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Power quality problems related with the interconnection of wind farms to the electrical grid: A survey

Emmanuel Hernández[1], Jesús A. Cela[2], Reynaldo Iracheta[3], Efraín Dueñas[4]

[1,3,4] Research-Professor, Universidad del Istmo, Av. Universitaria s/n, Tehuantepec, Oaxaca. 70760, México
[2] P.G. Student, Universidad del Istmo, Av. Universitaria s/n, Tehuantepec, Oaxaca. 70760, México

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Abstract - *In recent years, wind farms began playing an important role in the framework of renewable energies. The increase of such wind farms interconnected to the electrical grid is an important factor that must be considered due to the effects on power quality that can be derived from it; at the same time, wind farms can be affected by power quality problems from the electrical grid. In this regard, this paper describes how wind farms interconnected to the electrical grid affect the power quality and how these in turn can be affected by faults from the electrical grid. This paper shows the most representative solutions that have been addressed in several works to counter these problems.*

***Key Words**: Wind farm, renewable energies, electrical grid, power quality.*

1. INTRODUCTION

It is well known how the world has become deeply dependent on electricity, in such way that problems with the electricity supply can trigger other problems. Problems that range from data loss, damage to certain electrical device or equipment (critical loads), to commercial problems and even economic problems. Situations highlight the importance of ensuring, as far as possible, not only the availability and continuity of the electrical energy, but also, its quality.

The power quality has become a concept widely used in recent years due to the increase of sensitive loads, the proliferation of nonlinear loads and switching devices and, above all, to a greater awareness of the consequences associated with the use of electrical energy of poor quality [1]. Many problems related to the power quality are originated in the electrical grid, since it extends through thousands of miles of transmission lines it is subject to factors like: climatological conditions, the distribution components quality, the type of loads connected to it (e.g. nonlinear loads as switching devices), the operating condition of all of the energy sources, conventional or not, which provide energy to the grid, etc. [2]. The term "power quality", or more specifically, a disturbance in the power quality refers to a wide variety of electromagnetic phenomena that characterize the voltage and current at a given time interval and at a specific point in the electrical system [3]. In addition, the negative effects have become obvious, mainly to the environment that can be caused by the use of non-renewable energy sources (oil, gas and coal). Added to this, the fact cannot be discounted that these energy sources can sometimes get scarce or even used up completely. In this sense, wind energy is the more attractive energy source since it is abundant, clean and its use is feasible for the generation of electricity from the economical point of view. Recently, the wind farms interconnected to the electrical grid have grown exponentially due to technological advances in areas such as power electronics, electric machines and wind turbines. Since 1998, the total wind power capacity installed worldwide has submitted an annual average growth rate of 30% [4]; it is worth noting that most installed wind power capacity has taken place in the past five years. Due to these new installations, companies dedicated to the energy sector have faced new problems, mainly related to the reliability of the power supply and the quality of it. For this reason, many research works have focused their attention on these two main problems derived from the integration of wind farms to the electrical grid, proposing new alternatives and control approaches that contribute to improve the power quality and deal with these problems. Now, the fact that there are wind farms interconnected to the electrical grid is not synonymous of power quality problems and much less that the wind farm is the source of the power quality problems.

2. POWER QUALITY PROBLEMS OF WIND FARMS CONNECTED TO ELECTRICAL GRID

The power quality depends on the interaction between the wind farms and electrical grid. In addition, wind farms interconnected to the electrical grid do not only affect the power quality of grid, this last one can also affect the power quality of the entire wind farm. The power quality problems, in relation to the wind farms interconnected to the electrical grid can be tackle from two fundamentals perspectives:

a. *Power quality problems in electrical grid side.*
b. *Power quality problems in wind farm side.*

2.1. Power quality problems in electrical grid side

The electrical grid experiments a large number of power quality problems; in [3] are listed six categories of power quality problems in electrical power systems, those are transients, short and long duration rms variations, imbalance, voltage and current waveform distortions, voltage fluctuations and power frequency variations. Power quality problems can be cataloged in two main categories in relation with the characteristic of the disturbance [5]:

Steady state disturbances: The steady state disturbances refer to variation of the voltage or current of their nominal value, besides the distortion and the degree of balance between phases. In this category are included imbalance, waveform distortions and voltage fluctuations.

Transient disturbances: These are characterized by a voltage and current abnormal level; a transient disturbance can be detected when a maximum or minimum magnitude exceeds a specified threshold. In this category are included transients, short and long duration *rms* variations and power frequency variations.

On the other hand, it is well known that poor power quality in the electrical grid mainly affects the loads connected to it and even to the power generation plants. In this respect, wind farms interconnected to the electrical grid are not excluded of experiment the negative effects of some power quality disturbances from the electrical grid. According to [6-9], the most significant power quality problems in the electrical grid that affect the wind farms are the voltage harmonics and short duration *rms* variations – sags.

2.1.1 Voltage harmonics

The wind turbine is conformed by a transformer, the rotating machine and the turbine where the most common rotating machine used is the doubly fed induction generator (DFIG). The DFIG, as a fundamental part of a Wind Energy Conversion System (WECS), are interconnected to the electrical grid through the stator terminals of the machine; this configuration contains a three-phase wound rotor induction machine fed from the stator and the rotor windings as shown in Figure 1. Typically, wind farms are located in remote areas, at the end of the transmission lines, where the electrical grid is often weak and may contain harmonics of lower order and interharmonics components [7]. It has been shown that the spectral components that are present in the stator current at multiples of the fundamental frequency are mostly results from the voltage distortions of the electrical grid [11, 14]. Similarly, it was shown that this observed current is slip dependent and this relation of frequencies can be calculated through a set of analytical expressions. Besides, the harmonic components have different gains and different behaviours in relation to the rotor speed.

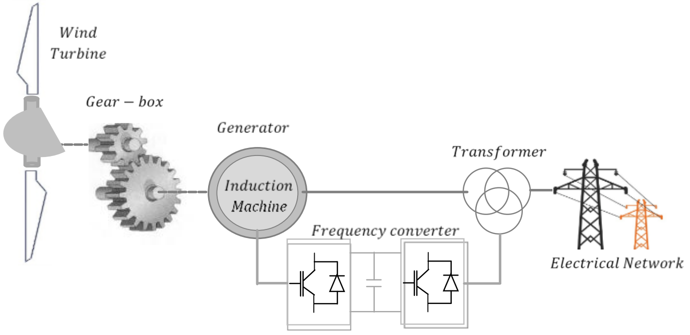

Fig -1: Configuration of the DFIG interconnected to the grid.

Therefore, the induced rotor voltage harmonic distortion is different from in the stator. This effect is more serious in the case of unbalanced stator voltage, which is very common in practical electrical grid. The stator current harmonics will create components of the magnetic field that rotate at a different speed from the fundamental speed resulting in undesired torque or power pulsations which may increase fatigue on the mechanical components; also can result in fluctuations in the dc bus voltage, reducing the reliability of converter as well as life time. Furthermore, these harmonics may also increase the core and copper losses (skin effects) reducing the generator efficiency. The inaccuracy in the control of active power and/or reactive is another problem that can occur. In this scenario, several control approaches have been implemented to reduce the presence of the main undesirable voltage harmonics from the electrical grid, such as the 5th, 7th, 11th and 13th order components [15]. On the other hand, in [10, 11, 16-18] have been proposed various control methods to remove the stator current harmonics in the presence of voltage harmonics content from the electrical grid.

2.1.2. Short duration rms variations – sags.

Short-duration voltage variations are usually caused by fault conditions, the energization of large loads, which require high starting currents or intermittent loose connections in power wiring. Depending on the fault location and the system conditions, the fault can cause temporary voltage rises (swells), voltage dips (sags), or a complete loss of voltage (interruptions). A sag is a decrease in rms voltage to between 0.1 pu and 0.9 pu for durations from 0.5 cycles to 1 minute [3]. In particular, the WECS based on DFIG are very sensitive to the voltage sag from the electrical grid, due to the stator is directly connected to the electrical grid; thus, the DFIG shows little ability to overcome sags and is necessary to consider control actions to prevent that a disturbance of this nature takes out of service to the WECS. Some of the negative consequences that the WECS based on DFIG experience in the presence of voltage sag are severe oscillations of the stator flux. The negative sequence and dc components in the stator flux have a large slip with respect to the rotor, which induces an electromotive force (EMF) in the rotor circuit, thus the machine behaves as a voltage source in series with the transient inductance and the rotor resistance as shown in Figure 2. In order to avoid losing the current control and considering no-control actions to prevent disturbances, the frequency converter should be sized to be able to deliver a voltage equal to the maximum supply voltage, i.e., a voltage similar to the stator rated voltage. Nevertheless, this would imply a frequency converter with a rated power similar to the generator, losing therefore one of the main advantages of this kind of power conversion device.

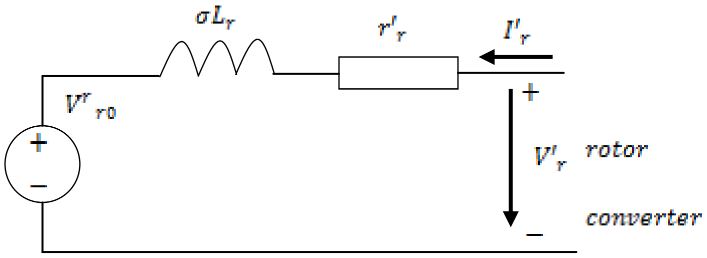

Fig -2: Equivalent circuit considering the behavior of the machine as a voltage source.

If the frequency converter is sized for a voltage lower than the voltage presented in the rotor terminals, the rotor current will remain uncontrolled transitorily. In this way, the overcurrent will depend on both the maximum value of the voltage that can generate the converter and the rotor transient inductance and resistance. These elements often have a small value, and therefore high overcurrent's are likely to appear and can eventually destroy the rotor side converter (RSC) if not protective measures are employed. On the other hand, another consequence of voltage sag is the increasing of the dc bus voltage due to the overcurrent flows to the dc link capacitor through the flywheel diodes of the RSC. All these sets of negative affectations lead to the DFIG to have an acceleration and torque pulsations since there is an imbalance between the power delivered to the electrical grid and the mechanical input power [12, 20-24]. Worth mentioning that when the voltage sag is present, the negative consequences appear mainly in initial stages and the end of the fault period, that is, the stages of the voltage sag start and the voltage recovery, occurring maximal torque, rotor current and dc bus voltage in the last one. Taking in account the description of undesired behaviors of the WECS variables in the presence of voltage sag, it is difficult to deal with voltage sags form the electrical grid just by implementing a control approach applied to the RSC. In the past, when a WECS had to deal with a voltage sag, the solution implemented by the operators of the WECS was to short-circuit the rotor terminals and disconnect the WECS from the electrical grid; the above in order to protect the frequency converter of overcurrent's and overvoltage's derived of such temporal voltage variation [20,25]. However, due to the high penetration of wind systems that are currently interconnected to the electrical grid, many countries have revised their grid codes and established new requirements for high availability and stability of electrical power systems. One of these requirements stipulates that WECS must provide LVRT capability, which means that the WECS must remain connected to the grid within a certain voltage range and for a period; even should provide a certain amount of reactive power to the system [21, 24]. Figure 3 shows an example of a typical LVRT requirement. The voltage vs time curve describes the minimum requirement of WECS immunity in the Point of Common Coupling (PCC), namely when the voltage at the PCC is above the LVRT curve (white area) the WECS must remain connected and should only disconnect from the electrical grid if voltage takes values below the curve. Several LVRT strategies have been developed in the literature in order to prevent damage and disconnection of the WECS during voltage sags as well as, in some cases, make the WECS provide support to the grid by supplying reactive power to the system. In this context, there are two perspectives to improve LVRT capability of a WECS: implementing protective measures outside the WECS [26, 27] and implementing control alternatives directly to WECS [28, 29]. The outer protective measure most commonly used to increase the LVRT capability is the Flexible AC Transmissions Systems (FACTS); a description of the contributions of different types of FACTS used to improve LVRT capability in the WECS is exposed in [26, 27]. On the other hand, in relation to control alternatives directly implemented in WECS, there are three basic solutions that can be distinguished in literature: the active crowbar circuit rotor [30, 31], the dc bus energy storage circuit [32-36] and the rotor current control through control of the machine flux [21,37-39].

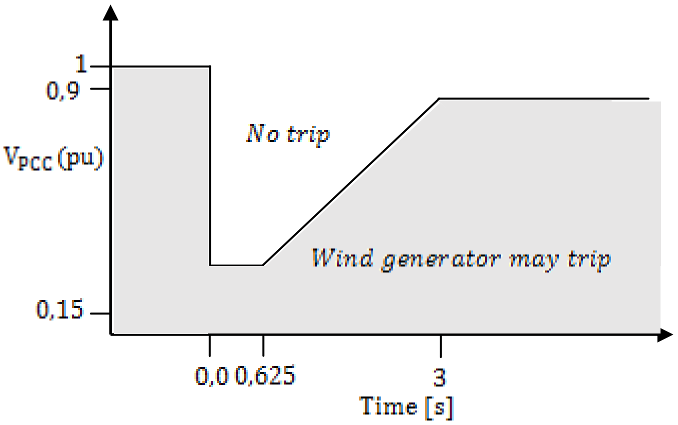

Fig -3: Example of typical LVRT requirement.

2.2. Power quality problems in wind farm side

It is necessary to remember that the WECS interconnected to the electrical grid are not only affected by the poor power quality, but they can also possibly affect the power quality in the electrical grid. There are a variety of disturbances in power quality, however, the disturbances that play a crucial role in the WECS interconnected to the electrical grid are: voltage variations (flicker), frequency variations and harmonics propagation [40-42].

2.2.1. Voltage fluctuations and flickers

The voltage fluctuations in the electrical grid are caused mainly by varying loads and by the energy production units. For its part, the amount of energy from the WECS may vary due to the different aerodynamic effects like the wind speed (turbulence), the tower shadow effect, the yaw error, misalignment and the wind gradient [43,44]. Tower shadow effect is produced owing to the wind turbine tower offers resistance to the wind flow and it disturbs wind flow. Far from the tower, influence wind speed is constant, while it increases when approaches the tower and decreases when coming closer. On the other hand, the wind speed gradient also produces torque oscillations along the size of the area covered by the blades. Some other effects that affect the power fluctuation may appear, for example, drive-train oscillations, the tower resonance, the emergency momentary stoppages (where the wind turbine goes from full production to a stop) and the starts with wind gusts at high speed. Because of all these issues the torque up to 20% of the mean value, in order of three times per revolution for a three bladed wind turbine. This frequency is normally referred to as 3*p*. Thus, power variations are in the region of 0.05 to 42 Hz and in a time interval of the order of 10 seconds, minutes or more (systematic fluctuations), or until very small as a fraction of a second (random fluctuations). The torque oscillations produce power fluctuations at PCC and in consequence voltage fluctuations too. In this way, it must be clear that the voltage fluctuations depend on the parameters of the wind, the turbine characteristics and the electrical grid parameters, such as short circuit capacity ratio (SCR) or X/R ratio [45]; however, power fluctuations depend of all of these factors except of the electrical grid parameters.

Voltage fluctuations are commonly called flicker, the flicker is defined as the visual impression of the fluctuation in brightness or color, which occurs when the frequency of the observed variation is between a few hertz and the frequency of image fusion, according to the Standard Dictionary of Electrical and Electronic Terms of IEEE (IEEE standard 100-1977). Previously, the flicker was considered a problem exclusive of power quality lighting loads, but now we know that it can affect other loads such as motors, electronic systems, and process controllers, among others [46]. In this context, flicker can become a limiting factor for connecting wind turbines at weak grids and even on relatively strong grids with a great amount of wind power connected. A flicker measurement at the PCC can be done to evaluate the flicker contribution from the WECS to the electrical grid; but doing the measure at the PCC has the disadvantage of measuring not only the contribution of the flicker produced by the WECS, but also the flicker contribution caused by others producers and consumers connected to the same PCC. For this reason, the flicker emission evaluation of a wind turbine is based on current or power measurements instead of voltage measurement. The flicker level can be measured either by the short-term flicker severity (Pst) or by long-term flicker severity (Plt). The choice of using one or the other lies in the particular working cycle of each source of flicker. The Pst is appropriate for evaluating individual disturbance sources with a short duty cycle, as in the case of WECS, and is measured in a time interval of ten minutes. Moreover, if there is a scenario where there are loads operating randomly (e.g. motors, welding machines) or loads with long and variable working cycles (such as arc furnaces), the Plt is more suitable and this is measured in a time interval of two hours. The design and operation of the flicker meter are specified in IEC Standard 868. One way to describe the relationship between the voltage variation, the grid impedance, the active and reactive power is through the analytical method. It uses a simple impedance model, which is shown in Figure 4, where VN is the nominal voltage of the grid, VPCC is the voltage at PCC, P and Q is the active and reactive power produced by the WECS respectively, Rg and Xg are the grid resistance and reactance, ΔV is the voltage droop over the grid impedance and Ig is the generator current. The expression (1) describes mathematically this relationship and from this once, it is evident that the voltage at PCC depends, among other parameters, on the active and reactive power.

$$V_{PCC} = R_g \frac{P}{V_N} + X_g \frac{Q}{V_N} + V_N \tag{1}$$

In the same sense, the voltage across the transmission line can be approximated with the following expression [45, 47]:

$$ZI_g = \Delta V = \frac{PR_g + QX_g}{V_N} \tag{2}$$

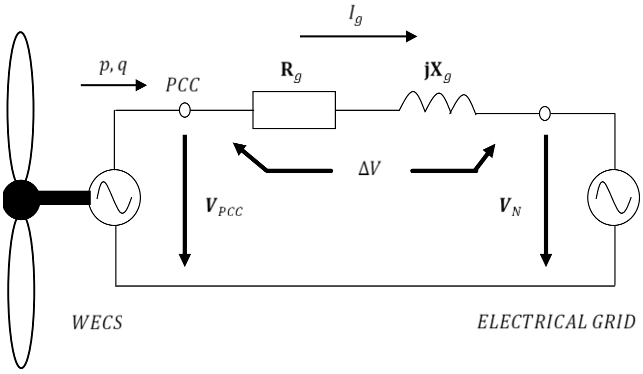

Fig -4: Representation of a WECS interconnected to the grid.

And taking into account to φk= *tan*$^{-1}$(Xg / Rg) as the grid impedance angle and φ= *tan*$^{-1}$ (Q / P) as the power factor angle, the equation (2) can be expressed as:

$$\Delta V = \frac{PR\cos(\varphi - \varphi_k)}{V_N \cos\varphi \cos\varphi_k} \tag{3}$$

The grid impedance angle has a crucial importance due to the voltage fluctuations and can be canceled by the appropriated flow of reactive power. The determining factor is the difference between the grid impedance angle and the power factor angle, which is operating the WECS.

A reduced voltage fluctuation and consequently a reduced level of flicker are obtained when the angle difference between the grid impedance and the angle power factor approximates to 90 degrees [45, 48]. WECS based on Synchronous Cage Induction Generator (SCIG) absorbs reactive power from the electrical grid while it is generating active power; for this type of WECS, the minimum flicker emission occurs at a grid impedance angle between 60 to 70 degrees [45], this configuration is shown in Figure 5. This scenario becomes different in the case of WECS based on DFIG, which is capable of controlling the output active and reactive power; commonly, the power factor in the output of a WECS remains close to a unity power factor, which means that the reactive power delivered or consumed by the WECS is almost zero. In this case, the value of the grid impedance is the factor, which affects the flicker emission from the WECS; when the grid impedance angle increases, the grid impedance decreases which results in reduced flicker emission. For its part, the relationship between the Short Circuit Capacity Ratio of the electrical grid and the short-term flicker severity is almost inversely proportional. This relationship also applies for the WECS based on DFIG. The higher the short circuit capacity ratio, the stronger the grid where the WECS is connected and is expected that WECS would produce greater levels of flicker in weak grids than in stronger grids. However, for a wind farm, each WECS may experience different instantaneous wind speeds, which results in different levels of active power in terminals of each WECS. Thus, the reactive power for each WECS also will be different. Therefore, it is inappropriate to represent wind farms using models built, so each WECS must be included as a separate module in the modeling of the complete system. Additionally, worth noting that power measurement from a single wind turbine usually shows a large fluctuation of output power.

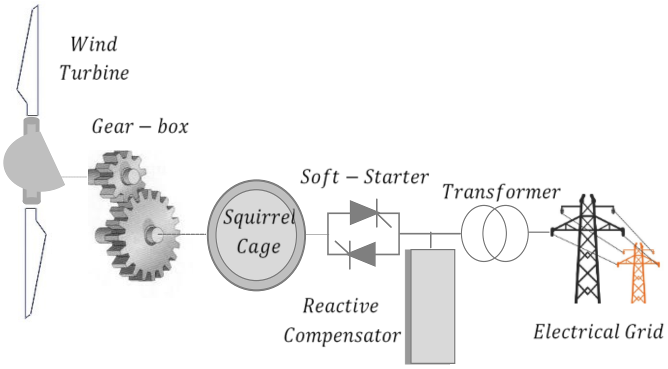

Fig -5: Configuration of synchronous cage induction generator interconnected to the electrical grid.

Because many turbines are connected in a wind farm, the power fluctuation from one turbine may cancel that of another, which effectively rectifies the power fluctuation of the overall wind farm [54]. However, an important point to consider is that when the wind speed is high and the angle of the grid impedance is low, it is difficult to mitigate flicker only by reactive power compensation [43].

Considering this limitation, in [52, 55] the incorporation of an ESS based on a supercapacitor is proposed. The base for this approach lies in the fact that in the presence of flicker, the dc bus also fluctuates. It is important to note that the addition of an ESS to the dc bus achieves to counter the negative effects of two problems of power quality: flicker and sags [29, 32]. Whatever the solution adopted, the flicker emission of a WECS based on DFIG will be mitigated when the difference of the angles φ-φk is controlled to be close to 90 degrees [45].

2.2.2. Current harmonics and resonance

The harmonic emissions are recognized as a power quality problem for modern WECS based on DFIG. Understanding the harmonic behavior of this kind of WECS is essential in order to analyze their effect on the electrical grids where they are connected. Taking into account that the rotor terminals of the DFIG are accessible, the rotor is fed by a variable frequency (f_r), variable magnitude three phase voltage generated by a RSC. This AC voltage injected into the rotor circuit will generate a flux with a frequency f_r if the rotor is standing still. When the rotor is rotating at a speed f_m, the net flux linkage will have a frequency f_r+f_m. When the wind speed changes, the rotor speed f_m will change and in order to have the net flux linkage at a frequency 60 Hz, the rotor injection frequency should be adjusted [56]. Thus, the stator current harmonics are mainly due to the operation of the RSC, and the rotor circuit harmonics depend on the switching of the Grid Side Converter (GSC), but their frequency is modulated by the operating slip of the generator; usually sinusoidal pulse width modulation (SPWM) is used to generate three phase sinusoidal rotor voltage. In order to reduce the switching losses, a six step switching technique is used resulting quasi-sine waveforms in rotor voltages [57, 58]. In addition, the induced frequencies in the rotor, due to the harmonics in the stator, are not harmonics of the rotor fundamental frequency and vice versa. However, it is important to mention that the harmonic frequencies of both, stator and rotor, will significantly affect the harmonic content of the current and voltage signals of the rotor and stator, and this will induce, with respect to WECS, speed ripple. This is because the change of operating condition will affect the interaction between a harmonic current and the fundamental magnetizing current, which gives rise to a pulsating torque. As the operating point changes, the damping effect of the generator to the speed ripple will also change [58]. In perspective, these harmonic conditions in the WECS also provide to the electrical grid a poor power quality. To solve the problem, the harmonics should be eliminated in the rotor supply voltage. This can be achieved either by modifying the switching strategy of the rotor supply inverter, using an active filter to reduce or eliminate the rotor harmonics or implementing a control strategy to minimize rotor current harmonics and its consequences in the variables of the WECS [56, 59].

On the other hand, most WECS use full or partial power electronics converters and they are not a significant source of harmonic injection by themselves due to all the harmonic emission that are below the limits imposed by the grid codes. Even if harmonics are within limits, they can be of significant concern when system resonance frequency is close to these harmonic frequencies [60]. The integration of WECS to the electrical grid will result in additional capacitance, which in turn will result in new harmonic resonances and in the shift to lower frequencies of harmonic resonances. The increase in capacitance comes in three forms:

- Capacitor banks for power-factor correction at the terminals of induction generators and/or at the PCC,
- Medium-voltage cables in the collection grid and
- Long high-voltage cables connecting large wind parks with the sub transmission or transmission grid [61].

One main objective of a harmonic analysis is to characterize the potential of the wind collector system for series and parallel resonance conditions. Series resonance problems are characterized by series inductance and capacitance driven by background harmonic voltages from the grid (see Figure 6). Series resonance point are identified by dips in the frequency scan on the high side of the interconnect transformer. The relatively small impedances at the series resonance points can result in high harmonic currents. Series resonance is a condition when a low impedance is seen at resonant frequency, producing high voltage distortion even in installations with a low emission. This voltage distortion might damage the electrical equipment installed in the same bus, such as capacitor banks. The high harmonic currents through the transformer may also result in overheating of the transformer or cause an unwanted trip of the transformer protection [62, 63]. Parallel resonance points magnify voltages and are identified by peaks in the driving point impedance on the medium voltage side of the transformer (see Figure 7). Parallel resonance concerns occur when wind turbine harmonic current sources excite resonant point (relatively high impedances) resulting in significant harmonic voltages. In other words, parallel resonances are associated with high impedance at harmonic frequencies resulting in high voltage distortion at the terminals of emitting loads, as in the case of WECS, or other installations; this voltage increase leads to a large harmonic current through the capacitor banks. Worth noting that potential problems due to harmonic resonance occur, more frequently than the problems directly related with problems due to harmonic emissions. This confirms that the main harmonic concern with wind farm installations is not their emissions, is their contribution to harmonic resonances. Thus harmonic resonance analysis is a vital part in the planning and operation of WECS inter-connected to the electrical grid. Several resonance analyses with different capacity of capacitor banks and operation modes have been studied by calculation and simulation in the literature, like in the case of [63, 64].

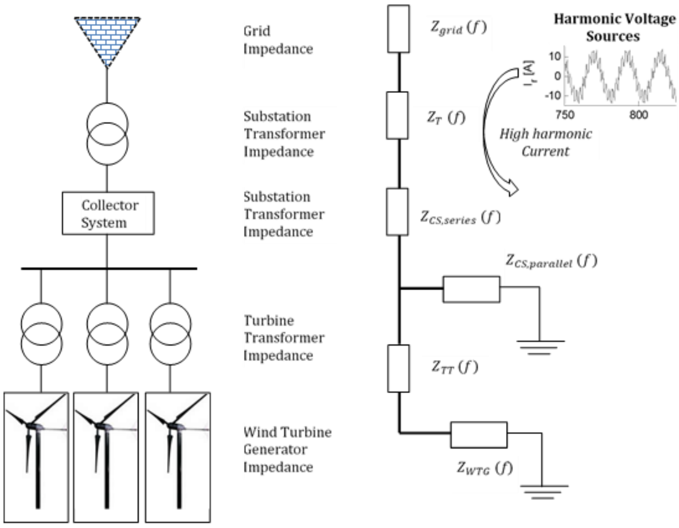

Fig -6: Illustration of series resonance in a wind power plant.

2.2.3. Frequency variation

Frequency control is essential for safe and stable performance in any power system. In past years, the majority of the available electrical power was generated from synchronous machines. The addition of synchronous generation to an electrical system inherently increases the inertia response of the system, which translates into an increased robustness. Nowadays, electrical systems face an increased penetration of WECS based on DFIG; this results in a reduction of inertia on the power system or, put another way, in a reduction of rotating mass "seen" by electrical grid. This is because the control system of the DFIG decouples the mechanical and electrical systems, avoiding in this way that DFIG responds to changes in system frequency. In this regard, increasing the WECS based on DFIG interconnected to the electrical grid; significantly affect the frequency regulation and system robustness regarding disturbances. Currently, Denmark, Ireland and Spain are among countries that are facing this problem of power quality due to the high penetration of WECS interconnected to their electrical systems [65].

Nevertheless, given the latest technological advances in relation to the increment of WECS control capacities, these have been allowed to participate in the frequency control, providing increased robustness of the electrical grid to which they are interconnected, making sure wind energy penetration can be carried out safely. According to the literature, there are two general approaches to support the frequency control, these are: the control of inertia, which uses the kinetic energy stored in the rotor of the DFIG [66-69]; and the primary frequency control (control deloaded), which is based on the fact of move the optimal operation point if the WECS and thereby exploit the kinetic energy now available [69-72].

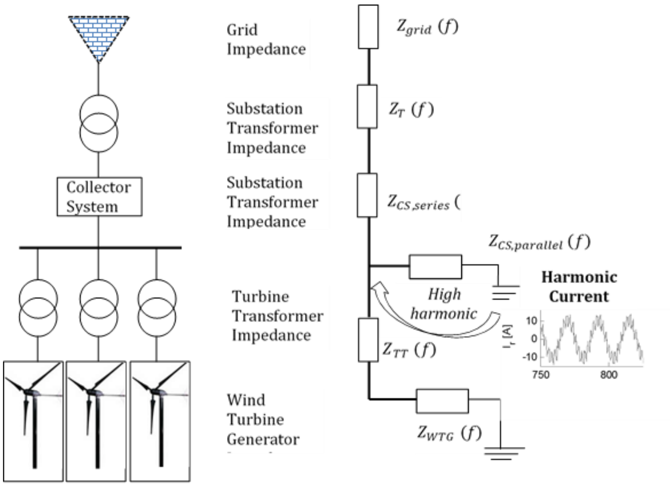

Fig -7: Illustration of parallel resonance in a wind power plant.

3. CONCLUSIONS

Recently the implementation of wind power as a clean energy source has experienced significant growth both in installed capacity and in the implementation of new technologies. However, this increase has generated new problems within the electricity sector in the wind industry related to the power quality. For its part, the International Electricity Commission (IEC) has decreed the standard 61400-21 where it establishes the requirements and the grid codes for the power quality at the common coupling point between the wind farm and the electricity grid. In this paper the main power quality issues wind farms and the electrical grid undergo when they interconnect were exposed. The review of the literature has led to the conclusion that the most important aspects of power quality in the electric grid that affect wind farms are the voltage harmonics and the short-term rms variations, on the other hand, the electricity grid experiences issues with voltage variations, frequency variations and harmonic propagation from wind farms.

Table -1:

MAIN POWER QUALITY ISSUES IN WIND FARMS AND THE GRID.

Power quality issues	**Wind farm**	**Electrical grid**
Transients [3]		X
Short and long duration rms variations [3, 6-9, 12,20-39]		X
Imbalance [3][5]		X
Voltage and current waveform distortions [3][5]		X
Voltage fluctuations [3, 5, 29, 32, 43-45, 48, 52, 54, 55]	X	X
Power frequency variations [3, 65-72]		X
Harmonic propagation [6-11,14-18, 56-64]	X	X
Flickers [3, 5, 29, 32, 43-45, 48, 52, 54, 55]	X	

These phenomena can cause oscillations in the generator torque, voltage fluctuations, fatigue in the mechanical components, and decrease in efficiency and in general a reduction in the useful life time of the wind turbine, causing great economic losses. Table 1 shows a summary of the main power quality issues in wind farms and the electrical grid.

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REFERENCES

[1]Bhattacharyya S., Myrzik J.M.A., Kling W.L., “Consequences of poor power quality - an overview”, 42nd International Universities Power Engineering Conference, pp. 651-656, September 2007.

[2] Joseph Seymour, Terry Horsley, “The seven types of power problems”, American Power Conversion, white paper No.18, Vol.1, pp. 1-24, 2005.

[3] IEEE Power & Energy Society, “IEEE Recommended Practice for Monitoring Electric Power Quality”, IEEE Std 1159, pp. 1-81, June 2009.

[4] Renewable Energy Policy Network for the 21st Century, “Renewables 2012”, Global Status Report, pp. 1-171, 2012.

[5] D. Saxena, K.S. Verma, S.N. Singh, “Power quality event classification: an overview and key issues”, International Journal of Engineering, Science and Technology, Vol.2, No.3, pp. 186-199, 2010.

[6] Amini J., “Novel control method of grid connected converter of doubly fed induction generator to achieve disturbances rejection”, 10th International Conference on Environment and Electrical Engineering, pp.1-5, May 2011.

[7] Wenjie Chen, Jun Xu , Nan Zhu , Changjin Liu, Min Chen, Dehong Xu, “Stator harmonic current suppression for DFIG wind power system under distorted grid voltage”, 3rd IEEE International Symposium on Power Electronics for Distributed Generation Systems, pp.307-314, June 2012.

[8] Hua Geng, Cong Liu, Geng Yang, “LVRT Capability of DFIG based WECS under Asymmetrical Grid Fault Condition”, IEEE Transactions on Industrial Electronics, Vol.60, No.6, pp. 2495-2509, 2013.

[9] I. Erlich, H. Wrede, C. Feltes, “Dynamic Behavior of DFIG-Based Wind Turbines during Grid Faults”, Power Conversion Conference - Nagoya, pp. 1195-1200, 2007.

[10] Changjin Liu, Wenjie Chen, Frede Blaabjerg, Dehong Xu, “Optimized Design of Resonant Controller for Stator Current Harmonic Compensation in DFIG Wind Turbine Systems”, Twenty-Seventh Annual IEEE Applied Power Electronics Conference and Exposition, pp. 2038-2044, 2012.

[11] Wenjie Chen, Jun Xu , Nan Zhu , Changjin Liu, Min Chen, Dehong Xu, "Stator harmonic current suppression for DFIG wind power system under distorted grid voltage", 3rd IEEE International Symposium on Power Electronics for Distributed Generation Systems, pp.307-314, June 2012.

[12] Hua Geng, Cong Liu, Geng Yang, "LVRT Capability of DFIG based WECS under Asymmetrical Grid Fault Condition", IEEE Transactions on Industrial Electronics, Vol.60, No.6, pp. 2495-2509, 2013.

[13] I. Erlich, H. Wrede, C. Feltes, "Dynamic Behavior of DFIG-Based Wind Turbines during Grid Faults", Power Conversion Conference - Nagoya, pp. 1195-1200, 2007.

[14] Djurović S., Williamson S., "Influence of Supply Harmonic Voltages on DFIG Stator Current and Power Spectrum", XIX International Conference on Electrical Machines, pp. 1-6, 2010.

[15] "Integrated Doubly Fed Electric Alternator/Active Filter (IDEA), a Viable Power Quality Solution, for Wind Energy Conversion Systems"

[16] Hailiang Xu, Jiabing Hu, Heng Nian, Yikang He, "Dynamic modeling and improved control of DFIG under unbalanced and distorted grid voltage conditions ", International Symposium on Industrial Electronics, pp. 1579-1584, 2012 .

[17] Jiabing Hu, Heng Nian, Hailiang Xu, Yikang He, "Dynamic Modeling and Improved Control of DFIG Under Distorted Grid Voltage Conditions ", IEEE Transactions on Energy Conversion, Vol.26, No.1, pp. 163-175, March 2011.

[18] Changjin Liu, Frede Blaabjerg, Wenjie Chen, Dehong Xu, "Stator Current Harmonic Control With Resonant Controller for Doubly Fed Induction Generator", IEEE Transactions on Power Electronics, Vol. 27, No. 7, pp. 3207-3220, July 2012.

[19] "Wind Turbines Based on Doubly Fed Induction Generator Under Asymmetrical Voltage Dips"

[20] Jesús López, Pablo Sanchis, Xavier Roboam, Luis Marroyo, "Dynamic Behavior of the Doubly Fed Induction Generator During Three-Phase Voltage Dips", IEEE Transactions on Energy Conversion, Vol.22, No.3, pp. 709-717, September 2007.

[21] Shuai Xiao, Geng Yang, Honglin Zhou, Hua Geng, "A LVRT Control Strategy based on Flux Linkage Tracking for DFIG-based WECS", IEEE Transactions on Industrial Electronics, pp. 1-13, 2011.

[22] Lu Zhang, Xinmin Jin, Liangyu Zhan, "A Novel LVRT Control Strategy of DFIG based Rotor Active Crowbar", Asia-Pacific Power and Energy Engineering Conference, pp. 1-6, 2011.

[23] Francisco K. A. Lima, Alvaro Luna, Pedro Rodriguez, Edson H. Watanabe, Frede Blaabjerg, "Rotor Voltage Dynamics in the Doubly Fed Induction Generator During Grid Faults", IEEE Transactions on Power Electronics, Vol.25, No.1, pp. 118-130, January 2010

[24] K.H. Phani Shree,T.Niteesh Reddy, "Novel Techniques to Enhance the LVRT Capability Of DFIG in Wind Power Plant", International Journal of Advanced Engineering Sciences and Technologies, Vol.10, No.2, pp. 360-365, 2011.

[25] R.P.S. Leão, J.B. Almada, P.A. Souza, R.J. Cardoso, R.F. Sampaio, F.K.A. Lima, J.G. Silveira, L.E.P. Formiga, "The Implementation of the Low Voltage Ride-Through Curve on the Protection System of a Wind Power Plant", International Conference on Renewable Energies and Power Quality, April 2010.

[26] Gong Wenming, Wang Yun, Hu Shuju, Xu Honghua, "A Survey on Recent Low Voltage Ride-Through Solutions of Large Scale Wind Farm", Asia-Pacific Power and Energy Engineering Conference, pp. 1-5, 2011.

[27] R.P.S. Leão, T. Degner, F.L.M. Antunes, "Overview of FACTS Devices for Wind Power Plants Directly Connected to the Transmission Network", International Conference on Renewable Energies and Power Quality, pp. 1-9, March 2007.

[28] Chad Abbey, Wei Li, Loic Owatta, Geza Joos, "Power Electronic Converter Control Techniques for Improved Low Voltage Ride Through Performance in WTGs", IEEE Power Electronics Specialists Conference, pp. 1-6, June 2006.

[29] G. Joós, "Wind Turbine Generator Low Voltage Ride through Requirements and Solutions", Power and Energy Society General Meeting - Conversion and Delivery of Electrical Energy in the 21st Century, pp. 1-7, July 2008.

[30] Maurício B. C. Salles, Kay Hameyer, José R. Cardoso, Ahda. P. Grilo, Claudia Rahmann, "Crowbar System in Doubly Fed Induction Wind Generators", Energies, pp. 738-753, April 2010.

[31] Haihui Lu, Zhenhuan Yuan, Lixiang Wei, Russel J Kerkman, Richard A Lukaszewski, Ahmed Sayed Ahmed, "LVRT Performance Limit of DFIG with Traditional AC Crowbar and DC-link Brake Approach", IEEE International Symposium on Industrial Electronics (ISIE), pp. 692-699, May 2012.

[32] Thanh Hai Nguyen, Dong-Choon Lee, "LVRT and Power Smoothening of DFIG-based Wind Turbine Systems using Energy Storage Devices", International Conference on Control, Automation and Systems 2010, pp. 1070-1074, October 2010.

[33] Qicheng Ling, Yuping Lu, "An Integration of Super Capacitor Storage Research for Improving Low-Voltage-Ride-Through in Power Grid with Wind Turbine", Asia-Pacific Power and Energy Engineering Conference, pp. 1-4, 2012.

[34] Liyan Qu, Wei Qiao, "Constant Power Control of DFIG Wind Turbines With Supercapacitor Energy Storage", IEEE Transactions On Industry Applications, Vol. 47, No. 1, pp. 359-367, January 2011.

[35] Abbey C., Joos G., "Supercapacitor Energy Storage for Wind Energy Applications", IEEE Transactions on Industry Applications, Vol.43, No.3, pp. 769-766, 2007.

[36] Liyan Qu,Wei Qiao, "Constant Power Control and Fault-Ride-Through Enhancement of DFIG Wind Turbines with Energy Storage", Industry Applications Society Annual Meeting, pp. 1-8, 2009.

[37] Shuai Xiao, Geng Yang, Honglin Zhou, Hua Geng, "A LVRT control strategy based on flux tracking for DFIG-based wind power systems", IEEE International Conference on Power Electronics and ECCE Asia, pp. 76-82, 2011

[38] Hongbing Ma, Xueguang Zhang, Xinlong Liu, Dianguo Xu, "A novel flux damping control strategy of DFIG based on voltage vector oriented", 7th International Power Electronics and Motion Control Conference, Vol.3, pp. 2168-2172, 2012.

[39] Dawei Xiang, Li Ran, Tavner P.J., Yang S., "Control of a doubly fed induction generator in a wind turbine during grid fault ride-through", IEEE Transactions on Energy Conversion, Vol.21, No.3, pp. 652-662, 2006.

[40] J.J. Gutierrez, J. Ruiz, P. Saiz, I. Azcarate, L.A. Leturiondo and A. Lazkano, "Wind turbines", chapter 24:Power Quality in Grid-Connected Wind Turbines, pp. 547-569, 2011.

[41] V.Suresh Kumar, Ahmed F.Zobaa, R.Dinesh Kannan, and K.Kalaiselvi, "Power Quality and Stability Improvement in Wind Park System Using STATCOM", Jordan Journal of Mechanical and Industrial Engineering, Vol. 4, No. 1, pp. 169-176, January 2010.

[42] Linh N. T., "Power quality investigation of grid connected wind turbines", ICIEA 2009, pp. 2218 – 2222, May 2009.

[43] Zhe Chen; Yue Wang; Zhaoan Wang , "Flicker Mitigation by Active Power Control of Variable-Speed Wind Turbines With Full-Scale Back-to-Back Power Converters ", Transactions on Energy Conversion, IEEE , Vol. 24, No. 3, pp. 640-649, September 2009.

[44] Åke Larsson, "Flicker Emission of Wind Turbines During Continuous Operation", IEEE Transactions on Energy Conversion, Vol. 17, No. 1, pp. 114-118, March 2002.

[45] Tao Sun, Zhe Chen, Frede Blaabjerg, "Flicker study on variable speed wind turbines with doubly fed induction generators", IEEE Transactions on Energy Conversion, Vol. 20, No. 4, pp. 896-905, December 2005.

[46] Morcos, M. M., "Flicker Sources and Mitigation", IEEE Power Engineering Review, Vol. 22, No. 11, pp. 5-10, November 2002.

[47] Kim Yun-Seong, Won Dong-Jun, "Mitigation of the Flicker Level of a DFIG Using Power Factor Angle Control", IEEE Transactions on Power Delivery, Vol.24, No.4, pp. 2457-2458, 2009.

[48] Hu Weihao, Chen Zhe, Wang Yue, Wang Zhao-an A., "Flicker Mitigation by Active Power Control of Variable-Speed Wind Turbines With Full-Scale Back-to-Back Power Converters", IEEE Transactions on Energy Conversion, Vol.24, No.3 , pp. 640-649, 2009.

[49] Sun, T., Chen, Z., Blaabjerg, F., "Flicker mitigation of grid connected wind turbines using a STATCOM", Second International Conference on Power Electronics, Machines and Drives, Vol.1, pp. 175 – 180, 2004.

[50] Kayikçi Mustafa, Milanovic Jovica V., "Reactive Power Control Strategies for DFIG-Based Plants", IEEE Transactions on Energy Conversion ,Vol.22, No.2, pp. 389-396, 2007.

[51] Meegahapola Lasantha G., Littler Timothy B., Fox Brendan O., Kennedy Jason M., Flynn Damian, "Voltage and Power Quality Improvement Strategy for a DFIG Wind Farm during Variable Wind Conditions", Proceedings of the International Symposium Modern Electric Power Systems (MEPS), pp. 1-6, 2010.

[52] Thanh Hai Nguyen, Dong-Choon Lee, "Flicker mitigation in DFIG wind turbine systems", European Conference on Power Electronics and Applications, pp. 1-10, September 2011.

[53] Ali H. Kasem Alaboudy, H. H. Zeineldin, "Flicker minimization of DFIG based wind turbines with optimal reactive current management ", Conference on Innovative Smart Grid Technologies - Middle East , pp. 1-5, December 2011.

[54] Bialasiewicz Jan T., Muljadi Edumard, "The Wind Farm Aggregation Impact on Power Quality", 32nd Annual Conference on IEEE Industrial Electronics, pp. 4195-4200, 2006.

[55] Tan Luong Van, Thanh Hai Nguyen, Dong-Choon Lee, " Flicker Suppression Scheme for Variable-Speed Wind Turbine Systems", Journal of Power Electronics, Vol. 12, No.2, pp. 333-343, March 2012.

[56] Fan Lingling, Kavasseri Rajesh G., Yin Haiping, Zhu Chanxia, Hu Min-Qiang Q., "Control of DFIG for Rotor Current Harmonics Elimination", IEEE Power & Energy Society General Meeting, pp. 1-7, 2009.

[57] Fan Lingling, Miao Zhixin Lee, Yuvarajan Subbaraya, "A Unified Model of DFIG for Simulating Acceleration with Rotor Injection and Harmonics in Wind Energy Conversion

Systems", IEEE Power & Energy Society General Meeting, pp. 1-6, 2009.

[58] Tentzerakis Sokratis T., Papathanassiou Stavros A., "An Investigation of the Harmonic Emissions of Wind Turbines", IEEE Transactions on Energy Conversion, vol.22, No.1, pp. 150,158, 2007.

[59] Liao Yong, Ran L., Putrus Ghanim A., Smith Kenneth Scot, "Evaluation of the Effects of Rotor Harmonics in a Doubly-Fed Induction Generator with Harmonic Induced Speed Ripple", IEEE Transactions on Energy Conversion, Vol.18, No.4, pp. 508-515, 2003.

[60] Patel Dhaval, Varma Rajiv Kumar, Seethapathy Ravi, Dang Michael, "Impact of Wind Turbine Generators on Network Resonance and Harmonic Distortion", 23rd Canadian Conference on Electrical and Computer Engineering, pp.1-6, 2010.

[61] Bollen Mathias H J, Yao Liangzhong Z., Rönnberg Sarah Karolina, Wahlberg Mats G., "Harmonic and Interharmonic Distortion due to a windpark", IEEE Power and Energy Society General Meeting, pp. 1-6, 2010.

[62] Zheng Ruimin, Bollen Mathias H J, Zhong Jin, "Harmonic Resonances due to a Grid-connected Wind Farm", 14th International Conference on Harmonics and Quality of Power, pp. 1-7, 2010.

[63] Hasan K. N Md, Rauma Kalle, Rodriguez P., Candela J. Ignacio, Muñoz-Aguilar Raul S., Luna Álvaro, "An Overview of Harmonic Analysis and Resonances of Large Wind Power Plant", 37th Annual Conference on IEEE Industrial Electronics Society, pp. 2467-2474, 2011.

[64] Rauma Kalle, Hasan Khairul Nisak Bt Md, Gavriluta Catalin, Citro Constantino, "Resonance Analysis of a Wind Power Plant with Modal Approach", IEEE International Symposium on Industrial Electronics (ISIE), pp. 2042-2047, 2012.

[65] Meegahapola Lasantha G., Flynn Damian, "Impact on Transient and Frequency Stability for a Power System at Very High Wind Penetration", IEEE Power and Energy Society General Meeting, pp. 1-8, 2010.

[66] Janaka Ekanayake, Nick Jenkins, "Comparison of the Response of Doubly Fed and Fixed-Speed Induction Generator Wind Turbines to Changes in Network Frequency", IEEE Transactions on Energy Conversion, Vol. 19, No. 4, December 2004.

[67] Johan Morren, Sjoerd W. H. de Haan, Wil L. Kling, J. A. Ferreira, "Wind Turbines Emulating Inertia and Supporting Primary Frequency Control", IEEE Transactions on Power Systems, Vol. 21, No. 1, pp. 433-434, February 2006.

[68] Badrul H. Chowdhury, Hong T. Ma, "Frequency Regulation with Wind Power Plants", Power and Energy Society General Meeting - Conversion and Delivery of Electrical Energy in the 21st Century, pp. 1-5, July 2008.

[69] I. Erlich, M. Wilch, "Primary frequency control by wind turbines", Power and Energy Society General Meeting, pp. 1-8, July 2010.

[70] Rogério G. de Almeida, J. A. Peças Lopes, "Primary Frequency Control Participation Provided By Doubly Fed Induction Wind Generators", IEEE Transactions on Power Systems, Vol. 22, No. 3, pp. 944-950, August 2007.

[71] G. Ramtharan, J.B. Ekanayake, N. Jenkins, "Frequency support from doubly fed induction generator wind turbines", Renewable Power Generation, Vol. 1, No. 1, March 2007.

[72] Rogério G. de Almeida, J. A. Peças Lopes, "Participation of Doubly Fed Induction Wind Generators in System Frequency Regulation", IEEE Transactions on Power Systems, Vol. 22, No. 3, August 2007.