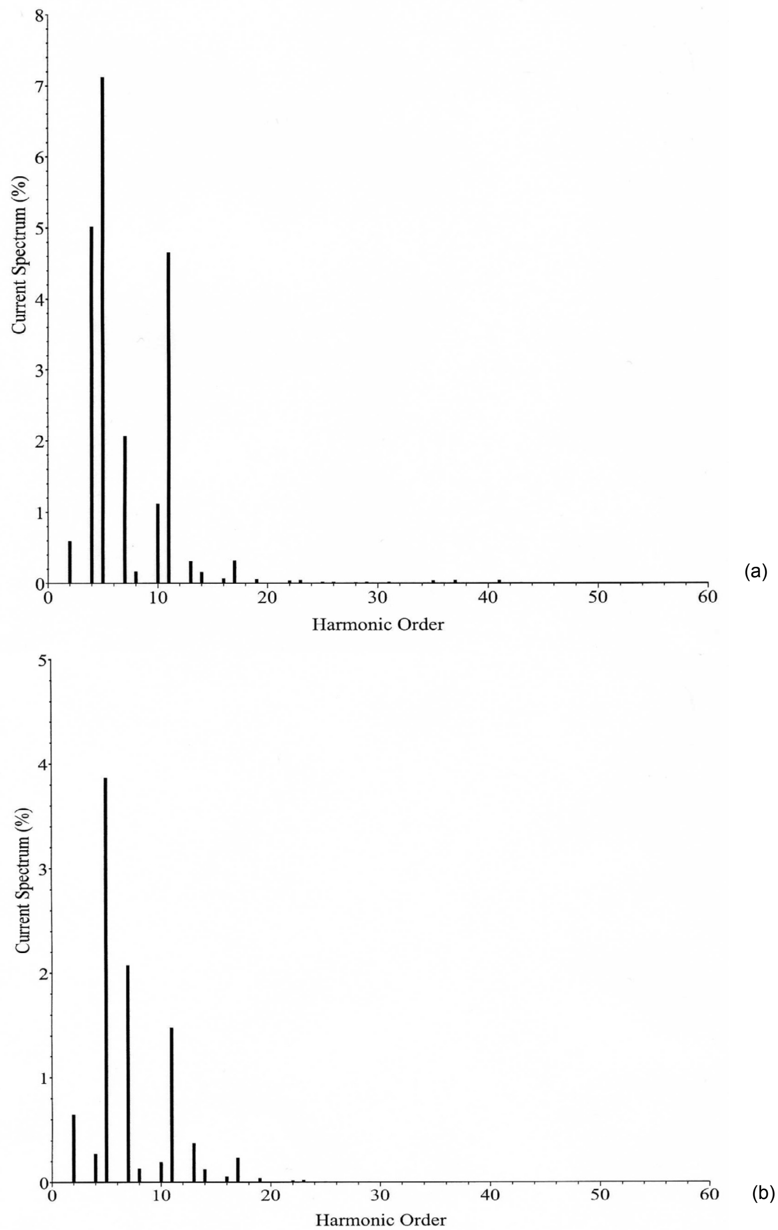

Fig. 11(a) Harmonic current spectrum at PCC with 30 Mvar ST 5th harmonic filter, (b) with multiple filters of 60 Mvar.

Study with STATCOM

This shows that selection of a STATCOM as a variable reactive power compensation device will be an appropriate choice. It can be controlled with respect to desired power factor and power output. It should be noted that STATCOM does give some harmonic emission. These harmonics should be modeled, and a manufacturer will supply the spectrum and harmonic phase angles for his product.

The results of the study with STATCOM supplying 30 Mvar of capacitive reactive power into the system are shown in Fig. 12. Fig. 12(a) and (b) show voltage spectrum and its waveform and Fig. 12(c) and (d) illustrate the current spectrum and its waveform at PCC.

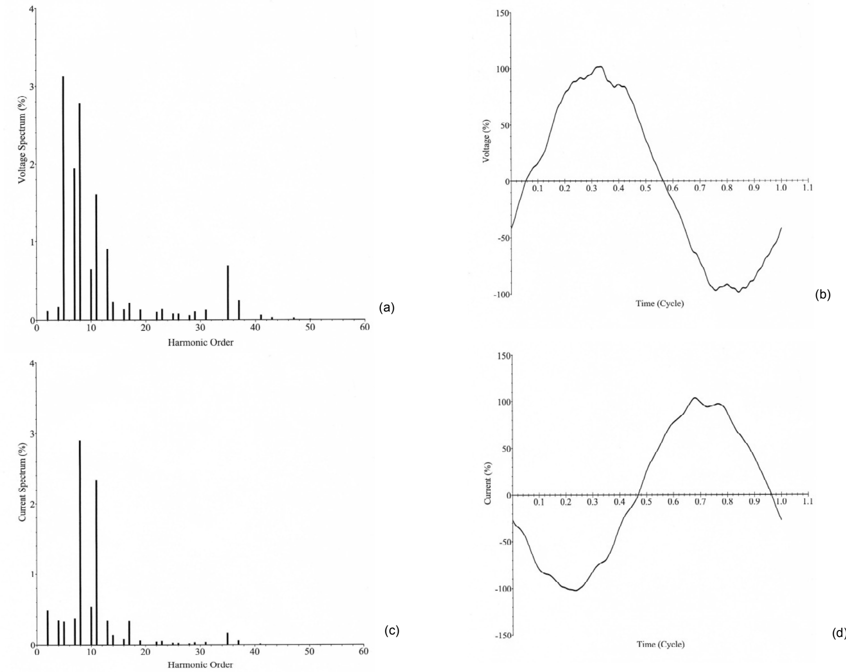

Fig. 12 (a)-(d) Harmonic voltage spectrum, voltage waveform, current spectrum and current waveform at PCC with STATCOM.

It is observed that he harmonics are reduced to almost ambient level. The summary results are also shown in Table 5. It is interesting to note that:

- 8th harmonic is amplified, showing resonance at this frequency. This exceeds IEEE limits. Note that for generating plants, the IEEE limits correspond to I_s/I_r <20, *irrespective of actual* I_s/I_r. (I_s=short-circuit current, I_r= load current demand)
- The importance of modeling even harmonics is illustrated. Resonance at even order harmonics is very possible, and such cases are on record.
- The total current distortion at PCC is 3.86% versus permissible level of 5% according to IEEE 519.
- The ambient harmonic voltage distortion modeled at 138 kV utility source is 4.06%. If the voltage distortion at PCC is to be limited to 5% it is a constraint, and the harmonic s at PCC should be further reduced.

Study with STATCOM and Filters

It looks frustrating that with various type of passive filters and then even with STATCOM, all the harmonics at PCC are not brought to within IEEE 519 permissible limits.

An obvious reason is that we assumed a highly polluted source with 4.03% ambient harmonics. This is not merely theoretical; though the ambient pollution may not be so high. The grid sources can be polluted with harmonics. Note that the standards do not specify that a user should not inject any harmonics whatsoever, but specify the limits based on the power system's characteristics.

The harmonic distortions at PCC are further reduced by reducing the capacitive reactive power output of STATCOM to 20 Mvar and providing two ST filters of 5 Mvar each. Various tuning frequencies and filter types are tried. The tuning frequencies selected are 147 Hz and 602; Hz, respectively which may seem rather an odd choice, but give the least harmonic distortions. Due to harmonics of 5^{th} , 7^{th} , 11^{th} , 13^{th} and 17^{th} at the source, the filters tuned to these frequencies will draw harmonic currents from the source.

Table 5
Harmonic current Distortion at PCC with STATCOM, 34.5 kV

Harmonic Order	With STTATCOM	IEEE Limits	Voltage Distortion
Fundamental	1572.3A (100%)		
2	0.49	1.0	0.12
4	0.35	1.0	0.17
5	0.32	4.0	3.13
7	0.38	4.0	1.95
8	**2.88**	1.0	2.78
10	0.53	1.0	0.64
11	**2.33**	2.0	1.61
13	0.34	2.0	0.90
14	0.13	0.5	0.23
16	0.07	0.5	0.14
17	0.32	1.5	0.21
19	0.07	1.5	0.13
22	0.04	0.375	0.11
23	0.05	0.6	0.14
25	0.03	0.6	0.08
26	0.02	0.15	0.08
28	0.02	0.15	0.06
29	0.03	0.6	0.11
31	0.03	0.6	0.13
35	0.17	0.3	0.69
37	0.05	0.3	0.25
41	0.01	0.3	0.06
43	0	0.3	0.03
47	0	0.3	0.02
50	0	0.075	0.01

Total permissible THD_I=5%
Calculated TDD THD_I=3.86. The values shown in bold exceed IEEE limits.
THD_V=5.18

Table 6

Harmonic current Distortion at PCC with STATCOM and Filters, 34.5 kV

Harmonic Order	With STTATCOM And Filters	IEEE Limits	Voltage Distortion
Fundamental	1572.3A (100%)		
2	0.34	1.0	0.10
4	0.31	1.0	0.20
5	0.96	4.0	3.57
7	1.77	4.0	0.07
8	0.26	1.0	0.32
10	0.95	1.0	1.48
11	1.98	2.0	2.19
13	0.04	2.0	1.08
14	0.12	0.5	0.26
16	0.06	0.5	0.15
17	0.23	1.5	0.27
19	0.04	1.5	0.13
22	0.03	0.375	0.11
23	0.04	0.6	0.14
25	0.02	0.6	0.08
26	0.02	0.15	0.07
28	0.01	0.15	0.05
29	0.02	0.6	0.10
31	0.02	0.6	0.11
35	0.07	0.3	0.37
37	0.09	0.3	0.51
41	0.01	0.3	0.09
43	0.01	0.3	0.04
47	0	0.3	0.03
50	0	0.075	0.01

Total permissible THD_I=5%
Calculated THD_I=3.09
THD_V=4.69
All the limits are complied with.

6. CONCLUSION

The paper has examined and analysed a difficult situation of controlling harmonic pollution in a large wind power generating plant and basis of providing the reactive power compensation.

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