Technical Requirements of Connecting Wind Farms to the Egyptian Grid Based on the Wind Farm Grid Connection Code

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Introduction

The objective of this article is to provide the basic information on the technical design specifications and criteria, technical terms and equipment parameters appeared in the wind farm grid connection code. For example, power quality issues, their cause and impact on the system performances, as referred to in the codes, will be discussed and explained. The technical specifications include permitted voltage and frequency variations in addition to power quality measures such as limits of harmonic distortion, phase unbalance, and flickers. Wind turbine generating unit operational limits, capability requirements, active power and frequency control, reactive power and voltage control, power factor, etc. will be explained and discussed. The article provides an updated summary of invited tutorials on codes presented at national and international conferences [1]-[3].

CONTENTS

1- WIND ENERGY IN EGYPT

According to the latest annual report (2022) of the New and Renewable Energy Authority (NREA), the capacities of installed, under construction and under development wind energy projects are listed in Table 1 [4].

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Table 1- Capacities of wind farms in Egypt

Project Place	**545**	**Governmental**	**Installed**
Zafarana	**580**	**Governmental**	**Installed**
Gulf of El-Zayt	**262**	**Private**	**Installed**
Ras Ghareb	**250**	**Private**	**Installed**
West Bakr	**252**	**Governmental**	**Under Construction**
Gulf of Suez	**1100**	**Private**	**Under development**
Gulf of Suez	**200**	**Private**	**Under development**
Gulf of Suez	**3 × 500**	**Private**	**Under development**
Gulf of Suez	**545**	**Governmental**	**Installed**

The total installed capacity of wind farms is 1637 MW, the capacity of the projects under construction is 252 MW, and the total capacity of the projects under development is 2800 MW. Figure 1 shows the target energy mix in the year 2035. The share of wind energy in 2035 will be 12%. Renewable share will reach 42%.

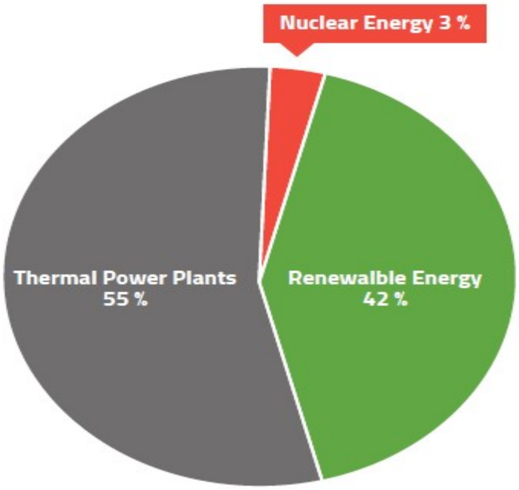

Fig. 1- Target energy mix in the year 2035 [4]

Figure 2 shows the wind velocity at potential locations in Egypt [4]. Many locations, especially the Gulf of Suez area, are attractive for projects of wind farms

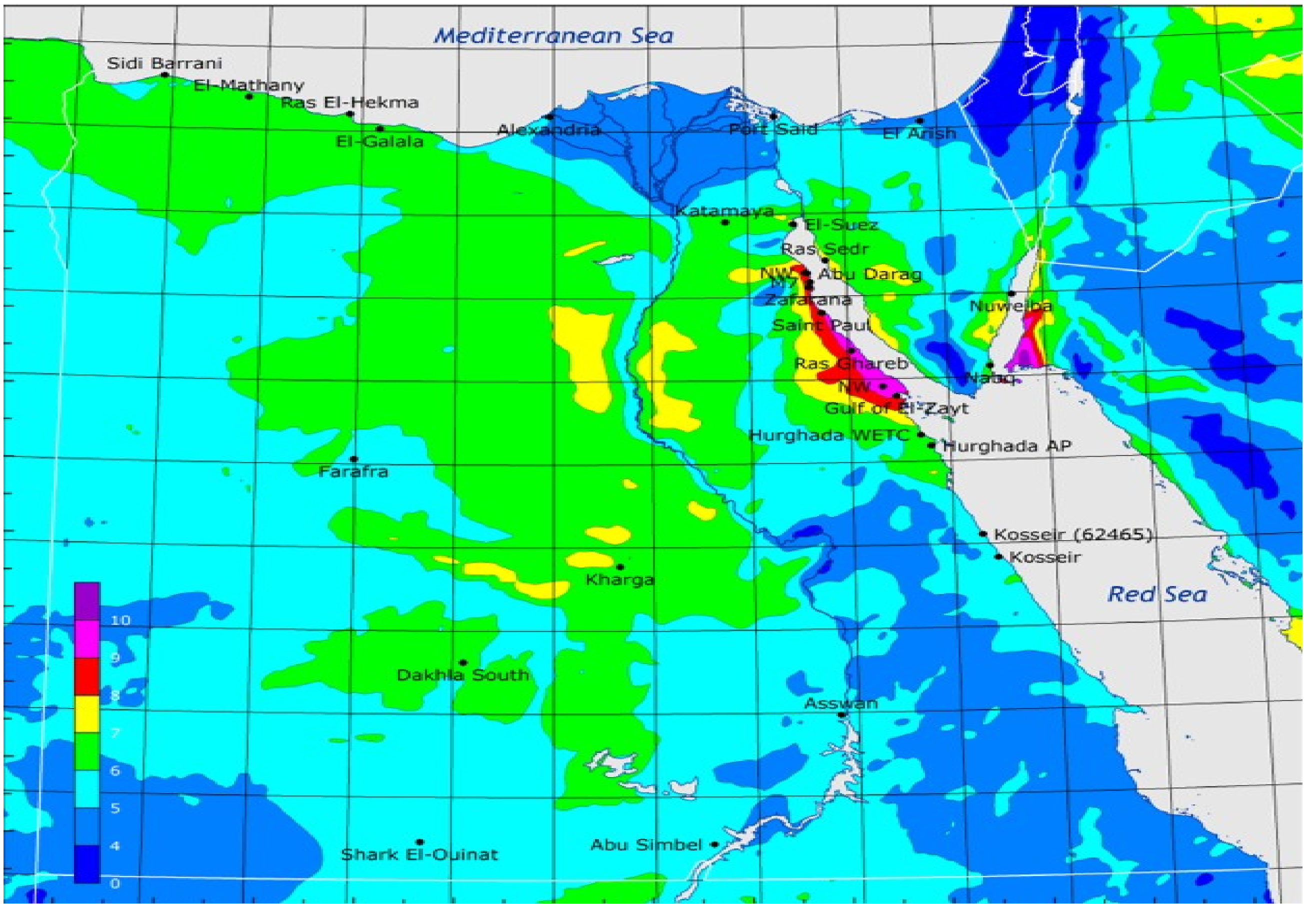

Fig. 2- Wind velocity Atlas in Egypt [4]

2- TYPES OF WIND TURBINES

The main types of wind turbine construction are the horizontal-axis and vertical-axis types as shown in Figure 3 and Figure 4 respectively.

Fig. 3- Horizontal-axis wind turbine in a wind farm [4]

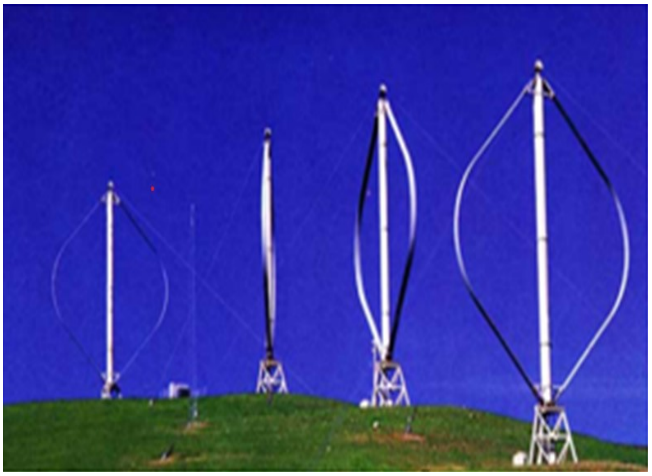

Fig. 4- Vertical-axis wind turbine in a wind farm

Figure 5 shows an offshore wind farm [5] which is installed in seas in some places around the world.

Fig. 5- Offshore wind farm [5]

3 – TYPES OF WIND-DRIVEN ELECTRIC GENERATORS

A review on the development of wind-driven electric generators across the world is presented in [6]. These include fixed-speed and variable-speed generators. Main types are squril-cage induction generators, doubly-fed induction generators and sychrounous generators. Details are also described described in [7]. Figure 6 shows the arrangemet of variable-speed wind-turbine system using a synchrounous generator supplying the generated electric power through a full-converter system [7]. Figure 7 shows the doubly-fed induction generator system. The stator is directly connected to the grid through a transformer, while the rotor is connected via a power converter [7]. Figure 8 shows the power/speed curve of atypical wind turbine system [8]. Steady-state analyses of isolated self-excited induction generator are presented in [9], [10].

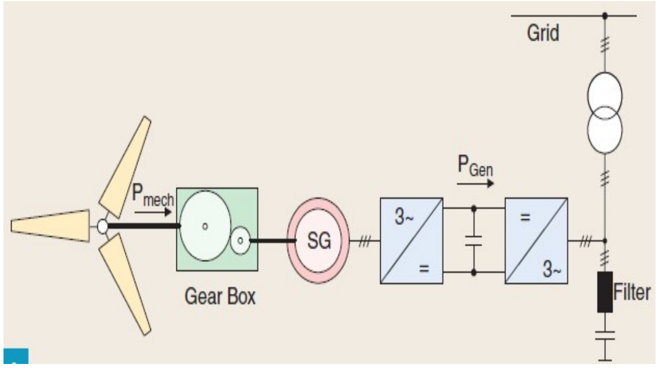

Fig. 6- Synchronous generator type [7]

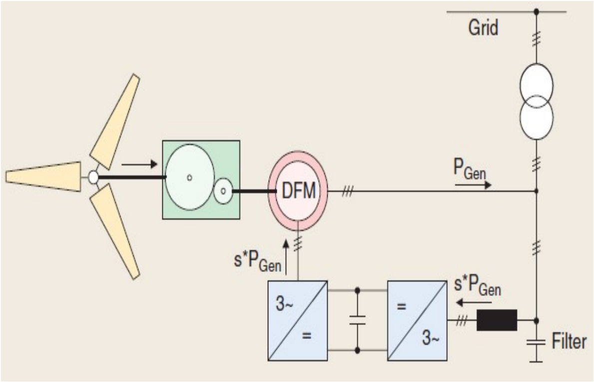

Fig. 7- Doubly-fed induction generator system [7]

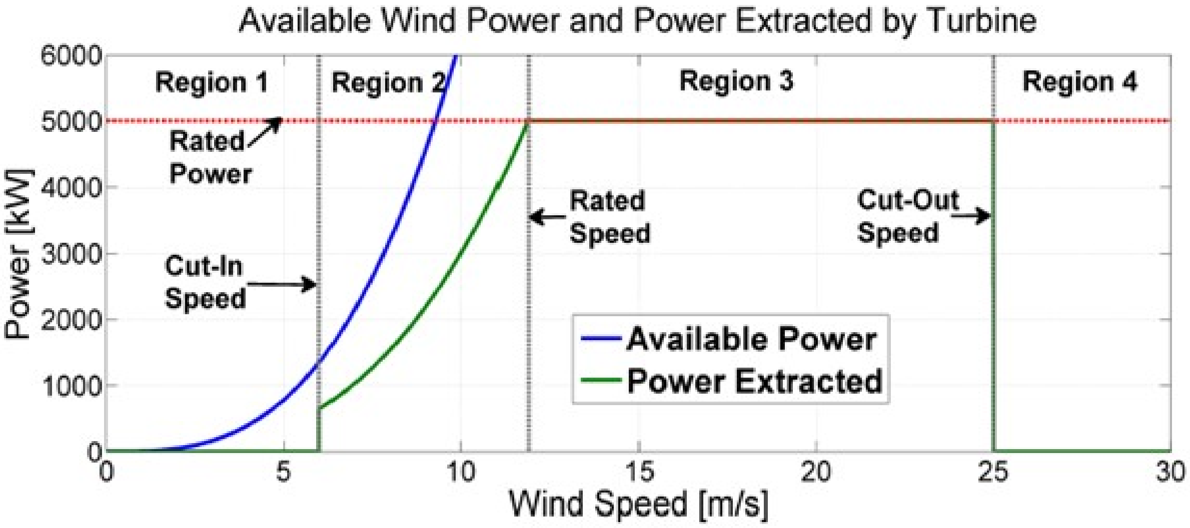

Fig. 8- Wind power, turbine power, and operating regions for an example 5 MW turbine [8]

4- ANALYSIS OF WIND CONVERSION SYSTEMS

This section provides a brief review of analysis, stability and control of wind conversion systems. Small-disturbance stability of wind turbine systems is investigated in [11], [12]. Studies of blade pitch control of a wind-turbine generator system are described in [13]. Simulation and experimental studies of wind energy conversion systems using asynchronous generator are presented in [14], [15]. Adaptive control of a wind driven induction generator is explored in [16]. State feedback controller of a wind driven synchronous generator is developed in [17]. Simulation and experimental studies of fuzzy logic controller for maximum power extraction from wind energy conversion system are performed in [18]. Modeling and control of a wind farm and electrolyzer system connected to an electrical grid are described in [19]. Long-term and short-term uncertainties of high share wind energy are considered in generation expansion planning [20]. Aggregation of a wind farm model for grid connection planning studies is presented in [21].

5- GRID CODE

A grid code [22], [23] is a document that contains a set of rules and procedures to regulate technical and legal relationship between a Transmission System Operator (TSO) and users of the transmission grid. The objective is to establish the obligations and responsibilities of each party; i.e. the TSO and all grid users. The objective is to maintain optimal operation, safety and reliability of the power system. A useful tutorial on technical background of the grid code of the Egyptian power grid is explored in [3].

A- Purpose of the Grid Code

The Egyptian Transmission System Code (ETSC) or "Grid Code" sets out the relationship between the TSO and transmission system users which include:

- Generation companies,
- Distribution companies, and
- EHV/HV customers directly connected to the transmission system

It imposes obligations on all parties [25] to ensure the safety, efficiency and security of the transmission system while ensuring that all users are treated equally and fairly.

B- Section One: Data Code

This section lists and collates all the data to be exchanged between each category of users and the TSO under the grid code and to identify the sections of the grid code under which each item of data is required. The procedures and schedules for the submission of that data for updating and recording temporary or permanent changes to that data are specified in the section in which the data is required.

C- Section Two: Connection Code

This section specifies the minimum technical, design and operational criteria at each connection point and to ensure that the basic rules for connection to the grid are nondiscriminatory for all users of the same category.

D- Section Three: Testing Code

This section defines the coverage of testing and monitoring to be conducted. Specifies the requirements, conditions, schedules, duration, frequency and type of tests. It specifies the procedures to be followed in coordinating, carrying out tests as well as evaluation of results. Also, it sets rules for the testing of ancillary service providers relative to their committed services.

E- Section Four: Protection Code

This section defines the minimum protection requirements for any equipment connected to the transmission system to minimize disruption due to faults.

F- Section Five: Performance Code

This section ensures the quality of electric power and the operation of the transmission system in a safe and efficient manner with a high degree of reliability and specifies safety standards for the protection of personnel in the work environment.

G- Section Six: Planning Code

This section specifies the planning requirements to be met by the TSO in planning and developing the transmission system. It also defines the requirements for all users to exchange data and information with the TSO so that TSO can discharge its planning obligations.

H- Section Seven: Operation Code

This section specifies the responsibilities and obligations of the TSO and all users related to grid operation planning (up to day-ahead) and to coordinate and integrate planned maintenance programs. It also identifies the requirements for the exchange of information between the TSO and users so that prompt action can be taken to maintain the integrity of the grid under different conditions.

I- Section Eight: Metering Code

This section establishes the requirements for metering the active and reactive energy input to and output from the grid, and ensures accurate and prompt procedures for providing and processing metering data for billing and settlements.

J- Section Nine: Scheduling and Dispatch Code

This section set the rules and procedures for scheduling and dispatch of generating plants under normal and emergency conditions in the timescales from day-ahead to real-time.

K- Section Ten: Wind Code

This section provides the requirements for wind generation, including the specific requirements for induction generators used by wind generators.

6- WIND FARM GRID CONNECTION CODE

The Wind Farm Grid Connection Code [24] (WFGCC) specifies the special requirements for the connection of wind farms to the power grid. The wind farm grid connection code and the grid code are two complementary documents that govern the integration of wind farms with the grid. Technical terms of these codes should be clearly understandable by all parties to correctly implement the rules and procedures described in the codes. Technical background on the WFGCC was presented in [1], [2].

A - Objective of the WFGCC

The objective of the wind farm grid connection code is to ensure that any new or modified wind farms, when established, shall neither suffer unacceptable effects due to its connections to the grid nor impose unacceptable effects on the grid.

B- Scope of the WFGCC

The wind farm grid connection code shall apply to wind farms that are connected to the grid after March 2014. Replacement of and radical changes in existing wind turbine generators shall be considered as new units. All changes relating to the properties of wind turbine generators mentioned in the wind farm grid connection code shall basically be considered as essential. The grid operator shall determine whether changes are essential.

C- The Point of Common Coupling (PCC)

The point of common coupling is the point where all wind turbine generators of a wind farm are connected to the grid. Figure 9 shows the PCC.

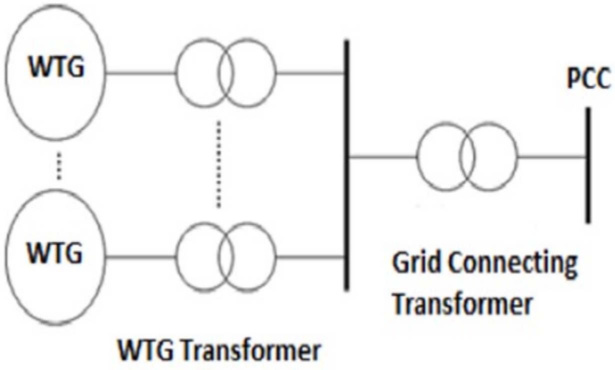

Fig. 9- Point of common coupling of a wind farm connection to the grid

D- Typical Connection of a Wind Farm

Figure 10 shows a typical connection of a 50 MW wind farm to the 132 kV grid in Dhofar area in the Sultanate of Oman [26]-[28]. The point of common coupling with the grid is shown at the upper 132 kV busbar. The wind farm consists of twenty 2.5 MW wind turbine generating units. Grid impact study of the first wind farm project in Dhofar transmission system is presented in [26]. Grid code compliance for integrating 50 MW wind farm into Dhofar power grid is described in [27]. Power quality of Dhofar network with 50 MW wind farm connection is presented in [28].

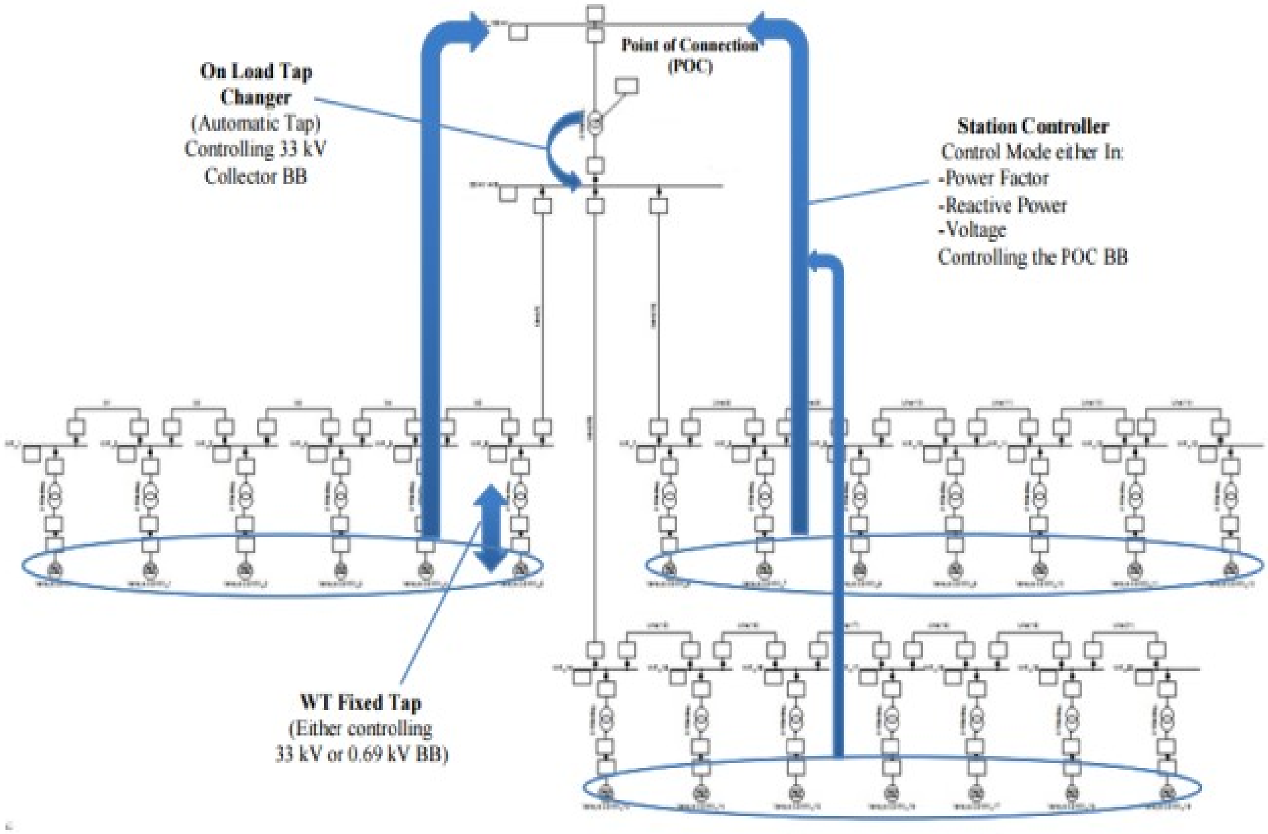

Fig. 10- Typical layout of a 50 MW wind farm [26]-[28]

7- Voltage and Frequency Ranges

A- Voltage Range at the PCC

The wind farm shall be able to deliver available active power according to wind conditions when the voltage at the PCC remains within the ranges specified in Table 2. Any automatic disconnection of the wind farm from the grid shall be prohibited due to the deviation within the voltage ranges.

Table 2- Voltage range of wind farm operation

Voltage Range	Period for Operation
0.85 pu – 0.90 pu	Unlimited
0.90 pu – 1.10 pu	Unlimited
1.10 pu – 1.15 pu	30 minutes

B- Frequency Range of Wind Farm

The frequency range of wind farm is 47.5 Hz to 51.5 Hz. Any automatic disconnection of the wind farm from the grid shall be prohibited within this frequency range.

8- ACTIVE POWER CONTROL

The wind farm is not allowed to reduce output power within the frequency range of 47.5 Hz up to 50.2 Hz due to variations in the grid frequency or in the grid voltage at the grid connection point for the time periods given in Figure 11.

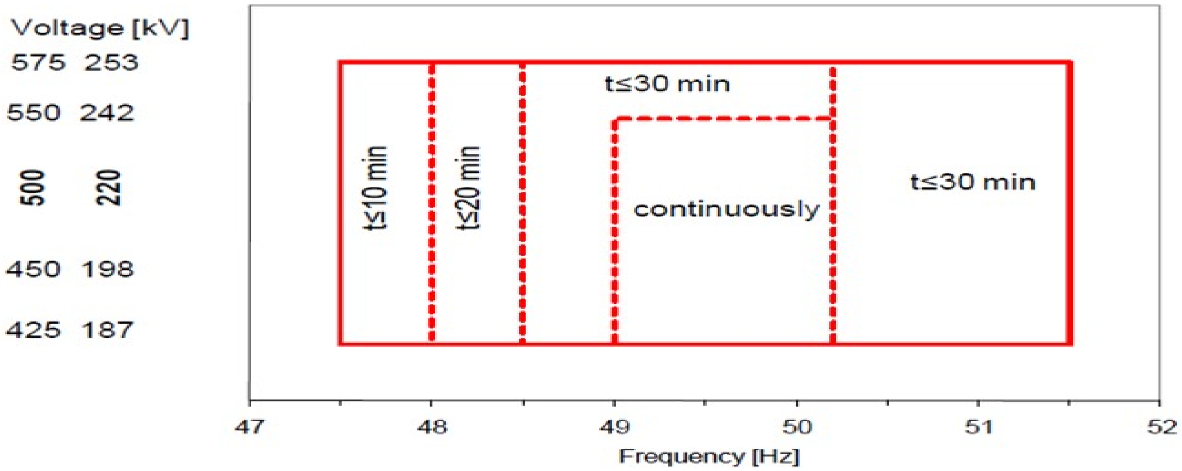

Fig. 11- Voltage and frequency ranges of wind farm

A- Active Power Reduction due to Over-Frequency

For grid frequencies in the range from 50.2 Hz to 51.5 Hz the wind turbine generators of the wind farm have to reduce active output power with a rate of 40% of actual active output power per Hertz, as shown in Figure 12. The following equation shows power reduction as the frequency increases above 50.2 Hz.

$$\Delta P = 0.4 \times \mathrm{Pout} \times \Delta f \qquad (1)$$

where

ΔP is the change in power, Δf is the change in frequency and P_{out} is the output power.

B- Start-Up of the Wind Farm

During the start-up of the wind farm or of the wind turbine generators of the wind farm the increase of the active power shall not exceed 10% of the rated power of the wind farm per minute.

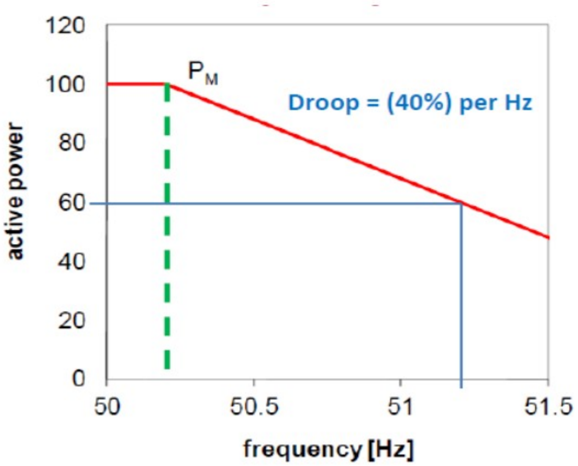

Fig. 12- Active power control

C- Conditions for Connection

The wind turbine generators of the wind farm shall only connect to the grid (start-up), if the frequency and the voltage at the grid connection point, or the PCC, are within the following limits:

Frequency: 48 Hz ≤ f ≤ 50.2 Hz

Voltage: 0.95 p.u. ≤ U ≤ 1.05 p.u.

9 - REACTIVE POWER CONTROL

The wind farm must be able to control reactive power as follows:

1- Set-point control of reactive power Q
2- Set-point control of power factor (cos φ)
3- Fixed power factor (cos φ)
4- Characteristic: power factor as a function of active power output of the wind farm, cos φ (P)
5- Characteristic: reactive power as a function of voltage, Q(V)

The mode of operation of reactive power control will be determined by the grid operator in the connection agreement.

A- P-Q Diagram

Figure 13 shows the capability chart of the wind farm as specified in the WFGCC. The limits of reactive power are shown. At rated active power the wind farm shall be capable to operate with power factor of 0.95 lag to 0.95 lead.

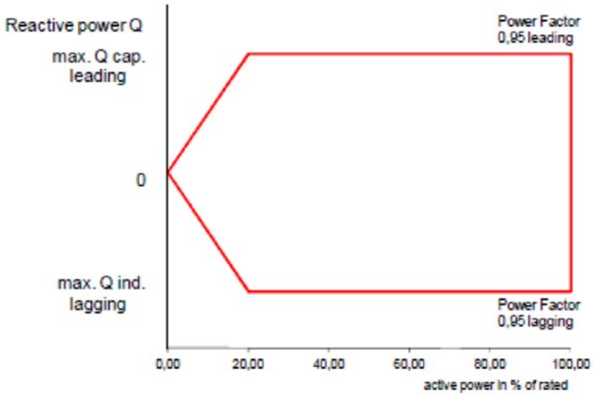

Fig. 13- P-Q capability chart of wind farm

B- Reactive Power Example

Figure 14 shows a case of incompliance of a 50 MW wind farm. Studies have shown that the wind farm owner needs to install a 4 MVAr mechanical switched capacitor bank or higher rating [26], [27] to overcome this incompliance problem.

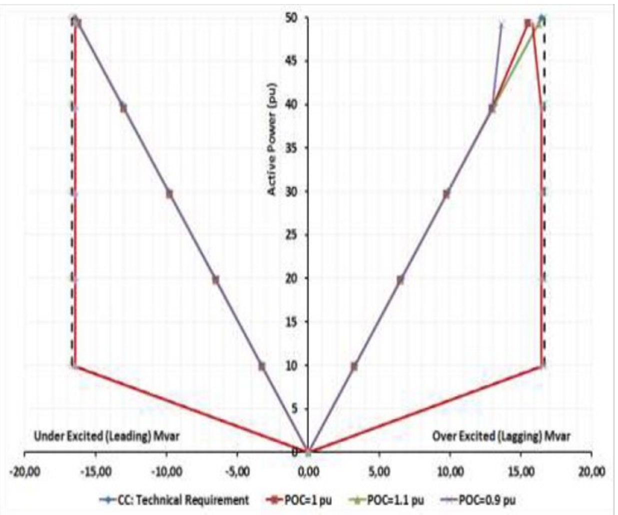

Fig. 14- Reactive power incompliance

10- FAULT RIDE-THROUGH (FRT) OF WIND TURBINE GENERATORS

In case of grid faults resulting in short voltage drops, the WFGCC requires that wind turbine generators have to ride-through the grid fault without disconnection from the grid. As shown in Figure 15, where at least one of the three phase-to-phase voltages is above the red curve, wind turbine generators should not disconnect.

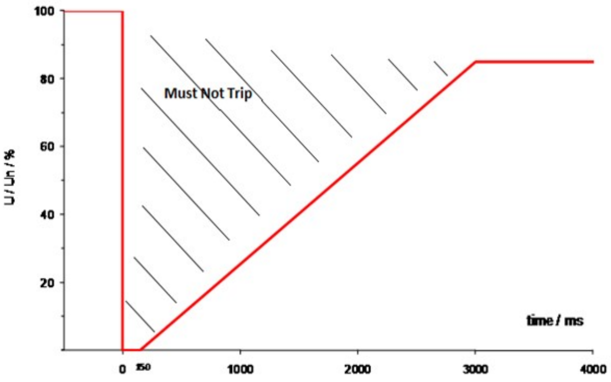

Fig. 15- Fault-ride through of wind farm

A- FRT of Different WFGCC Codes

Figure 16 shows the fault ride-through required in wind farm connection codes in various countries

[29]. All curves start at 1.0 pu voltage, but have different voltage dips and restoration times.

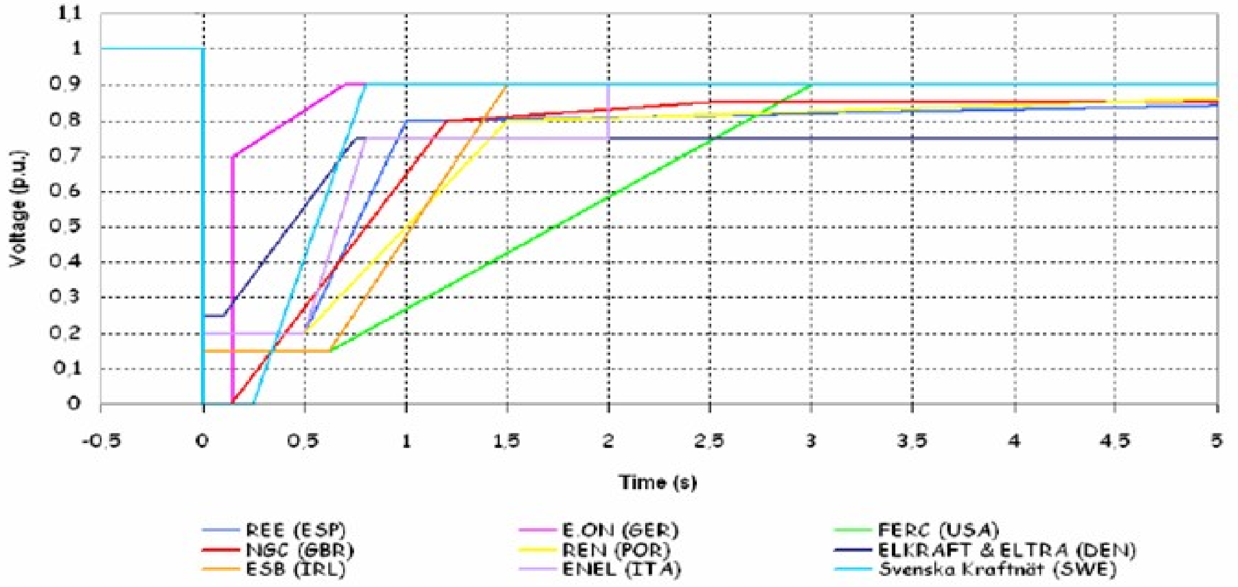

Fig. 16- FRT in different wind farm codes [29]

B- FRT Example

Figure 17 shows simulation results of a fault at the practical 50 MW wind farm [26], [27] having doubly-fed induction generators. The voltage at the PCC (green curve) is above the red curve required by the wind farm connection code in the Sultanate of Oman. The wind farm successfully rids-through the fault without disconnection from the grid. Additional requirements in temporary voltage drops are discussed in the next section.

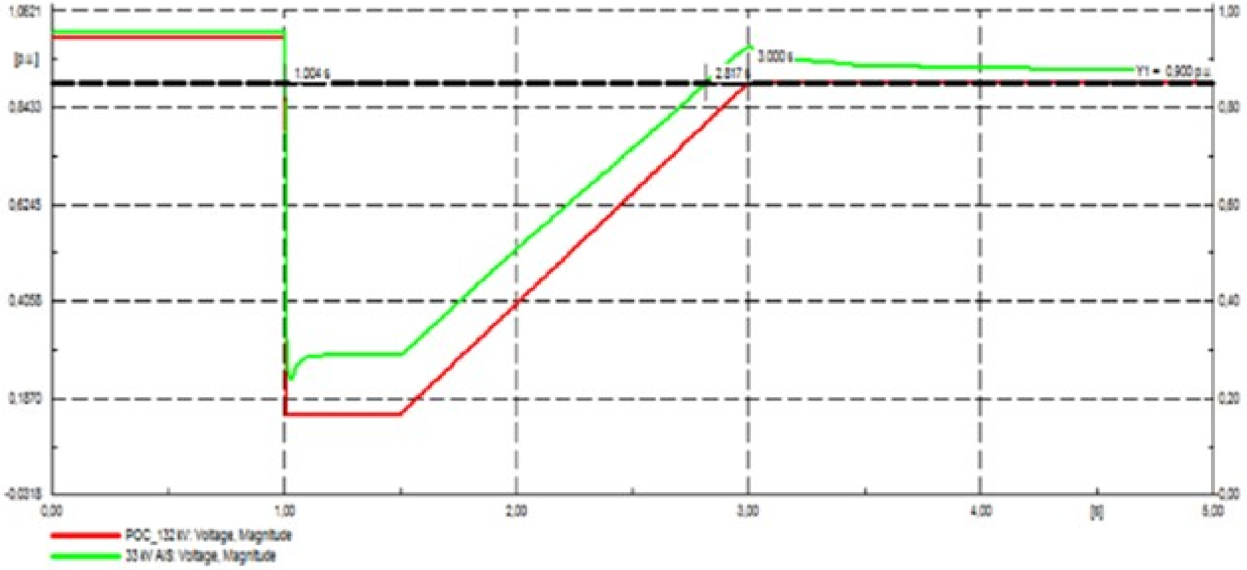

Fig. 17- Wind farm complince in case of 3-phase fault

11- TEMPORARY VOLTAGE DROP

During the temporary voltage drop wind, turbine generators must fulfill the following requirements concerning reactive power or reactive current:

A- Three-phase Faults

For 3-phase faults, the wind generators must inject reactive current according to Figure 18 and equations (2) and (3) for the time period 150 ms after the beginning of the fault until fault clearance.

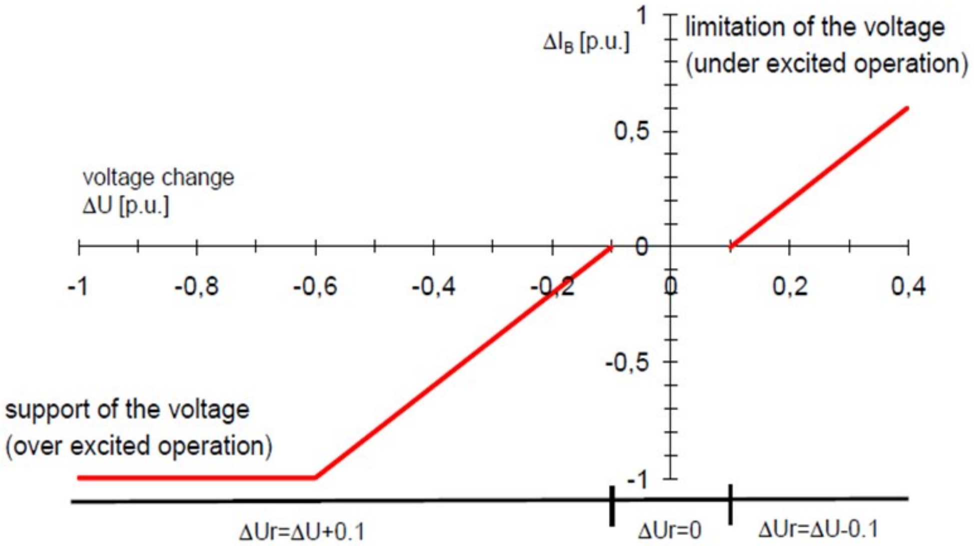

Fig. 18- Reactive current injection of wind farm

$\Delta I_B = k \times \Delta U_r$ (2)

ΔI_B = reactive current to be injected (p.u.)

k = constant (0 – 4), preferably = 2

U_r: relevant voltage change

$\Delta U = U - U_o$ (3)

U = Voltage during fault

U_o = Voltage before fault

B- Two-Phase and Single-Phase Faults

For 2-ph or 1-ph faults for all wind turbine generators the following are required:

During the time period 150 ms after the fault occurrence until fault clearance:

- the consumption of reactive power must be below 40 % of rated power of the wind turbine generator, and

- the consumption of active power must be below 30 % of rated power of the wind turbine generator in each grid cycle (20 ms).

After fault clearance the active power output of the wind farm must reach the same level as before the fault within a time period of 10 s after fault clearance. After fault clearance, the consumption of reactive power of the wind farm must be equal or below the consumption of reactive power before the fault.

C- Temporary Voltage Drops due to a Non-Successful Auto-Reclosure

In case of non-successful auto-reclosures two successive temporary voltage drops can occur. The WFGCC requires that the wind turbine generators have to ride-through both temporary voltages drops as shown in Figure 19.

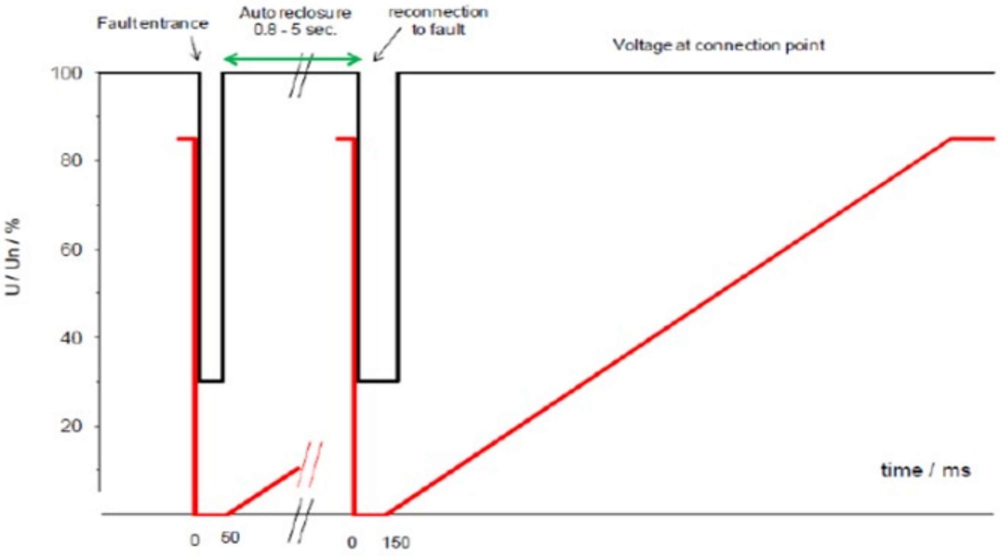

Fig. 19- Non-successful auto-reclosures case

12- HARMONIC DISTORTION IN WIND FARMS

A- Maximum Level of Harmonic Voltage Distortion

Table 3- Limits of harmonic voltage distortion

Voltage Level (kV)	Level of Harmonic Voltage Distortion (%)	
	Odd Harmonics	Total Harmonics
> 161	1.0	1.5
> 69 to ≤ 161	1.5	2.5
Up to 69	3.0	5.0

B- Maximum Level of Integer Harmonic Current Distortion in Frequency Range up to 2 kHz

Table 4- Limits of harmonic current distortion*

Short Circuit Ratio	Maximum Integer Harmonic Current Distortion as Percentage of I_L					
	Odd Harmonic Distortion					TDD
I_{SC}/I_L	<11	≥11 to <17	≥17 to <23	≥23 to <35	≥35	
< 50	2.0	1.0	0.75	0.3	0.15	2.5
≥ 50	3.0	1.5	1.15	0.45	0.22	3.75

*Notes on the Table 4:

I_{sc}: The maximum short circuit current at the PCC

I_L: The maximum load current (fundamental frequency component) at the PCC

The maximum level of even harmonics is 25% of odd harmonics.

Although the Tables 3 and 4 in the WFGCC are based on the old IEEE 519-1992 [30], but it is recommended to use the new version of this standard, i.e. IEEE 519-2014 issued in 2014 [31].

For the maximum level of harmonic current distortion in the frequency range above 2 kHz and for the maximum level of interharmonic current distortion up to 2 kHz, see the tables in the WFGCC [24].

C- Impact of Harmonics on Equipment and Systems

Linear loads draw currents proportional to applied voltages. Examples of linear loads are incandescent lighting, heating and similar loads. Non-linear loads draw current only a part of the voltage cycle. Examples of non-linear loads are computers, adjustable speed drives, etc. The resulting current from nonlinear loads contains 3rd, 5th, 7th, etc. harmonics. Harmonic currents permeate into the source casing harmonic currents. Source currents having harmonic content impact source voltage.

D- Problems Caused by Harmonic Currents

Currents within the Installation

* Overloading of neutral

* Overheating of transformers

* Nuisance tripping of circuit breakers

* Over-stressing of power factor correction capacitors

* Skin effect

Voltages within the Installation

* Voltage distortion & zero-crossing noise
* Overheating of induction motors

Harmonic currents in the supply

Harmonic currents flowing back into the supply cause harmonic voltages that spread around the network. Suppliers limit the level of harmonic current that a user can allow back onto the supply network.

Effect on Transformers

Transformers supplying harmonic loads must be appropriately de-rated. Harmonic currents, being of higher frequency, cause increased magnetic losses in the core and increased eddy current and skin effect losses in the windings. Triple-n harmonic currents circulate in delta windings, increasing resistive losses, operating temperature and reducing effective load capacity.

13- VOLTAGE FLICKER AND FLUCTUATIONS IN WIND FARMS (IEC61000-3-7)

A- Flicker Limits of Wind Farms

The flicker, caused by the wind farm at the PCC, must be within the following limits:

* Short term: $P_{st} \leq 0.35$

* Long term: $P_{lt} \leq 0.25$

where

P_{st} is the short-term flicker factor over time periods of 10 minutes

P_{lt} is the long-term flicker factor over time periods of 2 hours

The indicator P_{st} having a value of 1 represents the level of visual severity at which 50% of people would perceive flicker in 60 W incandescent bulb.

B- Voltage Flicker Definition

If loads such as arc furnaces cause variation in the distribution bus voltage which has a spectral characteristic which lies between a fraction of a Hertz and about one third of the system frequency, this condition is called flicker.

Flicker is a characteristic where a high frequency (ω_o) sinusoid is modulated by a low frequency sinusoid (ω_f). Mathematically,

$$v(t) = \left(1 + V_f \cos(\omega_f t)\right) V_m \cos(\omega_o t) \qquad (4)$$

Side-band frequencies of ($\omega_o \pm \omega_f$) will be present.

The intensity of flicker may be given by,

$$F = \frac{V_f}{V_m} = \frac{S_{scf}}{S_{sc}} \qquad (5)$$

where

S_{scf} = short-circuit kVA at electrode tip

S_{sc} = short-circuit kVA at the PCC

Perceptibility of flicker depends on V_f and ω_f.

C- Measuring Flickers

The IEC has developed a flicker meter which measures flickers in terms of fluctuating voltage magnitude and its corresponding frequency of fluctuations. It uses a software technique to convert flicker voltage fluctuations into the following two statistical quantities:

* Short-term flicker severity (P_{st})

* Long-term flicker severity (P_{lt})

The flicker meter takes measurements automatically at 10-minuts intervals. The short-term flicker severity is calculated every 10 min. The indicator P_{st} having a value of 1 represents the level of visual severity at which 50% of people would perceive flicker in 60 W incandescent bulb. The long-term flicker severity (P_{lt}) is a combination of 12 P_{st}.

D- Voltage Fluctuations

The voltage fluctuations in a wind farm can occur because of the switching operations (capacitor banks, wind turbine generator start/stop), inrush currents during wind turbine generator starting etc. The maximum voltage fluctuation is 5% from the voltage nominal value.

14- VOLTAGE UNBALANCE IN WIND FARMS

Voltage unbalance may be defined as the deviation between the highest and lowest line voltage divided by the average line voltage of the three phases. Wind farms shall be able to withstand voltage unbalance not exceeding 2%.

Figure 20 shows unbalanced voltages in a three-phase system.

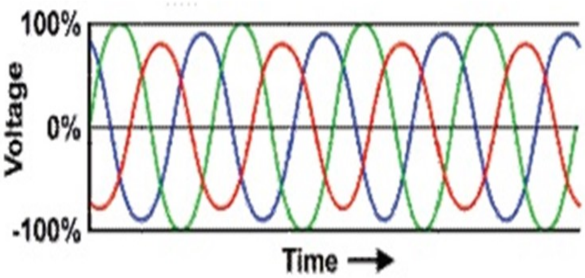

Fig. 20- Unbalanced three-phase voltages

A 3-phase power system is called balanced if the three phase voltages (and currents) satisfy the following conditions:

- They have the same amplitude, and
- They are phase shifted by 120^{o} with respect to each other

If either or both of these two conditions are not met, the system is called unbalanced.

A- Measure of Unbalance

$$\begin{bmatrix} V_0 \\ V_1 \\ V_2 \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix}\begin{bmatrix} V_A \\ V_B \\ V_C \end{bmatrix} \qquad a = e^{j120} \qquad (6)$$

$$V_{0U}\% = \frac{V_0}{V_1} \times 100 \qquad (7)$$

$$V_{2U}\% = \frac{V_2}{V_1} \times 100 \qquad (8)$$

Standards: EN-50160 IEC-61000-3-x

B- Limits of Unbalance

* The EN-50160 & IEC-61000-3-x series explore

the unbalance.

* Voltage unbalance ratio:

$V_{2U} < 1\%$ For HV

$V_{2U} < 2\%$ For MV & LV

* Measured as 10-minute average value with an instantaneous maximum of 4%

* No current unbalance limits are given

C- Causes of Unbalance

* Generators and transformers

* Unbalanced impedance of long, non-transposed low voltage lines

* Unbalanced load currents single-phase loads on three-phase systems

* Embedded generation

D- Effects of Unbalance

Motors

* Reduced torque

*Bearing wear

* Excessive heating leading to lower efficiency

Transformers

* Excess heat in delta windings

* Negative sequence transformed normally

Equipment Capacity

* RMS current includes ‘useless’ negative sequence currents

* Additional losses in cables etc.

* Affects protection settings

Electronic Power Converters

Generate harmonics leading to problems.

15- GRID PROTECTION SETTINGS

The grid protection of the wind farm shall be performed according to the protection code of the grid code. The settings of the grid protection device in the wind turbine generators of the wind farm must conform to Table 15, unless agreed otherwise with the grid operator in the connection agreement. Table 5 lists the setting of the grid protection at the wind turbines generators.

Table 5- Protection settings

Function	Setting Range	Recommended Settings	
		Level	Settling time
Over voltage U≥	1.00 – 1.30 U_n	1.2 U_n	≤ 3 s
Under voltage <	0.10 – 1.00 U_n	0.8 U_n	3 s
Under voltage ≤	0.10 – 1.00 U_n	0.3 U_n	300ms – 1 s
Over frequency	50.0 – 52.0 Hz	51.5 Hz	≤ 100 ms
Under frequency	47.5 – 50.0 Hz	47.5 Hz	≤ 500 ms

16- REAL-TIME CONTROL IN WIND FARMS

The grid operator shall be able to submit control signals to the common control system of the wind farm according to the connection agreement. The wind farm operator has to follow the grid operator's instructions and he has to decide which specific wind turbine generator (or generators) has (have) to be manipulated (load change, switch off) in order to achieve the desired (power) values at the interface to the transmission system.

17- SOLAR PLANTS GRID CONNECTION CODES

IN EGYPT

In addition to the wind farm grid connection code presented in this article, there are similar codes for connection solar power plants to the grid in Egypt. These are:

1- Technical Requirements for Connecting Small Scale PV (ssPV) Systems to Low Voltage Distribution Networks [32].

2- Solar Energy Plants Grid Connection Code - In addition to the Egyptian Transmission Grid Code and The Egyptian Distribution Network [33].

Technical background and studies on these solar systems grid connection codes are available in [34]-[39].

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