Power System Analysis for Wind Farm Connection Using Modern Power Systems Analysis Software

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Summary

The penetration of wind energy has grown significantly in past few years, resulting in the construction of large-scale onshore and offshore wind farms. The technical development of large wind turbine generators facilitates the connection of the large wind farm into the transmission network. Power system analysis study to design the grid connection and verify compliance with regulatory codes and international standards is required during the design stage.

In this paper a DFIG wind turbine is modeled using a power systems analysis software package (ERACS) to examine the voltage at the terminal of the wind turbine as a result of voltage dip on the grid. The fault ride through study allows verification that the WTG provides the reactive power during the fault and the voltage at the PCC is quickly restored to its initial value after the fault is cleared.

Another scenario discussed is determining the need for reactive power compensation. A wind farm with 24 2.3MW wind turbines was modeled. A reactive and power factor capacity study was conducted based on the model and the British grid code [1]. The results show that an 8.35MVAr of inductive compensation and a 10.9MVAr of capacitive compensation at PCC are required. If the compensation is applied at the 33kV bus, a 0.52MVAr of inductive compensation and a 0.68MVAr of capacitive compensation are required.

A harmonic study based on the Energy Networks Association Recommendation G5/4-1 was also conducted. Typical current harmonic injection data is used in this paper. The THD and harmonics with order 10 exceed G5/4-1 planning levels due to the high charging capacitance on underground cables used in wind farm collector systems. The harmonic study in this paper shows harmonic compliance is dependent on not only on the number of turbines operating and the power level, but also the configuration of the distribution circuits that are selected at any given time.

Study Techniques

The fundamental and classical study tools offered by power system analysis software are as follows:

- Loadflow
- Fault calculation
- Transient stability
- Protection coordination
- Harmonic analysis

Present day power system analysis (PSA) software also offers more specialised analytic techniques such as determination of eigenvalues and loss minimization, but the classical technique continues to be the backbone of the analysis required.

The study process starts with data collection and entering this data. All modern PSA software use a graphical entry approach that allows a single line presentation of the topology of the transmission system of wind farm with data entered into the model for each of the study element such as transformers, cables, switchgears, protection devices, etc.

With the data and network assembled the basic operational states need to be established. For example, this may include generation with minimum and maximum numbers of wind turbines connected, minimum and full power operation, operation at the extreme of the permissible power and reactive power envelop, minimum and maximum grid voltage, and so on. Loadflow studies for these operational states not only provide initial conditions as the basis for other types of study (fault, transient stability etc), they also provide results that support design and specification. For example:

- Current levels will allow equipment ratings to be specified and protection devices such as CTs selected.

- Voltage profiles confirm circuit impedances are acceptable and transformer tap change range.
- Power factor correction requirements determined by VAr flows
- Power flows confirm performance and assist in preparing rating specifications.

Normally the next study step is to determine fault levels and fault contributions. This is a fundamental design requirement for specifying switchgear and assessing compliance.

The studies discussed above require steady state analysis. Although the actual operating condition may only be short lived, studies such as loadflow and fault provide provided results specifically for those conditions. Certain other studies model the continuous time dynamic behavior of the wind turbine generators. One of the most important dynamic concerns are those relating to the ability of wind farms to ride through transmission faults, and the impact of wind farms on voltage and frequency regulation of the grid. Fault ride-through specifications listed in modern transmission and distribution grid codes specify that wind-turbine generators (WTGs) must remain connected to electricity networks at voltage levels well below nominal [2,3]. The idea is to avoid significant loss of wind turbines production in the event of grid faults to ensure the reliable operation of the grid and grid stability. Wind generation with directly connected induction generators do not have fault ride through capability. These generators were the common choice in early fixed speed variable pitch and stall regulated WTGs. As the connected capacity of WTGs has become a larger component of national generation capacity the need for WTGs to remain connected post fault has become increasingly important to grid security. For limited variable speed wind turbines the disturbance can be reduced if the blades can be pitched fast. The standard controllers for variable speed partial scale frequency converter wind turbines, and variable speed full scale frequency converter wind turbines, that are designed for reliable operation around nominal voltage levels, may not work as designed during low network voltages that can occur during a fault. A consequence of this is greatly increased converter currents, which may lead to converter failure. Therefore, fault ride-through capacity is one of key criteria that wind turbine generators must comply with.

According to British Grid Code of connection, some other requirements that need to be complied for wind farm connection include:

- Reactive power flow required from the wind farm
- Power factor compensation provision
- Harmonic sensitivity of transmission system and excitation from the wind farm

During the design stage of the wind farm collector system, reactive and power factor capacity study is normally carried out to identify the reactive compensation required. Harmonic resonance may occur due to the combination of the inductance and the charging capacitance of cables. This can include cables associated with the wind farm and on the utility network. Harmonic analysis is normally conducted to facilitate judicious design and/or application of filters. This can involve modeling the most directly coupled parts of the transmission system and using it to identify resonant modes. Extending this model to include harmonic injection from the wind turbines allows harmonic current flows and distributed voltage to be investigated and assessed for compliance with national standard such as G5/4.

Fault Ride-through Study

For balanced Supergrid Voltage dips on the Onshore Transmission System having durations greater than 140ms and up to 3 minutes the fault ride through requirement is defined in Figure 5 of grid code (Issue 4 Revision 2, 22nd March 2010) CC6.3.15.1 (b) (i). The figure is reproduced here in Figure 1 below.

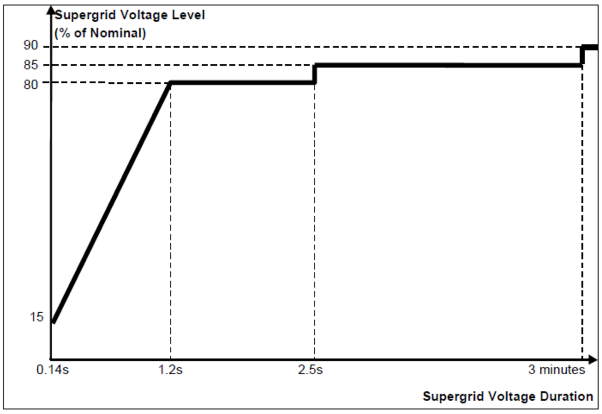
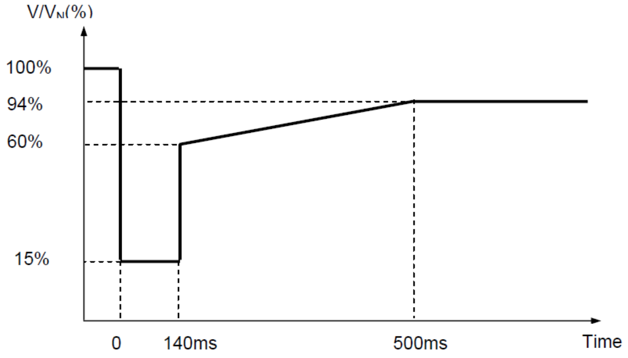


Figure 1: Fault ride through requirement on supergrid

In order to translate the conditions caused by a balanced or unbalanced fault which occurs on the Onshore Transmission System at the LV Side of the Offshore Platform, the fault ride through requirement for voltage dips on the LV Side of the Offshore Platform which last up to 140ms in duration is defined in the grid code CC.6.3.15.2 (a) (i) and Figure 6 which is reproduced here in Figure 2.



V/V_N is the ratio of the actual voltage on one or more phases at the **LV Side of the Offshore Platform** to the nominal voltage of the **LV Side of the Offshore Platform**.

Figure 2: Fault ride through requirement at LV side of the offshore platform

The objective of the fault ride through study is to estimate the retained voltages at the wind turbine terminal and associated durations that occur as a result of the balanced Supergrid voltage depressions given in Figure 1. These retained voltages and durations must be equal to or higher than the retained voltages and durations that the wind turbine is able to ride through during the type tests. In National Grid ‘Guidance Notes for Power Park Developers’ (September 2008 – Issue 2), some typical voltage levels and durations are provided (table 1 of the document).

To allow this to be investigated the wind turbine generator model must be capable of representing the fault current injection characteristic of the selected machine over the timescales defined by the connection code. Traditionally, this is the role of transient stability modeling using power analysis parlance. This requires modeling the electromagnetic characteristics of the generator and takes into account the generator speed over these timescales. The generator speed will vary and be determined by the speed governor and voltage control that depends on the voltage regulator response. Many standardised prime mover and AVR model have been developed over the last 40 years to represent the dynamics of conventional synchronous and induction generation driven by fossil fuel energies. Modern wind turbines are more complex and cannot be represented by equivalent models derived from the traditional models. They involve the wind speed/pitch characteristic of the turbine and the influence of the power electronic control. Modern PSA software must have the flexibility to represent the range of control strategies that have been developed and continue to evolve. In simple terms the software needs to incorporate generic representation of the form shown in Figure 3. This input and target parameters are defined during loadflow to allow a steady state solution to be achieved and to provide the basis for conducting transient study, such as the ride-through calculation.

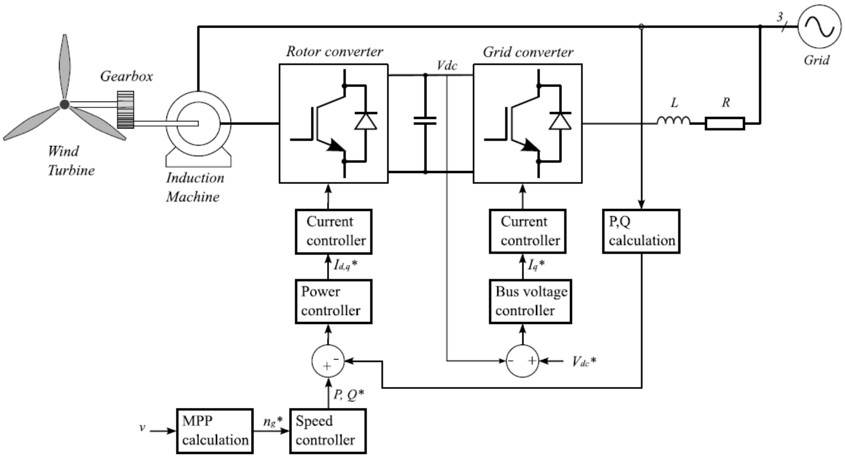


Figure 3: Block diagram of doubly-fed induction generator system

Using a DFIG model as an example, it must contain the dynamic representation shown in Figure 3. In the following example a GE model was implemented using universal Dynamic Modeller (UDM) provided in ERACS program.

A stability study was conducted to investigate the WTG transient voltage and the reactive power flow when a three-phase fault with zero fault impedance and duration of 140ms occurs at the PCC. Figure 4 demonstrates a simplified network and the study result, which shows that the WTG provides the reactive power during the fault. The system quickly restores the voltage at the PCC to its initial value after the fault is cleared.

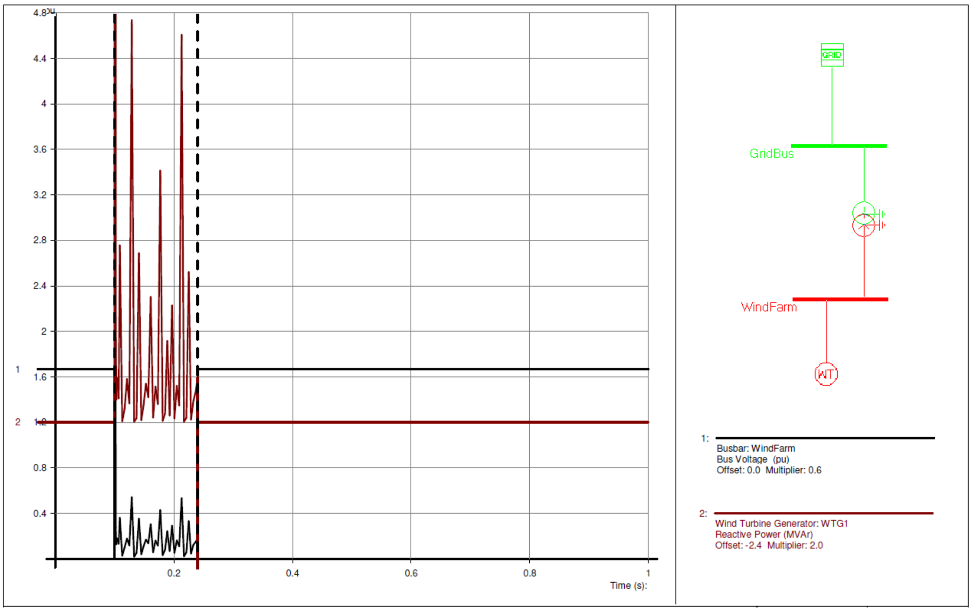


Figure 4: WTG reactive power output and voltage calculated during grid fault

Over/under voltage protections can be included in the system analysis model. Wind plants must not trip for events that are less severe than the thresholds and time durations which are defined in grid codes or interconnection agreements. A facility study is always conducted in the design phase to indicate acceptable settings for the actual protective devices, which can satisfy system requirements while providing adequate protection for the WTG equipment.

An Example Wind Farm

Since the increase of wind turbine size, it is important to understand the effect of connecting large-size wind farms to the transmission system, and how the wind farm will respond when disturbances happen on the system. A system analysis is carried out at the stage of the wind farm design to ensure the connection of the wind farm will not have detrimental effect on the system.

In this paper, a prospective wind farm with single line diagram shown in Figure 5 was used as an example to demonstrate the power system analysis required for wind farm connection. The wind farm consisting of 24 WTGs connected to individual step-up transformers was modeled in ERACS, which is ERA's suite of power systems analysis software. It provides program modules for loadflow, fault calculation, harmonic study, transient stability study and protection study. ERACS was used to model the wind farm network and to conduct grid connection studies in this paper.

In this example wind farm network, the WTG transformers step up voltages from 690-volt to 33kV. Three arrays each collecting 8 WTGs are connected to a collector bus at the low voltage side of a grid transformer which further steps up the voltage to 132kV. The high voltage side of the grid transformer was defined as the point of connection (PCC) where the grid code requirements are associated with.

As mentioned in previous section, the wind turbine can use a DFIG, induction machine or synchronous machine. If an induction machine or synchronous machine is employed, the turbine will be represented in the electrical network by a machine of the appropriate type. In this paper, a DFIG machine with maximum rating of 2.3MW was used. The rating of the WTG is listed in Table 1.

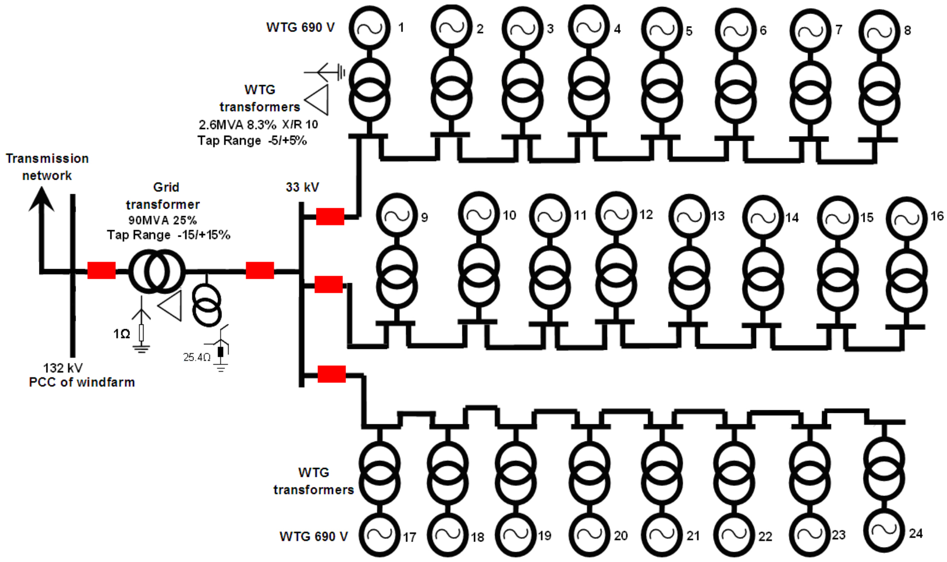


Figure 5: System analysis model for a windfarm with 24 WTGs

Table 1: WTG Ratings

WTG's	Max (MW)	Min (MW)	MVA	V_n (Volt)	I_n (Amp)	PF Lead	PF Lag
	2.3	0.052	2.598	690	2173	0.95	0.9

For the purpose of loadflow study, the DFIG was modeled as a shunt connected load with negative real power. As far as steady state fault level study was concerned, the DFIG wind turbine was modeled as an induction machine with the sub-transient reactance selected to be equivalent to the DFIG fault contribution at the point in time for which the fault level was relevant. Dynamically induction generators rely on terminal voltage excitation and therefore their fault current contribution to short-circuit levels will decay rapidly. The DFIG wind turbine generator, depending on design, may by comparison aggressively bring back terminal currents to nominal levels (if not tripped in the process) even before the fault is cleared. In the worst case that the rotor winding is shorted and the converter blocks, the fault current contribution will reach peak values of four to six times of rated current before decreasing to zero in about 100 to 200 ms. On most types, however, the blocking of the rotor converter will cause the unit to disconnect from the network within 25 to 100 ms. Therefore, in the modelling it was assumed the positive sequence impedance of the wind turbine generators producing three-phase fault current contribution of six times rated current (6×FLC) for 'make' and one time (1×FLC) for 'break'. The ratio of reactance to resistance for DFIG was assumed to be 50 (X/R=50). Based on IEC 909, the peak factor κ is:

$$\kappa = 1.02 + 0.98e^{-3R/X} = 1.94$$

As the peak value has the following relationship with the initial current according to IEC 909:

$$i_p = \kappa\sqrt{2}I_k''$$

Therefore, considering the rated current for 'make' is 6 times of FLC, the equivalent locked rotor impedance of the DFIG was set as:

$$Z_M = \frac{\sqrt{2}\times 1.94}{6} = 0.46\,\text{pu}$$

It was assumed that the cables connecting between WTGs and between WTGs and collector bus were 1 core 630 mm² aluminum with 35 mm² copper screen cables each with length of 500 meters.

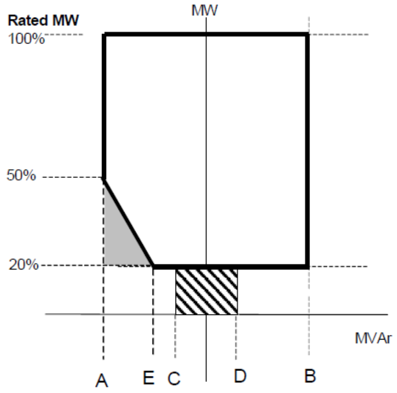
Reactive and Power Factor Capacity Study

Using the latest technologies, even the DFIG wind turbines are not able to maintain the voltage level and power factor capacity required by the network operator. Therefore, a study of reactive and power factor capacity aims to calculate the reactive compensation required at the PCC of the windfarm.

According to the British Grid Code, the wind farms directly connected to the Onshore Transmission System at 132kV must be capable of supplying Rated MW output at any point between the limits 0.95 Power Factor lagging and 0.95 Power Factor 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. 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, and will reduce linearly below 50% Active Power output. The wind farm performance chart is shown in Figure 6. The Reactive Power output of the wind farm under steady state conditions should be fully available within the voltage range ±5% at 132kV. An assumption was made for the study, that at reduced MW output, the power factor only applies at the nominal operating voltage at the PCC.

The maximum rating of the wind turbine is 2.3MW. Considering the loss due to the resistance of the circuit, the rating output of the wind farm at the PCC was calculated as 54.46MW in ERACS. Therefore, the respective points in the performance chart for the wind farm is given in Table 2.

As the wind turbine was modelled as a fixed P and Q load in the loadflow study, the current would be inversely proportional to the voltage. Consequently, the reactive power absorbed by the transformers would increase with the decrease of the voltage. Therefore, in order to examine the worse case the voltage of 0.95pu at PCC was considered for lagging output and that of 1.05pu was considered for leading output. Based on the wind turbine capability listed in Table 1, the wind turbine output and the voltage at PCC for the calculation were tabulated in Table 3.



Point A is equivalent (in MVAr) to: 0.95 leading **Power Factor** at **Rated MW** output
Point B is equivalent (in MVAr) to: 0.95 lagging **Power Factor** at **Rated MW** output
Point C is equivalent (in MVAr) to: -5% of **Rated MW** output
Point D is equivalent (in MVAr) to: +5% of **Rated MW** output
Point E is equivalent (in MVAr) to: -12% of **Rated MW** output

Figure 6: Performance Chart GB Grid Code

Table 2: Grid code requirements of example wind farm

	Rated output %	MVAR	MW
Point A	100%	-17.90	54.46
Point A	50%	-17.90	27.23
Point E	20%	-6.54	10.89
point C	20%	-2.72	10.89
point C	0%	-2.72	0
point D	0%	2.72	0
point D	20%	2.72	10.89
Point B	20%	17.90	10.89
Point B	100%	17.90	54.46

Table 3: Wind turbine output for modelling

	Rated output %	MW	MVAr	PF	Voltage at PCC (pu)
Point A	100%	2.30	-0.35	-0.95	1.05
Point A	50%	1.15	-0.38	-0.95	1.05
Point E	20%	0.46	-0.15	-0.95	1.05
point C	20%	0.46	-0.15	-0.95	1.05
point C	0%	0.05	-0.02	-0.95	1.05
point D	0%	0.05	0.03	0.90	0.95
point D	20%	0.46	0.04	1	0.95
Point B	20%	0.46	0.22	0.90	0.95
Point B	100%	2.30	1.11	0.90	0.95

The blue curve and the pink curve in Figure 7 demonstrate the grid code requirement and the capability of the wind farm at the PCC, respectively.

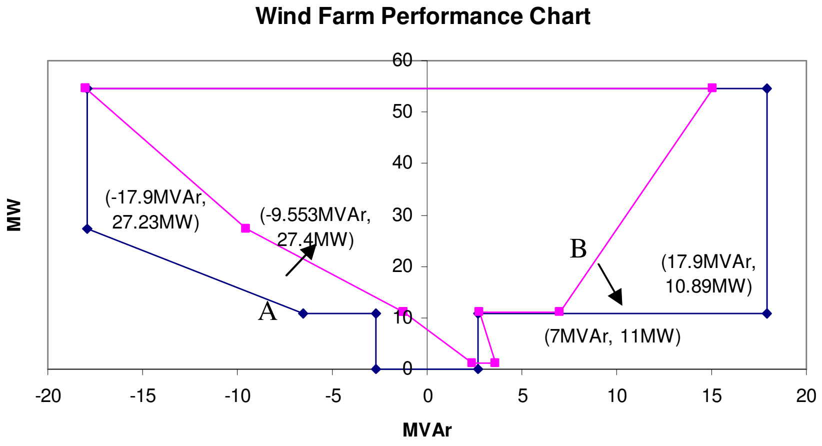


Figure 7: Performance Chart requirements of sample WF as per Grid Code

The maximum differences exist at point A for leading capability and point B for lagging capability. In order to satisfy the grid code, an 8.35MVAr of inductive compensation and a 10.9MVAr of capacitive compensation at PCC are required. If the compensation applied at the 33kV bus, a 0.52MVAr of inductive compensation and a 0.68MVAr of capacitive compensation are requirement.

Harmonics Study

In general there are two ways in which harmonic can be generated by wind turbine generators:

- due to saturation in direct connected electrical machines
- due to harmonic injection by power electronic equipment such as soft start thyristor (as used for induction generators during initial connection) and frequency converters (as used by DFIGS and fully converter connected synchronous generators).

During the design stage of the wind farm collector system, the power plant developer must ensure that there is no adverse harmonic resonance. The Energy Networks Association Recommendation G5/4-1 is normally used as a criterion in the UK.

The Engineering Recommendation introduces the following definitions:

- Calculated Harmonic Voltages, V_{hc}

The calculated voltage distortion expressed as a percentage of the phase voltage at the PCC.

$$V_{hc} = \frac{V_k}{U_N / \sqrt{3}} \times 100\%$$

where V_k is k^{th} harmonic component of rms voltage at the PCC.

- Predicted Harmonic Voltage, V_{hp}

The predicted voltage distortion is the aggregate of the level of distortion already existing on the system and the distortion which is caused by the new equipment.

- Total Harmonic Voltage Distortion, THD

The RMS value of individual harmonic voltages expressed as a percentage of the fundamental RMS voltage, and calculated using the following expression:

$$THD = \sqrt{\sum_{k=2}^{50} V_{hc}^{2}}$$

The Planning Levels for Harmonic Voltage Distortion in Systems >20kV and <145kV which are recommended in the G5/4-1 are tabulated in Table 4. The summary of THD planning levels is tabulated in Table 5.

Table 4: Planning levels for harmonic voltages in systems > 20kV and <145kV

Odd harmonics (Non-multiple of 3)		Odd harmonics (Multiple of 3)		Even harmonics	
Order 'h'	**Harmonic Voltage (%)**	**Order 'h'**	**Harmonic Voltage (%)**	**Order 'h'**	**Harmonic 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 5: Summary of THD planning levels

System Voltage at the PCC	THD Limit
400V	5%
6.6, 11 and 20kV	4%
22kV to 400kV	3%

The harmonic currents based on the nominal current I_n at the MV side of step-up transformer of the WTG are normally measured by manufacturer. Table 6 gives an example of the measurement data. It was assumed that all injections had 0 degree phase angle in the absence of specific phase data.

Table 6: Example data of harmonic emissions for WTG

Order	*Harmonic current (% In)*	*Order*	*Harmonic current (% In)*	*Order*	*Harmonic current (% In)*
2	1.0	**3**	0.5	**4**	0.4
5	1.3	**6**	0.4	**7**	1.1
8	0.2	**9**	0.1	**10**	0.1
11	0.1	**12**	0.1	**13**	0.2
14	0.1	**15**	0.3	**16**	0.1

The nominal current I_n at 33kVe is given by:

$$I_n = \frac{MVA_{WTG}}{\sqrt{3} \times V_L} = 45.45A$$

where MVA_{WTG} is the rating of the wind turbine generator which is 2.598MVA; V_L is the line voltage which is 33kV.

The harmonic current injected from the wind turbines will propagate into the system and react with the network impedance to cause harmonic voltage distortion at PCC. Figure 8 shows the impedance at the collector bus over a range of frequencies. Curve 1 is the impedance when no wind turbine arrays are connected. As the transformer inductance dominates the circuit, the impedance is linear with frequency. Curve 2, 3 and 4 respectively show the harmonic impedances in the scenarios that when one, two or three wind turbine arrays are connected.. Due to the introduction of the cable capacitance, a resonance appears at 16th when only one array is connected, 12th when two of three arrays are connected and 10th when all of three arrays are connected. However, the magnitude of the harmonic impedance deceases with the connection of more arrays. Figure 9 shows voltage magnitude spectrum of the harmonics at PCC for the above three scenarios comparing to the planning levels specified in G5/4-1.

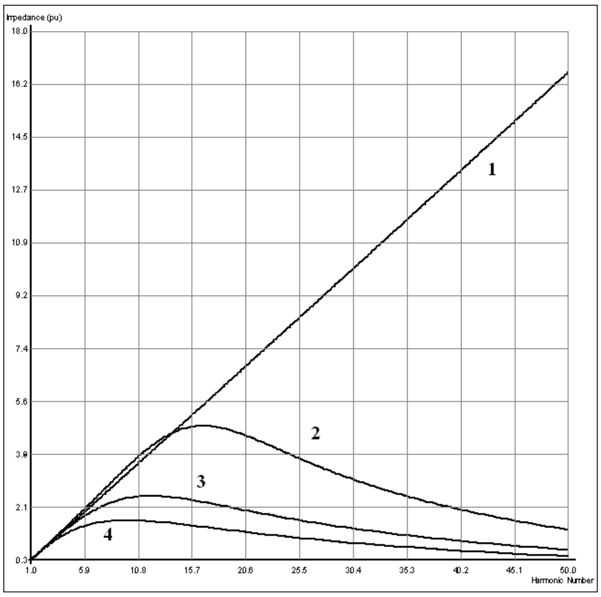


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Figure 8: Harmonic impedance at collector bus

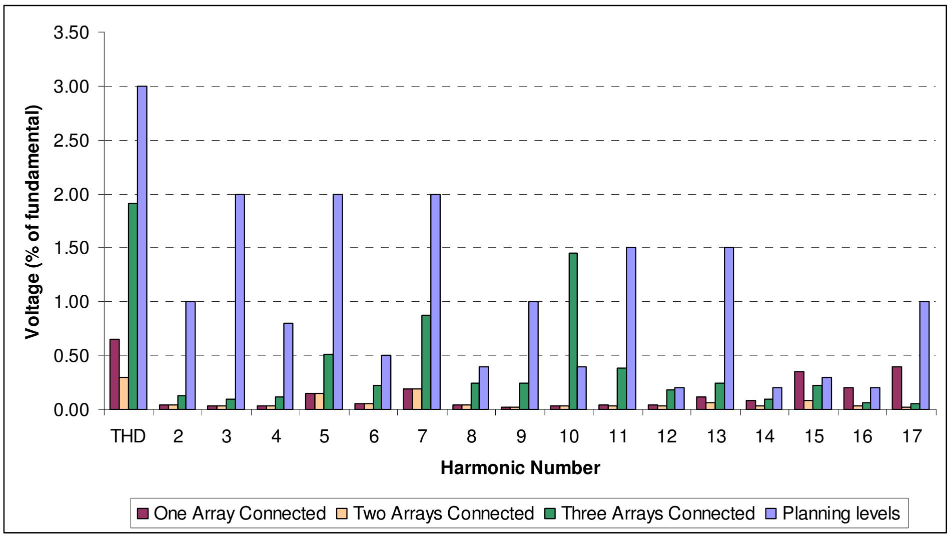

Figure 9: Harmonic voltage magnitude spectrum at PCC

The results show that the harmonics voltage with order 10 exceeds G5/4-1 planning levels when all of the three wind turbine arrays are connected. It also shows that the harmonics voltage with order 15 exceed G5/4-1 planning levels when only one wind turbine array is connected. This is caused by the resonant interaction between the capacitance on underground cables used in wind farm collector systems and the transformer supply inductance. In addition, there may be a potential for voltage magnification if shunt capacitor banks near the wind turbine generators or the collector system were introduced. The harmonic resonance issue can be resolved by judicious cable specification and/or application of filters. If high voltage capacitors are introduced in filters then minimizing switching surges may require synchronously switched breakers, where possible. Alternatively, surge arresters may be applied at the lower voltage capacitors banks to protect them. Thus, during the design of the wind farm electrical system these and other equipment application issue should be reviewed to ensure proper design and integrity of the entire wind farm electrical system.

Conclusion

The result of the study examples is reasonably typical and showed:

- Voltage recovery at PCC following fault clearance;
- Reactive compensation of 8.35MVAr inductive and 10.9MV capacitive required meeting the British grid code;
- Voltage THD and harmonics at order 10 exceed the planning levels due to resonance established by wind farm cable capacitance. This showed cable specification or harmonic filter was design options.

Calculating the performance and regulatory compliance at wind farms require steady state and transient studies be conducted, which can only be feasibly achieved using power systems analysis software.

Loadflow and fault calculation can be achieved using equivalent steady state generator models. The flexibility to enter wind farm and grid topology and network parameters is important.

The harmonic study in this paper shows harmonic compliance is dependent on not only on the number of turbines operating and the power level, but also the configuration of the distribution circuits that are selected at any given time.

Fault ride-through requires that validated models of the wind turbine dynamics be supplied by the wind turbine manufacturer. The software must be compatible with the format of the data presented by the manufacturer. It is in the interests of end users that this data be compatible with the range of commercially available power system analysis software to encourage competitive study pricing from consultants.

Reference:

[1] THE GRID CODE, Issue 4 Revision 2, 22nd March 2010

[2] Wind Power Integration: Connection and System Operational Aspects (Power & Energy), ISBN 978-0-86341- 449-7, published by the Institution of Engineering and Technology, London, United Kingdom, 2007

[3] I. Erlich and U.Bachmann, Grid code requirements concerning connection and operation of wind turbines in Germany, in *Proc. IEEE Power Eng. Soc.* General Meeting, Jun. 2005, pp.2230-2234.