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MSC DEGREE IN AUTOMATION ENGINEERING

SMALL WIND TURBINE :  
THREE-PHASE GRID SIMULATION  
FOR 'G83' COMPLIANCE TESTING

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*To my husband and my son...*



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# Sommario

Le turbine eoliche partecipano attivamente alla produzione di energia elettrica in diversi paesi in tutto il mondo. La penetrazione dell'energia eolica nella rete elettrica solleva questioni sulla compatibilità della produzione di energia dalla turbina eolica alla la rete elettrica, in particolare il comportamento della turbina durante errori nella rete di potenza.

I codici di rete esistenti richiedono che i generatori delle turbine eoliche comportino come le convenzionali centrali elettriche: soprattutto essi richiedono che le turbine eoliche rimangono collegate alla rete durante e dopo alcuni errori.

L'obiettivo principale di questo progetto è quello di sviluppare un impianto di prova basato sul PC+DSP che permetta di simulare la rete di tensione trifase e permetta all'utente di inserire una serie di differenti errori che si possono incontrare su tale rete : variazioni di tensione e di frequenza ,vector shift(o sfasamento) and RoCoF .Lo scopo di questo impianto di prova è di verificare la conformità del 'G83' delle turbine eoliche della **GAIA WIND company** in commercio

Questo impianto di prova permetterà alla Gaia wind di analizzare il comportamento delle loro turbine durante errori nella rete, cioè controlleranno se le loro turbine rimangono o meno connesse alla rete, verificando se soddisfano i requisiti imposti dalla 'EREC G83' for **Small-Scale Embedded Generators (SSEGs)** nel Regno Unito.

Il progetto prevede la programmazione in "C" di un DSP avente come output tre tensioni sinusoidali sfasate di 120 gradi, con risoluzione appropriate di tensione e di frequenza .

Ho quindi sviluppato un interfaccia utente con Labview, che comunica con il DSP attraverso un serial link. Nell'interfaccia di figura 1, l'utente potrà inserire

dati tali che : i valori di frequenza e di tensione per il normale funzionamento e quelli durante gli errori , il tempo di errori ,il valore dello sfasamento (vector shift) e della velocità di cambiamento di frequenza (RoCoF). l'obiettivo di questo

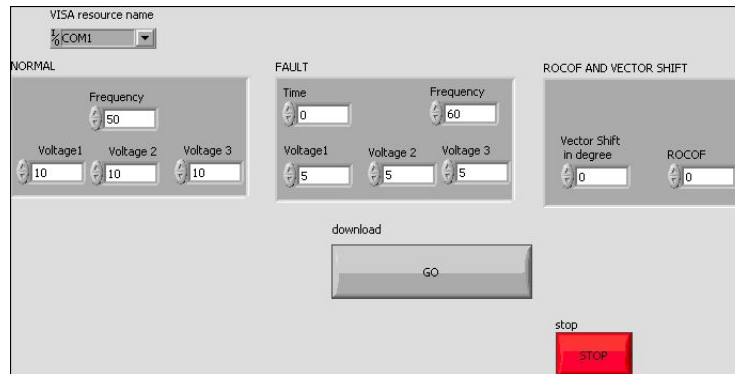


Figure 1: INTERFACCIA UTENTE IN LABVIEW

progetto è pertanto quello di :

- ottenere un'accurata risoluzione sui valori di tensione e frequenza di ogni forma d'onda
- simulare la durata degli errori di tensione e/o di frequenza (figura 2)
- infine, implementare i due tipi di perdita di protezione di rete come richiesto dalla G83 : sfasamento (vector shift) e velocità di cambiamento della frequenza in Hz/s (RoCoF : Rate od Change of Frequency)

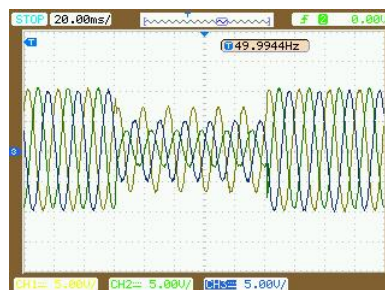


Figure 2: DURATA ERRORE DI TENSIONE



# Abstract

Wind turbines participate actively in the power production of several countries around the world. The penetration of wind energy in the grid raises questions about the compatibility of the wind turbine power production with the grid ,in particular the behavior of the turbines during faults on the power grid.The existing grid codes require wind turbines generators to behave as the conventional power plants: Especially the requirements for wind turbines to stay connected to the grid during and after some grid faults when voltages and frequency of the 3-phase are inside the required limits .

The main objective of this project is to developed a PC + DSP based tests facility which simulated 3 phase grid voltages and allowed the user to inject a range of different fault conditions such as over/under-voltage , over/under-frequency , vector shift and RoCoF . The purpose of this test facility is to verify G83 compliance of a commercially available Gaia Wind turbine.

These tests will allows the **GAIA WIND company** to analyze the behavior of their turbines during the faults: control whether the turbines remains connect or not to the network and check if they meet the requirements set by the 'EREC G83' for **Small-Scale Embedded Generators (SSEGs)** in the UK.

The project involved development of DSP code (C) which output 3 sinusoidal voltage waveforms with appropriate resolutions in voltage and frequency control. The project also developed a LabView PC interfaced with the DSP via a serial link and which allowed the user to specify a range of grid faults including the ability to control the length of time of fault.

To achieve this goal our work will consist of three steps :

- the first one is to have an accurate resolution on frequency and voltages of

the waveforms.

- The second one is to simulate a time fault changing the Normal value of the frequency or the amplitude of each sine wave for a time required by the user and then return to the previous operating .
- The third and last step is to implement the two types of loss of mains protection as required in the 'EREC G83' : Vector Shift (in degree) and the Rate of Change of Frequency (RoCoF in Hz/s).

# Introduction

Renewable energies are inexhaustible and there are a great way to minimize carbon emissions , in recent years Technological progress has contributed to make them ever cheaper and efficient in generating electricity.

Wind energy is one of the fastest growing industries nowadays , his use is increasing at an annual rate of 20% , with a worldwide installed capacity of 238,000 megawatts (MW) at the end of 2011 [1][2][3]. The increased penetration of wind energy into the power system over the last years is directly reflected in the wind turbines grid connection requirements .

In United Kingdom (UK) there are two grid connection standards that ensure the safety of people and equipment. These are termed 'G83' and 'G59'. Both standards require synchronisation with the grid voltage cycle and loss of main detection with automatic disconnection within 0.5 seconds. The 'G83' standard is the simpler of the two; the 'G83' standard only allows for an output of up to 16Amps per phase, single or multi-phase,230/400 V ACv.The Engineering Recommendation 'G83' provides guidance on the technical requirements for the connection of **Small-Scale Embedded Generators (SSEGs)** in parallel with public low-voltage distribution network. It is, therefore, very common for small wind turbines such as the **GAIA WIND** turbines [4]

To analyze the behavior of their wind turbines during grid disturbances, and to meet the standards required by 'G83' on the Interface Protection , the GAIA WIND needed a three-phase grid voltages simulator which can interact with their turbine's generators.

The simulator has been created by programming a DSP in C through the Code Composer program (CCS) and the user interface is implemented with LABVIEW

interacting via a serial link with the DSP which send an array of 11 elements useful for simulate the 3-phase grid voltages.

The first part of this simulation will be to create three waveforms shifted by 120 degree between them with a resolution of  $\pm 0.01\text{Hz}$  on the frequency and  $\pm 0.1\text{V}$  on the voltages In order to have realistic values as The 'G83' require that The manufacturer must ensure that the interface protection is capable of measuring voltage to an accuracy of  $\pm 1.5\%$  of the nominal value ( $\pm 3.45\text{V}$ ) and of measuring frequency to  $\pm 0.2\%$  of the nominal value ( $\pm 0.1\text{Hz}$ ) across its operating range of voltage, frequency and temperature. This would allow the GAIA wind to control if they meet this requirement.

The second part of the simulation is to represent a time-Fault for variation of the frequency and (or) the amplitudes of all (or one or two) of the waveforms and return to the normal values after this time . The 'EREC G83' require that when any parameter of frequency and voltages is outside of the respectively limits [184 273.7] V and [47 52] Hz The total disconnection time for voltage and frequency protection including the operating time of the disconnection devise shall be the trip delay setting with a tolerance of -0 s +0.5 s. This would allow to make tests on the Disconnection times requirements and control whether the turbine disconnects to the grid during a fault on voltage and (or) frequency .

As the 'EREC G83' required that the loss of mains protection should be able to detect the loss on a single phase of the supply network, the third and last part will be to represent the two current types of this loss of mains named : **Vector Shift** change of the sinusoidal waveform phase (in degree) and the **RoCoF** Rate of Change of Frequency(in Hz/s).this will allows The Gaia wind to detect with a vector shift relay and with a RocoF relay whether some phase is shifted and how fast the frequency is changing.

# Chapter 1

## Overview of wind power

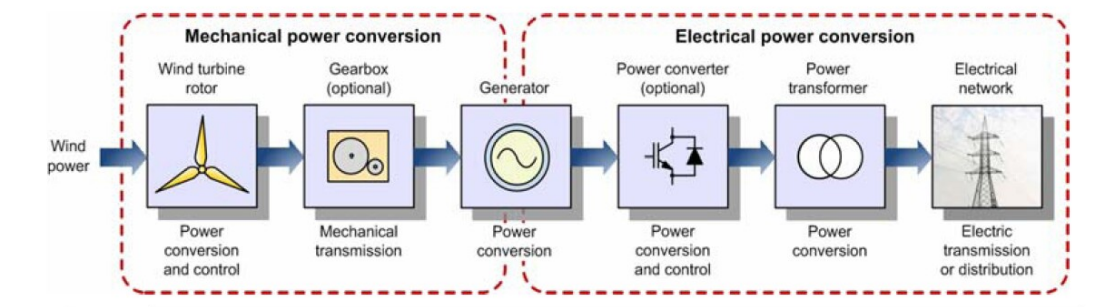


Figure 1.1: General description of a wind turbine system

Wind turbines transform the power from the wind to rotating mechanical power. This mechanical power is present in low-speed and high-torque power; in order to convert this power efficiently in electrical power usually a gearbox is used to transform it in high-speed mechanical power. The conversion into electrical energy is done by a generator, usually an induction machine.

The expression for the amount of power  $P_m$  that a wind turbine is capable of producing is shown in 1.1

$$P_m = \frac{1}{2} \rho A v^3 C_p(\lambda, \beta) \quad (1.1)$$

where :

$P_m$  = Mechanical power.

$C_p$  = Nondimensional power coefficient.

$\lambda$  = Tip speed ratio.

$\beta$  = Pitch Angle.

$\rho$  = Air density

$A$  = Swept area.

$v$  = Wind speed.

This relationship indicates that, for a given turbine, the output power depends of the wind speed and the power coefficient  $C_p$ . It represents the turbine efficiency, and is defined as the fraction of wind energy extracted by the turbine of the total energy that the flow should have through the area swept by the rotor blades.  $C_p$  is a nonlinear function of the tip speed ratio  $\lambda$  and therefore it changes with wind speed. In many instances, this is provided by the manufacturer documentation which is used in many control schemes as look-up tables to generate optimum target of the power references.

$\lambda$  is a function given by:

$$\lambda = \frac{R\Omega}{v} \quad (1.2)$$

where  $R$  is the radius of the turbine,  $\Omega$  the speed of the turbine and  $v$  the wind speed.

The expression 1.2 shows that to extract the maximum power of a given wind, the turbine rotor speed must be proportional at wind speed, as shown in 1.3, where  $\Omega_{opt}$  is the optimum speed or maximum power speed.

$$\Omega_{opt} = \frac{\lambda_{opt} \cdot v}{R} \quad (1.3)$$

From the expression 1.3, wind speed value is obtained when the power coefficient value is maximum. Replacing this wind speed value in 1.4 a new expression for

the power maximum is obtained 1.5 of the form:

$$P_{max} = \frac{1}{2} \rho A v^3 C_{p,max} \quad (1.4)$$

$$P_{max} = \frac{1}{2} \rho \pi R^2 \left( \frac{R \Omega_{opt}}{\lambda_{opt}} \right)^3 C_{p,max} \quad (1.5)$$

The expression 1.5 can be expressed by the following form:

$$P_{max} = K \Omega_{opt}^3 \quad (1.6)$$

$$K = \frac{1}{2} \pi R^5 \frac{C_{p,max}}{\lambda_{opt}^3} \quad (1.7)$$

Dividing in both terms of 1.6 between  $\Omega_{opt}$  the torque obtained is given by:

$$T_{opt} = K \Omega_{opt}^2 \quad (1.8)$$

Where  $T_{opt}$  is the optimum torque or torque of maximum power. In 1.6 is shown the maximum power that a wind turbine can extract for a given wind, is a cubical function of the optimal speed of the turbine. The relationship between torque and speed in the point of maximum power operation follows a quadratic law, as is shown in 1.8 .

## 1.1 Structure of modern Wind turbine

Basically , a wind energy conversion system consists of a turbine tower which carries the nacelle, and the wind turbine rotor, consisting of rotor blades and hub. Most modern wind turbines are horizontal-axis wind turbines (HAWTs) with three rotor blades usually placed up wind of the tower and the nacelle . On the outside, the nacelle is usually equipped with anemometers and a wind vane to measure the wind speed and direction ,as well as with aviation lights .The nacelle contains the key components of the wind turbine,i.e. the gearbox, mechanical brake,electrical generator, control systems, yaw drive, etc. The wind turbines are not only installed dispersedly on land, but also combined as wind

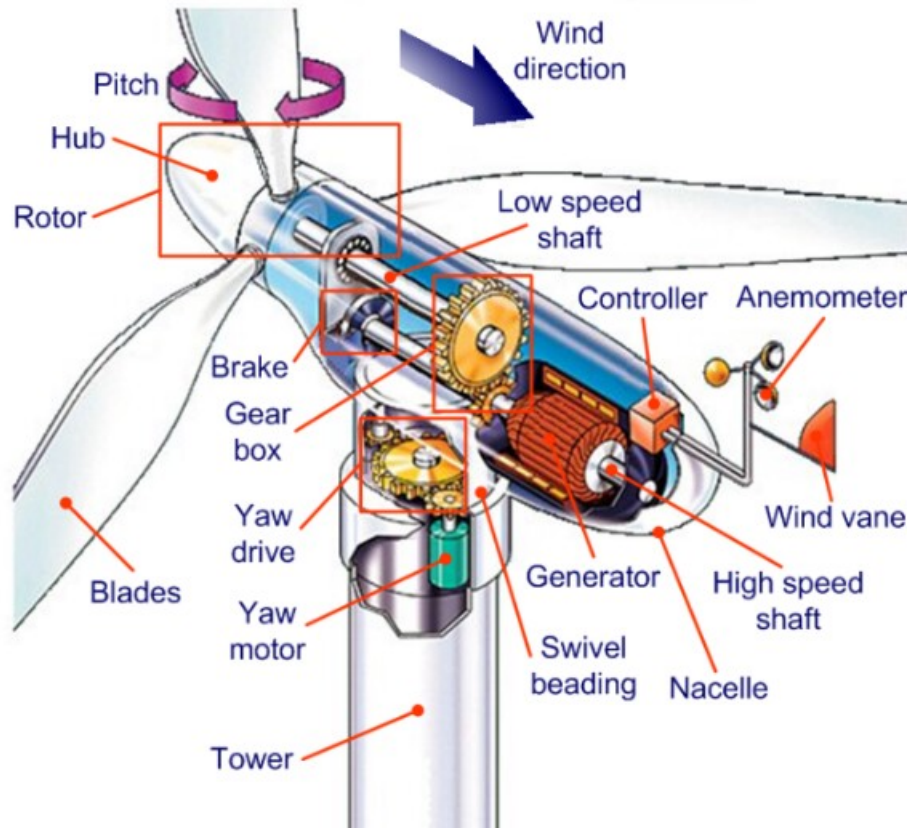


Figure 1.2: Horizontal axis wind turbine components [5]

farms (or parks) with capacities of hundreds MWs which are comparable with modern power generator units.

A figure 1.2 illustrates the major components placement in an horizontal axis wind turbine. Of the various wind turbine models found around the world , most operate in a similar way and have components that serve very similar functions. Based on this feature , major components that most wind turbines have in common are described below :

- **Anemometer and wind vane** : they measure the wind speed and wind direction. Wind speed data is transmitted to the controller, while the wind vane communicates with the yaw drive to orient the turbine properly with respect to the wind.
- **Blades** : Most turbines have either two or three blades.



- **Brake:** A disc, which can be applied mechanically, electrically, or hydraulically to stop the rotor in emergency situations, like the cut-out speed exceeding,
- **Controller :** The controller starts up the turbine at wind speeds above the cut-in wind speed and shuts it off above the cut-out speed. Turbines do not operate at wind speeds above a specified wind speed, because they might be damaged by the high wind speed and mechanical loads affecting the turbine parts.
- **Gearbox :** Gears connect the low speed shaft to the high-speed shaft and increase the rotational speed from the blades hub speed up to the rotational speed required by the installed generator to optimally produce electricity. The gear box is a very costly and heavy part of the wind turbine. That's why engineers are exploring direct-drive generators that operate at lower rotational speeds and do not need gearbox
- **Generator :** an induction generator, doubly-fed induction generator or a synchronous generator.
- **High-speed shaft :** a shaft driving the generator,
- **Low-speed shaft :** a shaft driving the turbine hub with blades.
- **Nacelle :** it is mounted on top of the tower and contains the gear box, low-speed and high-speed shafts, generator, controller and brake. In case of the largest wind turbines the nacelle can be large enough for a helicopter to land on it.
- **Pitch :** in case of the pitch-controlled wind turbines the blades are turned or pitched, out of the wind to control the rotor speed and keep the rotor from turning in winds that are too high or too low for it to produce electricity.
- **Rotor :** The blades together with the hub.

- **Tower** : Towers are made from tubular steel , concrete or steel lattice . Because wind is getting higher with the height,taller tower enable turbines to capture more energy and this way generate more electricity.
- **Yaw drive and yaw motor** : the turbines face perpendicular to wind blowing direction. The yaw drive is used to keep the rotor facing into the wind direction changes.

## 1.2 Wind turbine technology

Wind turbines transform the power from the wind to rotating mechanical power. This mechanical power is present in low-speed and high-torque power; in order to convert this power efficiently in electrical power usually a gearbox is used to transform it in high-speed mechanical power. The conversion into electrical energy is done by a generator, usually an induction machine. The asynchronous generator can be operated by fixed speed (squirrel cage) or variable speed (double fed asynchronous machine). Between the grid and the generator, a power converter can be inserted. Besides this typical wind turbine setup, other technical setups are possible: solutions with and without gearbox as well as solutions with or without power electronic conversion. The electrical output can either be ac or dc and a power converter can be used as an interface to the grid.

Applications of power electronics in wind turbine generation systems are greatly improving wind turbine behavior and performance. They are able to act as a contributor to the frequency and voltage control by means of active and reactive power control. [6]

The impact of wind generation in power systems depends on the used technology, the structure of the internal distribution network in the park, the control mechanism of each wind turbine and the overall control of the wind farm. All these factors should be known in order to analyze the impact on the power quality parameters at the connected grid.

The energy conversion of most modern Wind Turbines can be divided into two main concepts, fixed speed machines with one or two speeds and variable speed machines.

In fixed speed machines the generator is directly connected to the mains supply grid. The frequency of the grid determines the rotational speed of the generator and thus of the rotor. The low rotational speed of the turbine rotor  $n_{rotor}$  is translated into the generator rotational speed  $n_{generator}$  by a gear box with the transmission ratio  $r$ . The generator speed depends on the number of pole pairs  $p$  and the frequency of the grid  $f_{grid}$

$$\begin{aligned} n_{rotor} &= \frac{n_{generator}}{r} \\ n_{generator} &= \frac{f_{grid}}{P} \\ n_{rotor} &= \frac{f_{grid}}{r \cdot P} \end{aligned}$$

The greatest advantages of WT with induction generators is the simple and cheap construction. In addition no synchronization device is required. With the exception of bearings there are no wearing parts.

The disadvantages of induction generators are high starting currents, which usually are smoothed by a thyristor controller, and their demand for reactive power. In variable speed machines the generator is connected to the grid by an electronic inverter system. For synchronous generators and for induction generators without slip rings this inverter system is connected between the stator of the generator and the grid like fig. 3.3, where the total power production must be fed through the inverter. For induction generators with slip rings the stator of the generator is connected to the grid directly. Only the rotor of the generator is connected to the grid by an electronic inverter, see fig. 3.4. This gives the advantage, that only a part of the power production is fed through the inverter. That means the nominal power of the inverter system can be less than the nominal power of the WT. In general the nominal power of the inverter is the half of the power of the WT, enabling a rotor speed variation in the range of half the nominal speed. By the control of active power of the inverter, it is possible to vary the rotational speed of the generator and thus of the rotor of the WT.



# Chapter 2

## Generator systems for Wind turbines

### 2.1 The fixed-speed Squirrel Cage Induction Generator

A fixed-speed wind turbine is equipped with a Squirrel Cage Induction Generator (SCIG) directly connected to the grid via a step-up transformer, as shown in fig 2.1

The speed of the SCIG is therefore set by the grid frequency .To avoid large current transients during grid connection, fixed-speed wind turbines may be connected to the grid through a soft-starter (Hansen 2004)

Due to the stiff connection to the grid, a fixed-speed wind turbine cannot absorb the wind power fluctuations in its rotor kinetic energy. As a consequence, fluctuations in the torque and delivered power will result. Torque fluctuations may cause mechanical stresses to the turbine drive train, while power fluctuations may result in voltage flicker.

A SCIG needs to be magnetized through the network and to decrease the reactive power drawn from the grid in normal operation, capacitor banks are installed at the SCIG terminals. However in case of a voltage dip, the wind turbine accelerates and draws large amount of reactive power from the grid, well above its need in normal operating conditions. This complicates voltage recovery and could lead to

generator overspeeding and consequent disconnection (Ahkmatov 2005) to avoid voltage stability issues.

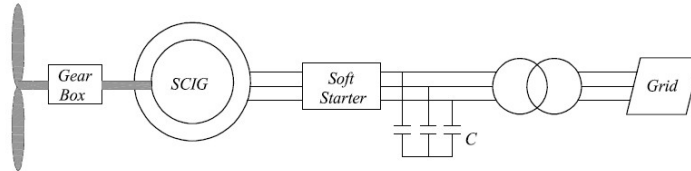


Figure 2.1: Fixed-speed wind turbine with SCIG

## 2.2 Limited Variable-Speed Wind Turbine

This wind turbine concept uses a wound rotor induction generator (WRIG) and an external resistance that can be connected to the generator rotor through a converter. By controlling the converter, the value of the effective external resistance can be controlled. A scheme of this wind turbine concept is shown in Figure 2.2. When increasing the total rotor resistance, the maximum torque of the slip-torque curve of the induction generator is shifted toward higher slip and higher generator speed. Consequently, if the mechanical power is assumed constant, this results in operation at higher speed.

Limited variable-speed wind turbines can be operated above rated speed, with a maximum slip range above 10%. The speed range is limited by the high heat losses in the external resistance (Burnham 2009).

This control is mainly used to absorb wind power fluctuations into kinetic energy of the wind turbine shaft and then dissipate them into heat in the external resistance (Ahkmatov 2005).

A major drawback of this wind turbine concept is that active and reactive power cannot be independently controlled (Burnham 2009). Just like the fixed-speed concept, this wind turbine draws reactive power from the grid and therefore capacitor banks are used to improve the power factor (Ahkmatov 2005).

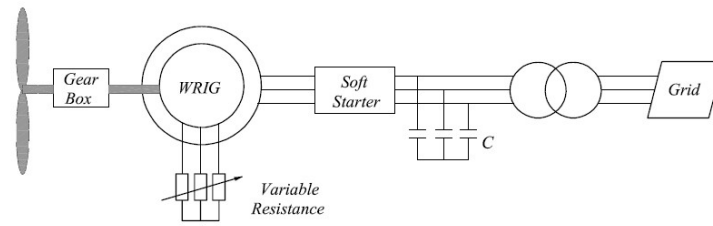


Figure 2.2: limited Variable-speed wind turbine with wound-rotor induction generator and variable rotor resistance

## 2.3 The variable-speed wind turbine with Doubly Fed Induction Generator

This type of wind turbine uses a DFIG. The stator of the generator is directly connected to the grid. The rotor is also connected to the grid, but through a back-to-back converter. A three winding step-up transformer may be used, as shown in Figure 2.3. The converter on the rotor side referred as the rotor side converter (RSC), and the converter on the grid side as the grid side converter (GSC).

The power flow through the rotor can be bidirectional (Akhmatov 2005). The power flows into the rotor when the wind turbine operates at subsynchronous speed, with low mechanical input power. The rotor power flow reverses at super-synchronous speed. Thus, with high mechanical input power, part of this power is fed to the grid through the stator and part through the back-to-back converter. The RSC is normally set to control the active and reactive power injection into the grid through the stator. Active and reactive power can be controlled independently by adjusting the external voltage applied to the rotor. By properly adjusting the external rotor voltage, the stator current can be controlled also to deliver a reactive power to the grid. This is a major advantage of this wind turbine type over types A and B. The fast control of the RSC makes it possible to feed a smooth active power into the grid. The RSC can be controlled to optimize the wind power extraction at low wind speeds (Akhmatov 2005).

During normal operation, the GSC controls the DC-link capacitor voltage and usually does not contribute to any reactive power exchange with the grid.

A major advantage of this type of wind turbines is that the back-to-back converter only needs to be sized to handle approximately 30 generator rated power (Petersson 2005(a)). This is a direct consequence of the fact that the power flowing through the rotor is given by the product of the stator power and the slip and that these wind turbines are operated within a slip range from -0.3 to +0.3. It is also important that the rotor-to-stator turns ratio be chosen properly to reduce the current rating of the converter. If this turns ratio is chosen around 3, the maximum rotor voltage in normal operating conditions will result close to 1 pu. Consequently the rotor current will not exceed 0.3 pu of the stator current.

The major drawback of this wind turbine concept is that it is very sensitive to grid disturbances. A dip in the voltage may in fact cause high currents in the rotor that may damage the RSC. In these situations the switching of the RSC is therefore blocked. There are different schemes to protect a DFIG wind turbine during faults and at the same time allow grid fault ride-through capability. Some of these schemes are exposed in Sections 2.2 and 2.4.

The short-circuit currents delivered by DFIG wind turbines during a fault are widely discussed in Chapter 3 and 4.

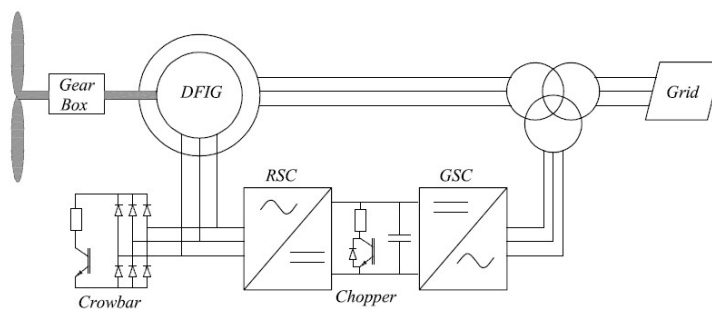


Figure 2.3: Variable-speed wind turbine with DFIG.



## 2.4 The variable speed wind turbine with Synchronous Generator

This wind turbine concept is connected to the grid through a full-scale back-to-back converter. The generator may be either of synchronous or induction type. In the first case, both options with a separately excited and a permanent magnet synchronous generator are available in commercial wind turbines (Manwell 2009). Gearless solutions using a synchronous generator with a high number of poles are also present in the market (Hansen 2004). If an induction generator is used, this needs to be magnetized by the generator side converter. Therefore, this has to be rated to handle not only the rated active power of the generator but also its reactive power. Reactive power can be provided also by capacitors installed at the generator terminals (Akhmatov 2005).

The generator side converter controls the speed of the generator to optimize power extraction from the wind. These wind turbines have a wider operating speed range than wind turbines with DFIG (Tsili 2008). The grid side converter controls the DC-link capacitor voltage feeding active power into the grid. It can also independently control the reactive power injection.

Wind turbines with FSC are easier to control during voltage dips in the grid, as compared to DFIG wind turbines. In this case, the voltage dip does not directly cause any transient in the generator. The main issue is the rise of the DC-link capacitor voltage when no active power can be delivered to the grid. A number of strategies to mitigate and solve this problem are presented in Section 2.4. The grid side converter can also provide fast reactive power support.

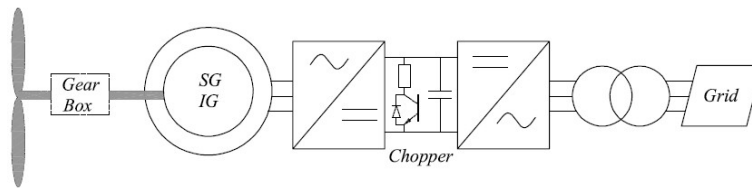


Figure 2.4: Variable-speed wind turbine with full-scale converter. The generator may be either of synchronous type, separately excited or permanent-magnet, or an induction generator.

# Chapter 3

## Wind turbines and three phase grid

### 3.1 The turbine's behavior during fault in the grid

In electricity supply and generation, variation of voltages and frequency and loss of main protection is what an electric device, especially wind generator, may be required to be capable of when there are disturbances in the grid. These problems can be seen in one, two or all the three phases of the AC grid.

Depending on the application the device may, during or after the disturbances, be required to:

- disconnect temporarily from the grid, but reconnect and continue operation after the fault
- stay operational and not disconnect from the grid
- stay connected and support the grid with reactive power (defined as the reactive current of the positive sequence of the fundamental [7] )

### 3.1.1 Voltage and frequency variation

The nominal voltage and frequency considering are 230V and 50 Hz. During this types of grid faults the turbine can :

- remain connected if the voltage and frequency are within the respective limits [184 273.7] V and [47 52] Hz.
- or disconnect from the network if it is outside these limits .The 'EREC G83' require that when any parameter is outside on setting shown in table 4.1 , The total disconnection time for voltage and frequency protection including the operating time of the disconnection devise shall be the trip delay setting with a tolerance of -0 s +0.5 s.

#### **An example : Voltage dip**

According to internationally-adopted definitions (under European standard EN 50160), a voltage dip occurs when the power voltage drops to a level below 90% of standard voltage for no longer than a minute. However, most voltage dips last for less than one-tenth of a second before the standard voltage of the power supply is restored. A voltage dip is not a power interruption. During the occurrence of a voltage dip, the power supply is not interrupted. Voltage dips are usually caused by weather conditions or third party damage (see illustration 3.1). For these reasons, occasional voltage dips are unavoidable.

In electricity supply and generation, low voltage ride through (LVRT), or fault ride through (FRT), is what an electric device, especially wind generator, may be required to be capable of when the voltage in the grid is temporarily reduced due to a fault or load change in the grid. The voltage may be reduced in one, two or all the three phases of the AC grid. The severity of the voltage dip is defined by the voltage level during the dip (may go down to zero) and the duration of the dip.

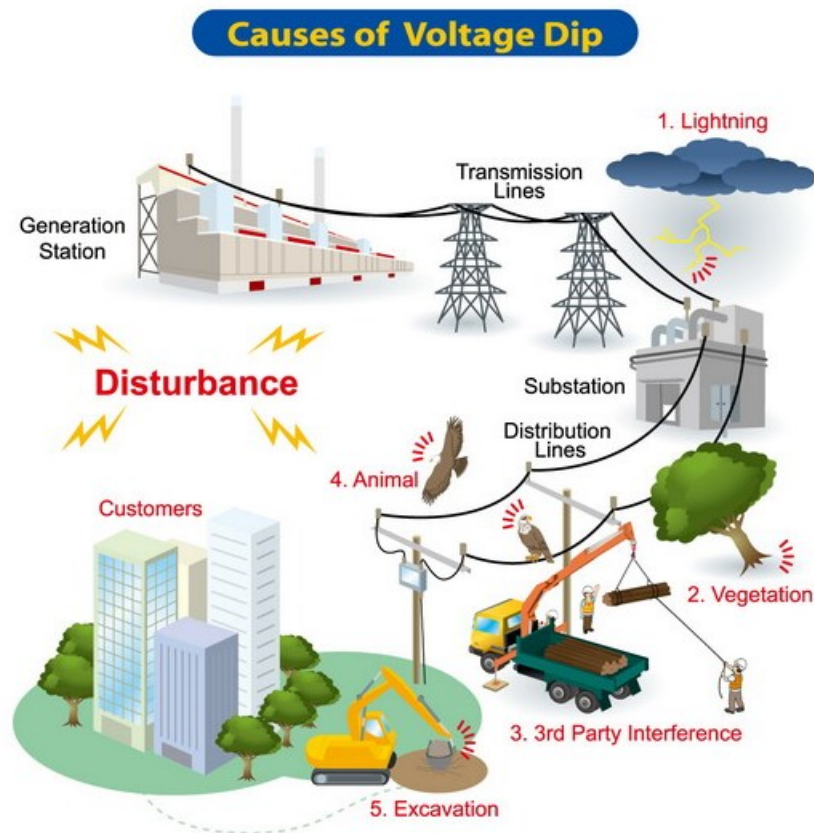


Figure 3.1: causes of voltages dips

### 3.1.2 loss of mains protection

'EREC G83' require that the SSEGs generator should be able to detect the loss of a single phase of the supply network.

1. disconnect the generator if RoCof is greater or equal to 0.2 Hz/s or the vector shift is greater or equal to 12 degree . in figure 5.16

2. the generator should remain connected during each and every test.

- RoCoF 0.19 Hz per second from 49.5 Hz to 51.5 Hz (see figure 5.17 ) and from 50.5 Hz to 47.5Hz
- Vector shift 9 degree plus from 49..5 Hz and 9 degrees minus from 50.5 Hz

## 3.2 The impacts of Wind Turbines on the Electricity Systems

The wind farms have different impacts and functions on the performance of the grid than conventional power plants, because of variation of wind speed in time. Many studies have been performed on grid connected wind farms and related power system issues. Different techniques and models have been used for determining problems; the impacts of wind farms on technical and operational characteristics of power systems and technical requirements for wind farm-grid connections were analyzed. The doubly fed and squirrel cage induction generators are widely used in wind energy conversion systems. These generators are usually grid-coupled via power electronic converters in order to control the voltage, frequency and power flow during the variation of wind speed. As a consequence, wind turbines affect the dynamic behaviour of the power system in a way that might be different from hydrolic or steam turbines [8]. The factors that cause these affects will be analyzed in this section

### 3.2.1 Location of the Wind Farm in the Electric Power System

The point of common coupling(PCC) of wind farms and the power system, including the parameters of the power system, the parameters of wind farm and the structure of the grid are of essential significance in further operation of the wind farm in the power system and their influence on each other. The size and the location of the considered wind farm and the parameters of the grid in that region highly influences the appropriate PCC.

Wind farms must be located in the regions that have favourable wind conditions. These regions can be shorelines and islands where the power network in these regions can be named as **weakly developed**. A part of power grid can be named as **weak** when it is electrically far away from the infinite bus of the interconnected power system. The weak grids have lower short circuit power than strong grids relatively. The short circuit power level in a given point in the electrical network

represents the system strength.

Figure 3.2(a) illustrates an example of one line diagram of wind farm connection to a grid and (b) shows phasor diagram. Wind

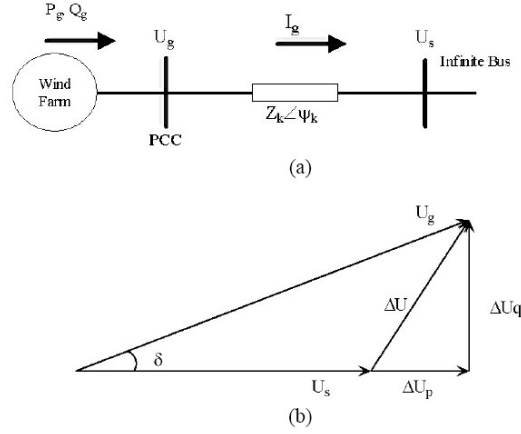


Figure 3.2: (a) One line diagram of wind farm connection to a grid  
(b) Phasor diagram

farm is connected to the network with equivalent short circuit impedance ,  $Z_k$  . The network voltage at the assumed infinite bus bar and the voltage at the PCC are  $U_s$  and  $U_g$ , respectively. The output power and reactive power of the wind farm are  $P_g$  and  $Q_g$ , which corresponds to a current  $I_g$ .

$$I_g = \left( \frac{S_g}{U_g} \right)^* = \frac{P_g - jQ_g}{U_g} \quad (3.1)$$

The voltage difference,  $\Delta U$ , between the infinite system and the PCC is given by

$$U_g - U_s = \Delta U = Z_k \dot{I}_g = (R_k + jX_k) \left( \frac{P_g - jQ_g}{U_g} \right) \quad (3.2)$$

$$\Delta U = \frac{R_k P_g + X_k Q_g}{U_g} + \frac{P_g X_k + R_k Q_g}{U_g} = \delta U_p + j\delta U_q \quad (3.3)$$

The short circuit impedance, the real and reactive power output of the wind farm determines the voltage difference. The variations of the generated power will result in the variations of the voltage at PCC. When the impedance  $Z_k$  is small, then the grid can be named as strong and when  $Z_k$  is large, then the grid can be

named as weak. Since strong or weak are relative concepts, for a given electrical wind power capacity  $P$ , the ratio,

$$R_{sc} = \frac{S_{sc}}{P} = \frac{U_s^2}{Z_k P} \quad (3.4)$$

stated as the measure of the strength, where  $S_{sc}$  is short circuit power. The grid may be considered as strong with respect to the wind farm installation if  $R_{sc}$  is above 20. It is obvious from 3.4 that for large wind farm-grid connections, the PCC voltage level have to be as high as possible to limit voltage variations [9]

Local wind farms are the most typical forms of distributed generation. Although distribution systems are planned for unidirectional power flow from transmission system to the consumers, the amount of distributed generation located at the distribution level of electrical networks is showing rapid growth worldwide. Issues such as new energy sources, efficiency of local energy production and modularity of small production units are promoting this growth. On the other hand, large power rated wind farms connected directly to the transmission level do not actually meet the definition of distributed generation since those are named as the members of generation system [10].

In case of wind farm installations on islands and offshore platforms the underwater transmission of power to the mainland power system has to be performed by cable. For long distance transmission, the transmission capacity of cables may be mainly occupied by the produced reactive power, therefore ac transmission will meet difficulties. In this situation high voltage direct current (HVDC) transmission techniques may be used. Figure 3.3 shows different wind farm connections to grid.

### 3.2.2 Impacts of Wind Farms on Power Quality

The currently existing power quality standard for wind turbines, issued by the International Electrotechnical Commission (IEC), IEC 61400- 21: “Measurement and assessment of power quality characteristics of grid connected wind turbines“, defined the parameters that are characteristic of the wind turbine behavior in terms of the quality of power, and also provides recommendations to carry out measurements and assess the power quality characteristics of grid connected wind



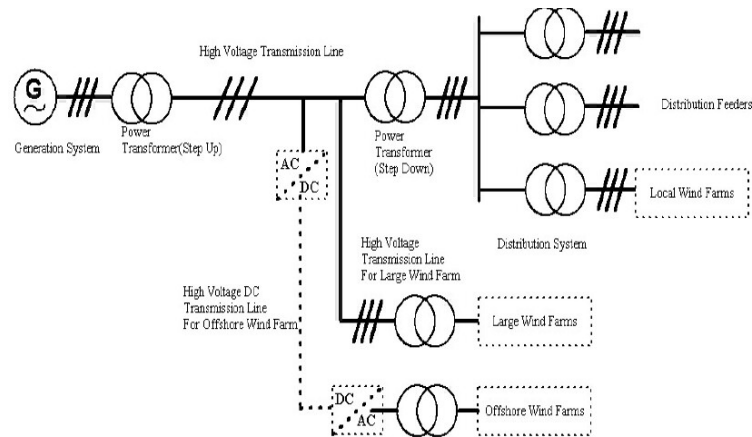


Figure 3.3: Different wind farm connections to a grid.

turbines. Although the standard mainly describes measurement methods for characterizing single wind turbines, there are methodologies and models developed that enable, for well pre-defined conditions, to extrapolate the single turbine unit parameters to the typical quality characteristics of wind farms.

Since voltage variation and flicker are caused by power flow changes in the grid, operation of wind farms may affect the voltage in the connected network. On the local level, voltage variations are the main problem associated with wind power. This can be the limiting factor on the amount of wind power which can be installed. If necessary, the appropriate methods should be taken to ensure that the wind turbine installation does not bring the magnitude of the voltage at PCC outside the required limits.

### 3.2.3 System Stability

Stability analysis of the power system is a large area that covers many different topics. A formal definition of power system stability is provided by "IEEE/CIGRE Joint Task Force on Stability Terms and Definitions" as the ability of an electric power system, for a given initial operating condition, to regain a state of operating equilibrium after being subjected to a physical disturbance, with most system variables bounded so that practically the entire system remains intact.

Tripping of transmission lines, loss of production capacity and short circuits are

named as power system faults which are related to system stability. These failures affects the balance of both real and reactive power and change the power flow. Though the capacity of the operating generators may be adequate, large voltage drops may occur suddenly. The unbalance and re-distribution of real and reactive power in the network may force the voltage to vary beyond the boundary of stability. A period of low voltage may occur and possibly be followed by a complete loss of power. Many of power system faults are cleared by the relay protection of the transmission system either by disconnection or by disconnection and fast reclosure. In all the situations the result is a short period with low or no voltage followed by a period when the voltage returns. A wind farm nearby will see this event. In early days of the development of wind energy only a few wind turbines, named earlier as local wind turbines, were connected to the grid. In this situation, when a fault somewhere in the lines caused the voltage at the PCC of local wind turbines to drop, local wind turbines were simply disconnected from the grid and were reconnected when the fault was cleared and the voltage returned to normal. Because the penetration of wind power in the early days was low, the sudden disconnection of a wind turbine or even a wind farm from the grid did not cause a significant impact on the stability of the power system. With the increasing penetration of wind energy, the contribution of power generated by a wind farm can be significant. If a large power rated wind farm is suddenly disconnected at full generation, the system will loss further production capability. Unless the remaining operating power plants have enough "spinning reserve" , to replace the loss within very short time, a large frequency and voltage drop will occur and possibly followed by a blackout. Therefore, the new generation of wind turbines is required to be able to LVRT during disturbances and faults to avoid total disconnection from the grid. In order to keep system stability, it is necessary to ensure that the wind turbine restores normal operation in an appropriate way and within appropriate time. This could have different focuses in different types of wind turbine technologies, and may include supporting the system voltage with reactive power compensation devices, such as interface power electronics, SVC, STATCOM and keeping the generator at appropriate speed by regulating the power etc[9].

# Chapter 4

## Grid Codes

The relationship of grid operators with all users of the transmission system is outlined in grid codes. The objectives of the grid codes are to secure efficient and reliable power generation and transmission, to regulate rights and responsibilities of the entities acting in the electricity sector.

### 4.1 Grid connection requirements

The connection of wind generation to electrical power systems influences the system operation point, the load flow of real and reactive power, nodal voltages and power losses. At the same time, wind power generation has characteristics with a wide spectrum of influence [11]:

- Location in the power system
- Voltage variation of amplitude and frequency
- Flicker
- Harmonics
- Short circuit currents and protection systems
- Stability
- Self-excitation of asynchronous generators

- Real power losses

The rising impact of wind power generation in power systems causes system operators to extend grid connection requirements in order to ensure its correct operation. We can divide grid connection requirements into two categories:

1. General grid code requirements
2. Special requirements for wind generation

The first category represents requirements valid for every generator in the grid; these are general requirements regarding the system operation point. Some of the most important requirements are:

- Steady state voltage variation
- Line capacity
- Short circuit power at the connection point
- Frequency variations
- Protection
- Contingency

Special requirements for wind generation were introduced to insert wind power generation in the power system without an impact on power quality or system stability. There are two different types of requirements: requirements established by system operators and national or international standards. A comparison of the first set is presented in the following section, where active power control, frequency limitations, reactive power control and fault ride through capability are analyzed.

Active power control is required in order to limit overproduction of wind power that can lead to instabilities due to island conditions (for example Denmark). New wind turbine technologies also allow its participation in frequency regulation.

Frequency in the power system is an indicator of the balance between production

and consumption. For normal power system operation, frequency is stable and close to its nominal value. In the UTCE area the frequency is usually between  $50\pm 0.1\text{Hz}$  and falls out of 49- 50.3 Hz range very seldom during major faults in the UTCE system.

The control of reactive power at the generators is used in order to keep the voltage within the required limits and avoid voltage stability problems. Wind generation should also contribute to voltage regulation in the system; the requirements either concern a certain voltage range that should be maintained at the point of connection or certain reactive power compensation that should be provided. Until now, in case of short-circuits or instability of the grid, the wind parks disconnected immediately from the power system. Due to the high penetration of wind generation, system operators observe a certain risk for the system stability during major disconnections. Therefore, in the new regulations require that wind farms stay connected during a line voltage fault and participate in recovery from the fault.

National and international standards are applied to wind power generation regarding power quality issues for the emission of disturbances in the power system by wind generators. General standards regarding power quality, like EN 50160, are used as well as particular wind turbine ones, like IEC 61400-21. This standard defines the measurement and assessment of power quality characteristics of grid-connected wind turbines and is widely accepted by wind turbine manufacturers and utilities. The power quality is assessed by considering power system parameters and wind turbine parameters, evaluated by test laboratories through empiric measurements

## **4.2 Grid code requirements for wind farm connection**

Worldwide, the new grid connection requirements have identified three areas to be considered in the operation of wind farms; voltage and reactive power control, fault ride through capability and frequency range of operation

### 4.2.1 Voltage and reactive power control

In general, wind farms have to be able to afford automatic voltage control at the point of connection by continuous control of the reactive power at their terminals, according to a certain characteristic specified in a site specific bilateral agreement. In the UK, the general reactive power capability requirement of a wind farm is defined in Section CC.6.3.2 in the UK grid code [12] (see in Fig 4.1). The wind farm 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 point of connection with the GB transmission system.

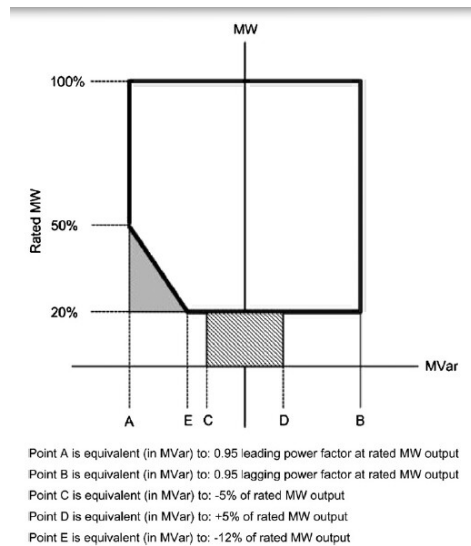


Figure 4.1: Required reactive power capability of wind farms. (Fig. 1 of connection conditions of the grid code [12])

From the UK grid code, with all plant in operation, the reactive power limits defined at rated MW at lagging power factor will be valid at all active power output levels above 20% of the rated MW output as defined in Fig. 1. With all plant in operation, the reactive power limits defined at rated MW at leading power factor will be valid at all active power output levels above 50% of the rated MW output as defined in Fig. 1. With all plant in service, the reactive power limits will reduce linearly below 50% of active power output as shown in

Fig. 4.1 unless the requirement to maintain the reactive power limits defined at rated MW at leading power factor down to 20% active power output is specified in the bilateral agreement. These reactive power limits will be reduced pro rata to the amount of plant in service. The reactive power limits for active power output below 20% shall be adjustable within the area of  $Q = -5\%$  of rated MW output to  $Q = -5\%$  of rated MW output [12].

### 4.2.2 Fault ride through capability

Voltage swing and power oscillations must not result in the triggering of the generating unit protection. The wind turbine generator shall be equipped with voltage and frequency relays for disconnection of the wind farm at abnormal voltages and frequencies. The relays shall be set according to agreements with the regional grid company and the system operator [13].

The voltage characteristic of fault ride through requirement of a wind turbine is defined by a minimum voltage throughout the duration of the fault followed by a ramping up with a given slope to the nominal level as the voltage recovers. Each country has its own fault ride through capability chart. fig 4.2 shows the UK fault ride through capability chart, as defined in Section CC.6.3.15 in the UK grid code [12]. From 4.2 , it can be inferred that the wind farm shall stay transiently stable and connected to the system without tripping for a close-up solid three-phase short circuit fault or any unbalanced short circuit fault on the transmission system with a total fault clearance time of up to 140 ms. During the operating range of the wind farm, these types of faults must not result in instability or isolation from the network. For supergrid voltage dips of duration longer than 140 ms, the wind farm has to remain connected to the system for any dip duration on or above the heavy black line in Fig 4.2 . For system faults cleared within 140 ms, upon the recovery of voltage to 90% of nominal, a wind farm has to provide active power to at least 90% of its pre-fault value within 0.5 s. For voltage dips of duration greater than 140 ms, a wind farm has to supply active power to at least 90% of its pre-fault value within 1 s of restoration of voltage to 90% of nominal. It should be noted that in cases of less than 5% of the turbines in operation, or under very high wind speed conditions where more than

50% of the turbines have been shutdown, a wind farm is allowed to trip [12].

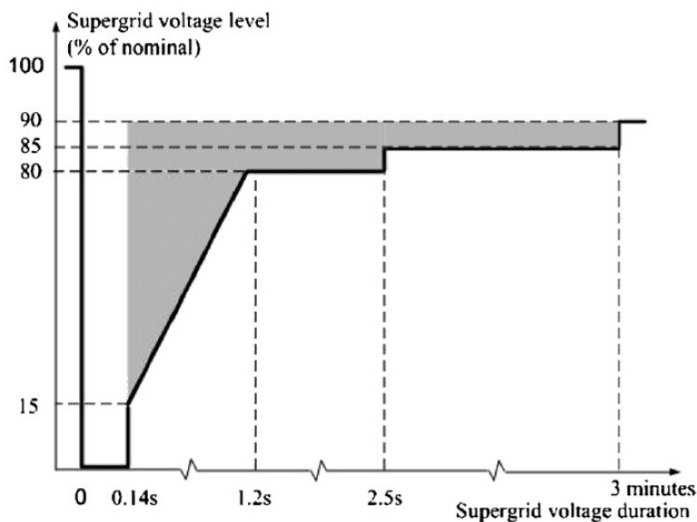


Figure 4.2: Required ride through requirement for UK.

### 4.2.3 Frequency range of operation

The design of generator plant and apparatus must enable operation in accordance with a certain frequency range specified in the grid code of each country. For example, according to the frequency requirements in the UK grid code (Section C.C.6.1.3), wind farms are required to be capable of operating continuously between 47.5 and 52 Hz and at least 20 s for system frequencies between 47 and 47.5 Hz. This is a relatively wide range in relation to realistic events [12].

## 4.3 the 'EREC G83' Grid connection requirements for small wind farm

The purpose of the Engineering Recommendation G83 prepared and approved under the authority of the **Great Britain Distribution Code Review Panel** is to simplify and standardize the technical requirements for connection of **Small Scale Embedded (SSEGs)** for operation in parallel with a public low-voltage



**Distribution System**, by addressing all technical aspects of the connection process from standards of functionality to site commissioning it provides information to allow :

- a) **SSEG Manufacturers** to design and market a product that is suitable for connection to the public low-voltage **Distribution System**;
- b) **Users, Manufacturers and Installers of SSEG** to be aware of the requirements that will be made by the **Distribution Network Operator(DNO)** before the **SSEG** installation will be accepted for connection to the **DNO's Distribution System**.

For the purposes of this Engineering Recommendation a **SSEGs** is a source of electrical energy rated up to and including 16 Ampere per phase, single or multi-phase , 230/400 V **AC**

this correspond to 3.68 kilowatts (kW) on a single- phase supply and 11.04 kW on a three-phase supply. The kW rating shall be based on the nominal voltage (ie 230 V).

#### 4.3.1 Interface Protection requirements

The purpose of the **Interface Protection** is to ensure that the connection of a **SSEG** system will not impair the integrity or degrade the safety of the **DNO's Distribution System**. The interface protection may be located in a separate unit or integrated into the **SSEG** (The inverter in case of technologies which connect via an inverter)

##### Interface Protection Settings and test Requirements

**Interface Protection** shall be installed which disconnects the **SSEG** system from the **DNO's Distribution System** when any parameter is outside of the settings shown in table 4.1 The total disconnection time for voltage and frequency protection including the operating time of the disconnection device shall be the trip delay setting with a tolerance of 0s + 0.5 s. The **Manufacturer** must ensure

---

<sup>1</sup>A value of 230 V phase to neutral

Table 4.1: Protection Settings

Protection Function	Trip Setting	Trip Delay Setting
U/V stage 1	$V_{\varphi-n^1} -13 \% = 200.1V$	2.5
U/V stage 2	$V_{\varphi-n^1} -20 \% = 184V$	0.5
O/V stage 1	$V_{\varphi-n^1} +14 \% = 262.2V$	1s
O/V stage 2	$V_{\varphi-n^1} +19 \% = 273.7V$	0.5s
U/F stage 1	47 .5Hz	20s
U/F stage 2	47 Hz	0.5s
O/F stage 1	51.5 Hz	90s
O/F stage 2	52 Hz	0.5s
Vector Shift	12 degrees	0.0s
RoCoF	0.2 Hz per second	0.0s

that the interface Protection is capable of measuring voltage to an accuracy of  $\pm 1.5 \%$  of the nominal value ( $\pm 3.45 V$ ) and of measuring frequency variations within the settings shown in Table 4.1 plus the measurement error inherent in the device its self

### Loss of Mains Protection

Loss of mains protection shall be incorporated and tested as defined in the relevant annex. Active methods which use impedance measuring techniques by drawing current pulses from or injecting ac currents into the DNO's system are not considered to be suitable. for SSEGs which generate on more than one phase then the loss of mains protection should be able to detect the loss of a single phase of the supply network. this should be tested during type testing and recorded on in

### Frequency Drift and Step Change Stability Test

The Rate of Change of Frequency (RoCoF) and Vector Shift are two common methods used to detect loss of mains in SSEG's .

The stability tests are to be carried out and the generator should remain connected during each and every test.

#### 4.3. THE 'EREC G83' GRID CONNECTION REQUIREMENTS FOR SMALL WIND FARM 31

- RoCoF-0.19Hz per second from 49.5Hz to 51.5 Hz and from 50.5 Hz to 47.5 Hz
- Vector shift- 9 degrees plus from 49.5 and 9 degrees minus from 50.5 Hz



# Chapter 5

## 3-Phase Grid Simulation

Our work consist on generating a three phase grid Voltages to be able to simulate grid faults as listed in the G83 requirements and currently present on a grid .

### 5.1 Programming a DSP and User Interface on LABVIEW

For implementation of the project we have use LABVIEW program as user interface which is interacting with the DSP programed in C through the Code Composer Studio (CCS)program , see fig : 5.1

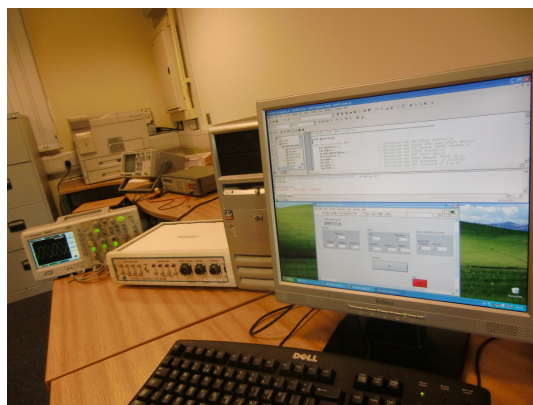


Figure 5.1: (a) DSP(b)LABVIEW INTERFACE(c) CCS

An array of 11 elements(see figure 5.2 ) is sent to the DSP 5.3

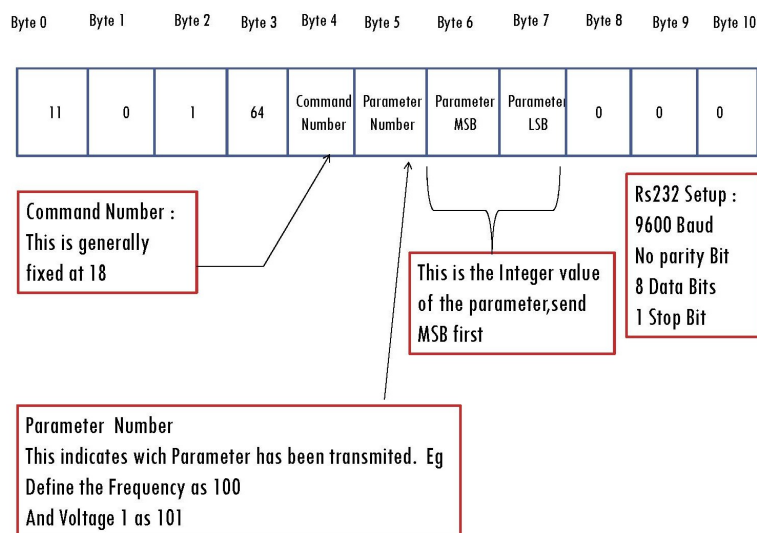


Figure 5.2: Sending Array of 11 elements

each element is a byte.

All the value of the array are read only if the bytes 0 is set to 11

all values are echoing to the PC if bytes 4 is 18 if is 30 the return values are 0 for each bytes

the bytes 5 contains a parameter Number it indicates which parameter has been send. In our simulation we have 11 parameters

1. Normal frequency : parameter is 100
2. Normal Voltage for phase 0 : parameter is 101
3. Normal Voltage for phase 120 : parameter is 102
4. Normal Voltage for phase 240 : parameter is 103
5. Fault frequency :parameter is 104
6. Fault Voltage for phase 0 : parameter is 105
7. Fault Voltage for phase 120 : parameter is 106

8. Fault Voltage for phase 240 : parameter is 107
9. Time.Fault : parameter is 108
10. Go.Fault : parameter is 109
11. Vector Shift and RoCoF : parameter is 110



Figure 5.3: DSP

The bytes 6 and 7 contains the integer value of Parameter. there are divided as MSB(mostst significant bit) and LSB(least significant bit) the integer is calculate as <sup>1</sup> :

$$\text{Elt\_JumpN} = \text{RSRx}[6] * 256 + \text{RSRx}[7];$$

Every  $50\mu\text{s}$  the DSP

- read all these elements;
- control which frequency and voltages to use
- reads the values of the positions of the pointers in the look up table

---

<sup>1</sup>as 11 is the maximum number of parameters vector shift and rocof which are usually low value are sending with the same parameter rocof in the LSB and vector shift in the MSB

- calculates the three values to send to the DAC
- updates the pointers
- writes the values to the input of the DAC.

The block diagram in LABVIEW operates how to send the 11 elements From PC to the DSP as shown in figure 5.4

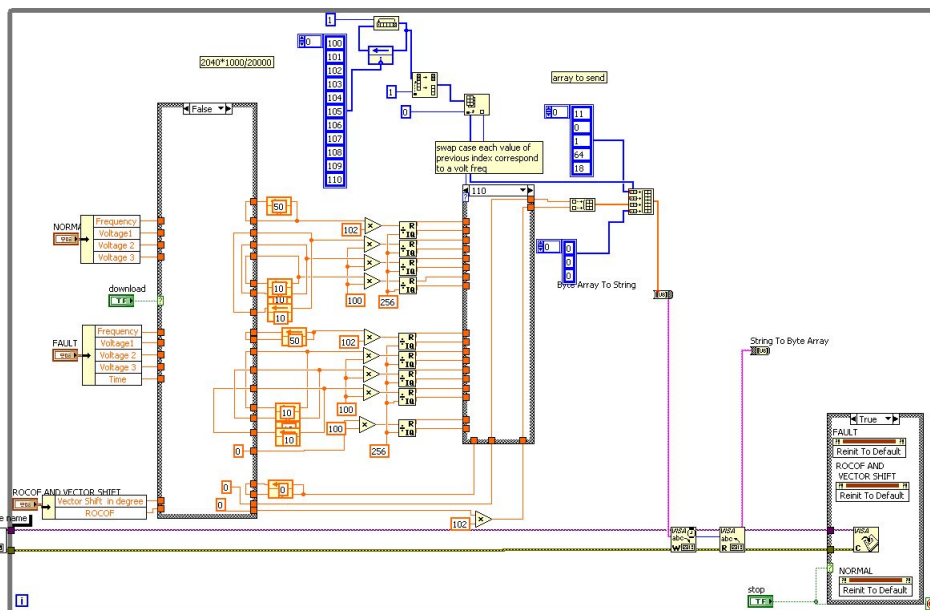


Figure 5.4: LABVIEW Block diagram



The user interface in LABVIEW (see figure 5.5 )allows to insert all the integers values of each Parameter listed above.

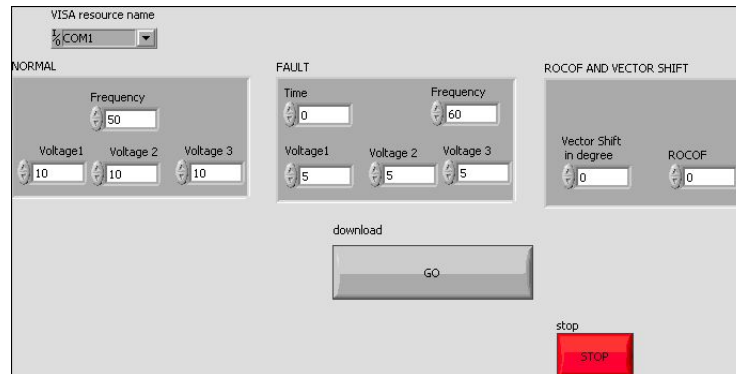


Figure 5.5: User Interface on LABVIEW

In the 'normal' block the user can fill the normal value of voltage frequency. In the 'Fault' block the user can insert the time of the fault he wishes to simulate and the values of voltages for each phase or the frequency for all the phase. In the block 'Vector Shift and RoCoF' the user can insert the value of the vector shift in degree and the value of the rate of change of frequency in (Hz/s).

## 5.2 the step of our work

The first Step is to have an accurate resolution on frequency and voltages. The second is to simulate a time fault changing the current frequency or the amplitude of each voltage and return to the operating conditions after this time fault. The third and last step is to implement two types of loss of mains named : Vector Shift and the RoCoF (Rate of Change of Frequency )

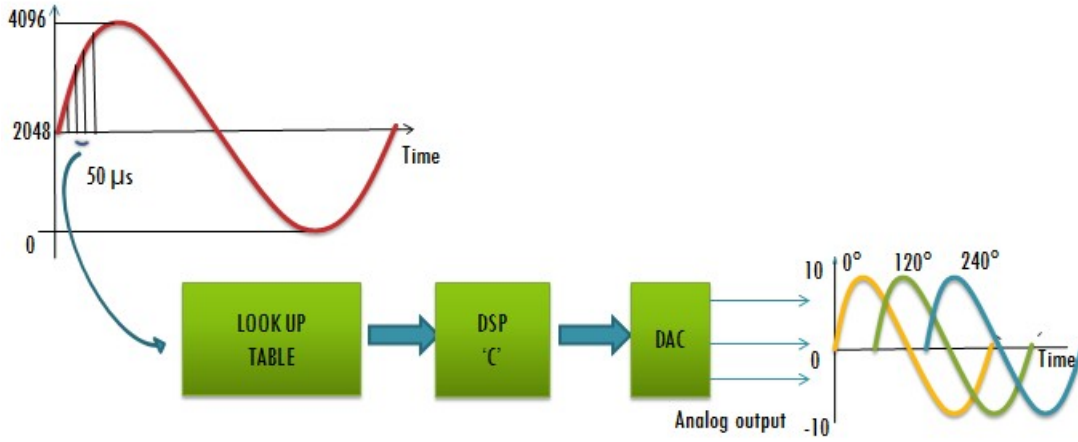


Figure 5.6: structure of our work

The first objective is to generate three waveforms with the same frequency and different(or same ) amplitudes.To achieve this ;a sine wave is converts discretized and all the values are filled into an array which is the look up table ;the values of this array are send cyclically to the DSP(Digital Signal Processing) the position of the value to send cyclically to the DSP is determined by the required frequency. There is DAC(Digital to Analog Converter) at the output of DSP which converts the elaborate signal into an analog output see fig 5.6.

The value on each position of the array derived from the usual equation of the sampled sine wave

$$X(kT) = \begin{cases} A.\sin(2\pi f_0 kT), & k = 0, \dots, N - 1, \\ 0, & otherwise, \end{cases}$$

$A = 2048$  Maximal amplitude. to write on a DAC the value of the output of the DSP is translated to 2048 because the limit of input signal in the DAC is  $[0 \ 4096]$ .  $N = 2040$  correspond to the length of the array where the sampling period  $T = \frac{1}{F_s}$  of the signal is the same as the time of interrupts between two communications 5.7 . to simplify the equation we have choose the frequency of the sine wave as

$$f_0 = F_s/N = 1000/102 = 908kHz$$

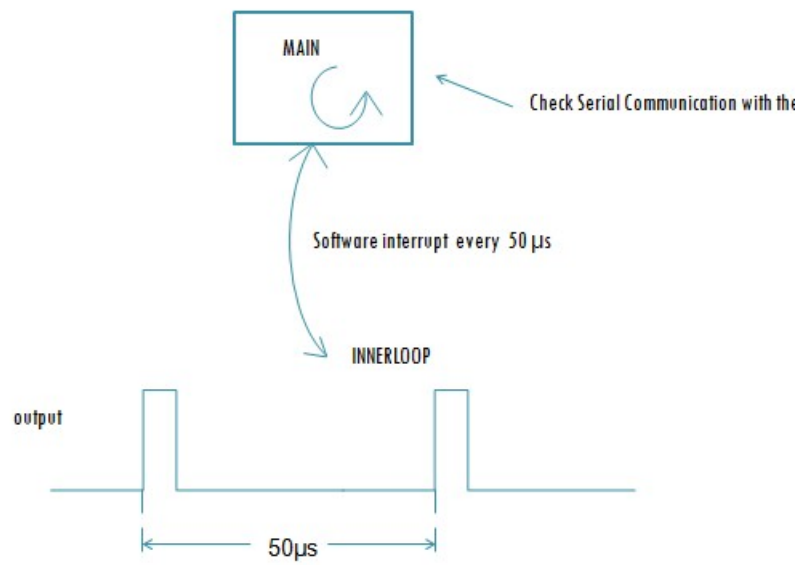


Figure 5.7: Time of interrupt between two communications

then the equation becomes

$$X(kT) = A \cdot \sin\left(2\pi \frac{k}{N}\right), \quad k = 0, \dots, 2039, A = 2048$$
$$0, \quad \text{otherwise,}$$

### 5.2.1 Frequency and Amplitude Resolution

The 'G83' require that The manufacturer must ensure that the interface protection is capable of measuring voltage to an accuracy of  $\pm 1.5\%$  of the nominal value ( $\pm 3.45\text{V}$ ) and of measuring frequency to  $\pm 0.2\%$  of the nominal value ( $\pm 0.1\text{Hz}$ ) across its operating range of voltage, frequency and temperature.

In order to have realistic values of frequency and voltage , we have developed an algorithm that allows us to have a resolution of  $\pm 0.01\text{Hz}$  on the frequency and  $\pm 0.1\text{V}$  on the voltages. 5.8

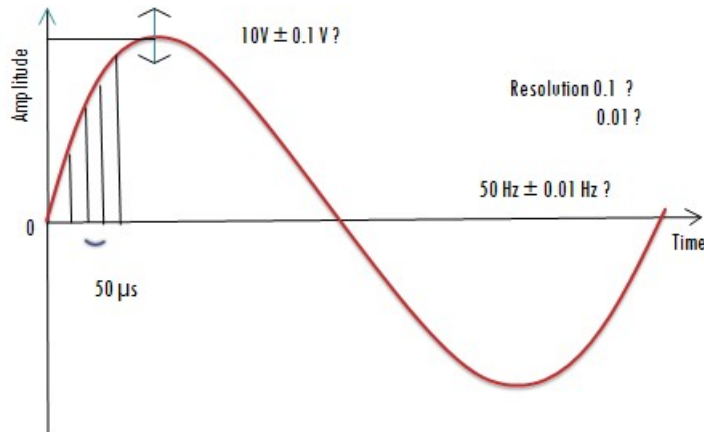


Figure 5.8: Resolution is  $\pm 0.01\text{Hz}$  for the frequency and  $\pm 0.1\text{V}$  for voltage

#### Frequency resolution

The value from the array is send after  $T = 50\mu\text{s}$  and the position of that value is determine by the requires frequency . to generate the three waveforms shifted by 120 degree between them we have created three pointers initialized as :

```

pt_1 = 0; // currents pointers
pt_2 =(int)(N_tot/3);
pt_3 = 2*pt_2;

```

Frequency	Integer part of elements to be skipped multiplied by 1000
50Hz	5100
50.01Hz	5101
50.1Hz	5110
50.2Hz	5120
51Hz	5202
60Hz	6120

Table 5.1: Frequency and correspondents elements to skip

the number of elements to jump between two values to sent is normally calculated in the following way

$$Elt\_Jump = \frac{Freq}{f_0} = \frac{Freq * N}{F_s}$$

to have a good resolution ,this value is multiplied by 1000 and added to the value of pointers also multiplier per 1000 and then divided by 1000 this is viewed in the follow code :

```

pt_1cc = pt_1cc + Elt_Jump ;
pt_2cc = pt_2cc + Elt_Jump;
pt_3cc = pt_3cc + Elt_Jump;

pt_1= pt_1cc/1000;
pt_2= pt_2cc/1000;
pt_3= pt_3cc/1000;

```

in this way we obtained a resolution of 0.01 on frequency this is explain in table 5.1 summarizing 1 Hz corresponds to 102 elements to be skipped multiplied by 1000 .

When the estimate value of the next pointers is greater than or equal to the length of the array minus one the pointers are reinitialize in the follow way :

```

if(pt_1>N_tot-1) //control if is the end of the array

```

```

{
pt_1cc= pt_1cc-1000*N_tot;
pt_1= pt_1-N_tot;

}

```

$N_{tot} = 2040$  is the length of the array ; the new value of the pointer is the difference between the estimate previous value of pointer and the length of the array

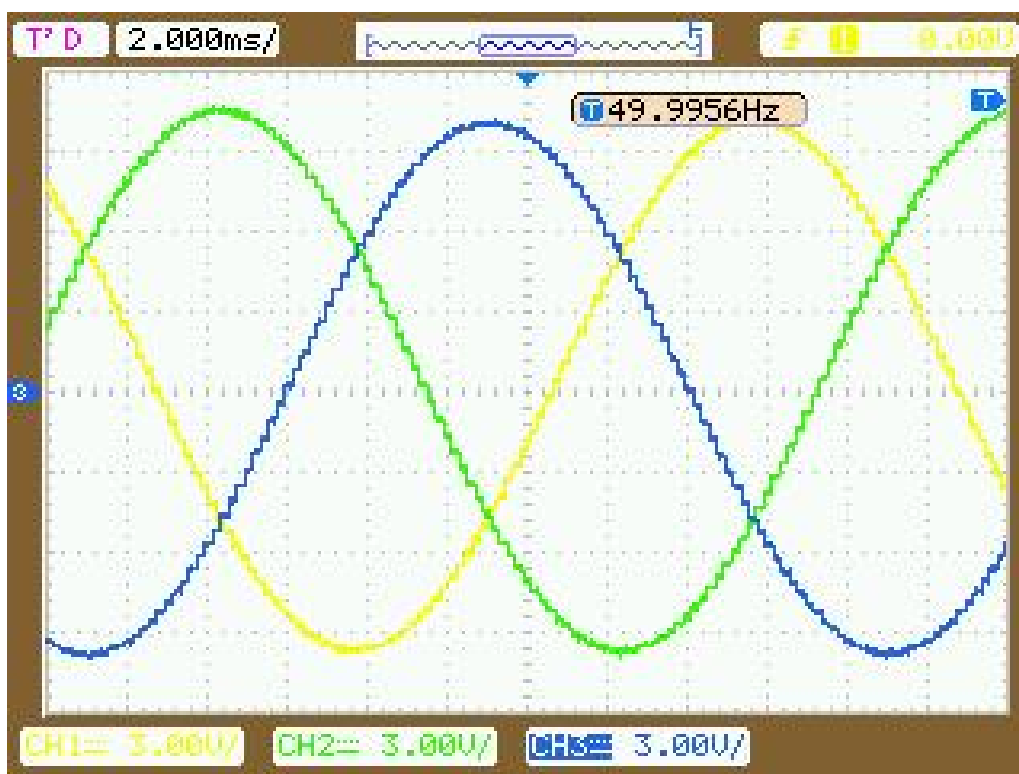


Figure 5.9: Frequency 50 Hz for all waveformson frequencymeter : 49.99Hz

### Voltage resolution

The range in the output of the DAC is set to  $[-10 \ 10]$ V where 10 V is considered as the nominal value in our simulation . As mentioned at the beginning this range correspond to  $[0 \ 4096 ]$  for the input of the DAC . As each waveforms can have

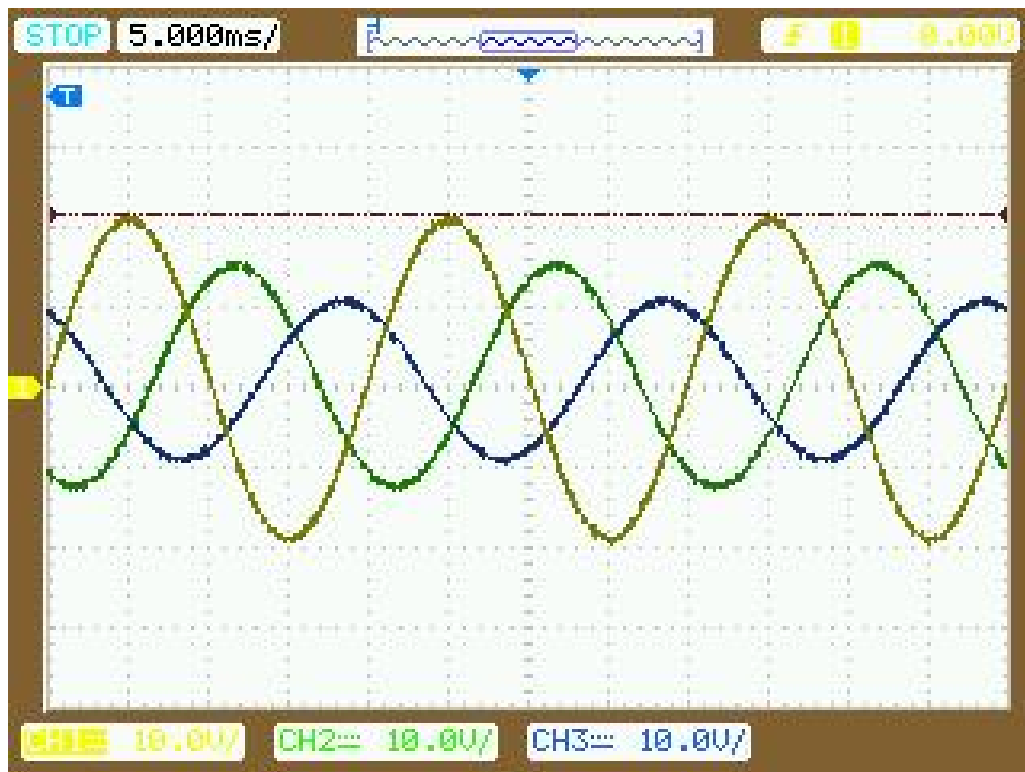


Figure 5.10: Channel1 :10 V ,Channel2: 7 V,Channel3: 9 V Frequency : 50 Hz

different amplitudes 5.10 we have three different multiplicative coefficients for each waveform which are the required amplitude multiplied by 100 .

after each interrupt The value pointed in the array is multiplied by the coefficient and then divided by 1000 before sending it to the DAC

```

value_1 = Coef_1*IrefPhase1[pt_1]; // first sinusoide
value_2 = Coef_2*IrefPhase1[pt_2]; //second sinusoide
value_3 = Coef_3*IrefPhase1[pt_3]; //tthird sinusoide

value_1 = value_1/1000;
value_2 = value_2/1000;
value_3 = value_3/1000;

```

### 5.2.2 Time fault over/under voltage and Frequency

The 'EREC G83' require that when any parameter is outside on setting shown in table 4.1 , The total disconnection time for voltage and frequency protection including the operating time of the disconnection devise shall be the trip delay setting with a tolerance of -0 s +0.5 s.

In this section we have implement a Time fault during which the frequency and (or) the amplitude of all 5.11 (or one)the waveforms change

This time fault simulation will allows the GAIA WIND to

1. test the behavior of their turbines during the grid fault i.e.
  - remains connected if the voltage and frequency are within the respective limits [184 273.7] V and [47 52] Hz.
  - or disconnect from the network if it is outside these limits
2. check if They can meet the requirement on the total disconnection time as required by the 'G83' .

Starting from the normal operation of the network i.e. from the nominal values of voltages and frequency,In this section we want to represent the duration of the fault on frequency or voltage and return to the normal condition when fault end. To simulate the duration of the fault on voltages or frequency or both, we have used the following equation :

$$N\_sample = time * F_s$$

where 'time' ( the duration of the fault multiplied per 100) is received from the user interface on LABVIEW

and  $F_s = 20000Hz$  is the frequency of interrupt.

N\_sample allows us to calculate the number of sample to be modified if we are in the presence of error on the voltage or frequency or both N\_sample is decremented by 100 after each interrupt.

until N\_sample is resets , the value of the voltage and frequency correspond to those of faults.

The end of the time fault is marked by the reset of the N\_sample and this is control



by sending the normal value of voltage and frequency as done in the follow code :

```
    if(N_sample!=0)
    {
N_sample = N_sample-100;
    }
else
Go_Fault =0;
if(Go_Fault ==1)
    {
    Coef_1=Coef_1F; // voltage Fault
    Coef_2=Coef_2F;
    Coef_3=Coef_3F;
Elt_Jump=Elt_JumpF; // frequency fault
    }
else if (Go_Fault ==0)
    {
    Coef_1=Coef_1N; // normal voltage
    Coef_2=Coef_2N;
    Coef_3=Coef_3N;
Elt_Jump=Elt_JumpN;// normal frequency
    }
```

Different simulation have been done for the time\_fault :

- In figure 5.11 the value of the voltage and the frequency are both changed during the fault time

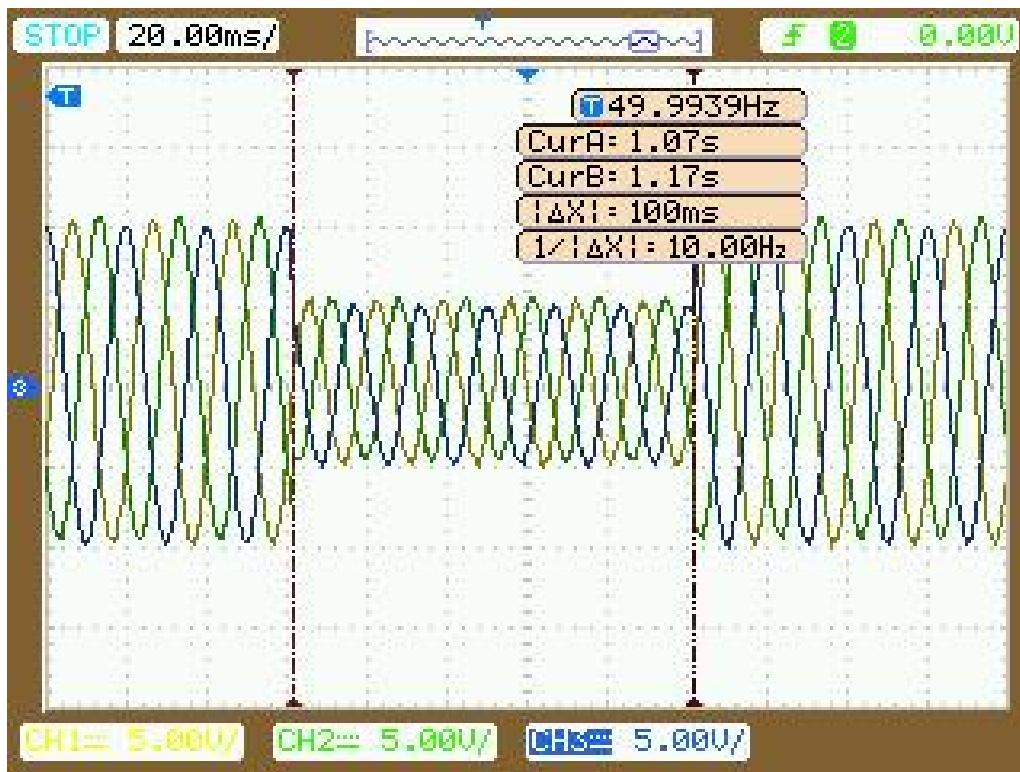


Figure 5.11: time fault for 0.1 s Voltage: 5 V Frequency : 60 Hz

- The voltage may be changed in one, two or all the three phases of the AC grid see figure 5.12
- The situation where the voltage can go to zero is shown in figure 5.13 where all the voltages 0V

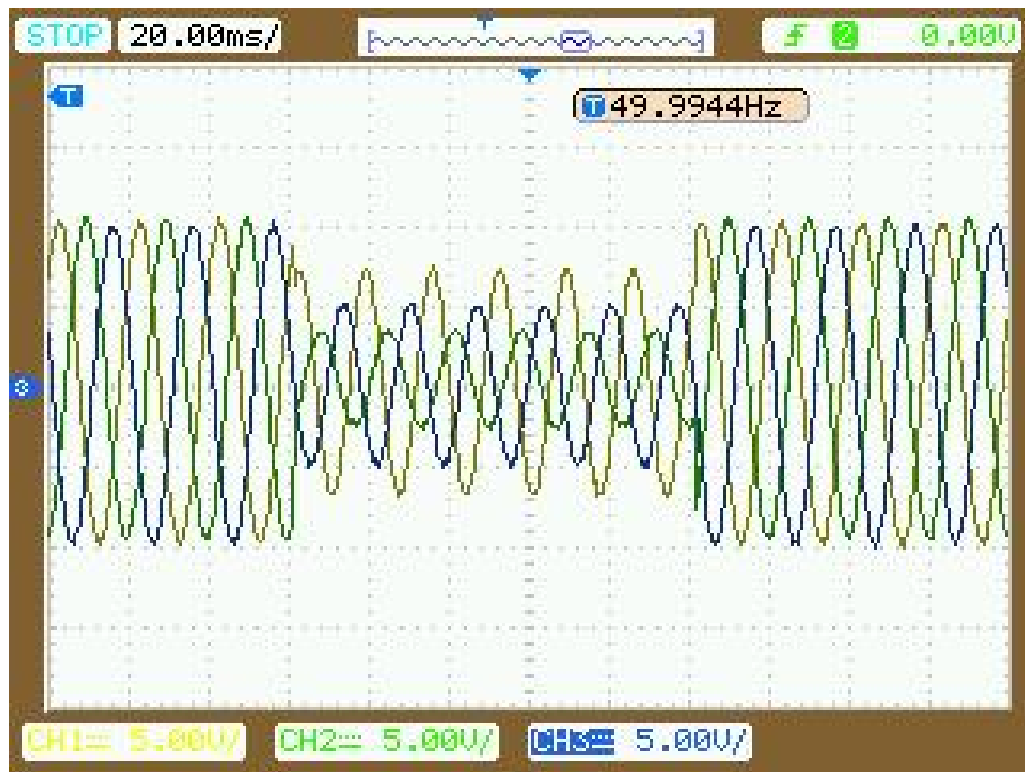


Figure 5.12: time fault for 0.1s Amplitude phase 1 :7 V

Amplitude phase 2 :3 V

Amplitude phase 3 :5 V

Frequency 60 Hz

- In these simulations we are also able to represent fault for a very short time like 0.01s as shown in figure 5.14

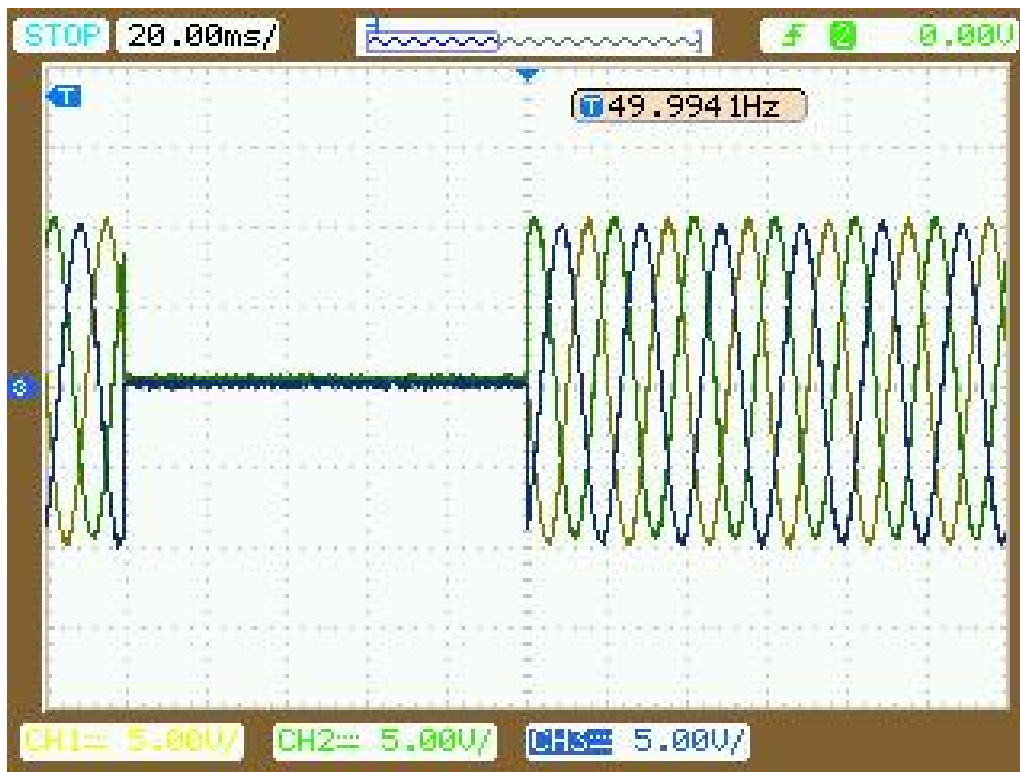


Figure 5.13: time fault for 0.1 s Voltage: 0V Frequency : 60 Hz

- There are situation where only the frequency can change as shown in figure 5.15

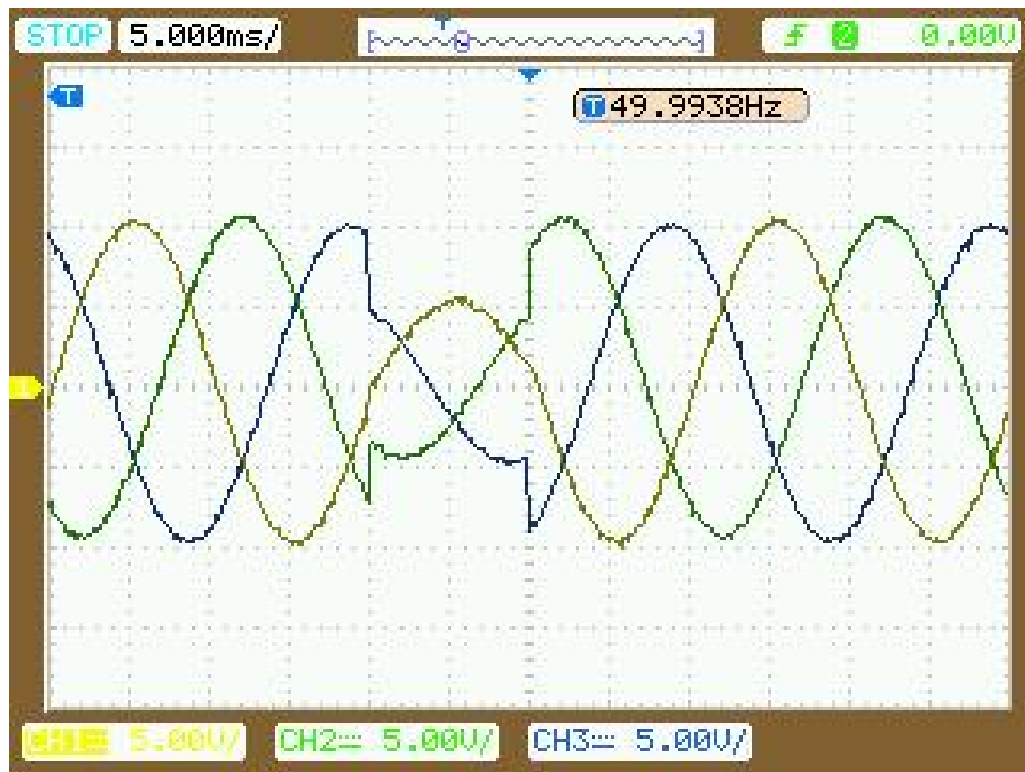


Figure 5.14: time fault for 0.01s : Amplitude 5 V for all sinusoid  
Frequency with normal value 50 Hz

### 5.2.3 Loss of mains protection : Vector Shift and RoCoF

Loss of Mains protection (LOM) is the requirement for the connection of Generation to the UK distribution network. his rule is to prevent the generator from accidentally energizing an electrically isolated section of network. Such requirements are derived from Statutory Regulations, and the method of achieving it are described in 'EREC G83' which require that the SSEGs which generate on more than one phase then the loss of mains protection should be able to detect the loss of a single phase of the supply network.

1. disconnect the generator if RoCof is greater or equal to 0.2 Hz/s or the vector shift is greater or equal to 12 degree . in figure 5.16 we have represent a Vector Shift of 12 degree on
2. the generator should remain connected during each and every test.
  - RoCoF 0.19 Hz per second from 49.5 Hz to 51.5 Hz (see figure 5.17 )

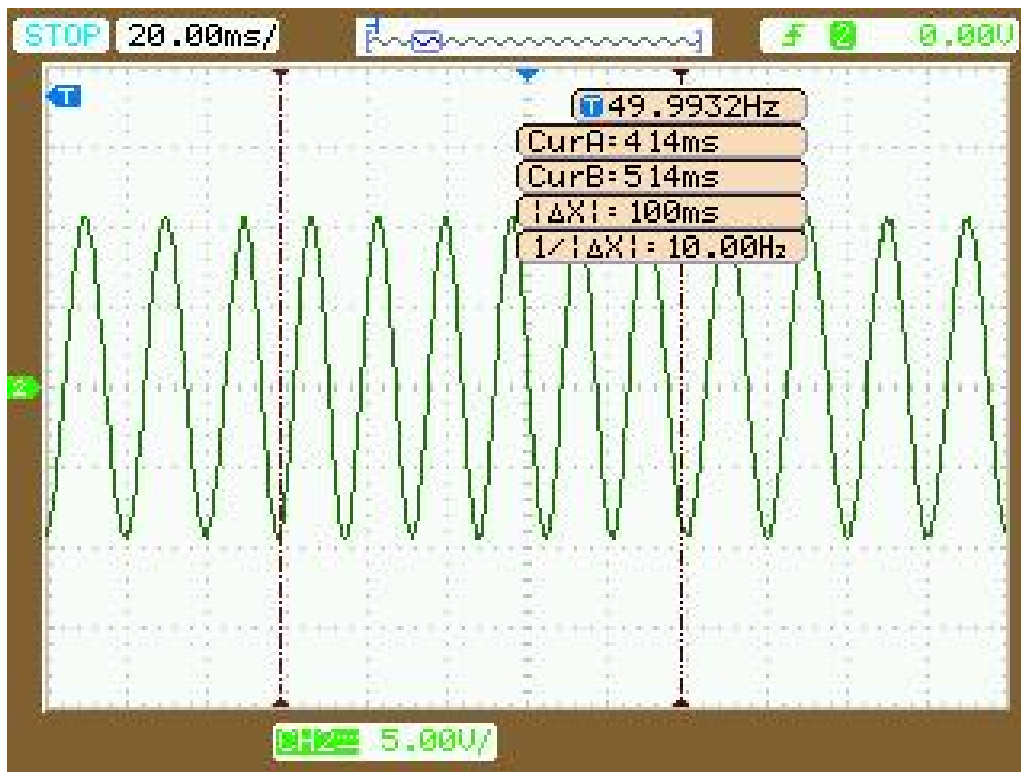


Figure 5.15: Channel 1 : time fault = 0.1s : Voltage :10 V(Normal value)  
Frequency: 60 Hz Fault

and from 50.5 Hz to 47.5Hz

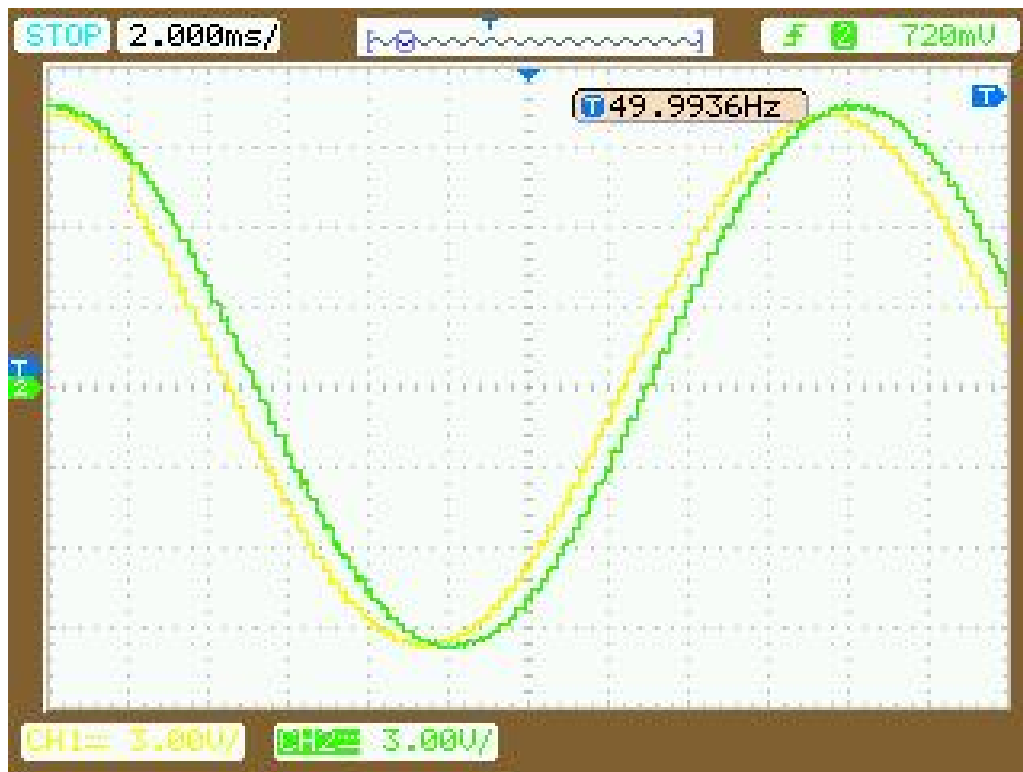


Figure 5.16: Vector Shift of 12 degree on Phase 1 : single

- Vector shift 9 degree plus from 49.5 Hz and 9 degrees minus from 50.5 Hz

The change in the generator/grid system during the time required by the grid code can be detected by a

1. Rate of Change Of Frequency (ROCOF) relay which detects a change of frequency over time i.e. if frequency keeps changing for several time periods the relay will operate to open the generator breaker and enforce a controlled re-synchronisation procedure
2. and vector shift relay This relay will trip the breaker in case it detects a phase shift in the generator voltage.

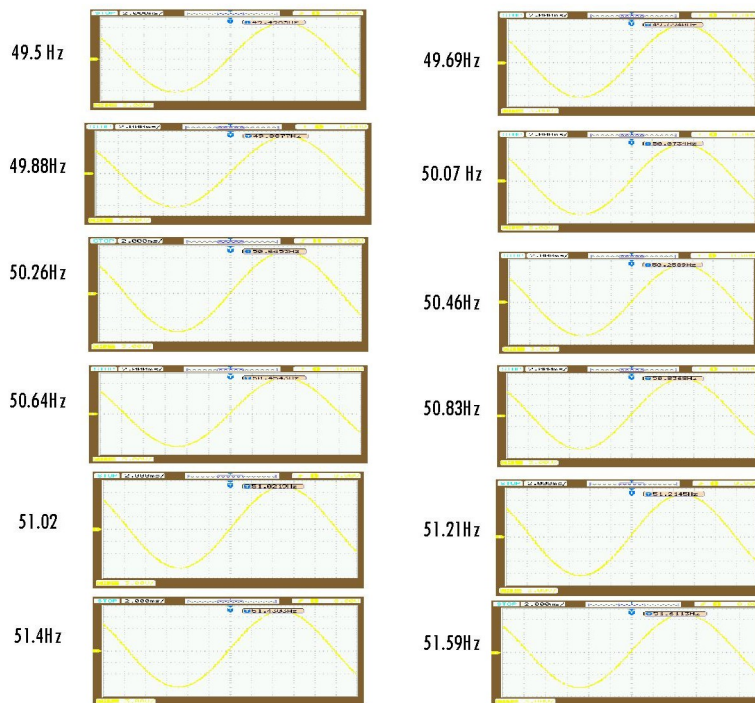


Figure 5.17: RoCoF of 0.19 Hz/s from 49.5 to 51.5



# Conclusion

The main objective of this project has been to simulate the three-phase grid voltages behavior. To achieve this work we have programmed a DSP which does many tasks as : control which frequency and voltages to use ,reads the values of the positions of the pointers in the look up table ,calculates the three values of the sine to send to the DAC and updates the pointers, interacts also with the User interface create on LABVIEW where the user can : change the values of frequency or voltages ; implements some time-fault and also the vector shift and the RoCoF.

The resolution on the frequency and on the voltage obtained are useful to test the requirements set by the 'G83' on measuring with an accuracy the nominal value of voltage and frequency.

The simulation of Time-fault provided can be used to control if the requirements on the disconnection time of the turbines from the grid when the values of voltages and frequency are outside of the limits are met and also be helpful to control the behavior of the turbine during a fault on the grid.

The loss of mains techniques implemented will be useful to test the capacity of the vector shift relay and of the RoCof relay to be able on detect a loss of mains on a single phase as required by the 'G83'.

This simulator of the three grid voltages can also be use for another Small-Scale Embedded Generators (SSEGs) like : Photovoltaic Fuel Cells Hydro and Energy store device; as the 'G83' is a standard for all thus renewable energy generators.







# Appendix A

## Appendix

### A.1 C Code

```
/******  
* File: lab12_main.c -- Solution File for Lab 12  
* History: 09/18/02 - original (based on DSP28 header files v0.58)  
*****/  
#include "DSP28_Device.h" // Peripheral address definitions  
#include "wave.h" //  
int CalCount2;  
/*contain the value send to the channel---D*/  
long int IRT1;  
int CalRxF;  
int RSRx[11];  
/*the eleven bits where the 5 is parameter  
*and 6 and 7 is the value of the parameter*/  
int Iph1,Iph2,Iph3,Iph4;  
int CalRP;  
int CalIRefPh1;  
long int CalIRefPh1_L;  
int DutyC1,DutyC2,DutyC3;  
int Iph1_1,Iph1_2,Iph1_3;  
long int Iph1_L;  
int CalDigIn1,CalDigIn2,CalDigIn;  
int AI1,AI2,AI3,AI4,ASCB;  
int Command;  
int TxErr1;  
  
long int value_1,value_2,value_3;  
int pt_1,pt_2,pt_3, pt_Shift;  
int N_tot= 2040;  
long int F_c = 20000;//=[hz]  
double R_jump,Add_jump , N_T;  
double Freq,Voltage, Voltage_2, Voltage_3 ;  
long int time=0, N_sample =0,VectShift=0;  
int Go_Fault;  
  
int CurrentRef,CurrentRef1; // contents the value of the current sinusoide ---D  
int Change_CH,Change_CH1; // to change channel  
int Write_CH , Val_CHA ,Val_CHB,Val_CHC,Val_CHD;  
int max=2047;  
  
int CalIRefPh10;//riferimento alla sinusoide
```

```

long int pt_1cc, pt_2cc,pt_3cc, pt_1ccb, pt_2ccb, pt_3ccb,Elt_Jump ,Elt_JumpN,Elt_JumpF, Rocof=0,Var_Rocof =0,In_Rocof=0;
long int Coef_1 , Coef_2,Coef_3,Coef_1N , Coef_2N,Coef_3N,Coef_1F , Coef_2F,Coef_3F;

/* Skeleton Code Definitions */

int Cval_1,Cval_2 ,Cval_3,Cval_4, CalSR;
int One_sec=0;

/* Definitions for PC Comms */

#define cmdC1 100 // Parameter 1 Command ID (frequency)
#define cmdC2 101 // Parameter 2 Command ID (Modulation Parameter1)
#define cmdC3 102 // Parameter 3 Command ID (Modulation Parameter2)
#define cmdC4 103 // Parameter 4 Command ID (Modulation Parameter3)

#define cmdC5 104 // Parameter 1 Command ID (fault frequency)
#define cmdC6 105 // Parameter 2 Command ID (fault Modulation Parameter1)
#define cmdC7 106 // Parameter 3 Command ID (fault Modulation Parameter2)
#define cmdC8 107 // Parameter 4 Command ID (fault Modulation Parameter3)
#define cmdC9 108 // Parameter 3 Command ID (time fault)
#define cmdC10 109 // Parameter 4 Command ID (GoFaultt)
#define cmdC11 110 // Parameter 4 Command ID (VectShift) AND (ROCOF)
//#define cmdC12 111 // Parameter 4 Command ID (ROCOF)

/* Definitions for Serial DAC Control */

#define DAC_CHA 0x0000;
#define DAC_CHB 0x4000;
#define DAC_CHC 0x8000;
#define DAC_CHD 0xC000;

/*****
* Function: main()
*
* Description: Main function.
*****/
void main(void)
{
    /*** Initialization ***/
    InitSysCtrl(); // Initialize the CPU (FILE: SysCtrl.c)
    InitGpio(); // Initialize the shared GPIO pins (FILE: Gpio.c)
    InitPieVectTable(); // Initialize the PIE Vectors (FILE: PieVect.c)
    InitPieCtrl(); // Enable the PIE (FILE: PieCtrl.c)
    InitAdc(); // Initialize the ADC (FILE: Adc.c)
    InitEv(); // Initialize the Event Manager (FILE: Ev.c)
    InitSCI(); // Initialise the SCI Interface CC 28/10/03
    InitSPI(); // Initialise the SPI Interface CC 5/11/03

    /*** Enable the Watchdog interrupt ***/
    PieCtrlRegs.PIEIER1.bit.INTx8 = 1; // Enable WAKEINT (LPM/WD) in PIE group #1
    PieCtrlRegs.PIEIER5.bit.INTx1 = 1; // Enable T4 Period Interrupt
    IER |= 0x0011; // Enable INT1 & INT5 in IER to enable PIE group 1

    /*** Enable global interrupts ***/
    asm(" CLRC INTM"); // Enable global interrupts

    /*** Reset Variables: Initialise Variables HERE *****/

    Coef_1N = 1000; // for 10 v ==100 *10
    Coef_2N = 1000;
    Coef_3N = 1000;

    Elt_JumpN =5100; // <----> 50 hz
    pt_1 = 0; // pointers

```

```
pt_2 =(int)(N_tot/3);
pt_3 = 2*pt_2;

pt_1cc = 0; // pointers
pt_3cc =2040000/3;
pt_2cc = 2*pt_3cc;

Add_jump =0 ;

Change_CH = 0; //to switch channels
Change_CH1 = 0;

CalSR = 0;
CalCount2 = 0;
TxErr1 = 0;

EvaRegs.ACTRA.all = 0x0666; // Enable PWM Outputs

GpioDataRegs.GPACLEAR.bit.GPIOA15 = 1; /* DAC RESET Pulse Low */
DelayUs(10);
GpioDataRegs.GPASET.bit.GPIOA15 = 1;

/** Main Loop **/
while(1) // Dummy loop. Wait for an interrupt.
{

while (!(SciaRegs.SCIRXST.all & 0x40)); /* NEW APPROACH 29/1/04 */
{
RSRx[0] = (SciaRegs.SCIRXBUF.all)&0x00FF;

/**** 11 Byte Select Test Parameter Interface ****/

if (RSRx[0] == 11)

{
while (!(SciaRegs.SCIRXST.all & 0x40));
RSRx[1] = (SciaRegs.SCIRXBUF.all)&0x00FF;

while (!(SciaRegs.SCIRXST.all & 0x40));
RSRx[2] = (SciaRegs.SCIRXBUF.all)&0x00FF;

while (!(SciaRegs.SCIRXST.all & 0x40));
RSRx[3] = (SciaRegs.SCIRXBUF.all)&0x00FF;

while (!(SciaRegs.SCIRXST.all & 0x40));
RSRx[4] = (SciaRegs.SCIRXBUF.all)&0x00FF;

while (!(SciaRegs.SCIRXST.all & 0x40));
RSRx[5] = (SciaRegs.SCIRXBUF.all)&0x00FF;

Command = RSRx[5];

while (!(SciaRegs.SCIRXST.all & 0x40));
RSRx[6] = (SciaRegs.SCIRXBUF.all)&0x00FF;

while (!(SciaRegs.SCIRXST.all & 0x40));
RSRx[7] = (SciaRegs.SCIRXBUF.all)&0x00FF;

while (!(SciaRegs.SCIRXST.all & 0x40));
RSRx[8] = (SciaRegs.SCIRXBUF.all)&0x00FF;

Rocof = RSRx[8];
```

```

while (!(SciaRegs.SCIRXST.all & 0x40));
RSRx[9] = (SciaRegs.SCIRXBUF.all)&0x00FF;

while (!(SciaRegs.SCIRXST.all & 0x40));
RSRx[10] = (SciaRegs.SCIRXBUF.all)&0x00FF;

if (RSRx[4] == 18)
{
/* Echo command */

while (!(SciaRegs.SCICTL2.all & 0x80));
SciaRegs.SCITXBUF = RSRx[0];

while (!(SciaRegs.SCICTL2.all & 0x80));
SciaRegs.SCITXBUF = RSRx[1];

while (!(SciaRegs.SCICTL2.all & 0x80));
SciaRegs.SCITXBUF = RSRx[2];

while (!(SciaRegs.SCICTL2.all & 0x80));
SciaRegs.SCITXBUF = RSRx[3];

while (!(SciaRegs.SCICTL2.all & 0x80));
SciaRegs.SCITXBUF = RSRx[4];

while (!(SciaRegs.SCICTL2.all & 0x80));
SciaRegs.SCITXBUF = RSRx[5];

while (!(SciaRegs.SCICTL2.all & 0x80));
SciaRegs.SCITXBUF = RSRx[6];

while (!(SciaRegs.SCICTL2.all & 0x80));
SciaRegs.SCITXBUF = RSRx[7];

while (!(SciaRegs.SCICTL2.all & 0x80));
SciaRegs.SCITXBUF = RSRx[8];

while (!(SciaRegs.SCICTL2.all & 0x80));
SciaRegs.SCITXBUF = RSRx[9];
// SciaRegs.SCITXBUF = Go_Fault;

while (!(SciaRegs.SCICTL2.all & 0x80));
SciaRegs.SCITXBUF = RSRx[10];
}

else if (RSRx[4] == 30)
{
/* Status Bytes 1 sent to PC */

CalSR = CalSR + 1;

if (CalSR > 1000)
CalSR = 1000;

while (!(SciaRegs.SCICTL2.all & 0x80));
SciaRegs.SCITXBUF = CalSR/256;

while (!(SciaRegs.SCICTL2.all & 0x80));
SciaRegs.SCITXBUF = CalSR%256;
}

```



```

while (!(SciaRegs.SCICTL2.all & 0x80));
SciaRegs.SCITXBUF = 0;

while (!(SciaRegs.SCICTL2.all & 0x80));
SciaRegs.SCITXBUF = 0;

while (!(SciaRegs.SCICTL2.all & 0x80));
SciaRegs.SCITXBUF = 0;

while (!(SciaRegs.SCICTL2.all & 0x80));
SciaRegs.SCITXBUF = 0;

while (!(SciaRegs.SCICTL2.all & 0x80));
SciaRegs.SCITXBUF = 0;

while (!(SciaRegs.SCICTL2.all & 0x80));
SciaRegs.SCITXBUF = 0;

while (!(SciaRegs.SCICTL2.all & 0x80));
SciaRegs.SCITXBUF = 0;

while (!(SciaRegs.SCICTL2.all & 0x80));
SciaRegs.SCITXBUF = 0;
}

}

}

if (Command != 0)
{
    /*****/

    /* Check PC Command Paramter and store value */

    /*****/

    switch (Command)
    {
        case cmdC1:
            Elt_JumpN = RSRx[6]*256 + RSRx[7]; //external value of the frequency
            break;

        case cmdC2:
            Coef_1N = RSRx[6]*256 + RSRx[7]; //external value of the voltage
            break;

        case cmdC3:
            Coef_2N = RSRx[6]*256 + RSRx[7]; //external value of the voltage
            break;

        case cmdC4:
            Coef_3N = RSRx[6]*256 + RSRx[7]; //external value of the voltage
            break;

        // ----FAULT-----
        case cmdC5:
            Elt_JumpF = RSRx[6]*256 + RSRx[7]; //external value of the frequency
            break;

        case cmdC6:

```

```

Coef_1F = RSRx[6]*256 + RSRx[7]; //external value of the voltage
    break;

case cmdC7:
Coef_2F = RSRx[6]*256 + RSRx[7]; //external value of the voltage
    break;

case cmdC8:
Coef_3F = RSRx[6]*256 + RSRx[7]; //external value of the voltage
    break;

case cmdC9:
time = RSRx[6]*256 + RSRx[7]; //external value of the voltage

    break;

case cmdC10:
Go_Fault = RSRx[6]*256 + RSRx[7]; //external value of the voltage
    if(time!=0)
    {

N_sample = time*20000;
    }

    break;

//VectShift

case cmdC11:

VectShift =RSRx[6]*2040000/360; //256 + RSRx[7]; //external value of the voltage
Rocof = RSRx[7];
if(VectShift!=0)
{

pt_1cc = pt_1cc+ VectShift;
    pt_1 = pt_1cc/1000;
}

    break;
/* case cmdC12:

Rocof = RSRx[6]*256 + RSRx[7]; //external value of the voltage

    break;
*/
default:
    TxErrr1 = TxErrr1+1;
    break;

}

/*****/

}

}

```

```

} //end of main()

/**** end of MAIN *****/

/*****
* Function: Inner Loop Timer 4 Interrupt Service Routine every 100us
*
* Description: InnerLoop called from DefaultIsr.c
*****/
void InnerLoop(void)
{
    if(N_sample!=0)
    {
        N_sample = N_sample-100;
    }
    else
        Go_Fault =0;

    if(Rocof!=0)
    {
        Var_Rocof = Rocof;
        In_Rocof =Rocof;
        //Elt_Jump = Elt_Jump +Var_Rocof;
        One_sec =20000;
    }

    if(One_sec==0 && Rocof==0 )
    {
        Var_Rocof= Var_Rocof +In_Rocof;
        //Elt_Jump = Elt_Jump +Var_Rocof;
        One_sec =20000;
    }

    if(Go_Fault ==1)
    {
        Coef_1=Coef_1F;
        Coef_2=Coef_2F;
        Coef_3=Coef_3F;
        Elt_Jump=Elt_JumpF+Var_Rocof;
    }
    else if (Go_Fault ==0)
    {
        Coef_1=Coef_1N;
        Coef_2=Coef_2N;
        Coef_3=Coef_3N;
        Elt_Jump=Elt_JumpN+Var_Rocof;
    }

    One_sec =One_sec -1;

    if(Elt_Jump >= 6120)
    {
        //Elt_Jump=Elt_Jump - Var_Rocof;
        Var_Rocof = 0;
        In_Rocof =0;
    }

    if(pt_1>N_tot-1) //control if is the end of the array

    {
        pt_1cc= pt_1cc-1000*N_tot;
        pt_1= pt_1-N_tot;
    }

```

```

    }
    if(pt_2>N_tot-1) //control if is the end of the array

    {
        pt_2cc= pt_2cc-1000*N_tot;
        pt_2= pt_2-N_tot;

    }
    if(pt_3>N_tot-1) //control if is the end of the array

    {
        pt_3cc= pt_3cc-1000*N_tot;
        pt_3= pt_3-N_tot;

    }

    CalRP = EvaRegs.T2CNT;          // Read Encoder Rotor Position
    /*----- Fetch value from Look-Up Table ---- */
    value_1 = Coef_1*IrefPhase1[pt_1]; //take the value of the first sinusoide
    value_2 = Coef_2*IrefPhase1[pt_2]; //take the value of the second sinusoide
    value_3 = Coef_3*IrefPhase1[pt_3]; //take the value of the third sinusoide

    pt_Shift =pt_1;

    value_1 = value_1/1000;
    value_2 = value_2/1000;
    value_3 = value_3/1000;

    pt_1cc = pt_1cc + Elt_Jump ;
    pt_2cc = pt_2cc + Elt_Jump;
    pt_3cc = pt_3cc + Elt_Jump;

    pt_1ccb= pt_1cc/1000;
    pt_2ccb= pt_2cc/1000;
    pt_3ccb= pt_3cc/1000;

    pt_1 = pt_1ccb;
    pt_2 = pt_2ccb;
    pt_3 = pt_3ccb;

    // /*----- DAC Output Test Code ----- */

    GpioDataRegs.GPASET.bit.GPIOA12 = 1; /* DAC CS (July 08) */
    GpioDataRegs.GPACLEAR.bit.GPIOA14 = 1; /* LOADDAC Pulse Low */
    DelayUs(10);
    GpioDataRegs.GPASET.bit.GPIOA14 = 1;
    GpioDataRegs.GPACLEAR.bit.GPIOA12 = 1; /* DAC CS (July 08) */

    if (Change_CH1==1)
    {
        Val_CHA = 2048+value_1 ;
        Write_CH = Val_CHA|DAC_CHA;//
        GpioDataRegs.GPFCLEAR.bit.GPIOF11 = 1; // test Apr 2012
    }
    else if (Change_CH1==2)
    {
        Val_CHB = 2048+ value_2;
        Write_CH = Val_CHB|DAC_CHB;
    }

    else if (Change_CH1==3)

```

```

{
Val_CHC = 2048+ value_3;
Write_CH = Val_CHC|DAC_CHC;
}
else if (Change_CH1==4)
{
//Val_CHD = 2048+ CurrentRef;
Write_CH = CalCount2|DAC_CHD;
}

SpiaRegs.SPITXBUF = Write_CH;
CalCount2 = CalCount2+1;

if (CalCount2 > 4094)
CalCount2 = 0;

Change_CH1=Change_CH1+1;

if(Change_CH1>4)
Change_CH1=1;

Change_CH = 0;

//}

Change_CH=Change_CH+1;

/*----- Read Digital Inputs -----*/

CalDigIn1 = GpioDataRegs.GPFDAT.all;
CalDigIn1 = CalDigIn1&0x0700;
CalDigIn2 = GpioDataRegs.GPEDAT.all;
CalDigIn2 = CalDigIn2&0x002;
CalDigIn1 = CalDigIn1>>7;
CalDigIn2 = CalDigIn2>>1;
CalDigIn = CalDigIn1|CalDigIn2;

/*****

GpioDataRegs.GPFSET.bit.GPIOF11 = 1;

}

*****/

Function: Phase Current Sampling Interrupt Subroutine (every 50us)

This routine stores the ADC samples of all 4 phase current sensors and
all 4 back panel analog inputs into the appropriate location

Description: Called from ADC ISR

*****/
void IphSample(void)
{

static volatile Uint16 GPIOF14_count = 0; // Counter for pin toggle

GpioDataRegs.GPFCLEAR.bit.GPIOF12 = 1; // test Apr 2012

PieCtrlRegs.PIEACK.all = PIEACK_GROUP1; // Must acknowledge the PIE group

/**/ Manage the ADC registers **/
AdcRegs.ADCTRL2.bit.RST_SEQ1 = 1; // Reset SEQ1 to CONV00 state
AdcRegs.ADCST.bit.INT_SEQ1_CLR = 1; // Clear ADC SEQ1 interrupt flag

```

```

/** Read the ADC results */

    if (ASCB == 1)
    {
Iph1 = AdcRegs.ADCRESULT0 >> 4; // Read the result
Iph1 = Iph1 - 40;           // remove offset
Iph2 = AdcRegs.ADCRESULT1 >> 4; // Read the result
Iph2 = Iph2 - 40;
Iph3 = AdcRegs.ADCRESULT2 >> 4; // Read the result
Iph3 = Iph3 - 40;
Iph4 = AdcRegs.ADCRESULT3 >> 4; // Read the result
Iph4 = Iph4 - 40;
AdcRegs.ADCCHSELSEQ1.bit.CONV00 = 2; // Convert Phase 1 CS
    AdcRegs.ADCCHSELSEQ1.bit.CONV01 = 3; // Convert Phase 2 CS
    AdcRegs.ADCCHSELSEQ1.bit.CONV02 = 4; // Convert Phase 3 CS
    AdcRegs.ADCCHSELSEQ1.bit.CONV03 = 5; // Convert Phase 4 CS
    ASCB = 2;
    }
else
{
AI1 = AdcRegs.ADCRESULT0 >> 4; // Read the result
AI1 = AI1 - 40;           // remove offset
AI2 = AdcRegs.ADCRESULT1 >> 4; // Read the result
AI2 = AI2 - 40;
AI3 = AdcRegs.ADCRESULT2 >> 4; // Read the result
AI3 = AI3 - 40;
AI4 = AdcRegs.ADCRESULT3 >> 4; // Read the result
AI4 = AI4 - 40;
AdcRegs.ADCCHSELSEQ1.bit.CONV00 = 0; // Convert Analog Input 1
    AdcRegs.ADCCHSELSEQ1.bit.CONV01 = 8; // Convert Analog Input 2
    AdcRegs.ADCCHSELSEQ1.bit.CONV02 = 1; // Convert Analog Input 3
    AdcRegs.ADCCHSELSEQ1.bit.CONV03 = 9; // Convert Analog Input 4
    ASCB = 1;
}

/** Example: Toggle GPIOF14, which is connected to the LED on the eZdsp board */
if(GPIOF14_count++ > 20000) // Toggle slowly to see the LED blink
{
// GpioDataRegs.GPFTOGGLE.bit.GPIOF14 = 1; Toggle the pin
GPIOF14_count = 0; // Reset the counter
}

GpioDataRegs.GPFSET.bit.GPIOF12 = 1; // test Apr 2012
}

/*****/

```

## A.2 Definitions

- **GAIA WIND Company** is a small wind turbines constructor 133-11kW which produces an energy yield ideally suited to farms, rural properties, businesses, and community projects In Scotland.
- **DSP** Digital Signal Processor
- **EREC G83** is a Engineering Recommendation it provides guidance on the

technical requirements for the connection of Small-Scale Embedded Generators (SSEGs) in parallel with public low-voltage distribution network.





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